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On the Circulation of a Coastal Channel Within the Abrolhos Coral-Reef System - Southern Bahia (1740' S), Brazil

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ABSTRACT

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The Abrolhos coral-reef system is the most important coral-reef area of the South-Atlantic Ocean, and is cut by two main channels about 20 km wide and 20 m deep. The channel closest to mainland, Canal de Sueste, has been the target of extensive hydrodynamic monitoring since January 2002, with 2 Interocean S4's recording the average current speed and direction, wave height and turbidity level every 30 minutes, 3 m above the bed, in two stations 14 km apart. The aim of this paper is to perform a first description of the current record from the two stations, trying to define the most important driving forces of the flow and its general pattern. The results show that local winds and tides, the latter presenting the highest ranges in all of the Eastern Brazilian coast, has secondary importance in explaining the observed current variability. The large scale wind field and sub-inertial flows are the most important driving mechanism of the circulation in the area, defining events of northeast- and southwest bound sub-inertial flows that have a recurrence time of about 8.8 days. Current speeds at the two stations had different magnitudes owing to the different cross-section areas. The average magnitude of the observed currents were around 20 cm.s^{-1}, tidal currents around 13 cm.s^{-1}, and the sub-inertial currents 12 cm.s^{-1} and 19 cm.s^{-1} at the two stations. Intense alongshore currents tend to impose a hydraulic barrier that limit the exchange of particles between the more turbid coastal waters and the remaining continental shelf.

ADDITIONAL INDEX WORDS: *Abrolhos, sub-inertial circulation, wind-driven currents, coastal channel*

INTRODUCTION

The Abrolhos Reef Complex is the largest and richest coral-reef system in the South Atlantic Ocean, with an approximate area of 6000 km^2. It is located at 17° 40' S, which is approximatelly the parallel where the NE trade winds (return trades) start to prevail yearround as fair weather winds (MARTIN *et al*., 1998). The associated continental shelf has an average width of 50 m, but can reach up to 200 km in front of Caravelas (Figure 1). The reef complex is shallower than 30 m (LEÃO and GINSBURG, 1997) and is cut by two main channels (≅20 km wide and 50 km long), namely Canal de Abrolhos and Canal de Sueste (Figure 1), both with a NE-SW orientation.

The region is not only important for its biodiversity, but also for its high economic potential, with prospects of large gas and oil reserves in the continental margin (in regions as shallow as 14 m). Therefore, a good comprehension of the water circulation is imperative to assess the environmental sensitivity of the coastal and offshore zones to potential oil spillings.

To date, information on the water circulation and associated water masses is restricted to LEIPE *et al.* (1999), that is based on a three-day long hydrographic survey performed in the summer of 1995. The survey was carried out at two stations located inside Canal de Abrolhos e Canal de Sueste (Figure 1), and the results indicated a strong residual flow directed to S-SW that was modulated by the tides.

The need to monitor the water and suspended-sediment circulation inside Canal de Sueste (Figure 1), to evaluate the impact of harbor dredging activities upon the nearby coral reefs, has prompted Aracruz Celulose to contract the deployment of two Interocean S4 since January 2002. The availability of this extensive data set has made possible the evaluation of how representative the study of LEIPE *et al*. (1999) is. It has also posed some important scientific questions, which we intent to address, that will be significant to any future studies in the region. These questions are related to: i) the magnitude and direction of the the prevailing currents, ii) the relative contribution of each forcing mechanism and iii) the associated time scales and their seasonality.

METHODS

The instruments were deployed at two stations, namely station #106 and #506 (in the northern and southern part of the domain, respectively Figure 1). The moorings, standing 3 m above the seabed and at an average depth of 7 m and 8 m, respectively, were set up to register currents, turbidity and water level every 30 minutes (2 minutes average with a sampling frequency of 2 Hz). The data was downloaded mostly on a week basis between January 04 2002 and July 21 2003, resulting in 548 days (# 106) and 563 days (#106) of measurements.

