Revista Brasileira de Geofísica
RBGf
Brazilian Journal of Geophysics

Revista Brasileira de Geofísica (2012) 30(1): 5-14

ISSN 0102-261X
www.scielo.br/rbg

LOW-FREQUENCY VARIABILITY OF SEA LEVEL ALONG THE MID-ATLANTIC COAST OF SOUTH AMERICA, IN 1983

Alessandro Filippo[1], Björn Kjerfve[2], Audálio Rebelo Torres Jr.[3] and Alexandre Macedo Fernandes[4]

Recebido em 22 dezembro, 2010 / Aceito em 29 março, 2012
Received on December 22, 2010 / Accepted on March 29, 2012

ABSTRACT. Meteorological events cause pronounced low-frequency sea level variations along the Mid-Atlantic coast of South America. Spectral analysis of hourly sea level data during 1983 from tide gauges at Puerto Madryn and Mar del Plata, Argentina, and Cananeia and Ilha Fiscal, Brazil, yielded energetic variance peaks with periods between 2 and 28 days, with good coherence among the four gauges. These results suggest that coherent low-frequency sea level disturbances may propagate along the Mid-Atlantic coast of South America towards the northeast, mostly as barotropic shelf waves. The principal long waves were identified with heights up to 1 m, periods of 7.8 and 9.0 days, with variances of 2.5-5.4 m^2 and coherences in the order of 0.88 to 0.98. These long waves recur every 5-16 days, propagate towards the equator with an average phase speed of 11 m/s, and require 77 hours to travel the 3,010 km distance from Puerto Madryn to Ilha Fiscal.

Keywords: variation of the sea level, long waves, cold fronts, dynamic oceanography, South-Southeast of the South America.

RESUMO. A variação do nível do mar em função de eventos meteorológicos de baixa frequência ao longo da costa da América do Sul, no Atlântico Sul, é bem acentuada. Da análise espectral em séries temporais do nível do mar, durante o ano de 1983, das estações maregráficas Puerto Madryn e Mar del Plata, Argentina, e Cananeia e Ilha Fiscal, Brasil, observou-se flutuações altas de energia a baixas frequências, com os períodos mais enérgicos, entre 2 e 28 dias, exibindo boa coerência. Essa variação de energia se propaga para o nordeste, na forma de ondas de plataforma barotrópicas, ao longo da costa do Meio-Atlântico da América do Sul com amplitudes de até $\sim$1 m. A variância das ondas longas principais, com período de 7,8 dias e 9,0 dias, que passam por todas as estações, ficou numa faixa de 2,5-5,4 m^2, enquanto que a coerência ficou na faixa de 0,88-0,98. Estas ondas longas propagam em média para o equador com velocidade de fase de 11 m/s a cada 5-16 dias. Com esta velocidade média, uma onda longa leva aproximadamente 77 horas para se propagar de Puerto Madryn até Ilha Fiscal, percorrendo uma distância de 3.010 km.

Palavras-chave: variação do nível do mar, ondas longas, frentes frias, oceanografia dinâmica, sul-sudeste da América do Sul.

[1]Department of Physical Oceanography, School of Oceanography, Universidade do Estado do Rio de Janeiro, UERJ, Rua São Francisco Xavier, 524, 4° andar, bloco E, sala 4017E, Rio de Janeiro, RJ, Brazil – E-mail: amfilippo@gmail.com

[2]World Maritime University, S-201 24 Malmö, Sweden & Departments of Geography/Oceanography, Texas A&M University, College Station, TX 77843, USA – E-mail: kjerfve@wmu.se

[3]Department of Meteorology, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil – E-mail: audalio@lamma.ufrj.br

[4]Department of Physical Oceanography, School of Oceanography, Universidade do Estado do Rio de Janeiro, UERJ, Rua São Francisco Xavier, 524, 4° andar, bloco E, sala 4015E, Rio de Janeiro, RJ, Brazil – E-mail: alxmfr@gmail.com

INTRODUCTION

Low-frequency sea level variations are the response of the ocean to the changes in atmospheric pressure and wind speed with typical time scales of a few days (LeBlond & Mysak, 1978; Gill & Schumann, 1979; Brink, 1991). In the Mid-Atlantic coast of South America, these changes are associated with passages of cold fronts that occur frequently during the entire year (Stech & Lorenzzetti, 1992; Filippo, 1997; Tomczak, 2000). The Atlantic coast of Argentina and Brazil south of Cabo Frio (22°S) exhibits long waves, which propagate towards the north-northeast with the coast to the left of wave propagation (Castro, 1985; Castro & Lee, 1995; Dragani et al., 2002).

In the present study, we seek to identify low-frequency variability of sea level along the east coast of South America, from 43°S to 22°S, in order to determine the characteristics of the long (low-frequency) waves and the conditions of their propagation towards the equator, as expected from theory and observations.

We conducted time series analysis of historical data from four tide gauge stations along the south-southeast coast of South America: Puerto Madryn and Mar del Plata, Argentina, and Cananeia and Ilha Fiscal (Baía de Guanabara), Brazil. The water level data are hourly and synoptic for the four stations and extend for the entire 1983 *El Niño* year. The 1982-83 *El Niño* was one of the stronger occurrences since records have been kept (CPTEC, 2002). With the weakening of the prevailing South Atlantic Subtropical Anticyclone (SASA) by *El Niño* or other meteorological anomalies, there is a significant increase in the frequency of energetic meteorological events and cold fronts passages at high latitudes (Serra & Rastibonna, 1959; Philander, 1990). Such meteorological events generate Kelvin waves with periods from 5 to 18 days, which propagate along the coast towards the equator (Brink, 1991; Filippo, 1997). The purpose of choosing an *El Niño* year is not to estimate the intensity in comparison with non *El Niño* years but to ensure statistical robustness in terms of number of events that can characterize the coastal trapped shelf waves.

METHODOLOGY

Theoretical revision

Atmospheric events, wind-induced storm surges, or earthquakes can generate long shelf waves (LeBlond & Mysak, 1978). Once generated, long waves can propagate as free waves along the shelf away from the area of generation, or they can propagate as forced waves under the continuous action of wind stress (Clarke, 1977). The long-wave amplitude is usually small ($\sim$ 10 cm), the wavelength is greater than the shelf width ($>$200 km), phase speed exceeds 3 m/s, and the wave frequency is lower than the Coriolis parameter ($\omega <$ f) (LeBlond & Mysak, 1978).

