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COASTAL SEA LEVEL RESPONSE ASSOCIATED WITH FRONTAL SYSTEMS USING CONVENTIONAL AND NCEP/NCAR REANALYSIS DATA, A CASE STUDY: PARANAGUÁ BAY, BRAZIL

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1. Introduction

The astronomical tide and meteorological driving forces constantly affect the coastal zone. These driving forces explain the variability of the low-frequency oscillations in the mean sea level, causing rise and fall in the high and low tides along the coast (Thompson, 1981).

Meteorological disturbances in the sea level oscillations are detected through variations in the mean sea level, which are identified from the water level time series.

Atmospheric pressure variations modify an equilibrium condition, with an inverse relation between these variations. A theoretical model explains this relation using the hydrodynamic equations for an ocean with a constant depth, known as the inverted barometer (Proudman, 1953). The effect of a wind on the sea level varies inversely with the water depth, and it is more pronounced when it blows on an extensive shallow water region, as is observed along the continental shelf or in a bay (Gill, 1982; Pugh, 1987).

The oceanic tides are modified in estuaries because of variations in the width, depth, and flow of water from the river to the sea (Marone and Camargo, 1993).

The passage of frontal systems introduces variations in the sea level records, resulting in spurious water level values or a time lag in the tide. The interaction between meteorological and oceanic factors is of great importance and it affects the sea conditions in coastal regions, mainly the navigation in restricted waters such as bays.

The estuarine complex of Paranaguá Bay (PB) is an area that is sufficiently affected by meteorological disturbances (cold fronts) over 3-5 day periods, causing drastic alterations in the prevailing weather conditions. The Port of Paranaguá (PP), located in PB, is strategic for the agribusiness sector of the country, and so there is a keen governmental interest in maintaining the security of the navigation in the access channels and evolution basins, Figure 1.

Figure 1: The map shows the localization of Paranaguá Bay-Paraná State-Brazil.

For safer access to the Port is necessary to study the conditions prevailing in the sea continuously. Dredging is carried out in the internal areas of PB to deepen areas affected by the Syzygya low tides so that more ships may enter (APPA, 2003).

The availability of conventional meteorological data obtained close to the tide gauge station and NCEP/NCAR Reanalysis data (Kalney, 2001) from the grid points in the oceanic region of interest allowed this research to be carried out. Thus, it was possible to analyze the variability of the sea level in PB, as well as the relationships between the local and remote meteorological conditions in that bay.

2. Study area

The study area (Fig. 2) is situated in the southeastern coastal region or Crystalline Scarps, extending from Cabo Frio, in Rio de Janeiro State, to the Santa Marta Cape, in Santa Catarina State (Villwock, 1994).

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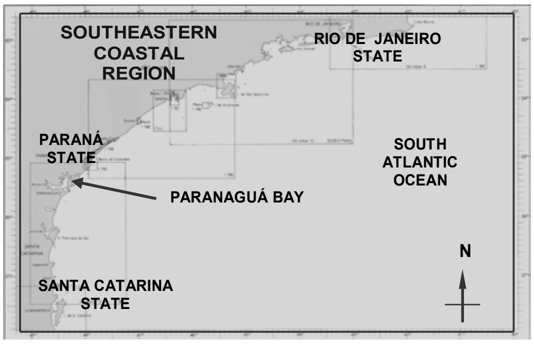


Figure 2: Nautical Chart nº 80/64 (CHM) shows the study area in the Brazilian coast, situated in the southeastern coastal region.

Paranaguá Bay is located between coastal plains and estuaries on a coastline extending from the city of São Vicente in São Paulo State to the Ponta do Vigia in Santa Catarina State. This coastline has wide coastal plains, long beach barriers, and large estuaries. This region is located on the continental shelf of the southeastern coast of Brazil, which is wider than the shelf of the northern coast. The characteristics of the astronomical tide in the PP are the semidiurnal components*, M_2 and S_2 followed by the shallow water components†, M_3 and $M_{4;}$ these indicate the influence of the propagation of the tide wave in the PB and the adjacent continental shelf, respectively.

The climate of this area is characterized by the presence of a high-pressure system over the SAO with northeast winds predominant, the sea and land breezes have local effects. This circulation is disturbed, periodically, by the passage of frontal systems caused by migratory anticyclones that blow from the southwest to the northeast in this region. During the El Niño–Sul Oscillation (ENSO) phenomenon, great climatic disturbances occur in the South Region of Brazil (SRB) leading to abundant rain.

