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A STUDY OF THE CIRCULATION IN BAY OF ILHA GRANDE AND BAY OF SEPETIBA*

PART I. A SURVEY OF THE CIRCULATION BASED ON EXPERIMENTAL FIELD DATA

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Synopsis

A discussion of the tidal, wind-driven, and density-driven aspects of the circulation in Bay of Ilha Grande and Bay of Sepetiba (Brazil), based on historical data and hydrographic and current meter data collected in September of 1977, is presented in this paper. The data analysis has shown a remarkable contrast between the circulations of these two adjacent Bays. The circulation in Bay of Sepetiba is strongly tidal, whereas Bay of Ilha Grande has a weak tidal circulation superimposed by a quasi-steady flow induced by density gradients. The stratification is maintained because Bay of Ilha Grande, beeing deeper, allows colder and saltier shelf water to flow eastward towards the fresher and warmer water flowing out of Bay of Sepetiba, highly influenced by river runoff. The velocity and density fields have shown seiche oscillations that agree very well with theoretically derived modes inherent to the local geometry and density stratification.

Introduction

Bay of Ilha Grande consists of two bodies of water separated by a constriction formed between the continent and an island, Ilha Grande (Fig. 1).

Hydrographic data collected in the past years by various investigators have indicated that the combination of Bay of Ilha Grande and Bay of Sepetiba, an estuarine body of water connected to Bay of Ilha Grande on its eastern side, which provides most of the fresh water to the region, forms a partially mixed estuarine system.

The circulation within such systems is known to be of both tidal and non-tidal origin. Extensive research in the past few decades has focused upon gravitational convection, which is one aspect of the non-tidal portion. This quasi-steady motion is a distinctive property of estuaries arising from the combined effects of river and ocean water density differences and tidal mixing.

Superimposed upon the gravitational convection, there are tidal oscillations and wind-driven motions. There is reason to believe that all these driving mechanisms are important in Bay of Ilha Grande. A quasi-steady clockwise circulation around Ilha Grande, with reported durations far larger than tidal periods, has been observed on many occasions (Ikeda 1977, and by the author in a survey taken in September 1977).

In this clockwise non-tidal flow, salty shelf water would eventually enter the Bay through its western opening to the ocean, circulate around the island, probably mix with fresher water on the eastern side provided by the outflow of Bay of Sepetiba and finally work its way out to the ocean through the eastern opening. This non-tidal behaviour suggests that the circulation in the Bay might be driven by forces other than tidal. Experimental evidence shows that at least part of the non-tidal circulation might be controlled by the wind stress, but even in the absence of wind the same non-tidal pattern has been observed.

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Hydrographic data

In the September 1977 survey, time series of temperature and salinity were taken by means of hourly hydrocasts in sites L, B and C, from which the density time series were computed. These results will be discussed later.

Besides the field work undertaken in September 1977, a few more sources of hydrographic data are available. Four oceanographic cruises, one for each season of 1970, were undertaken by the Instituto Oceanográfico da Universidade de São Paulo in the shelf region off the coast of Rio de Janeiro. Seven stations fall within the limits of the open boundaries adopted for the region to be studied, four along western ocean boundary and three along the eastern one. The location of these stations are shown in Figure 1 by means of blank squares. On the western side only two squares were plotted because there are two stations with coincidental positions.

Figure 2 shows sigma-T vertical profiles for the stations near the western opening. They show an upper 15-meter layer where a seasonal pycnocline starts to develop in the spring with gradients increasing towards the summer months. The lower layers below 15-meter depths, however, are remarkably isopycnal with a sigma-T value fairly close to 26.00. The T-S relationship for this water indicates that it has characteristics of South Atlantic Central Water usually found much deeper (around 200-meter depth) on the shelf edge of the region. Although the mechanisms by which South Atlantic Central Water finds its way into these shallow areas remains to be proven, some mechanisms involving the dynamics of the Brazil Current and upwelling off the coast of Cabo Frio (Cabo Frio lies to the east of Bay of Ilha Grande and it is not shown in Figure 1) were suggested by Signorini (1978).

A T-S diagram for the combined time series from sites B, L and C is shown in Figure 3. For temperatures greater than 20°C, which correspond to depths shallower than 15 meters, the data points for site L, which is on the western side of the Bay, indicate significantly higher salinities than the data points for sites B and C. The salinity at site B is influenced by the fresher water outflow from Bay of Sepetiba and has a somewhat lower salinity than site C (at the constriction).

For the data points with temperatures less than 20°C, corresponding to depths higher than 15 meters, the three sites show almost identical T-S behaviour, an indication of horizontal homogeneity for this water mass which is likely to derive from the mixing of the South Atlantic Central Water anomalously located on the shelf and coastal water.

Figure 4 contains a 25-hour sigma-T time series for site B (eastern side), the surface tidal elevation prediction computed from data collected nearby, and the 25-hour sigma-T series for site L (western side). The inclusion of the tidal signal is to show that the 5 to 10 meter oscillation in the pycnocline at site B could not be a result of contamination of the record due to the barotropic tides which span only a meter in amplitude. However, based on these short time measurements alone it is almost impossible to derive any conclusions about the nature of these internal oscillations.

Figure 5 shows the sigma-T time series at site C for 9 hours of observations. Again, internal oscillations with amplitudes near 5 meters are present. At this site the period of the oscillations seems to be close to 6 hours. It will be shown in the next section that current oscillations with the same period were observed on the same site in August 1975 and September 1977.

The density time series of Figures 4 and 5 are useful to illustrate internal motions in the density field but it is also important to estimate the density differences between the three sites in order to investigate the possibility of density gradients that could favor the existance of density driven flows.

Since the observations on the three sites were not simultaneous and the time series for site C is only 9 hours long as opposed to 25 hours for sites L and B, the density time series were time averaged in order to produce a single vertical density profile for each site (Fig. 6).

These mean density profiles were then used to compute the integrated pressure from the surface down to 20-meter depth and, from the pressure differences between sites, the pressure gradients were finally computed. The mean density