Along the Brazilian coast, long waves can contribute significantly to the total sea level variance (Mesquita, 2003). Gill & Schumann (1979), Church et al. (1986), Brink (1991), Tomczak (2000) and others have investigated the characteristics of long waves. In general, such waves are caused by wind stress acting locally, causing either onshore or offshore surface Ekman transport. To conserve mass, a compensatory offshore/onshore flux occurs in the bottom layer. As this flux crosses isobaths, it enhances the local relative vorticity. The vorticity is expressed in terms of speed along the coast and, in the presence of variability along the coast $(\partial/\partial_y \neq 0)$, explains the propagation of coastally trapped long Kelvin waves (Brink, 1991).

Long coastal waves depend on the coastal border, bottom topography, and water column stratification (Wang & Mooers, 1976; Clarke, 1977; Huthnance, 1978; Brink, 1982). At the inner limit of the shelf, within 100 km of the coast (Tomczak, 2000), coastal-trapped long waves become Kelvin waves (Wang & Mooers, 1976; Gill & Schumann, 1979). These waves have maximum amplitudes near the coast and decreases exponentially seaward, what make up a significant portion the variance of the observed tidal motion (LeBlond & Mysak, 1978), and where stratification disappears, the waves become barotropic Kelvin waves (Brink, 1991). Brink (1982) concluded that the presence of stratification weakens the effect of bottom friction, through the inhibition of vertical water exchange.

Study area

The study area extends from 22°30′S and 42°30′W to 47°45′S and 65°55.1′W, covering 3010 km of the Mid-Atlantic coast of South America (Fig. 1). It includes the central and northern coast of Argentina, the coast of Uruguay, and the south-southeast coast of Brazil. The sea level data (Table 1) for 1983 were obtained from the Diretoria de Hidrografia e Navegação (DHN) (Brazil) and Servicio Hidrográfico de la Armada (Argentina). Unfortunately, we were unable to locate reliable and continuous water level data for 1983 between Mar del Plata and Cananeia.

Table 1 – Water level stations used in the analysis of the 1983 hourly data, where n = number of data points.

Stations	W° Longitude	S° Latitude	N	Missing data (%)
Puerto Madryn	–65.03	–42.77	8760	0
Mar del Plata	–57.52	–38.03	8760	0
Cananeia	–47.93	–25.02	8760	0
Ilha Fiscal	–43.17	–22.9	8760	0

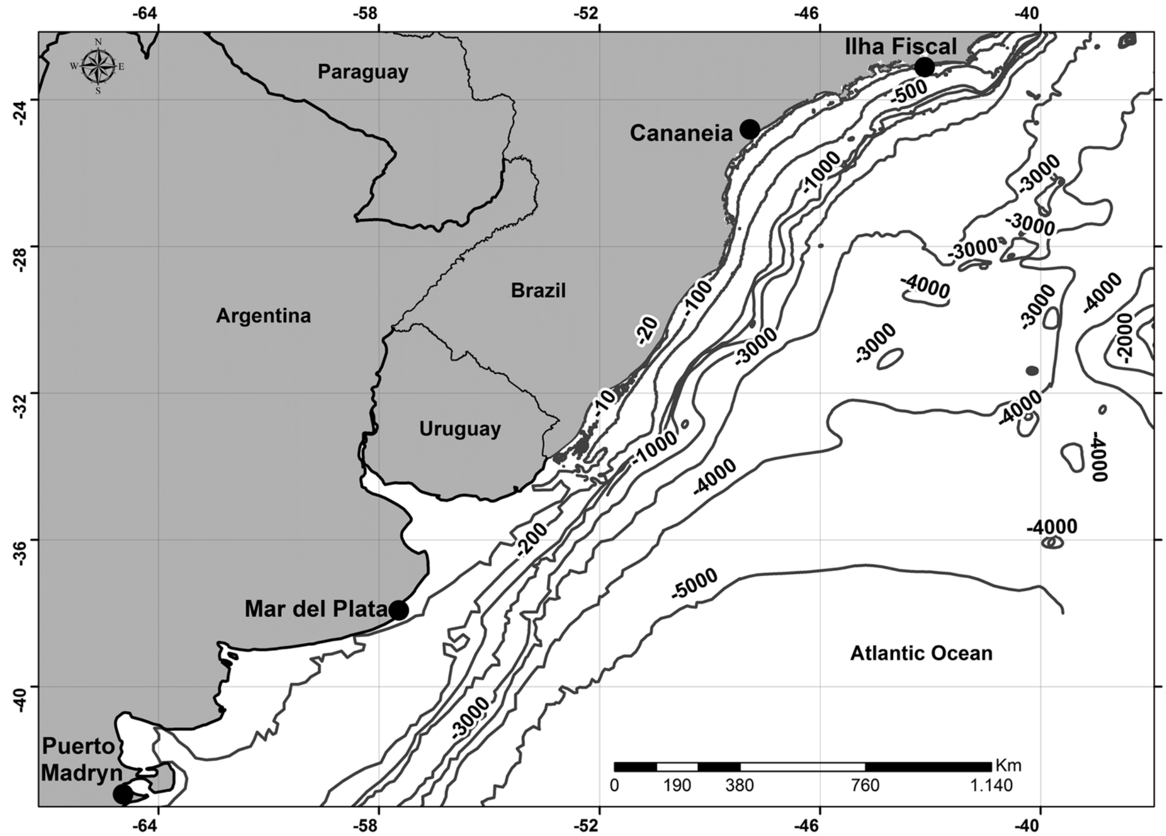

Figure 1 – Locations of tide gauges showing isobaths (m).

The map (Fig. 1) shows the narrowing of the continental shelf from a width of more than 400 km in the south to approximately 100 km in the north. The shelf width at Puerto Madryn measures 540 km with an average coast-normal shelf slope of $\sim 1.8 \times 10^{-4}$ radians; at Mar del Plata 270 km with a slope of $\sim 3.7 \times 10^{-4}$ radians; at Cananeia 218 km with a slope of 4.6×10^{-4} radians. In all three stations the coast is oriented SSW-NNE. The shelf width near Ilha Fiscal is 110 km with a coast-normal slope of $\sim 9.2 \times 10^{-4}$ radians, and with the coast oriented W-E. The sea level data was hourly sampled in all stations.