* M_2 – principal lunar semidiurnal; S_2 – principal solar semidiurnal

† M_3 – third-diurnal lunar; M_4 – quarter-diurnal lunar.

3. Meteorological and sea level data

Hourly sea level records from Wharf West in the PP, and hourly averages of the atmospheric pressure and wind velocity in the city of Pontal do Sul (PR) for the 1997-1999 period were used. The atmospheric pressure and wind components at 2,5º x 2,5º and 1,817º x 1,817º grid points (latitude and longitude, respectively), at 00:00, 06:00, 12:00, and 18:00 UTC from the NCEP/NCAR Reanalysis data for the geographic coordinates of 25º00'S and 27º30'S and for the shoreline up to 45º00'W for the 1997-1998 period were used too. Meteorological analyses and forecasts from the Forecast Daily Bulletins prepared by Centro de Hidrografia da Marinha (CHM) during the period 1997-1999 were used.

Figure 3 corresponds to Nautical Chart number 80/1964 (CHM), covering an area from Rio de Janeiro (Rio de Janeiro State) up to Santa Catarina Island (Santa Catarina State), and shows the locations of the tide gauge and the meteorological stations, as well as the NCEP/NCAR Reanalysis grid points. The numbers 1, 3, and 5 refer to the atmospheric pressure and 2, 4, and 6 refer to the wind components.

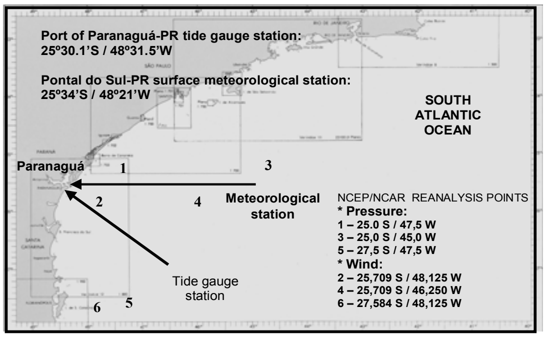


Figure 3: Geographic coordinates of the stations and grid points of NCEP/NCAR Reanalysis data.

4. Statistical analysis

The time series was analyzed statistically by evaluating the extreme average values, variances, and standard deviation. Spurious values that had compromised the quality of the information were removed. The data for the period from January 1997 to September 1998 were then used for studying the behaviour of the sea level in PB in relation to the meteorological variables. All the tide gauge records were used to study the behavior of the mean sea level (MSL) in this region.

5. Filtering data using a low-pass filter

The present work was related to the oscillations in the coastal sea level caused by low-frequency atmospheric changes lasting from 3 to 5 days. So we used a Thompson low-pass filter to eliminate the oscillations leading to tide phenomena and those of diverse scales characterizing the ocean-atmosphere interactions caused by the passage of a frontal system (Thompson, 1983). The effect of the high frequencies related to the astronomical tide observed in the tide gauge records was eliminated. The filter allowed us to impose a null function for the frequencies selected by the user, as well as two cut frequencies for a constant weights (n) amount.

The Thompson optimal filter uses the following aspects: cut frequencies of Ω_1 = 6.4º/h and Ω_2 = 11.2º/h, with periods of 56.25 and 32.14 h, respectively; 16 frequencies with imposition of null response, ten of these being local main tide components and five being adherence frequencies the local inertial component or Coriolis ($f = 2\Omega \sin\phi$); and the weight number N = 120. The hourly average data of atmospheric pressure and zonal and meridional wind components from the conventional station were filtered using this filter (Walters and Heston, 1982; Thompson, 1983; Paiva, 1983; Castro and Lee, 1995).

The NCEP/NCAR Reanalysis data were also filtered using this filter adapted by Uaissone (2004), with the number of weights, N = 20, reported for the data at intervals of 6 h with cut frequency of Ω_1 = 38.4º/6 h and Ω_2 = 67.2º/6 h.

The influences on the MSL with periods of 3 to 7 days in relation to the local and remote atmospheric systems were analyzed after filtering.

Because the NCEP/NCAR Reanalysis data had intervals of 6 h between observations, we used the same time intervals for the meteorological and tide gauge station so that the results could be compared with the respective points.

6. Series analysis in the time and frequency domain

The cross-correlations between the mean sea level, atmospheric pressure, and zonal and meridional wind components were calculated. In view of the strong relation between the wind stress and the variations found in the coastal sea level, we analyzed the correlations existing between them to evaluate the importance of this force in the fluctuations of the coastal sea level

Spectral analyses of the meteorological data and the mean sea level were carried out. Fast Fourier Transformed was used. Cross-spectral analyses were carried out to identify the frequency characteristics of the local and remote meteorological events that have an influence on the variation of the sea level at that point. The coherence between the peaks of the two decomposed series was analyzed to verify that a linear correlation existed between the components of the bivaried process.