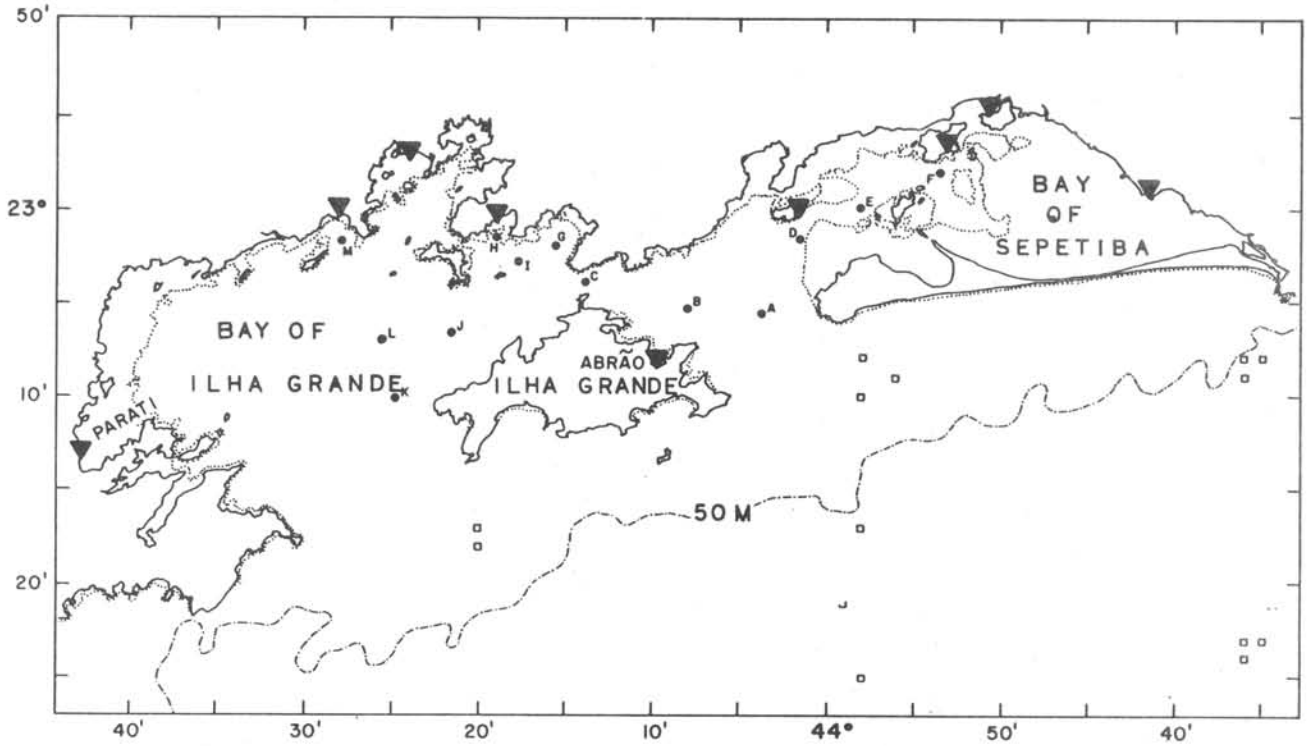

Fig. 1. Map of Bay of Ilha Grande and Bay of Sepetiba. The black triangles indicate the positions of tide gauges, the black circles are the positions of current meter stations, and the blank squares indicate hydrographic stations.

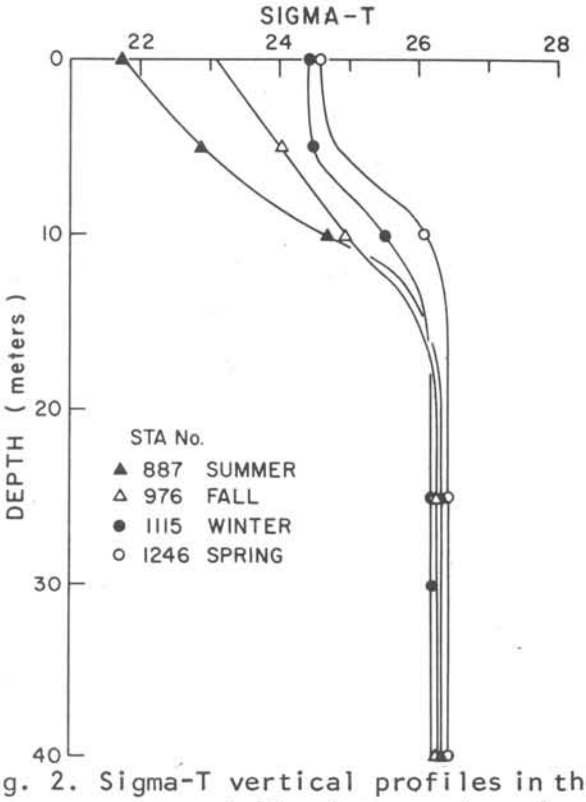

Fig. 2. Sigma-T vertical profiles in the summer, fall winter and spring from hydrographic data collected near the western opening of Bay of Ilha Grande.

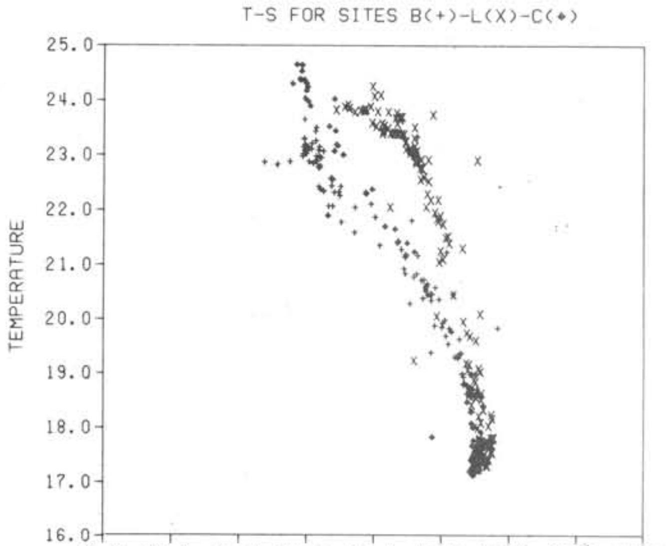

Fig. 3. Combined T-S plot for sites B, L and C containing data collected during a period of 25 hours on each site every hour.

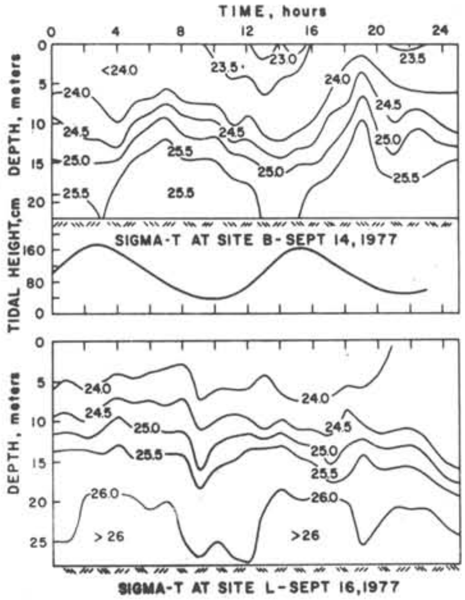

Fig. 4. Combined plot of the 25-hour Sigma-T vertical profile time series for sites B and L and the surface tidal signal from data of a tide gauge nearby.

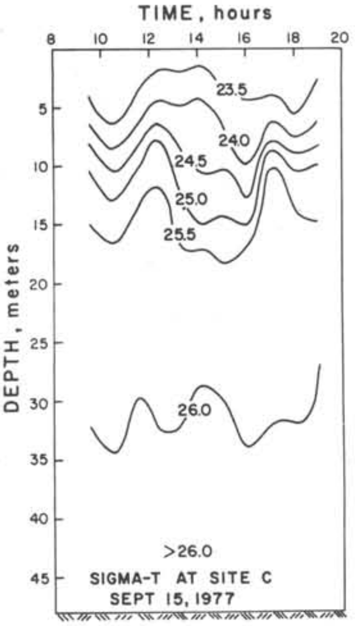

Fig. 5. 9-hour Sigma-T vertical profile time series for site C.

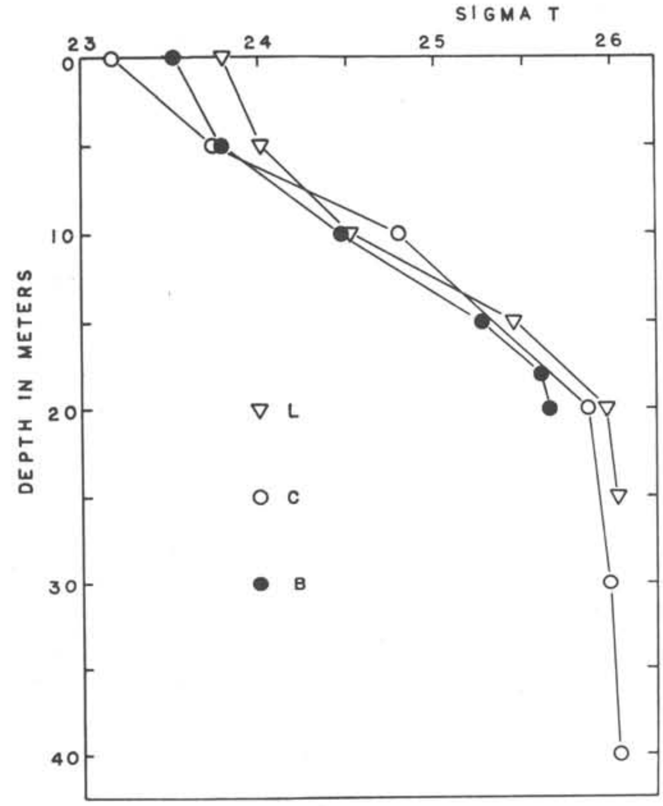

Fig. 6. Time averaged Sigma-T vertical profiles for sites L, C and B from data collected in September 1977. The series is 25 hours long for sites L and B, but only 9 hours long for site C.

stratification and the corresponding pressure gradients are shown in Table I.