Laboratory measurements

The data for each station analyzed (Table 1) were plotted and subjected to quality control. A few spurious values due to transcription mistakes or malfunctioning of a tide gauge were removed and data points were interpolated using a piecewise polynomial form of the cubic spline interpolating function from MatLab software. Overall, the data quality of the four time series is excellent. We demeaned the time series by subtracting the mean annual sea level averages from each time series and corrected them from the inverted barometer effect, using the local atmospheric pressure anomaly, water density and gravity acceleration.

To remove astronomical tidal effects, each time series was filtered using a recursive lowpass Butterworth digital filter (Ackroyd, 1973) of order 8, with a 48-hour cut-off period and phase-corrected. An eighth order filter was selected after experimentation, yielding an optimal filter for removing tidal variability of small order and with good gain characteristics. The cut-off frequency fc = 0.042 cph was normalized to the Nyquist Frequency (in this case 0.5 cph). This procedure resulted in four time series of low-frequency sea level anomaly oscillations around a zero-mean annual value.

The Butterworth filter is a recursive digital filter (Ackroyd, 1973; Hanselman & Littlefield, 1996). The main advantage of recursive over non-recursive filters is a steep gain cut-off, thus resembling an ideal filter. All filters, recursive and non-recursive, have the disadvantage of producing phase lags between the raw and filtered data. Although it is not possible to design a filter that produces exactly an ideal lowpass, it is possible to approximate the ideal behavior with a Butterworth filter (Ackroyd, 1973).

To correct for the phase shift the filter was applied both ways, forward and backward, and hence the original phase was recaptured.

The spectral analysis of the sea level data was accomplished by applying a Fast Fourier Transform, averaged using the Welch Method (Middleton, 2000), and smoothed using a Hanning window, with 8 degrees of freedom. In the analysis, we used the input data with: (i) Hanning window = 4096; (ii) noverlap (specifies the number of signal samples that are common to two adjacent segments) = 10; (iii) f_s (sampling frequency) = 1 cph. The cross-spectral analysis yields information about the propagation of long waves from the phase frequency spectrum. This analysis is the product of the FFT of one series and the conjugate of the FFT of the other series. The coherence of the peaks for each series pair expresses the linear correlation index between the two components of the bivariate process as a function of frequency (Pereira et al., 1986). It quantifies the extent to which an event, that took place at one station, is related to the same event at another station.

The identification and propagation characteristics of low-frequency waves is accomplished by comparing the energy of the spectra at locations along the coast, both with respect to the frequency of variance spikes, coherence, and phase difference between the signals. We calculated the phase (propagation) velocity C from

$$C = \left(\frac{360°}{\theta}\right) \cdot \omega \cdot D \qquad (1)$$

where θ is the phase lag (degrees), ω is the frequency (cph), and D is the distance between the stations (km). The results are shown in Table 3. The time phase shift was calculated from

$$Tps = \left(\frac{\theta}{360°}\right) \cdot \text{Period (days)} \cdot 24h \qquad (2)$$

RESULTS

The filtering process effectively eliminated the variance associated with frequencies higher than 0.021 cph (or a period of 48 hr), thus removing the effects of semidiurnal and diurnal astronomical tides. The remaining time series reflect sea level anomaly responses to local and far-field meteorological forcing, including propagating long waves, long-term tidal waves and steric effects. The four lowpass frequency filtered water level time series along the Mid-Atlantic coast of South America are shown in Figure 2.

The filtered time series show significant reduction in variances as compared to the raw time series (Table 2), indicating that semidiurnal and diurnal astronomical water level variations explain most of the measured variance. These astronomical components have the greatest raw water level variance of the four gauges. The low-frequency water level variability accounts for only 2% of the overall variance at Puerto Madryn (Table 2). Mar del Plata experiences the highest low-frequency water level variance, 33% of the overall variance, probably because of the prevalence of meteorological events for generation of Kelvin waves at this latitude.

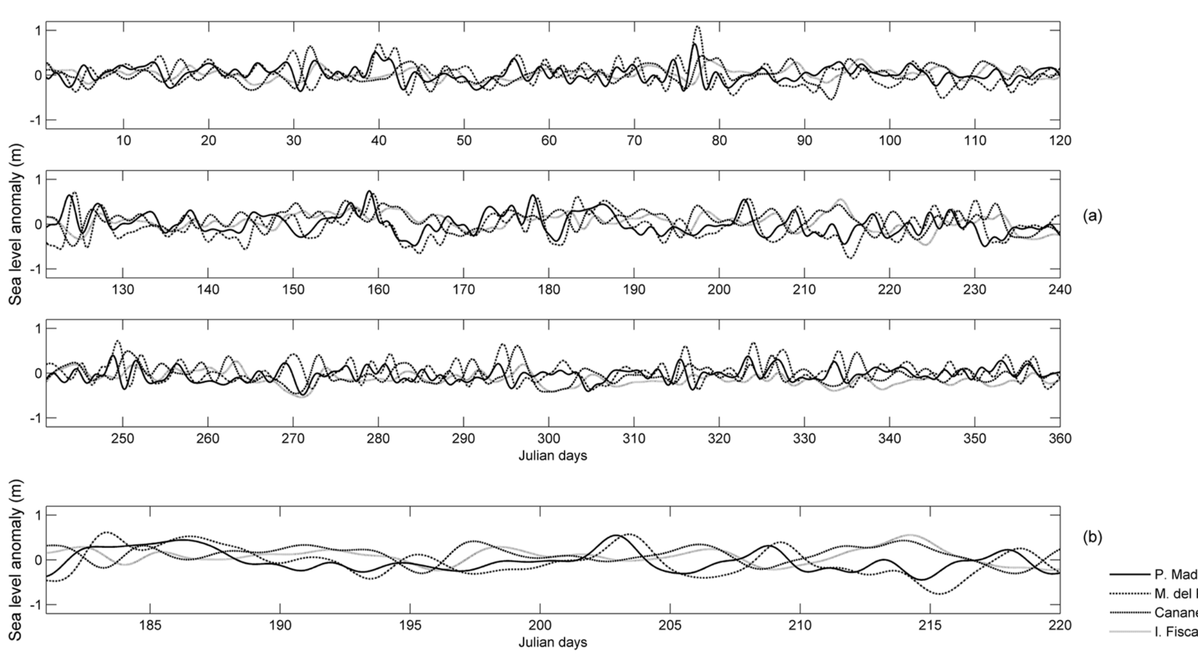

Figure 2 – Filtered tide series for the 1983 hourly water level data for Puerto Madryn, Mar del Plata, Cananeia, and Ilha Fiscal stations.