7. Results and Discussions

Figure 4 shows the monthly variations of the sea level, where we can observe the periodic movement corresponding to the phases of the moon (Syzygya and Quadrature). The astronomical tide behavior found in the records is semidiurnal, with diurnal influences. The thick curve shows the series filtered using the low-pass filter. These variations are relative to the normalized values, showing the positive and negative fluctuations of both.

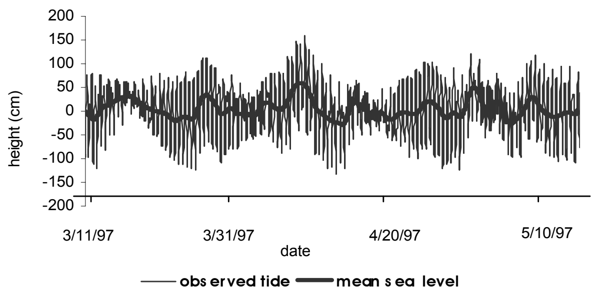


Figure 4: Variations of the sea level from the gauge tide records (observed tide) and the mean sea level (thick line) after the filtering with the low-pass filter, period of March 11 to May 10, 1997.

The variance analysis of the sea level is presented in the Table 2, where we observe oscillations of 12.29% about the MSL related mainly to the influences of low-frequency meteorological phenomena. These oscillations are also called meteorological tides or surges in the literature. Although these oscillations have a small contribution compared with the astronomical and physiographical factors, it becomes relevant when it is compared with the sea level records, mainly when significant meteorological events occur.

Table 2: Sea level variance for the period 1997/1999

Sea level	Variance	Standard Desviation	%
Observed	2705,19	52,04	100
Astronomical tide	2338,37	48,36	86,47
Mean-sea level	**332,71**	**18,19**	**12,29**

Source: Oliveira *et al*., 2004a.

The monthly variation of the MSL for 1997, 1998, and 1999 has different magnitudes for the analyzed period. These can be related to the intense El Niño phenomenon that occurred between 1997 and 1998, followed by the moderate La Niña phenomenon of 1999. Figure 5 shows a peak in February 1998 and 1999, which is not observed in 1997. For this year, a peak in April is noted. The oscillations observed for these 3 years show a peak in June that can be related to the influence of the warm water of the Brazil Current in the Southeastern coast (Mesquita, 1997). A rise occurs in November dropping in January because of the subtropical cold water that reaches this region in summer.

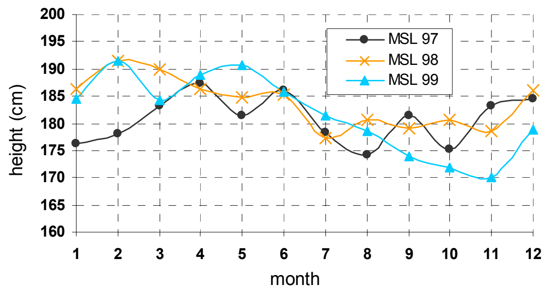


Figure 5: Mean sea level monthly variation for the period of 1997, 1998, and 1999 in Paranaguá bay (Oliveira, 2004).

The atmospheric disturbances generated in the high latitudes and spreading in the direction of the Equator near the coastal regions can generate Kelvin waves with periods of 5 to 18 days, characterizing the response of the ocean to the weather changes (Brink, 1991).

The spectral analysis of this variation, with maximum peaks around 3, 6, and 18 days, characterizes the response of the coastal sea level to the low-frequency driving forces (Fig. 6).

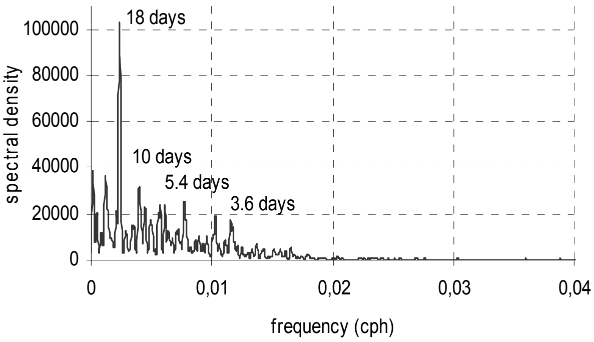


Figure 6: Spectral analysis of the mean sea level with the peaks of the low-frequency (Oliveira, 2004).