The pressure gradient between sites L and C shows little variation with depth and it is always positive (or eastward), favoring a clockwise density driven flow around Ilha Grande. On the other hand, the pressure gradient between sites C and B shows more variation with depth and the values are negative (westward) at the surface and 5 meters and positive (eastward) at 10 and 20 meters. The negative values of the pressure gradient in the top 10 meters could be related to the fact that near site B the surface density changes occur much faster than the other two sites due to the strong alternating tidal flow mixing fresher surface water from Bay of Sepetiba with ocean water from the shelf region and the fact of the data was not simultaneously collected could reflect more on the computation of the pressure gradients between sites C and B than sites L and C.

The available current meter data have shown no indication of a non-tidal two-layer flow through the channel between the two Bays and therefore it seems unlikely that any opposing gradients, due to a possible free-surface slope, would be competing with the pressure gradients due to the density stratification favoring the eastward flow through the channel.

Another source of information about the horizontal distribution of density in Bay of Ilha Grande comes from temperature and salinity survey made by Miranda *et al.* (1977) in June 21 of 1975. They employed a continuous temperature and salinity recorder which allows a quick coverage of large areas since the data collection is done with the ship under way. The result is a very synoptic view of the salinity and temperature distributions in the area. Their survey of the entire region of Bay of Ilha Grande took only 12 hours.

The surface distribution of sigma-T, computed from their salinity and temperature continuous records, is shown in Figure 7. The horizontal density gradients in Bay of Ilha Grande are positive in the eastward direction, favoring a clockwise density flow around Ilha Grande. The influence of the fresher water runoff from Bay of Sepetiba is indicated by the low density tongue near the eastern ocean boundary.

Current and wind measurements

Wind and current observations collected in 1975 were kindly made available to the author by the Hydrographic Office of the Brazilian Navy (Diretoria de Hidrografia e Navegação). The observations were made at 13 sites scattered throughout the Bay. These are labeled A through M in

Table I - Mean density stratification and pressure gradients between sites L, C and B

	MEAN DENSITY (σt)			PRESSURE (10^5 dynes/cm^2)			PRESSURE GRADIENT (10^{-5} cm/s^2)	
DEPTH (m)	SITE L	SITE C	SITE B	SITE L	SITE C	SITE B	L - C	C - B
0	23.802	23.172	23.524					
				5.0171	5.0149	5.0159	10.1	-9.0
5	24.011	23.736	23.779					
				10.0360	10.0338	10.0341	10.1	-2.5
10	24.517	24.792	24.467					
				15.0584	15.0566	15.0559	8.3	6.4
15	25.442	25.333	25.262					
				20.0844	20.0821	20.0807	11.1	13.2
20	25.973	25.874	25.647					

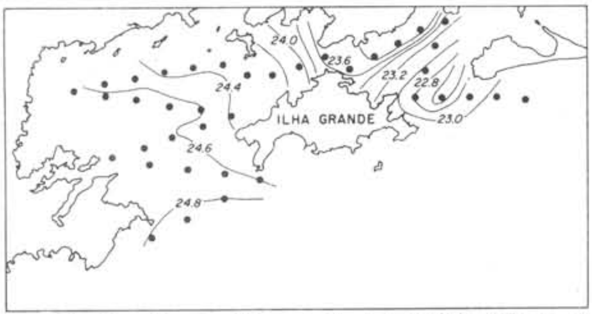

Fig. 7. Surface Sigma-T distribution derived from a thermosalinograph data. The dots represent the data points along the ship's track used to draw the density distribution (Adapted from Miranda *et al.*, 1977).

Figure 1.

A statistical monthly distribution of wind force and direction, as well as some current observations inside Bay of Sepetiba, were made available by the Instituto Nacional de Pesquisas Hidroviārias (INPH, 1977 *a*, *b*).

In addition, in September 1977 a field work was undertaken on board the University of São Paulo R/V "Prof. W. Besnard" in order to gather further information on tides, currents, winds and the hydrography of the region. The ship was moored for 25 hours at sites L and B and on-deck readings were taken at intervals of 30 minutes for the wind speed and direction, and intervals of 15 minutes for the current speed and direction.

A current meter was also moored at a depth of 25 meters in site C for a period of 4 days (see Fig. 1 for location of sites).

Figure 8 shows the longest time series available for the region taken at site C in August 1975 (located at the center of the passage between the island and the continent). The wind and currents are divided into two components, the x component being along the longest dimension of the Bay (061.7° clockwise from the true north) positive eastward, and the y component normal to it and positive northward (331.7° clockwise from the true north). This coordinate system will be used throughout this study.

The current velocity series in Figure 8 is about 12 days long with a sampling interval of one hour. A simple visual inspection of the current signal shows that high frequency, small amplitude oscillations, appear to be superimposed upon a much stronger low frequency signal with periods greater than one day

There is a 5 to 6 day oscillation in the beginning of the record, both at the surface and at 10 meters, which apparently does not correlate with any of the wind velocity components. This is a feature that still remains to be explained.

In order to further investigate the nature of the current signal, the power spectrum of the U and V velocity components at the surface was computed. These are shown in Figures 9*a* and 9*b*. The Fast Fourier Transform algorithm was used and the time series that originated the spectrum had 256 data points with a sampling interval of one hour.

The spectrum shows high energy density at the lower frequency range (red spectrum) and this can be explained by the fact that the energy has been leaked out of the low frequency oscillations that appeared on the record for only one or two periods. In order to resolve the low frequency signal the series should have been at least ten times longer.

However, it seems that the high frequency content of the record has

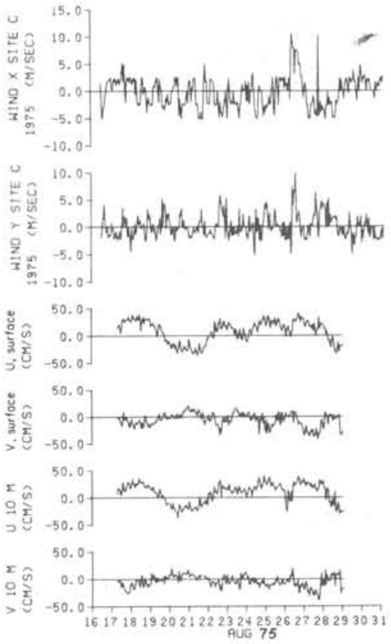

Fig. 8. Composite plot of the x and y components of the wind, U and V components of the current at the surface and 10-meter depth for site C.

enough frequency resolution so that a significant peak appears at a period of six hours. The 80% confidence interval is indicated by vertical bar in Figure 9.

The two tick marks on the upper side of the frequency axis correspond to the semi-diurnal tide period (12.42 hours) and the inertial period for the latitude of the Bay (30.7 hours). There is no peak at the semi-diurnal tide period. This suggests that the semi-diurnal tide is not significant in the flow near site C.