Table 2 – Statistics of filtered and non-filtered 1983 hourly water level data for Puerto Madryn, Mar del Plata, Cananeia, and Ilha Fiscal stations.

Stations	N	Raw series				Filtered series				% variance Filtered / Raw
		Max (m)	Min (m)	SD (m)	Var (m^2)	Max (m)	Min (m)	SD (m)	Var (m^2)	
Puerto Madryn	8760	4.13	–3.18	1.42	2.03	0.74	–0.50	0.19	0.04	2
Mar del Plata	8760	1.70	–1.51	0.43	0.18	1.10	–0.76	0.25	0.06	33
Cananeia	8760	1.28	–1.14	0.40	0.16	0.65	–0.63	0.20	0.04	25
Ilha Fiscal	8760	0.93	–1.07	0.34	0.12	0.56	–0.54	0.17	0.03	26

The results of the spectral and cross-spectral analysis, the coherence and phase of the signals of the four station sea level filtered series are presented in Figures 3, 4 and 5. A list of the characteristics of the largest waves, and the propagation speeds are shown in Table 3.

There is very good coherence among spectra from Puerto Madryn and Mar del Plata (Fig. 3). This means that the signals for the waves with high variance and periods, ranging from 3 to 28 days, induced by low-frequency meteorological forcing, propagate from Puerto Madryn station to Mar del Plata station with a lag time varying from 9 to 50 hours. The propagation speed of the long waves varies 5-28 m/s for the 870 km distance between the two stations (Table 3). The most energetic peaks have a period of 7.7 days (0.0054 cph), 10.4 days (0.0040 cph) and 27.8 days (0.0015 cph) all with a power spectrum above 2.0 m^2 of variance (Table 3). The coherence ranges from 0.91-0.98 (Table 3). Both data series most energetic frequency peaks are similar to the cold fronts passages frequency, suggesting that the passage of these fronts dominate the long wave generation (Filippo, 1997).

A similar pattern was found in the cross-spectral analysis between the sea level series of the Mar del Plata and Cananeia (Fig. 4). Although the distance between the stations is great (1650 km), there is good coherence (0.86 to 0.99) between the wave signals with periods of 3-28 days (Table 3). Lag times varied from 34-124 hr and the propagation speed of the waves range 4-13 m/s. The most energetic events have periods of 5.2 days (0.0080 cph) and 7.7 days (0.0054 cph) with above 3.0 m^2 of variance (Table 3).

The cross-spectral analysis between the sea level series of Cananeia and Ilha Fiscal stations (Fig. 5) also shows a good coherence (0.88 to 0.98). The wave periods ranged from 3 to 28 days and the lag time between the two stations varied from 11 to 24 hr, for the 490 km distance (Table 3). The propagation speed of the waves varied from 6 to 12 m/s. The peaks with the high magnitudes have periods of 7.7 days (0.0054 cph), 5.2 days (0.0080 cph) and 3.5 days (0.0118 cph) (Table 3) all with a variance ranging from 1.0 to 4.2.0 m^2.

DISCUSSION

The most significant spectral peaks are in a band of high coherence, implying strong interaction among the events on each pair of stations. Moreover, the fact that the phase was predominantly negative indicates that the waves are propagating towards the equator, thus traveling apparently as Kelvin waves or regular continental shelf waves.

Castro & Miranda (1998) described the physical processes of the Brazil continental shelf, including the Mid-Atlantic coast of South America, but did not address the propagation of Kelvin waves. However, they noted that the typical weather pattern of this region is the almost continuous passage of northward propagating atmospheric waves and cold fronts. Generally, these systems form over the Pacific Ocean, move eastward until they reach the Andes, and then turn towards the northeast along the east coast of South America. These frontal systems often propagate along the coast between 40°S and 20°S, although they can reach latitudes as low as 13°S during the southern summer (Kousky, 1979). Frontal systems between 34°S and 20°S average 5 per month throughout the year, typically every 5-10 days between passages. Oliveira (1986) showed that the frequency of occurrence of frontal systems tends to decrease towards the equator and increase during the austral winter. The fewest frontal systems occur in February (3 per month) and the maximum in October (5 per month) (Filippo, 1997). This is in agreement with our findings of the sea level higher fluctuations periodicity (3-7.7 days) in the 1983 data sets.

Despite of frontal systems, another mechanism that regulates the formation of long waves is the presence of a mean alongshore flow on the continental shelf. This flow can alter the propagation of free waves through Doppler shifts, modifying the background vorticity field, and causing the growth of instabilities (Brink, 1991). The Brazil Current propagates southwestward, meandering near the shelf edge along the South Brazil Bight, and associated mesoscale eddies form a nearshore counter current with flow towards the northeast (Castro & Miranda, 1998).