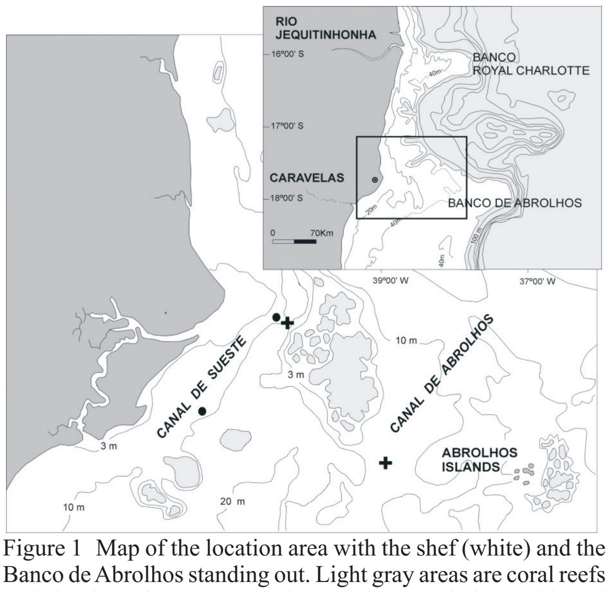

Figure 1 Map of the location area with the shef (white) and the Banco de Abrolhos standing out. Light gray areas are coral reefs and, depth are in meters. Circles (crosses) mark the position of the S4 (Leippe *et al*.) mooring sites.

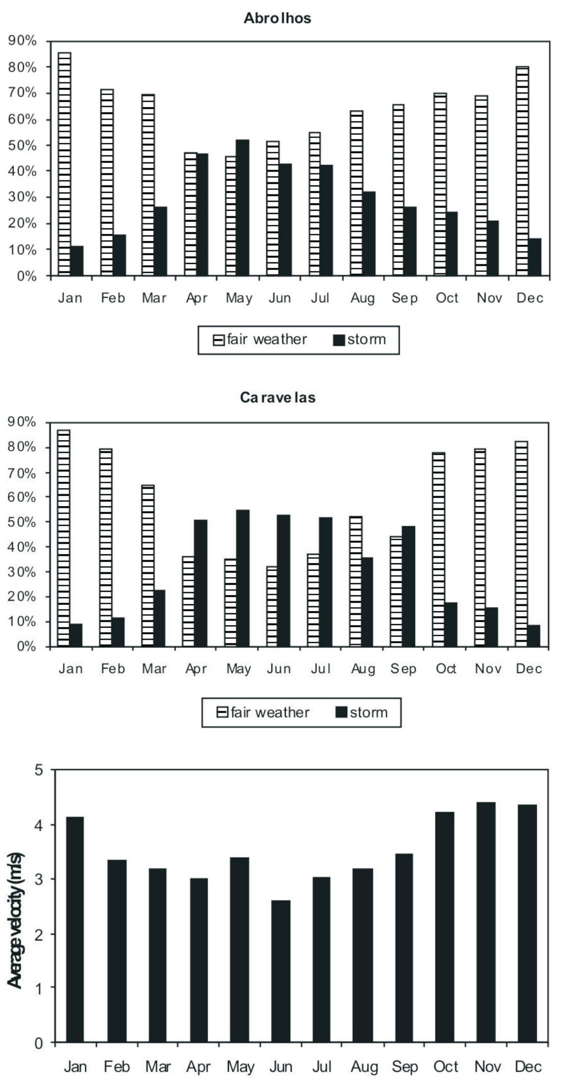

Figure 2. Frequency of occurrence of fair weather (N+NE+E) and storm winds (SE+S+SW) during the year in Abrolhos (A) and Caravelas (between Jan 2002 and Jul 2003) (B). Monthly averaged wind velocities in Caravelas (between Jan 2002 and Jul 2003) (C).

Wind speed and direction was recorded with a Campbell weather station positioned 12 km inland from the coast, at an elevation of 114 m (altitude of 45 m above ground level and varying height above the eucalyptus canopy), since January 2001. Wind speed and direction were also averaged every 0.5 hour. Wind velocities at 10 m, at the site, were calculated based on the logarithmic power law, assuming *k* equal to 0.35 and roughness length equal to 0.25 (SCHOTZ and PANOFSKY, 1980). Since the weather station was located inside an eucalyptus logging area, the variation of the canopy elevation in time was also taken into account. It is emphasized that these are not velocities 10 m above the sea surface, which would tend to be somehow higher due to smaller roughness values.

Statistics on the wind-direction frequency between 1957 and 1997 from Abrolhos (60 km offshore Figure 1), was also obtained from the Brazilian Navy. The records total 50059 data points, indicating that the data was obtained about every 3 hours.