In an attempt to determine a possible low frequency correlation between wind and currents the time series of Figure 8 was low pass filtered with a cutoff frequency of approximately 9 hours. The low passed time series of wind and surface current are shown in Figure 10. There is no indication of any correlation between the local wind and the current at site C and an explanation for the existance of the 2 to 5 day oscillations on the U velocity record still remains to be seen. The mean flow is eastward averaging 10 cm/s.

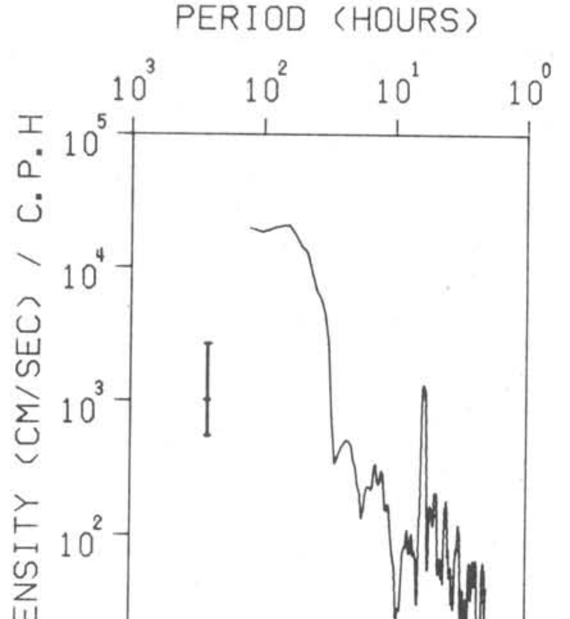

Fig. 9*a*. Power spectrum density plot for the surface U component of the current at site C from 12 days of data collected in August 1975. The vertical bar indicates the 80% confidence interval.

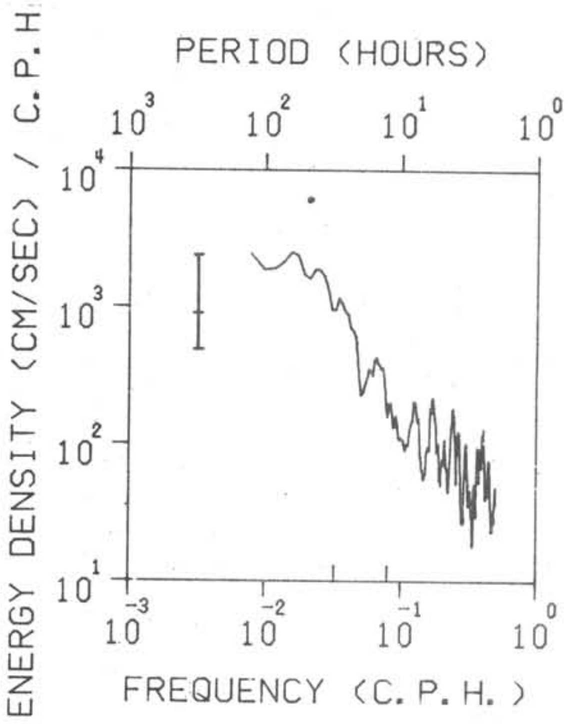

Fig. 9*b*. Power spectrum density plot for the surface V component of the current at site C from 12 days of data collected in August 1975. The vertical bar indicates the 80% confidence interval.

Figure 11 shows the U and V components of the current at 25 meters in site C from data generated two years later (September 1977) by a moored current meter for a period of four days. The average current is southeastward with a magnitude of 3 cm/s, but significant oscillations are superimposed upon this mean flow. The power spectrum for this record was computed following the same procedure used before. The time series consisted of 259 data points with a sampling interval of 20 minutes. The power spectra is shown in Figures 12a and 12b. Again, there is no indication of the semi-diurnal tide but the peak at 6 hours is obviously present this time too.

In contrast to Bay of Ilha Grande, a mixed tide (semi-diurnal and quarter-diurnal) is very evident inside Bay of Sepetiba at site E (Fig. 13).

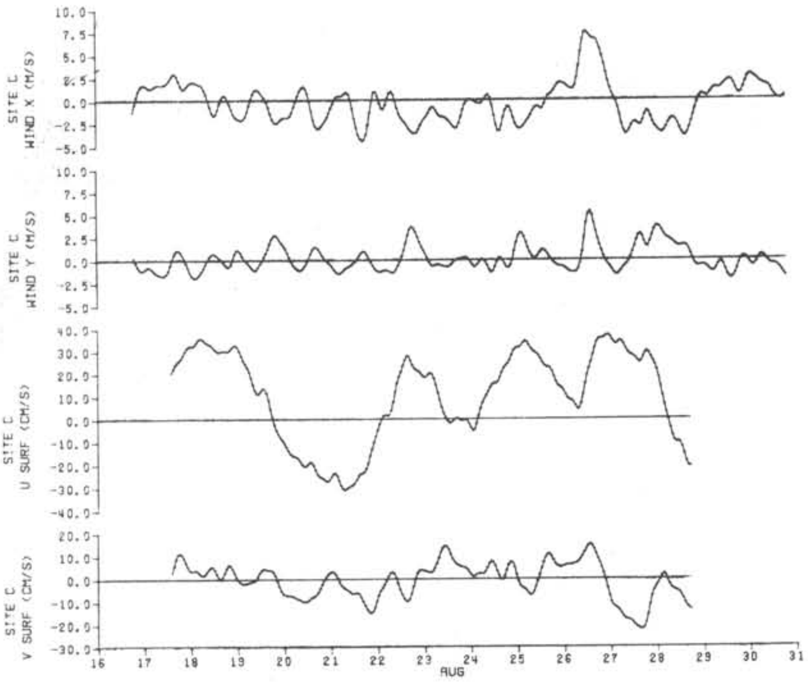

Fig. 10. Low pass filtered time series for wind and surface current at site C based on the same data showed in Fig. 8 (Part II).

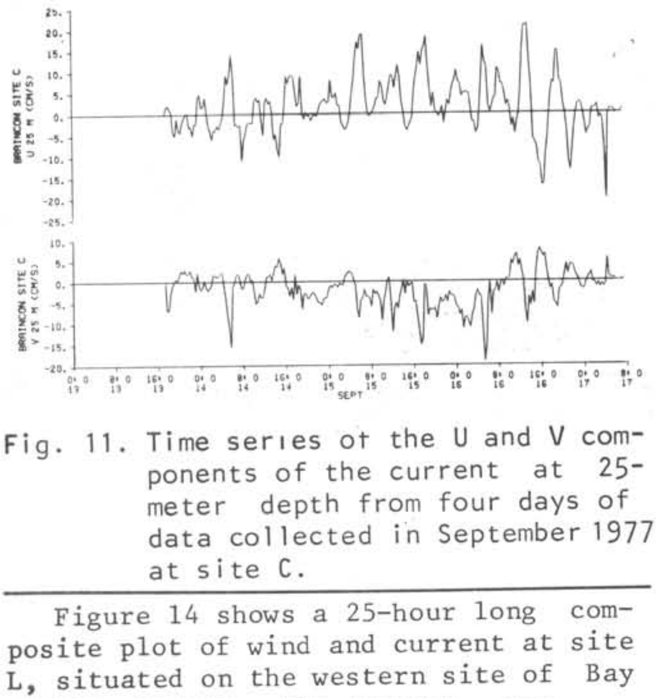

Fig. 11. Time series of the U and V components of the current at 25-meter depth from four days of data collected in September 1977 at site C.