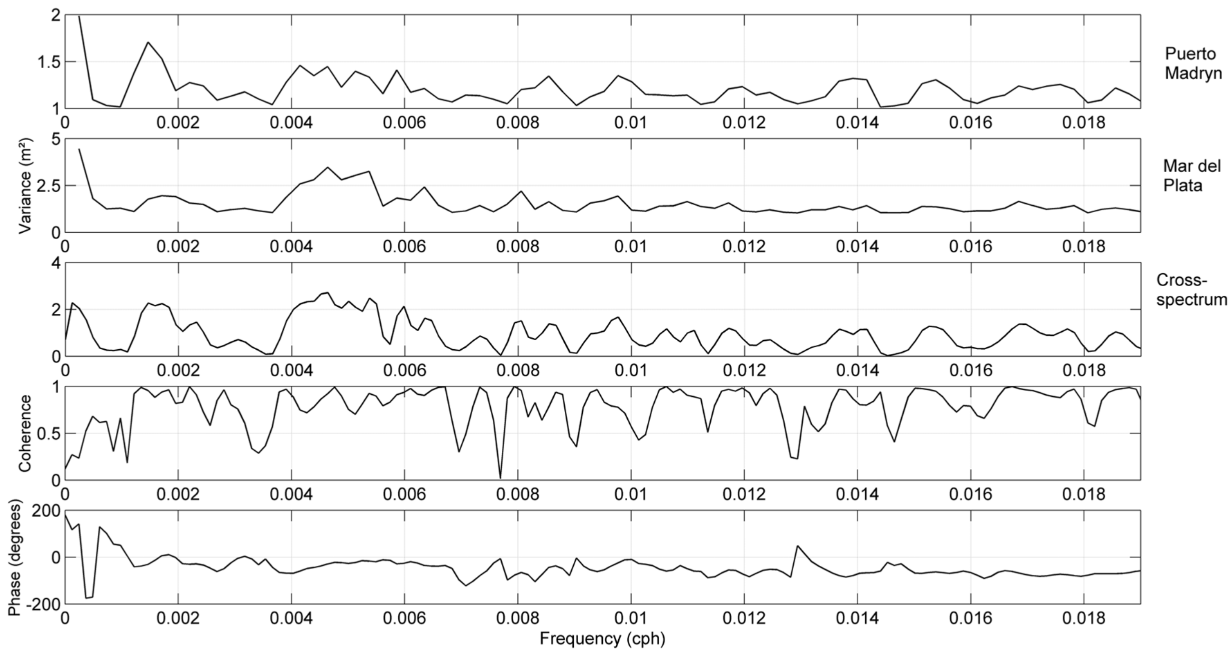

Figure 3 – Cross correlation analysis between Puerto Madryn and Mar del Plata 1983 sea level data.

Table 3 – Periods, variance, coherence, phase, time of phase shift and propagation speed of the main spectral peaks from the cross-spectral analysis between the Puerto Madryn and Mar del Plata (PM–MP, 870 km), Mar del Plata and Cananeia (MP–CA, 1650 km) and Cananeia and Ilha Fiscal (CA–IF, 490 km distance) stations.

Frequency (cph)	Periods (days)	Co-variance (m^2)			Coherence			Phase (degrees)			Time of phase shift (h)			Propagation speed (m/s)		
		PM-MP	MP-CA	CA-IF	PM-MP	MP-CA	CA-IF	PM-MP	MP-CA	CA-IF	PM-MP	MP-CA	CA-IF	PM-MP	MP-CA	CA-IF
0.0015	27.8	2.3	2.0	2.5	0.94	0.86	0.88	–27	–80	–7	–49.7	–124.2	–18.5	–4.9	–3.7	–7.3
0.0040	10.4	2.7	2.9	2.5	0.92	0.92	0.94	–41	–100	–32	–25.0	–71.2	–22.6	–9.7	–6.4	–6.0
0.0054	7.7	2.4	3.9	4.2	0.91	0.96	0.98	–17	–105	–22	–8.8	–53.9	–11.3	–27.5	–8.5	–12.0
0.0073	5.7	0.9	2.2	2.3	0.98	0.97	0.98	–76	–173	–37	–28.8	–65.9	–14.1	–8.4	–7.0	–9.6
0.0080	5.2	1.4	3.4	2.1	0.98	0.96	0.98	–66	–163	–41	–22.9	–56.7	–14.4	–10.6	–8.1	–9.4
0.0118	3.5	1.1	1.8	0.9	0.96	0.99	0.92	–56	139	–95	–13.2	34.8	–23.6	–18.3	13.2	–5.7

Between latitudes 34°S and 28°S, the Brazil and the Malvinas currents converge. These two currents systems form the western boundary of the Subtropical Convergence, and analytical studies and numerical experiments (Campos, 1990) indicate the existence of stationary or low-frequency temporally amplified and spatially damped long waves. When coastal trapped waves propagate in the opposite direction to the mean current, the possibility of critical coastal trapped waves exists, and the direction of wave propagation can locally be reversed due to the strength of the mean flow (Brinks, 1991). As can be observed in Table 3, a 3.5-day period wave exhibits positive phase speed, implying a local phase speed reversal towards the south between Mar del Plata and Cananeia.

The inner shelf is occupied mainly by "coastal water", which tends to be vertically homogeneous due to mixing, wind stress and tidal shear. A near bottom thermal front separates the inner and mid-shelf waters. The mean position of the thermal front changes seasonally, being closer to the coast (10-20 km) during the summer, and farther offshore (40-50 km) during the winter (Castro & Miranda, 1998). This typical stratification of the water column on the inner and mid-shelf facilitates the generation of barotropic shelf waves as opposed to baroclinic ones.

Our spectral results show that there are indeed coherent long waves with periods of 7.7, 5.2 and 3.5 days traveling towards the northeast along the Mid-Atlantic coast of South America with

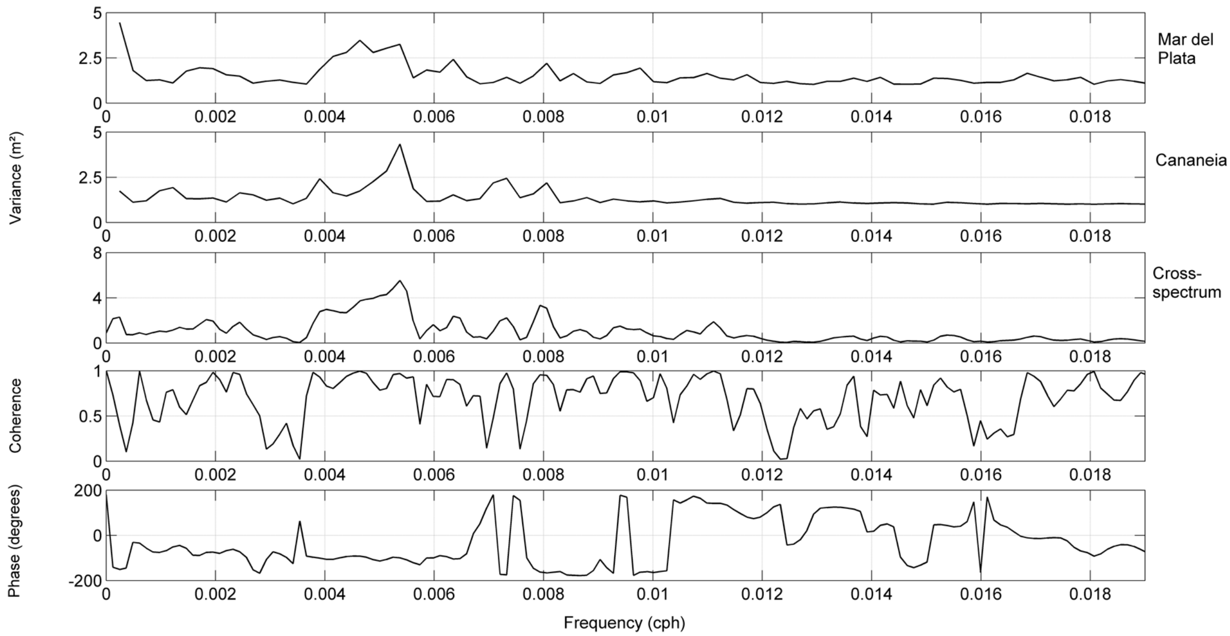

Figure 4 – Cross correlation analysis between Mar del Plata and Cananeia 1983 sea level data.