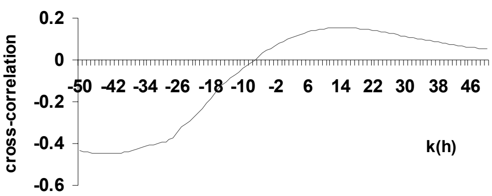
The Thompson low-pass filter removed a high percentage of the local effects of high-frequency systems, mainly the zonal (T_X) and meridional wind (T_Y) components, with 71.81% of zonal wind stress removed. For the pressure values from conventional station meteorological data series, only 11.90% of the total had been removed, showing that this variable is influenced mainly by low-frequency systems. The wind analysis showed that the local physiographical effect has a great influence in that region.

The NCEP/NCAR Reanalysis data from the points selected for this study had a lower removal compared with the data from conventional station. For the pressure, the values constituted about 2.58 % for the three points (1, 3 and 5). The greatest high-frequency removal was with zonal wind stress, with 33.45 % for point 2, near the coast.

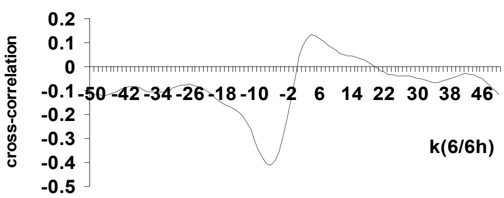
The variance values of the NCEP/NCAR Reanalysis data, compared with the conventional data, show there is a significant influence of the continent in these data. Although, points 1, 2, and 5 are near the coast, this influence is less than at the Pontal do Sul station. The greatest variances were for the zonal components of the wind for all the points with NCEP/NCAR Reanalysis and conventional data. This can be related to mesoscale effects such as breezes and the physiography of PB.

Figures 7(a)-(d) show the peaks of the cross-correlation between the pressure and the mean sea level at the station and in the reanalysis points (1, 3 and 5). Figures 8(a)-(h) show the peaks of the cross-correlation between the zonal and meridional wind stress and the mean sea level at the station and in the reanalysis points (2, 4 and 6). The lags (k) for the conventional data are hourly and for the points are in intervals of 6 hours, thus the values relating to lags of the reanalysis points must be multiplied by 6.

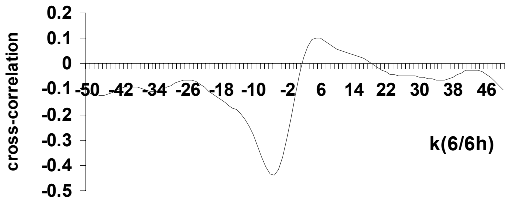
(a) Pontal do Sul



(b) Point 1



(c) Point 3



(d) Point 5

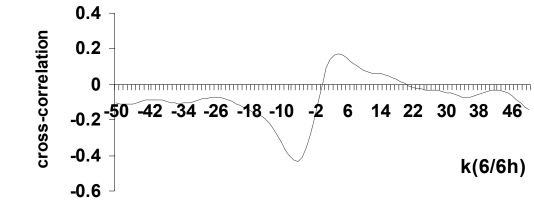
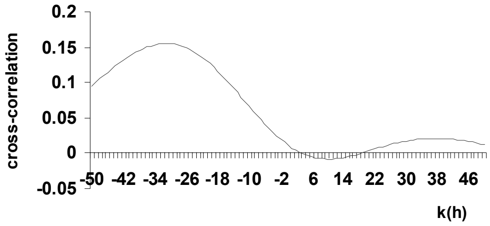
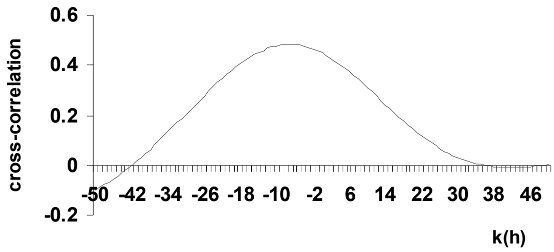


Figure 7 (a)-(d) show the peaks relating to the cross-correlation between the pressure and MSL at the station and reanalysis points. The k-lags to the dataset for the Pontal do Sul station are hourly and for the points (1, 3, 5) are 6 hours intervals.