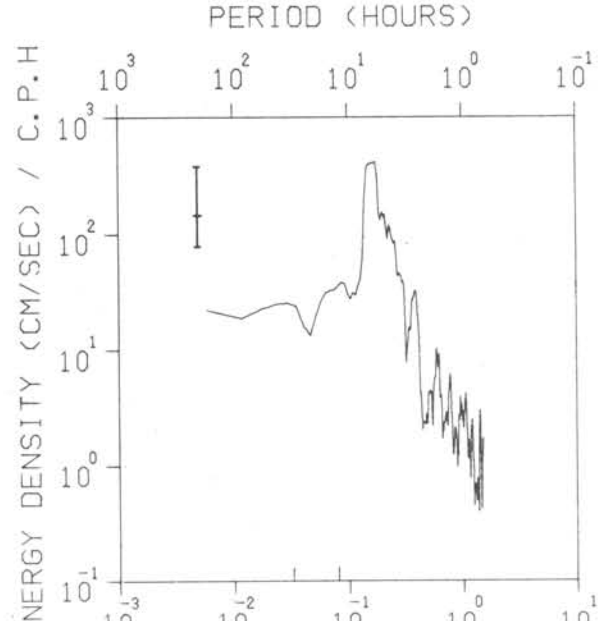

Fig. 12*a*. Power spectrum density plot for the U component of the current at 25-meter depth from four days of data collected at site C in September 1977. The vertical bar indicates the 80% confidence interval.

Figure 14 shows a 25-hour long composite plot of wind and current at site L, situated on the western site of Bay of Ilha Grande. The current was measured at 10 and 20 meters, but at 10 meters only the speed was plotted due to the fact that the current meter direction sensor was inoperative at that depth.

During the first 11 hours of this record the wind velocities were extremely weak or totally nonexistent. However, even though no noticeable wind was present, at 20 meters the water was flowing in the positive x direction at an average of 5 cm/s and at an average speed of 10 cm/s at 10 meters. The flow was

After these first 11 hours of data, the wind started to blow from the southwest in an impulsive fashion, increasing the strength of the current and, at the same time, triggered a noticeable seiche-like oscillation with a period of the order of an hour in the U component of the current velocity. This oscillation apparently died out as the wind ceased to blow.

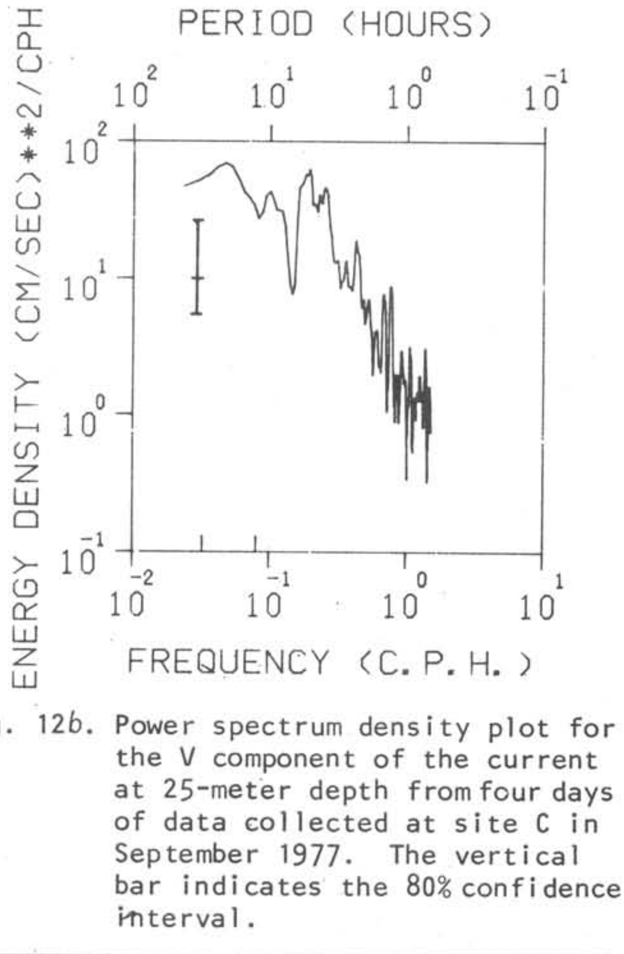

Fig. 12*b*. Power spectrum density plot for the V component of the current at 25-meter depth from four days of data collected at site C in September 1977. The vertical bar indicates the 80% confidence interval.

Figure 15 shows a 25-hour long time series of the *x* and *y* components of the wind velocity and the two components of the current at 15 meters for site B. There seems to be no apparent correlation between the local wind and the current at this site. The U velocity averages 11.5 cm/s and the V velocity -1.8 cm/s. Therefore the flow is mostly eastward, which fits the pattern discussed previously, i.e., a clockwise flow around Ilha Grande. Oscillations with periods ranging between 30 and 45 minutes are constantly present on the record.

The average wind direction frequencies near Bay of Ilha Grande, compiled from data taken by the Santa Cruz Air Force Base in the period between September 1974 and December 1975, are shown in Figure 16. The data shows two peaks, one at 50 degrees and one at 210 degrees, the latter being the most frequent average wind direction.

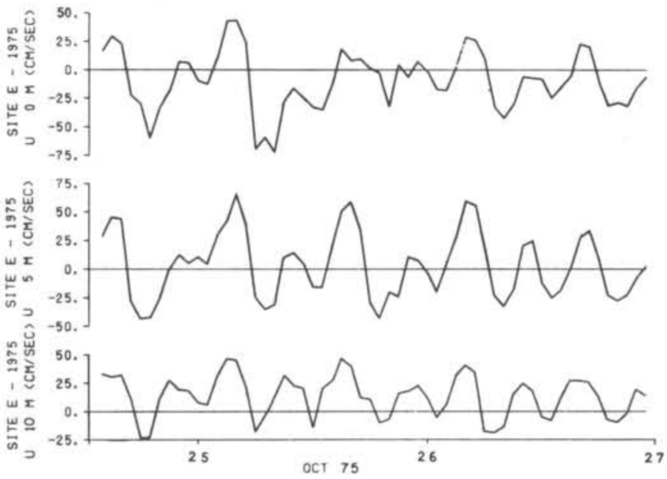

Fig. 13. Time series of the U component of the current at the surface, 5-meter and 10-meter depth for two days of data collected in October 1975 at site E.

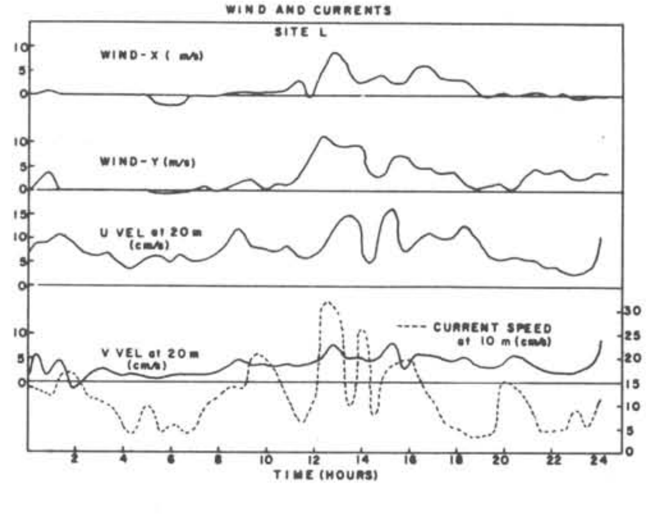

Fig. 14. Composite plot of the *x* and *y* components of the wind, U and V components of the current at 20-meter depth, and current speed at 10-mete depth (current meter direction sensor failed to work at this depth) for a 25-hour data collection in September 1977 at site L.