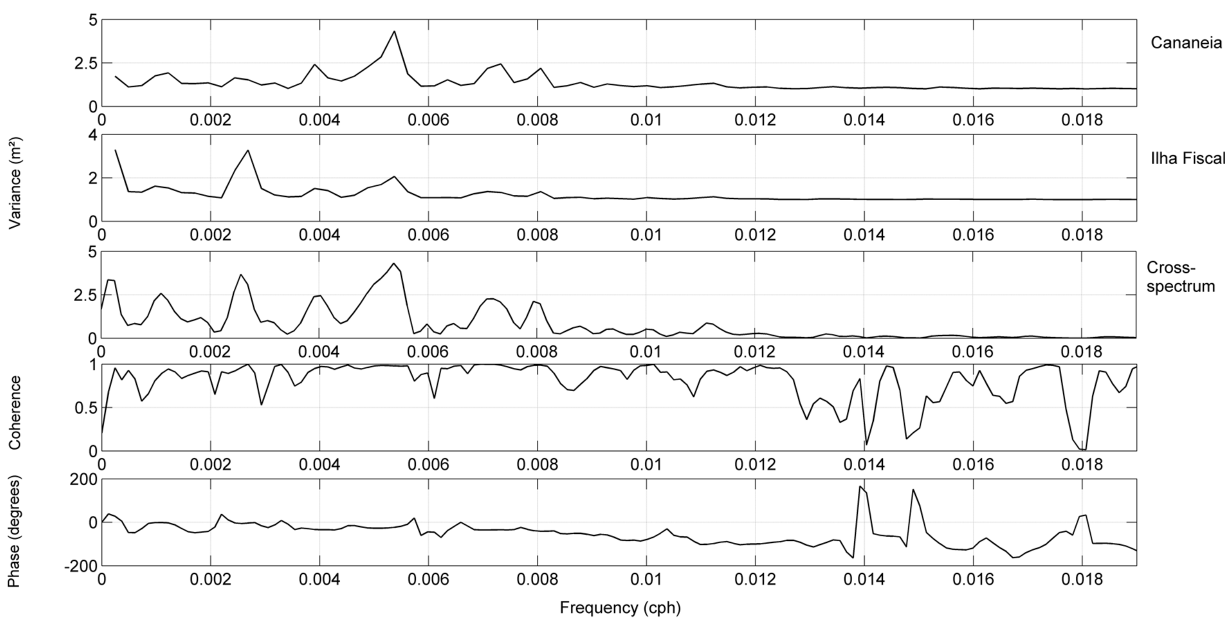

Figure 5 – Cross correlation analysis between Cananeia and Ilha Fiscal 1983 sea level data.

amplitudes of $\sim$1 m. This is in agreement with Castro & Lee (1995) findings that sea level fluctuations in the central and northern portions of the South Brazil Bight for both 9- to 12- and 6- to 7-day bands were better correlated with winds located southward and earlier in time than with the local wind at the time of sea level measurements. Other waves, with longer periods, appear only in individual records, possibly as a result of local meteorological forcing, but the energy/variance has dissipated by the time they reach the next tide gauge.

Another possibility is that the wave could exhibit differences of a few hours in period at different stations because of variations in width and depth of the continental shelf along the coast, as the

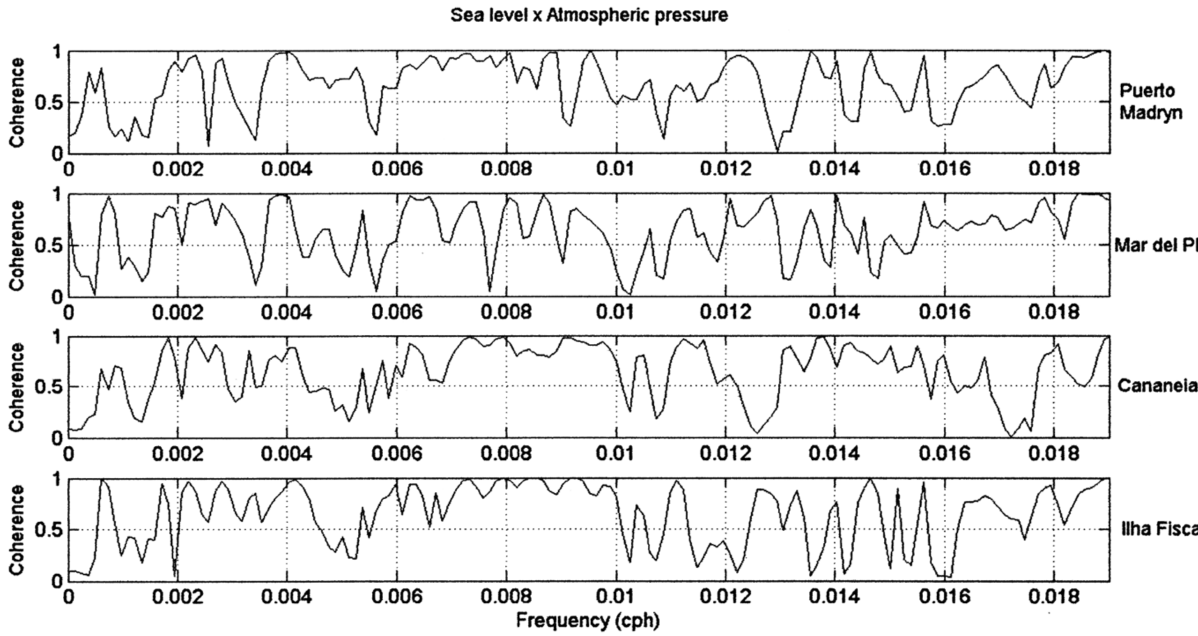

Figure 6 – Coherence of sea level and atmospheric pressure 1983 data series at the Puerto Madryn, Mar del Plata, Cananeia and Ilha Fiscal stations.

propagation of long waves depends on width, depth, and stratification of the water column (Huthnance, 1975, Wang & Mooers, 1976; Clarke, 1977; Huthnance, 1978; Brink, 1982). In addition, the irregular alongshore geometry between Mar del Plata and Cananeia is most likely affecting the phase propagation through wave diffraction (Wang, 1980). Both could cause the reduction in wave energy transmission and the amplification of the wave amplitude near depth convergence zones, generating strong local disturbances.