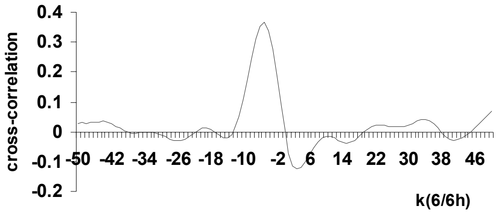
(a) T_X (Pontal do Sul)



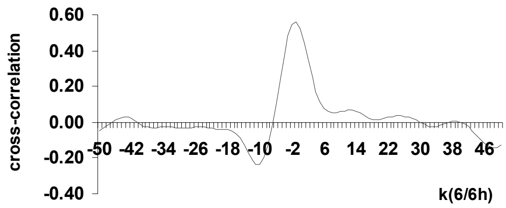
(b) T_Y (Pontal do Sul)



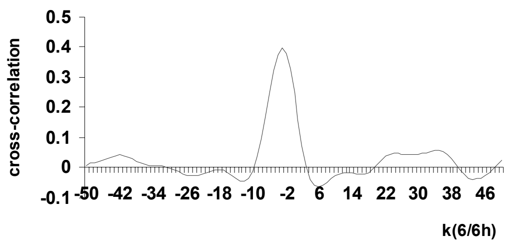
(c) T_X (Point 2)



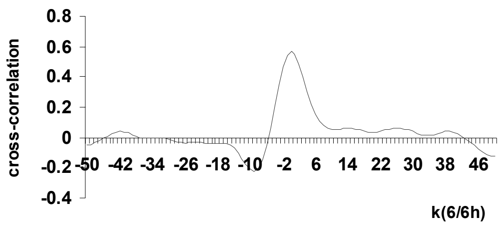
(d) T_Y (Point 2)



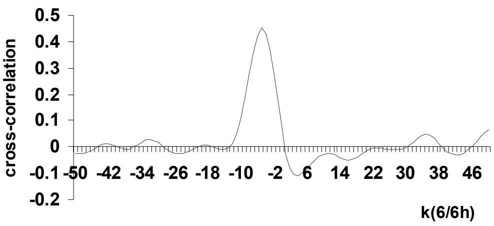
(e) T_X (Point 4)



(f) T_Y (Point 4)



(g) T_X (Point 6)



(h) T_Y (Point 6)

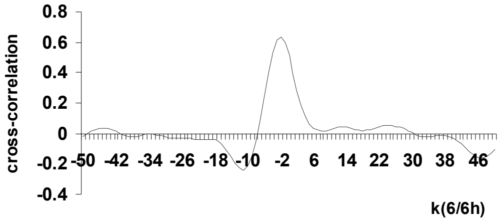


Figure 8 (a)-(h) show the peaks relating to the cross-correlation between the ZWS, MWS and MSL at the station and reanalysis points. The k-lags to the dataset for the Pontal do Sul and for the points (2, 4 and 6) are hourly and the 6 hours intervals too, respectively.

Table 3 lists the values of the crossed-correlations of the mean sea level with atmospheric pressure, zonal (U) and meridional (V) wind components and wind stress (T_X and T_Y). The response of the mean sea level to the atmospheric pressure has a lower value for more distant points of the tide gauge station around 43%. The maximum time lag was 43 h in the conventional station, which can be related to the physiographic effect of PB. For the wind components, the greatest percentage of crossed-correlation was found for more distant points.

Point 6, has the greatest values for wind components and showed same values of 30 h for the time lag for U and T_X. For V component and T_Y the values were about of 12 h, keeping the same intervals between these variables. On the point 2, U component had the same value of 30h for the time lag as the point 6.

Table 3: The maximum time lag verified in the conventional station and grid points.

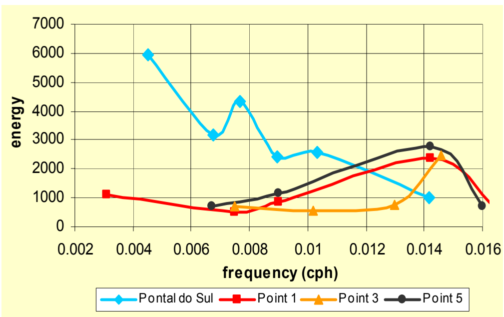
CONVENTIONAL STATION			**REANALYSIS**											
			1 (P)		**2 (W)**		**3 (P)**		**4 (W)**		**5 (P)**		**6 (W)**	
Variables	**lag**	**%**	**lag**	**%**	**lag**	**%**	**lag**	**%**	**lag**	**%**	**lag**	**%**	**lag**	**%**
P	43	44	36	41,2			30	43,8			36	43,3		
U	27	28,5			30	42,5			24	44,4			30	47,5
V	8	58,3			6	57,8			0	57,6			12	64,7
T_X	31	15,5			24	34,7			18	37,6			30	43,7
T_Y	7	48,4			0	55			0	56,5			12	62,7