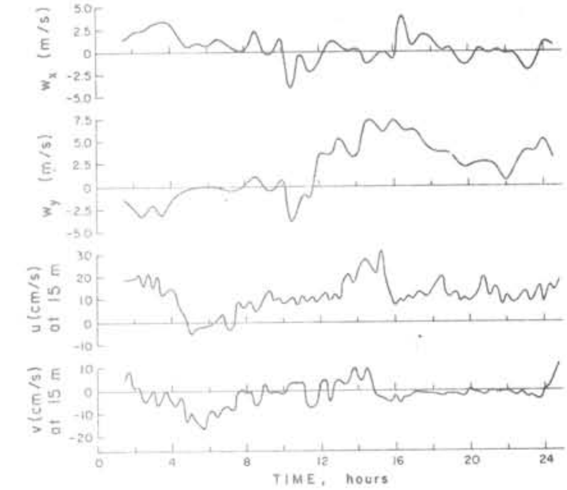

Fig. 15. Composite plot of the *x* and *y* components of the wind and U and V components of the current at 15-meter depth for a 25-hour data collection in September 1977 at site B.

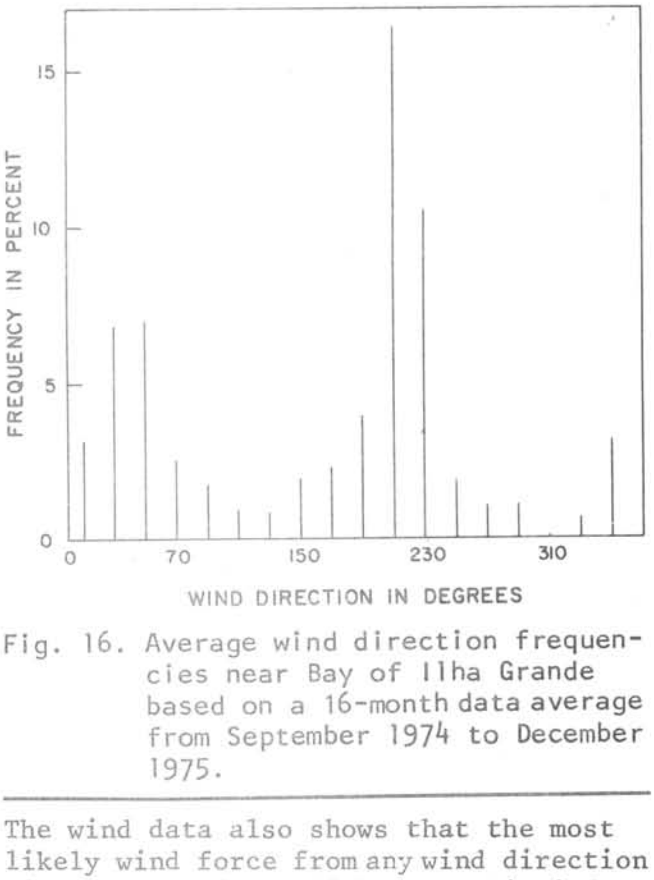

Fig. 16. Average wind direction frequencies near Bay of Ilha Grande based on a 16-month data average from September 1974 to December 1975.

The wind data also shows that the most likely wind force from any wind direction lies between 6 and 10 knots. This information will be later used in the wind driven numerical experiments which will be presented in Part II of this paper.

An overall view of one of the possible circulation patterns in Bay of Ilha Grande and Bay of Sepetiba is shown by the current roses at 5 meters depth throughout a complete tidal cycle illustrated in Figure 17. Although the current measurements were not made simultaneously, the records were long enough to select portions from each record corresponding to the same tidal amplitude. Those, shown in Figure 17, correspond very closely to spring tide. One can easily see the outstanding difference between the pattern in Bay of Ilha Grande and Bay of Sepetiba. In the former, the pattern is a quasi-steady clockwise flow around the island, whereas in the latter the flow pattern is dominated by the tides.

An unexpected source of evidence for the type of circulation just described became available in January 1978 when a major oil spill occurred in the vicinity of Ilha de São Sebastião (Fig. 18). The Brazilian news media published, based on various sightings of the spill reported by fisherman and residents all along the coast of São Paulo and Rio de Janeiro, a map containing the positions of the spill during January 10 to 18 reproduced in Figure 18. From Ilha de São Sebastião the spill followed the coastline in the northeast direction with an average velocity, judging from the successive positions on the map, of about 20 cm/s.

Once the spill reached the western opening of Bay of Ilha Grande it turned northward moving into the Bay and apparently continued to flow around Ilha Grande and out to the ocean through the eastern opening. Therefore, it seems fair to assume that the oil spill has followed the same pattern of circulation indicated by the current meter measurements.

Internal seiches

Hydrographic and current meter observations at site C have shown oscillations with a period of about 6 hours.

In an attempt to explain the nature of these oscillations, a simplified theory for an interfacial standing wave across a two-layer channel will be used (Sverdrup *et al.*, 1942, p. 600).

The density profile of Figure 2.6 for site C can be approximated by a two-layer density profile with equal layer thicknesses ($h_1 = h_2$) of the order of 20 meters, top layer density (ρ_1) of 1.0245 g/cm^3 and bottom layer density (ρ_2) of 1.0260 g/cm^3. The width of the

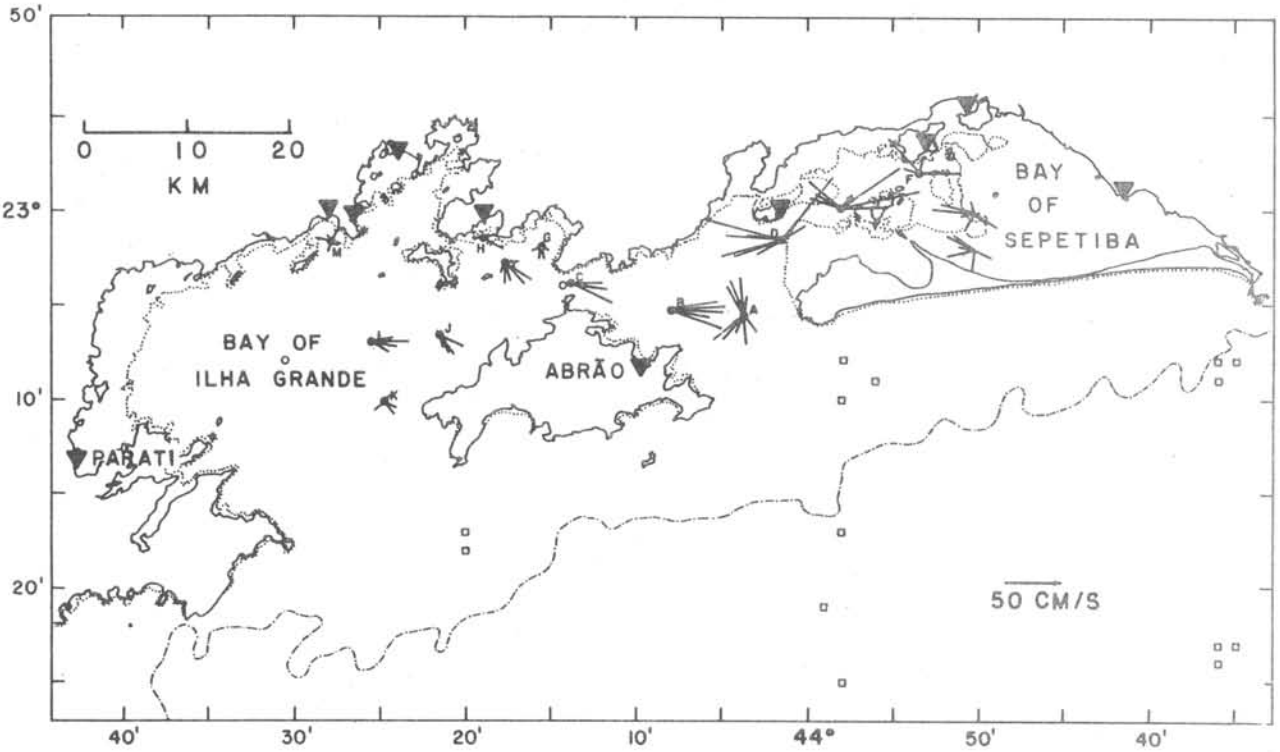

Fig. 17. Hourly current roses for Bay of Ilha Grande and Bay of Sepetiba based on current meter data collected between August 1975 and November 1975. The plot shows the variation throughout a whole tidal cycle.