Both current and wind data were rotated 35° clockwise in order to be orientated to the channel axis. Harmonic and spectral analysis of the currents were performed on the longest continuous time series, between January and June 2003 at station #506, totaling 7293 data points, and between December and May at station #106, totaling 6282 data points. Harmonic analysis of the sea level was performed on a 11223 data long time series, from November 2002 to July 2003. To evaluate the influence of sub-inertial frequencies (the inertial period for the region is 39 h), a low-pass filter with cut-off at 72 h was adopted in all the analyses.

RESULTS

Winds

The long-term wind record from Abrolhos was included to provide information on the wind climate in the area. The data shows that the most frequent wind directions are the NE (30% of occurrence), E (24% of occurrence), SE and S (14% of occurrence) and N (12% of occurrence). N, NE and E winds (fair weather winds) are characteristic in summer (Figure 2a), occurring for more than 69% of the time between October and March (maximum occurrence of 85% in January). SE, S and SW winds (storm winds) prevail during the autumn and the beginning of winter, occurring for more than 42% of the time between April and July (maximum of 52% in May).

Wind directions in Caravelas had the same seasonality (Figure 2b) but were slightly rotated to the north relative to Abrolhos. Fair-weather wind directions prevailed between October and March, occurring for more than 65% of the time (maximum of 87% in January). Storm winds prevailed between April and July, occurring between 50% and 54% of the time. It is observed that a marked seasonality occurred during the last two years (Figure 2b), with fair-weather winds being more frequent in summer (up to 10 times more frequent than storm winds) and storm winds more frequent in winter (almost twice more frequent than fair weather winds).

Monthly averaged wind velocities in Caravelas were higher during spring and summer, attaining a maximum of 5.6 $m.s^{-1}$ in November, and lower in the winter, with a minimum of 3.3 $m.s^{-1}$ in June (Figure 2c). Sea breezes were a common feature during the year, but especially strong in summer. On average, during the measurement period, wind velocities underwent a steep climb from an average of 3.1 $m.s^{-1}$ at 7:00 A.M. to 6.7 $m.s^{-1}$ at 3:00 P.M., when it started to decrease. A similar velocity profile is observed in winter, but here the highest average velocity was 4.7 $m.s^{-1}$. Land breezes were only observed during winter and early spring (September), occurring between 2:00 A.M. and 8:00 A.M., with maximum average speed of 3.6 $m.s^{-1}$.

Tides

A total of 21872 and 27004 data points were generated at stations #106 and #506, respectively, representing a recovery rate of 83% and 91%. Tidal ranges varied between 0.47 m and 3.39 m, with the meteorological tides explaining 98% of the sea level signal. The associated amplitudes of M_2 and S_2 were 0.91 m and 0.38 m, respectively.

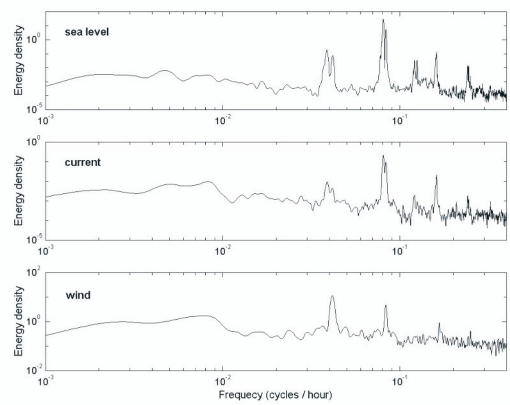

Figure 3. Spectral signature of the sea level and alongshore observed current time series at station #506, as well as the alongshore wind component at Aracruz station.

Mean sea level (MSL) oscillations, with maximum range of 33 cm, were directly related with the mean wind field. The long-term alongshore wind component (>3 days) had a correlation coefficient of 0.76 with the MSL oscillations. A fall in the MSL was generally associated with N-NE winds (maximum velocity of 16.0 m.s^{-1}) whereas the opposite was normally associated with S-SE (maximum velocity of 14.3 m.s^{-1}). This is likely to be related to the cross-shore Ekman transport along the associated shelf, which would drive offshore (lowering the MSL) and onshore flows (raising the MSL) and later propagate in the form of a long wave through the channel.

The sea level spectrum (Figure 3) shows significant energy concentration at 12.4 h and 12 h cycles, as well as in their sub-harmonics. A significant diurnal frequency is also observed, with peaks at 25 h and 24.8 h. Besides influences of diurnal and semi-diurnal solar components of the tides, it is likely that a daily sea breeze signal is also incorporated in the 24 h and 12 h frequency spectra. Also standing out is an 8.8-day (stronger) and 15-day (weaker) signals.