The importance of long waves in determining sea level variation is obvious. During the 1983 *El Niño* event, there were mean sea level variations of more than 1 meter. It seems that the highest sea level variations were found in the low-frequency portion of the spectrum along the Argentinean coast. The periods were several days to a few weeks, an indication that they manifest themselves through slow changes in water level as well as reversals of the inshore currents at a rate of approximately once a week, as successive regions of high and low pressure pass the measurement locations towards the equator as observed by Tomczak (2000). Being an year of *El Niño*, the possibility of Kelvin waves generated in the Equatorial Pacific could propagate until Cape Horn, turn around and enter in the Atlantic reinforcing (or attenuating) the wave train exists, once Valenzuela-Cuevas (1999) noticed these waves at Chilean cost moving poleward, although it is not the subject of this study. Based on spectral analysis on Mar de Ajó, Pinamar and Mar del Plata stations, on the coast of the province of Buenos Aires, Argentina, Dragani et al. (2002) concluded that the high coherence was an indication that the sea level oscillations were coherent regionally, as we observed in the present analysis.

In our observations low frequencies waves ranged from 0.0118 cph (3.5 days) to 0.0054 cph (7.7 days), all being lower than the inertial frequency for the region, from 0.033 cph ($\sim$31 hours) to 0.0615 cph ($\sim$16 hours) with the increase in latitude what indicate that these are a barotropic shelf waves (Brink, 1991). Also, the phase speed of these waves is similar to the shelf waves described by Castro & Lee (1995) in comparison to a theoretical Kelvin waves phase velocity, $\sim$200 m/s (Wang, 2002), which is higher.

A question that remains to be answered is: which of these waves are forced or free? A coherence analysis between the sea level and atmospheric pressure series was done to determine which of the 6 shelf waves observed (Table 3) were either forced or free waves (Fig. 6). The forced waves are influenced by atmospheric pressure effects (as a good proxy for the propagation of wind patterns) and are highly coherent with atmospheric pressure variations. Thus, the waves with frequency 0.0080 cph ($\sim$5.2 days), 0.0073 cph (5.7 days) and 0.0040 cph (10.4 days) are forced, whereas the 3 remaining low-frequency waves 0.0118 cph ($\sim$3.5 days), 0.0054 cph (7.7 days) and 0.0015 cph (27.8 days), non-coherent with pressure variations, are free shelf waves.

Although the results obtained in this study may suggested that Shelf Waves propagate coherently, the only four stations analyzed here are not enough for a conclusive statement. Attempts to compute a space-time diagram (Hovmoller diagram) were done but the long distance among the four tide gauges did not allow for clear results. The use of numerical models with suitable spatial resolution is required for better addressing this issue.

CONCLUSION

Most of the energy of long waves along the continent propagates as barotropic shelf waves (LeBlond & Mysak, 1978). We conclude that three waves in this study are free long waves and three are a forced barotropic shelf waves, as a result of atmospheric disturbances, somewhat modified by water column stratification and morphology of the local continental shelf (Wang & Mooers, 1976; Clarke, 1977; Huthnance, 1978; Brink, 1982).

Our main findings are:

- At Puerto Madryn, Mar del Plata, Cananeia and Ilha Fiscal, the sea level exhibits high-energy fluctuations at low frequencies, with the most energetic periods exhibiting good coherence between 3.5 and 28 days.
- The observed low-frequency waves along the Mid-Atlantic coast of South America are barotropic shelf waves, somewhat modified by the morphological characteristics of the continental shelf.
- The principal coherent long waves along the entire 3,010 km coast have periods of 5.2 days, 5.7 days and 7.7 days, all with variance above 1.0 m^2.
- The coherence of the most energetic long waves ranged from 0.86 to 0.98.
- Shelf waves propagate towards the equator with a phase speed of –10.9 m/s, on the average, every 5-16 days. These waves require 77 hr to propagate 3,010 km from Puerto Madryn, Argentina, to Ilha Fiscal, Brazil.

REFERENCES

ACKROYD MH. 1973. Digital Filters. D. W. Hill, 79 pp.

BRINK KH. 1982. The effect of bottom friction on low-frequency coastal trapped waves. Journal of Physical Oceanography, 12: 127–133.

BRINK KH. 1991. Coastal-trapped waves and wind-driven currents over the Continental Shelf. Annual Review of Fluid Mechanics, 23: 389–412.

CAMPOS EJD. 1990. Stationary Rossby waves in Western boundary current extensions. Ph.D. Thesis, University of Miami, Miami, 115 pp.

CASTRO BM. 1985. Subtidal response to wind forcing in South Brazil Bight during winter. Ph.D. Thesis, University of Miami, Miami, 211 pp.

CASTRO BM & LEE TN. 1995. Wind-forced sea level variability on the southeast Brazilian shelf. J. Geophys. Res., 100(C8): 16,045-16,056, doi: 10.1029/95JC01499.

CASTRO BM & MIRANDA LB. 1998. Physical Oceanography of the Western Atlantic Continental Shelf Located between 4°N and 34°S. In: ROBINSON AR & BRINK KH (Eds.). The Sea. John Wiley & Sons Inc., p. 209–251.

CHURCH JA, FREELAND HJ & SMITH RL. 1986. Coastal-Trapped Waves on the East Australian Continental Shelf Part I: Propagation of Modes. Journal of Physical Oceanography, 16: 1929–1943.

CLARKE AJ. 1977. Observational and Numerical Evidence for Wind-Forced Coastal Trapped Long Waves. Journal of Physical Oceanography, 7: 231–247.

CPTEC. 2002. El Niño e La Niña. n. 25 Novembro: Instituto Nacional de Pesquisas Espaciais.

DRAGANI WC, MAZIO CA & NUÑEZ MN. 2002. Sea level oscillations in coastal waters of Buenos Aires province, Argentina. Continental Shelf Research, 22: 779–790.