* The time lag in hours.
Source: Oliveira, 2004

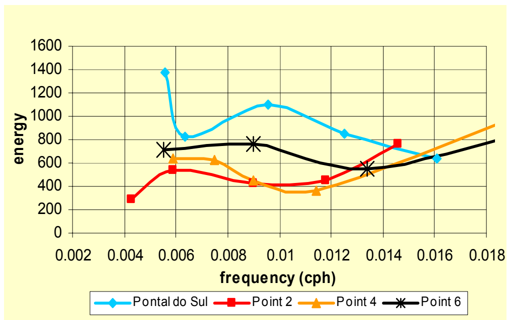
The crossed-spectral analysis using the conventional and NCEP/NCAR Reanalysis data for the mean sea level in PB is presented in Figures 8a to 8e, where we observe the results in terms of energy, frequency and period. Figures 9a to 9e show the coherence between the variables and the mean sea level. High coherence is found among the low-frequency events, with periods varying from 10 to 3 days.

The spectral densities show a concentration of energy for periods from 5 to 3 days decreasing for periods of less than 3 days and greater than 10 days with peaks for 17 and 20 day periods also. Similar results had been found by (Paiva, 1993; Castro and Lee, 1995) with respect to the effect of waves in the continental shelf. The corresponding peaks for periods between 3 and 6 days were identified by these researchers as being caused by the occurrence of meteorological events such as cold fronts, followed by low-pressure systems (Uaissone, 2004).

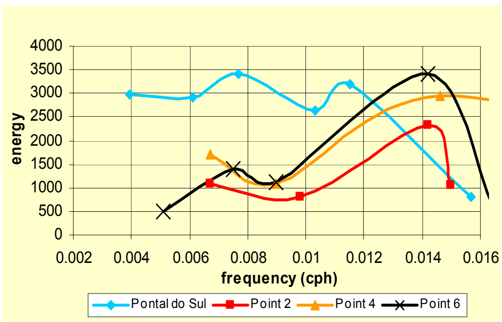
The crossed-spectrum of the pressure against the mean sea level (Fig. 8a) shows peaks related to events with periods of about 4 to 3 days at points 1, 3, and 5. High values of energy were found for events with smaller frequencies. For U and the zonal wind stress components, the energy values show equivalence to the three points with peaks in the Reanalysis data for periods less than 3 days. In the station, U had greatest values than the zonal wind stress (Figs. 8b and 8d). Figures 8c and 8e show that V and meridional wind stress components display a behavior similar to that of the four points. The V component had greatest energy values in the station compared with the three points of reanalysis dataset.



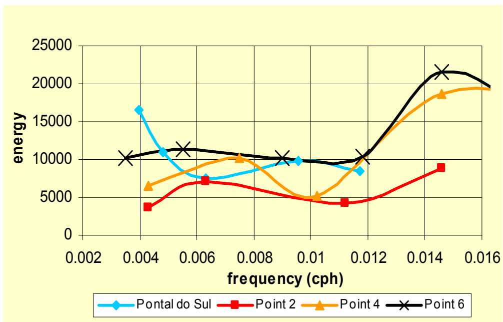
(a): Pressure



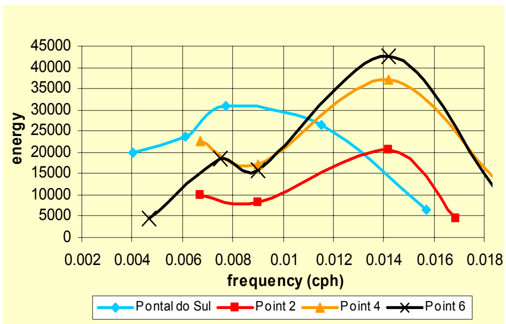
(b): U wind component



(c): V wind component



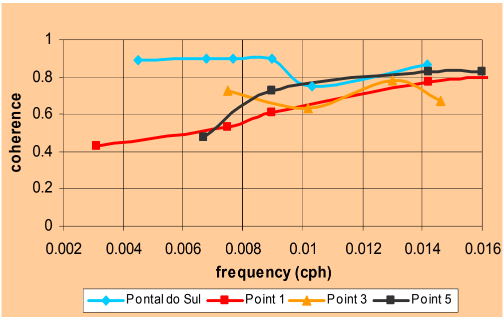
(d): Zonal wind stress



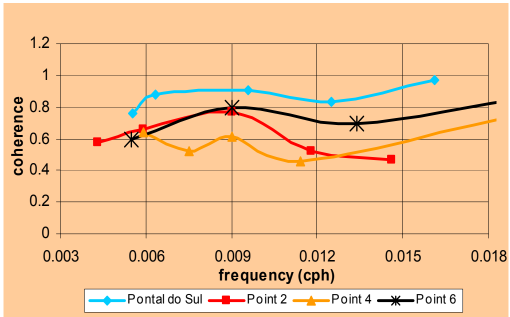
(e): Meridional wind stress

Figure 8 (a)-(e): Values of the crossed-spectrum between meteorological variables and the mean sea level for the station and reanalysis points (Oliveira, 2004).