Currents

The average magnitude of the observed currents for the total data set was 17 cm. s^{-1} (station #506) and 24 cm.s^{-1} (station #106), with maximum currents reaching 64 cm.s^{-1} and 93 cm.s^{-1}, respectively. As expected, the major currents had their prevailing flow along the channel axis, and to evaluate their occurrence we consider a SW flow to be within the range covered by directions between 220° and 260°. The opposite situation, *i.e.*, the NE flow, was related to directions between 20° and 80°. About 54% of the flow at station #106, and 39% at station #506, were directed to the SW. The NE flow prevailed for 17% and 19% of the time in these same stations. The remaining currents (29% at station #106 and 42% at station # 506) were considered to be in a transitional situation between the two scenarios.

The cross-shore velocity component at station #106 had, on average, magnitudes 2 times smaller than the alongshore component, which reached a value of 21 cm.s^{-1}. At station #506, which is less confined, the average magnitude for the alongshore and cross-shore components were 13 cm.s^{-1} and 8 cm.s^{-1}, respectively.

The tidal signal was extracted from the observed currents using a harmonic analysis based on FRANCO (1988). The predicted tidal-current velocities had an average magnitude of 12 cm.s^{-1} (station #506) and 14 cm.s^{-1} (station #106). Maximum tidal currents in both stations were about 21 cm/s. The tidal current ellipses tended to be rather circular, with average cross- and alongshore components equal to 7 cm/s at station # 506. At station #106 the alongshore component (9 cm/s) was slightly larger than the cross-shore (8 cm/s).

Astronomic tides explained 73% and 31% of the cross- and alongshore velocity variance at station #506, while at station #106 these numbers are slightly smaller and represent 70% and 27% of these quantities. The spectral signature of the alongshore-observed current (Figure 3) is similar to sea level, with an important 24 hour spectral signal apparently related to the wind effects on the coastal currents (the ratios moon/sun for the diurnal and semi-diurnal harmonic constituents decrease when compared to the respective energy values in the spectral analysis). Also evident is a 5 days signal that is similar to that observed in the wind spectral field (Figure 3).

The sub-inertial currents had a average magnitude of 12 cm.s^{-1} at station #506 and 19 cm.s^{-1} at station #106. Maximum velocities were 48 cm.s^{-1} at station #506 and 70 cm.s^{-1} at station #106. The sub-inertial magnitude of the cross-shore component (4 cm.s^{-1} at both stations) is much smaller than the alongshore component, the latter being 11 cm.s^{-1} at station #506 and 18 cm.s^{-1} at station #106.

The correlation between the observed alongshore component of the wind with the observed alongshore component of the velocity shows a correlation coefficient of 0.58. This correlation increases to 0.86 if the low-pass filter (>72 h) is applied to both series (Figure 4). The response of both the observed and the sub-inertial currents to the corresponding component of the wind speed appears to be instantaneous. On the other hand, the correlation coefficient between the high-pass filtered values (<72 hs) is very small, with a best coefficient of 0.27.

The high-pass filtered, tide-removed alongshore current at station #506 (#106), shows that these currents are only responsible for 24% (15%) of the variability of the observed currents, whereas sub-inertial currents (> 72 hs) explain more than 61% (65%). The former have an average magnitude of 8 cm.s^{-1} and 17 cm.s^{-1} at stations #506 and #106 respectively. Without considering the tidal currents, the magnitude of the high-pass filtered currents at these same stations, are 5 cm.s^{-1} and 7 cm.s^{-1}. As the results show, sub-inertial currents tend to be more important at station #106 than at station #506. Figure 4 also shows that north-eastward component of the sub-inertial flow is associated with rising mean seal levels, while the south-westward component is associated to an opposite trend.

Individual events of SW and NE sub-inertial currents were defined on the basis of zero crossings of the alongshore component. At station #506, where data integrity was higher, 66 events were distinguished, with 34 events associated with NE flows and 32 related to SW flows. The time involved with these events corresponded to 55% of the station's time-series length, or about 116 days and 194 days for NE and SW currents, respectively. The events average and maximum duration were 3.5 and 13 days for the NE currents, and 6 and 43 days for the SW currents. Fifty percent of the NE and SW events have a duration of 2.8 days and 4.5 days, respectively.