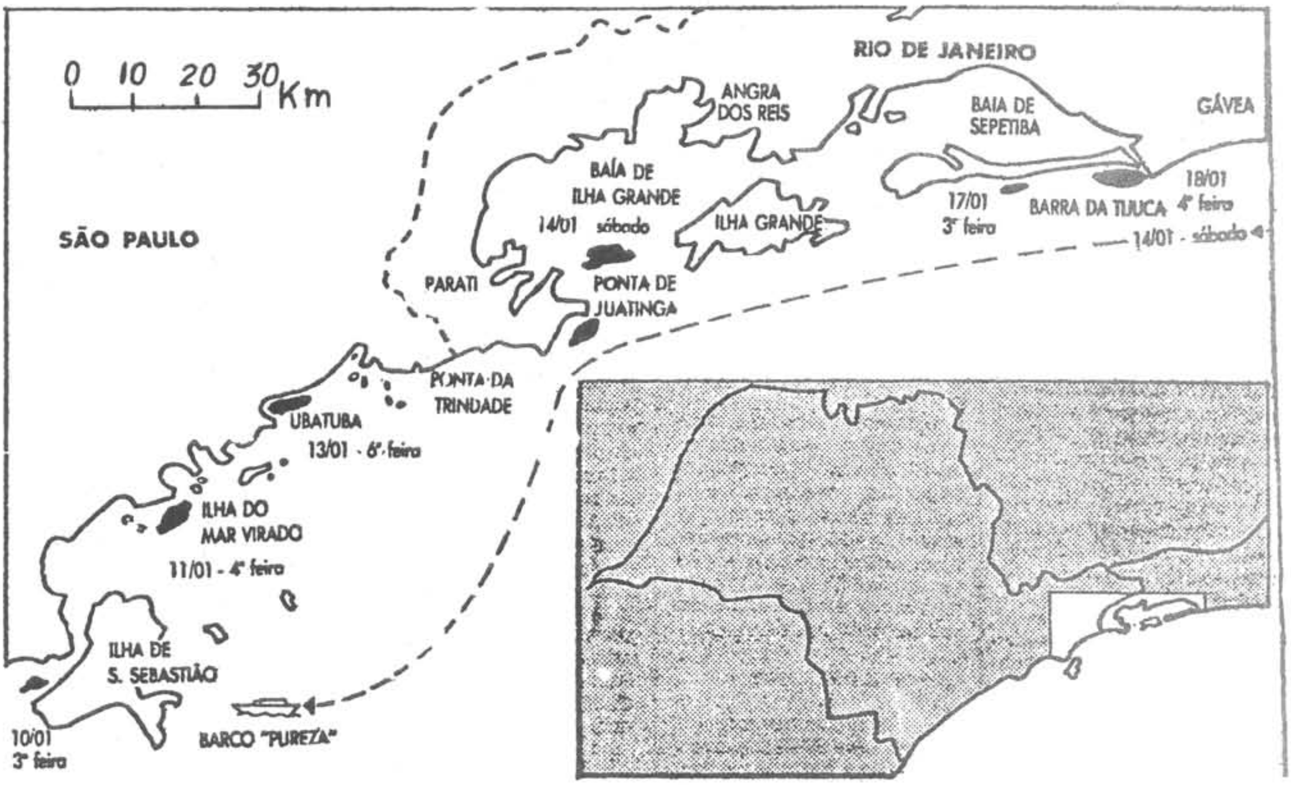

Fig. 18. Map showing the coastal region of São Paulo and Rio de Janeiro States (Brazil) with the positions assumed by the major oil slick of the January 1978 spill near Ilha de São Sebastião (lower left) (Adapted from "O Estado de São Paulo", January 19, 1978).

channel is the mean width of the passage between Ilha Grande and the continent, which is about 4 kilometers.

Since only vertical displacement is allowed at the solid boundaries, the fundamental wave will have one node at the center of the channel and one antinode at each side wall. Therefore, the wavelength λ of the fundamental standing wave across the channel will be $\lambda=2L$, where L is the width of the channel.

The period of the standing wave will be $T=\lambda/c$, where c is the phase velocity, which is given by

$$C = \left(\frac{g(\rho_2 - \rho_1)\ h_1\ h_2}{\rho_2(h_1 + h_2)}\right)^{1/2} \qquad (2.1)$$

hence, the period is finally given by,

$$T = 2L/\left\{\frac{g(\rho_2 - \rho_1)\ h_1\ h_2}{\rho_2\ (h_1 + h_2)}\right\}^{1/2} \qquad (2.2)$$

Substituting the values discussed previously into equation (2.2) one obtains a period of 5.8 hours. The period computed by means of this simplified approach seems to be very close to the period of the oscillations observed at site C and therefore it seems that internal seiches are a likely feature of the region.

Seiches in the system formed by Bay of Ilha Grande and Bay of Sepetiba

The current meter data at site C have shown oscillations with a period of about 6 hours. The period of these oscillations is many times longer than the seiche period of either Bay of Ilha Grande or Bay of Sepetiba.

In an attempt to explain this discrepancy, the problem will be treated as a coupled system of two water bodies connected by a narrow channel in the light of the theory developed by Neumann (1944), also described by Neumann & Pierson Jr. (1966, p.367-368).

Neumann's theory describes the seicheing in such systems by analogy to electrical systems. The analogy is to a network of inductances and capacitances in an electrical network, with resistances so small that they can be neglected.

The inductance and the capacitance can be connected in series or in parallel. At the resonance frequency, the circuit connected in series will have an impedance (a measure of the total opposition to current flow in an alternating-current circuit) equal to zero and a large electric current will flow across it. On the other hand, if the circuit is connected in parallel, the conductance (the reciprocal of the impedance) will be zero and a large voltage will develop across it.

By means of this analogy to electrical circuits, the impedances of a lake, a bay, and a wide channel can be shown to be, respectively

$$Z_\ell = -\frac{i\rho C_\ell}{S_\ell}\cot\left(\frac{\omega L_\ell}{C_\ell}\right)$$

$$Z_b = -\frac{i\rho C_b}{S_b}\cot\left(\omega L_b/C_b\right) \qquad (2.3)$$

$$Z_c = -\frac{i\rho C_c}{S_c}\tan\left(\omega L_c/C_c\right)$$

where the density ρ is assumed constant, S is the average cross-sectional area of the body of water, $c = \sqrt{g\ h}$ is the phase velocity, h is the water depth, and L_1, L_b and L_c the length of the respective bodies of water ($i = \sqrt{-1}$).

The impedance of the channel in (2.3), if the channel is short, can be written as

$$Z_q = \frac{i\rho C_c}{S_c}\ \frac{\omega L_c}{C_c} = \frac{i\rho\omega\ell}{q} \qquad (2.4)$$

where $S_c = q$ is the cross-sectional area of the channel, and ℓ is used to designate the channel length in this special case.

The impedances can be combined to find the frequency of oscillation of complex systems. One of these systems is the system formed by Bay of Ilha Grande and Bay of Sepetiba, connected by the relatively narrow constriction formed between Ilha Grande and the continent.