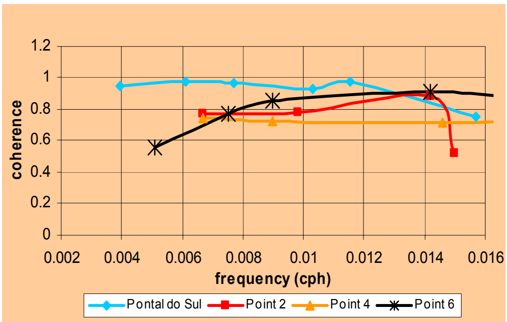
High coherence was found between the variations of the pressure and the MSL response for the station and reanalysis points for events with frequencies greater than 0.01 cph related to 4 days period (Fig. 9a). Figures 9b and 9d show a similar coherence between U and zonal wind stress components with the MSL for the station and reanalysis points, and Figures 9c and 9e show the coherence of V and meridional wind stress components, both for events around 5 and 3 day periods.



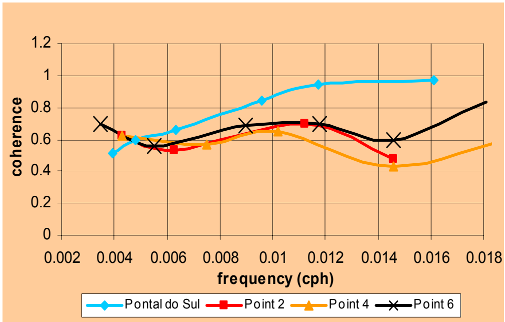
(a): Pressure



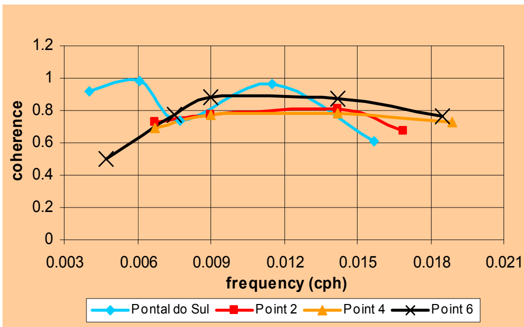
(b): U wind component



(c): V wind component



(d): Zonal wind stress (T_X)

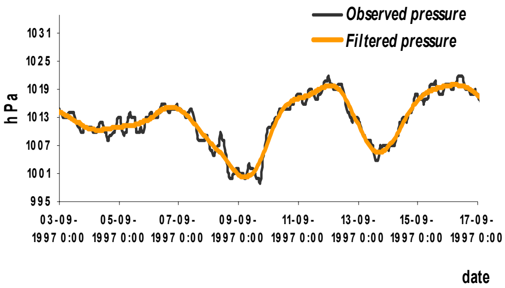


(e): Meridional wind stress (T_Y)

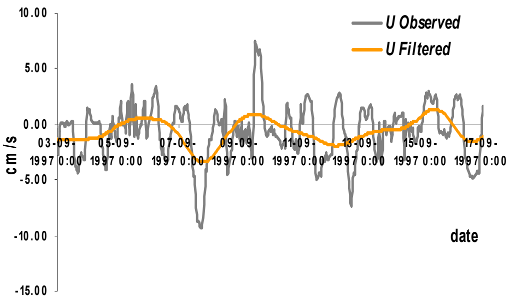
Figure 9 (a)-(e): Values of the coherence between meteorological variables and the mean sea level for the station and reanalysis points (Oliveira, 2004).

The southern region of Brazil and Uruguay is an area of strong cyclogenetic activity. In this study, high correlations were found between the meteorological systems and the response of the variability of the sea level in PB, mainly related to remotes points 5 and 6 from the NCEP/NCAR Reanalysis data, in the southern sector near Santa Catarina State.