DISCUSSION

Tidal ranges at Canal de Sueste are, as far as we know, the largest along the Eastern Brazilian coast, where the amplitude of tide increase from south to north. Whereas predicted equinoxial spring tide ranges for March 2003 varied from 0.9 m in Imbituba (28°14'S) to 2.9 m in Natal (4°46'S) (Brazilian Hydrographic Authority, http://www.dhn.mar.mil.br/), it reached 3.4 m (predicted height) in Sueste Channel. Such amplification is initially ascribed to shoaling effects along the wide shelf, since predicted ranges in Abrolhos island (60 km offshore Figure 1) is 2.68 m.

According to LEIPE *et al*. (1999), the water column in the summer is well mixed, with temperature and salinity values indicating the presence of the Tropical Water in the entire region, including Canal de Sueste. Hence, at least for summer conditions, barotropic forcings are the most important ones.

Although tides are rather energetic, at least for the alongshore observed currents, they are not a very good indicative of the current variability, accounting for only 31% of the total variance. The same occurs with other processes dominated by periods lower than 72 h (e.g. high-frequency local wind field), which explain less than 24% of the current variability. The dominant driving forces of the current field are sub-inertial, as the sub-inertial alongshore component explains up to 65% of the total variability. The fact that the low-pass filtered alongshore component of the wind speed is well correlated with the sub-inertial alongshore component of the currents, is a strong indicative that the winds are the main driving force of the flow in the region. The sub-inertial circulation is thus highly affected by the pattern of the atmospheric frontal systems that either pass by or remotely causes disturbances. Spectral analysis of the water-level record indicates an average frequency of 8.8 days for mean sea level disturbances, whereas current and wind spectrum indicate a 5.5 period. These frequencies are smaller than that indicated by the seal level spectra of Baía de Todos os Santos, 520 km to the north of Abrolhos, that shows a strong 13 day cycle.

The most frequent NE winds blows almost longitudinally to the channel, and the shore-parallel component of the wind stress becomes rather important in driving the coastal flow. Hence, predicted tidal currents has a higher degree of explanation in relation to the cross-shore than to the shore-normal flows.

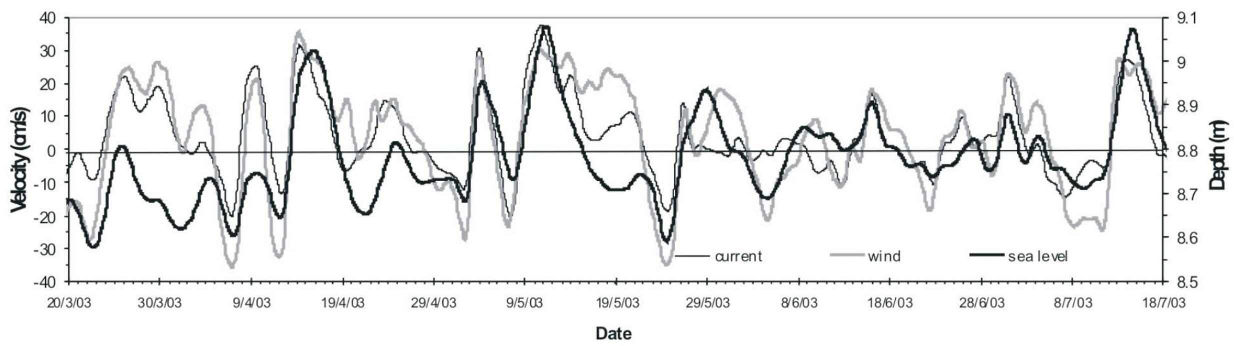

Figure 4. A time series sample, from station #506, of the low frequency oscillations of the sea level (m) and 72 h filtered alongshore components of the current (cm.s^{-1}) and wind speed (m.s-^{1}). The wind speed is scaled by a factor of 10.

The measurements made by LEIPE *et al.* (1999) of the surface and bottom currents in Canal de Abrolhos showed that the along-channel current components were also stronger (average magnitude of 22 cm.s^{-1} at the surface and 16 cm.s^{-1} at the bottom) than the cross-shore (average magnitude of 13 cm.s^{-1} at the surface and 9 cm.s^{-1} at the bottom). In addition, with the dominance of fair-weather winds during the measurements, the residual current (averaged over the 3 days of sampling) was directed southward (178°), with a magnitude of 16 cm.s^{-1} (56% of the magnitude in Canal de Caravelas). Smaller residual velocities in Canal de Abrolhos may be related to the i) geomorphology of the platform, which protrudes from the coast and is surrounded by larger water depths and ii) the farther distance of this station to the coastline. The smaller magnitude of the sub-inertial flow (here the residual flow) causes an increase of the relative importance of the tidal flows. The Neumann parameters were in average 0.66 in Canal de Abrolhos and 0.89 in Canal de Sueste (if the parameter is 0 (1) the flow is completely tidal (non-oscillatory)) (LEIPE *et al.*, 1999).