FILIPPO AM. 1997. Passagem de Frentes Frias na Baía de Guanabara: Impacto no nível do mar. M.Sc. Dissertation, Departamento de Geoquímica Ambiental, Universidade Federal Fluminense – UFF, 79 pp.

GILL AE & SCHUMANN EH. 1979. Topographically Induced Changes in Structure of an Inertial Coastal Jet: Application to the Agulhas Current. Journal of Physical Oceanography, 9: 975–991.

HANSELMAN D & LITTLEFIELD B. 1996. Mastering MatLab A Comprehensive Tutorial and Reference. The MatLab Curriculum Series, Prentice Hall, 542 pp.

HUTHNANCE JM. 1975. On trapped waves over a continental shelf. Journal of Fluid Mechanics, 69: 689–704.

HUTHNANCE JM. 1978. On Coastal Trapped Waves: Analysis and Numerical Calculation by Inverse Iteration. Journal of Physical Oceanography, 8: 74–92.

KOUSKY VE. 1979. Frontal influences on northeast Brazil. Mon. Weather Rev., 107: 1140–1153.

LEBLOND PH & MYSAK LA. 1978. Waves in the Ocean. Elsevier, 602 pp.

MESQUITA AR de. 2003. Sea Level Variations along the Brazilian Coast: A Short Review. J. Coast. Res. (SI), 35: 21–31.

MIDDLETON GV. 2000. Data analysis in the Earth Sciences Using MatLab. Prentice Hall, 260 pp.

OLIVEIRA AS. 1986. Interações entre sistemas frontais na América do Sul e convecção na Amazônia. M.Sc. Dissertation, Instituto de Pesquisas Espaciais, INPE-4008-TDL/239, São José dos Campos, SP. 115 pp.

PEREIRA BB, PAIS MBZ & SALES PRH. 1986. Análise Espectral de Séries Temporais - Uma Introdução para Engenharia, Economia e Estatística. Arte Final Leasing Editorial, 109 pp.

PHILANDER SG. 1990. El Niño, La Niña, and the Southern Oscillation. Vol. 46, International Geophysics Series, Academic Press, Inc., 291 pp.

SERRA A & RASTIBONNA L. 1959. As Massas de Ar da América do Sul. Revista Geográfica do Instituto Pan-Americano de Geografia e História, 25: 67–129.

STECH JL & LORENZZETTI JA. 1992. The response of the South Brazil Bight to the passage of wintertime cold fronts. Journal of Geophysical Research, 97: 9507–9520.

TOMCZAK M. 2000. Coastal trapped waves and other oscillations. Lecture notes Chapter 8. Available on: <http://www.es.flinders.edu.au/mattom/ShelfCoast/chapter08.html>. Access on: Oct. 15, 2009.

VALENZUELA-CUEVAS C. 1999. Sea level propagating coastal-trapped waves, circulation forcing influence along central Chile, 1991-1995. In: Ocean Circulation Science derived from the Atlantic, Indian and Arctic Sea Level Networks, 11 May 1999, Toulouse, France. Intergovernmental Oceanographic Commission – IOC. 171v. p. Annex III – 28–33.

WANG DP. 1980. Diffraction of Continental Shelf Waves by Irregular Alongshore Geometry. Journal of Physical Oceanography, 10: 1187–1199.

WANG B. 2002. Kelvin waves. SHANKAR M (Ed.). Elsevier Science Ltd., doi: 10.1006/rwas.2002.0191. 7 pp. Available on: <http://www.soest.hawaii.edu/MET/Faculty/bwang/bw/paper/wang_103.pdf>. Access on: Apr. 4, 2012.

WANG DP & MOOERS CNK. 1976. Coastal-trapped waves in a continuously stratified ocean. Journal of Physical Oceanography, 6: 853–863.

NOTES ABOUT THE AUTHORS

Alessandro Mendonça Filippo. Graduated in Oceanography at the Universidade do Estado do Rio de Janeiro – UERJ (1987), M.Sc. (1997) and Ph.D. (2003) in Geosciences (Geochemistry) at Universidade Federal Fluminense – UFF. Accumulated experience in environmental management and environmental impact assessment, management of multi-disciplinary teams, monitoring programs and water quality, Oceanography of bays, coastal lagoons, estuaries and coastal waters, mangrove ecology, numerical modeling of flow and transport in coastal systems, GIS applications to coastal systems, database development and coastal management. Currently is a Visiting Professor at Department of Physical Oceanography, School of Oceanography (UERJ).

Björn Kjerfve. Since 2009 is President of the World Maritime University, located in Malmö, Sweden, a post-graduate UN university under the auspices of the International Maritime Organization. Holds a Ph.D. degree in Physical Oceanography, is Professor of Geography and Oceanography on leave from Texas A&M University in College Station, Texas, USA. Since 1988 has offered post-graduate courses on physical and estuarine and coastal oceanography and supervised Ph.D. and M.Sc. students in the Environmental Geochemistry Program at Universidade Federal Fluminense – UFF, and also at other universities in Brazil.

Audálio Rebelo Torres Jr. Graduated in Meteorology at the Universidade Federal do Rio de Janeiro (1982), specialization in signal processing and in neural networks at Petrobras (1992), master's degree in Ocean Engineering at Universidade Federal do Rio de Janeiro (1995), Ph.D. in Ocean Engineering at Universidade Federal do Rio de Janeiro (2005). Currently is a professor at the Universidade Federal do Rio de Janeiro, reviewer for the International Journal of Remote Sensing, reviewer for the Brazilian Journal of Geophysics and reviewer for the Pan-American Journal of Aquatic Sciences. Has experience in the field of Oceanography, with emphasis on Physical Oceanography, mainly on the following themes: El Niño, ocean circulation, climate, numerical modeling, teleconnections and South Atlantic.

Alexandre Macedo Fernandes. Graduated in Physics at the Universidade Federal do Rio de Janeiro (1998), Master of Oceanography (Physical Oceanography) at Universidade de São Paulo (2001) and Ph.D. in Physical Oceanography at Florida State University (2007). Currently is an Adjunct Professor in the Department of Physical Oceanography, School of Oceanography, Universidade do Estado do Rio de Janeiro (UERJ). Works in the area of Physical Oceanography, with emphasis on physical variables of sea water and sea water movement, acting on hydrodynamic studies of small to mesoscale and ocean vertical mixing processes.