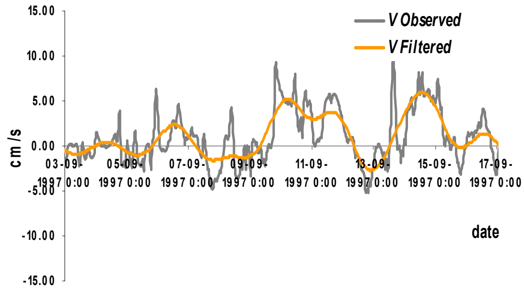
Figure 10(a)-(d) shows the occurrence of a meteorological event occurred on September 09, 1997 verified in the time series where we observed a rising of the sea level at the PB, 48 hours after a drop of the atmospheric pressure. The observed values of the high tides and eddies on September 11, 1997 were 242 cm at 00:00h, 164 cm at 06:00h, 263 cm at 11:00h e 180 cm at 20:00h and the predict values were 213 cm, 144 cm, 237 cm e 130 cm, respectively. The difference between these values was around 29 cm e 26 cm for high tides and 20 cm e 50 cm for eddies. The atmospheric pressure and wind fluctuations on this date showed the passage of the frontal system on this region. The relation between the pressure and the sea level occurred with approximately 48 hours time lag.



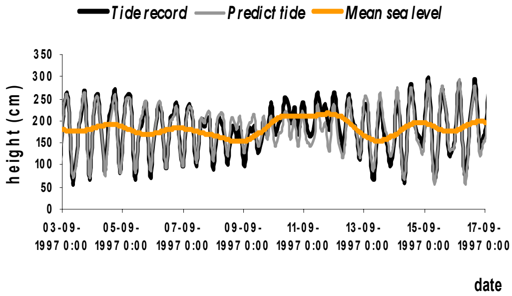
(a)



(b)



(c)



(d)

Figure 10(a)-(d): Graphics of the meteorological and sea level data at the period of a frontal system occurrence, September 03 to 17, 1997 (Oliveira, 2004).

According with the event above, these effects were observed in this work. Removing the high-frequencies of the conventional data gave values of 11% for the pressure and 65% for the wind. We believe that the continental area have a great influence in these results. For the NCEP/NCAR reanalysis points in the SAO the removal of the high-frequency values was around 2.5% for the pressure and 9% to 19% for the U and V wind components. These values showed that the greatest influence of the mean sea level variation is related to the passage of a frontal system of the cold-front type. Comparing these results with those from conventional meteorological station, we conclude that the NCEP/NCAR reanalysis data can be used to study the influence of the meteorological events that affect the PB region.

For reanalysis points 2 and 4, the meridional wind stress component showed a maximum linear correlation (t = 0), of around 56%, with the mean sea level. The correlations of the atmospheric pressure and the mean sea level from the station and reanalysis points (1), (3) and (5) were similar, around 43%, for a time lag of 42h and around 36h, 30h and, 36h, respectively. These relations support the results of the studies carried out on the Santa Catarina coast using the auto regressive integrated moving average (ARIMA) model of Mariotti and Franco, (2001).

The frequency domain analysis with the conventional data had shown the greatest values of the cross-spectral density of periods of around 5 days with coherence between 90% and 98%. This can be justified as being caused by the proximity of the two stations (tide gauge and meteorological), both suffering the local influences of the migratory atmospheric events. The spectral analysis for point 1, to the north of the tide gauge station, and point 2, near PB, gave lower values for the spectral density and coherence, around 80% for V and the meridional wind stress, and 70% for the other variables. At points 3 and 4, in the oceanic area, the analysis had shown a coherence of around 78% for events with period of 1.7 to 3 days. For points 5 and 6, southern of Paranaguá, the energy values are greater than for the other points, with values of coherence between 83% and 91%. We believe that it is associated with the atmospheric pressure variations caused by the approach of frontal systems with northwest winds, characterizing the weather change conditions in proximities of PB.

4. Conclusion

The statistical treatment of the data series in the time and frequency domain allowed us to know the maximum existing correlations in this physical process. These correlations showed the time lag between the variables, using conventional and NCEP/NCAR reanalysis data relating them with the local and remote meteorological influences at the tide gauge station.

The NCEP/NCAR reanalysis data compared with those obtained from the conventional station showed the influence of the low-frequency atmospheric phenomena in the response of the sea level at PB. This dataset showing that is a very good source of information for the SAO region, where the lack of data is still significant. Informations from numerous points, near that bay, contribute much clearer in the comprehension about these events that effect in the height of the observed coastal sea level.

The points selected on southern PB in the oceanic area suffer a great influence of the direction of the Brazilian coast in this place, where the meridional wind component has high values.

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