Neumann's theory is applied to many systems which combine lakes, bays and channels, but the most similar to the system under study is that of two lakes connected by a narrow channel. With subscripts 1 and 2 to designate the two lakes, the system can be considered hooked up in series. Thus

$$Z_1 + Z_q + Z_2 = \frac{C_1}{S_1} \cot \frac{\omega L_1}{C_1} + \frac{\omega \ell}{q} - \frac{C_2}{S_2} \cot \frac{\omega L_2}{C_2} = 0 \qquad (2.5)$$

which can be rewritten as

$$\frac{2\P}{T} = \omega = \frac{q}{\ell} \left(\frac{C_1}{S_1} \cot \P \frac{T_1}{T} + \frac{C_2}{S_2} \cot \P \cdot \frac{T_2}{T} \right) \qquad (2.6)$$

and

$$T_1 = \frac{2L_1}{\sqrt{gh_1}}, \quad T_2 = \frac{2L_2}{\sqrt{gh_2}}$$

(Merian's formula, due to J.R.Merian 1828)

where T_1 and T_2 are the periods of oscillation of the separate lakes and T is to be found. Equation (2.6) is a transcendental equation in T and can be solved graphically. The double lake system thus has periods of oscillation much longer than either lake alone. One lake rises in level as the other sinks. At the same time, also, the separate modes of oscillation still occur, but they have much shorter periods.

The numerical approximations for the case of Bay of Ilha Grande are:

L_1 = 25 km	L = 23 km	L_2 = 53 km
h_1 = 28 m	h = 18 m	h_2 = 14 m
b_1 = 25 km	b = 4 km	b_2 = 11 km

where b_1, b_2 and b are the breadths of the two bays and channel, respectively.

The graphic solution is shown in Figure 19. The solution for T is met when the right hand side and left hand side of equation (2.6) assume the same value. Beyond the values of T_1 = 0.86 hours and T_2 = 2.56 hours we find the long period T for the combined system with a value equal to 6.35 hours. As the theory predicted, the value of T is several times longer than the individual seiche period of the independent bays. Furthermore, the value of 6.35 hours agrees fairly well with the observed period at site C, located in the middle of the channel, as in Figure 8.

In order to establish error limits in the determination of the period of oscillation in the combined system, a simple error analysis is performed.

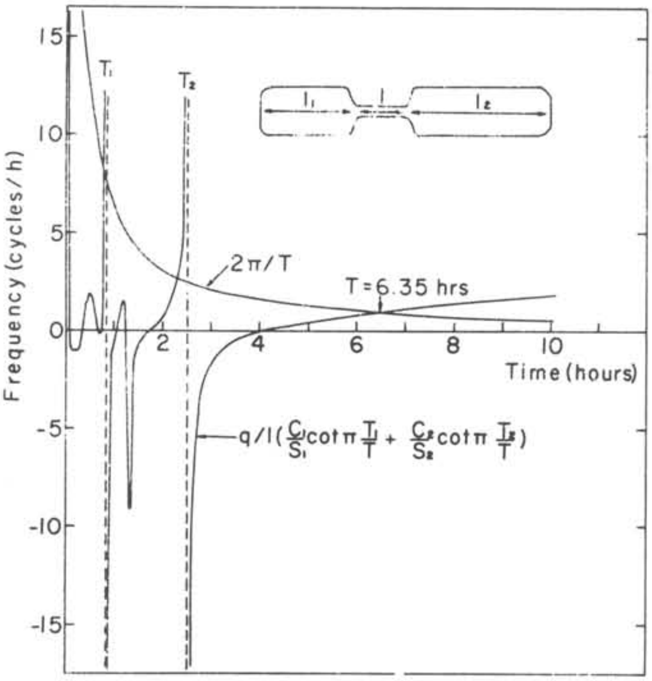

Fig. 19. Graphic solution for equation (2.6). The inset shows the geometry of the coupled system.

First, if the depths of the three bodies of water have an uncertainty of ± 10%, equation (2.6) predicts an uncertainty of ± 5.4% in T_1 and T_2 and ±0.8% in T. Thus depth error has a negligible effect on the longest period.

However, if the depths, lengths, and breadths all have an uncertainty of ±10%, the predicted uncertainty is ± 16% for T_1, T_2 and T. Thus it is estimated that the long period seiche of the combined system lies between 5.3 and 7.3 hours.

In short, the oscillations observed both on the current meter and hydrographic data were explained by a series of simple theoretical formulations. Table II summarizes the results, giving the location and depth of the observed oscillations and compares each oscillation period with its proposed theoretical prediction. The agreement seems to be very good.

Table II - Periods of oscillation derived from observational data and from theoretical estimation

SITE	LOCATION	DEPTH OF OBS (m)	PERIOD FROM DATA (hrs)	PERIOD FROM THEORY (hrs)	MODE	DATA ANALYSIS TECHNIQUE	THEORY USED
L	Bay of IG (western)	10	1. to 2.	0.9	Seiches	Direction from CM record	Merian's formula
C	Channel	Surface	6.9		Seiches in coupled system	Spectral Analysis	Neumann & Pierson Jr. (1966)
C	Channel	5	5.0	5.3 to 7.3			
C	Channel	10	6.2				
C	Channel	25	5.7				
B	Bay of IG (eastern)	15	0.5 to 1.0	0.5	Seiches	Directly from CM record	Merian's formula
C	Channel	Thermocline	5.0	5.8	Internal Seiches	Directly from Sigma-T series	Sverdrup *et al.* (1942)
B	Bay of IG (eastern)	Thermocline	12.0	12.42	Internal Tide	Directly from Sigma-T series	
E	Bay of Sepetiba	0,10,15	6.21 and 12.42	same	Tides (M2,M4)	Tide Gauge	Harmonic Analysis

Summary

Observational data has shown that the estuarine system formed by Bay of Sepetiba and Bay of Ilha Grande is partially mixed, where major driving mechanisms for the circulation were identified; tidal, wind-driven and gravitational or density driven.

The tidal portion in Bay of Ilha Grande is very weak, while the tidal signature is evident in Bay of Sepetiba where strong alternating tidal flows of 75 cm/s, with a period of 6.21 hours (M 4 tidal constituent), were measured.

There are two probably reasons for this contrast between the tidal circulation in the two Bays. Firstly, Bay of Ilha Grande is connected to the ocean by two openings at which the tidal wave arrives in phase synchronism and splits into two separate waves that enter the Bay and propagate in opposite directions, having its effects partially cancelled, especially at the reflection point (point which the two waves meet at).

Secondly, the total length of Bay of Sepetiba is very close to one quarter wavelength of the M 4 tidal constituent (6.21 hours), which could certainly have an amplifying effect on the standing tidal wave of that frequency. The length of Bay of Ilha Grande is far from the quarter wavelength of either the M 2 (12.42 hours) or the M 4 (6.21 hours) tidal constituents.

The presence of a clockwise quasi-steady flow around Ilha Grande with velocities averaging 10 cm/s was detected by current meter measurements and attributed to the density stratification as indicated by the pressure gradients computed from the hydrographic data (Table I). In this clockwise flow, salty shelf water enter Bay of Ilha Grande through its western opening to the ocean, circulate around Ilha Grande, eventually mix with fresher water on the eastern side provided by the outflow of Bay of Sepetiba and finally work its way out to the ocean through the eastern opening. In this process, salt and fresh water sources are provided in order to maintain the density stratification.

Conversely, the wind and current time series were much too short to establish a statistically significant correlation between wind and currents. However, a numerical experiment on the wind effects, based on the wind statistics discussed in "Current and wind measurements", will be offered in Part II of this paper.

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