To our knowledge there are two features that could be somehow compared to Canal de Sueste along the Brazilian coast, namely Canal de Ilha Grande (in the State of Rio de Janeiro) and Canal de São Sebastião (in the State of São Paulo). The Canal de São Sebastião is similar in length and width to Canal de Sueste, but twice as deep (up to 40 m). Larger depths are conducive to baroclinic circulation that is apparently absent from Canal de Sueste. There, on the presence of NE wind events, the South Atlantic Central Water (SACW) upwells onto the platform during the summer and penetrates the southern end of São Sebastião Channel, creating density gradients that causes a two-layer circulation (CASTRO and MIRANDA, 1998). However, as it occurs in Canal de Sueste, the circulation is mainly driven by low frequency flows parallel to the channel axis, with the tides playing little role (SILVA *et al.*, 2001).

Strong alongshore currents impose, as noted by LEIPE *et al.* (1999) for a summer situation, a hydraulic barrier that inhibit the exchange of particles between the coastal and more turbid waters of Canal de Sueste and the remaining of the platform. This scenario may be representative of the coastal hydrodinamic condition for some distance towards the south, given that reef structures occur for more 12 km to the southwest of station #506.

CONCLUSIONS

Based on an extensive set of current meter data, this study was able to provide a first characterization of the hydrodinamics for a costal channel within the Abrolhos coral reef system. The variability of the currents are mainly driven by sub-inertial processes (<72h), with tides and high-frequency events playing a secondary role. After removing the high-frequency events from the wind and current data sets, a very good correlation between alongshore winds and currents were found, indicating that the wind is an important mechanism in forcing the sub-inertial currents.

It is important to mention that the strait itself is very small compared to the local Rossby radius, which means that flows driven by coastal-trapped waves will simply not feel the presence of the strait. The presence of offshore islands will also act as a barrier for the surface Ekman transport. Considering that the current meters are located in a very shallow region, it is quite possible that the main balance, at low frequencies, would be between the surface wind stress and the bottom friction, although that would require a more detailed analysys of the momentum balance terms.

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LITERATURE CITED

CASTRO, B.M. and MIRANDA, L.B., 1998. Hydrographic properties in the São Sebastião Channel: daily variations observed in March 1980. *Revista Brasileira de Oceanografia*, 46(2),111-123.

EMILSON, I., 1961. The shelf and coastal waters off Southern Brazil. Bolm Inst. Oceanogr., S. Paulo, 17(2):101-112.

FRANCO, A.S., 1988. *Tides: Fundamentals, Analysis and Prediction.* São Paulo, Brazil: Fundação Centro Tecnológico de Hidráulica, 249 p.

LEÃO, Z.M.A.N. and GINSBURG, R.N., 1997. Living reefs surrounded by siliciclastic sediments: the Abrolhos coastal reefs, Bahia, Brazil. *In:* LESSIOS, H.A. and MACINTYRE, I.G.(eds.), *Proceedings of the 8th International Coral Reef Symposium,* Panama, pp. 1767-1777.

LEIPE, T.; KNOPPERS, B.; MARONE, E. and CAMARGO, R., 1999. Suspended matter transport in coral reef waters of the Abrolhos Bank, Brazil. *Geo-Marine Letters*, 19,186-195.

MARTIN, L; DOMINGUEZ, J.M.L., and BITTENCOURT, A.C.S.P., 1998. Climatic control of coastal erosion during a sea-level fall episode. *Anais Academia Brasileira de Ciências*, 70(2),249-266.

SCHOTZ, S. and PANOFSKY, H. , 1980. Wind characteristics at the Boulder Atmospheric Observatory. *Boundary Layer Meteorology*, 19,155-164.

SILVA, L.S.; MIRANDA, L.B. and CASTRO, B.M., 2001. Relatório do projeto "Oceanografia da Plataforma Interna de São Sebastião" (OIPISS), Subprograma Oceanografia Física. *Relatórios Técnicos do Instituto Oceanográfico*, Universidade de São Paulo, 47,1-31.