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The Low Frequency Sea Level Oscillations in the Northern Coast of Santa Catarina, Brazil

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ABSTRACT

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The response of the subtidal sea level to atmospheric forcing in the northern coast of Santa Catarina State, Southern Brazil, was examined from a five-month sea level, wind and atmospheric pressure hourly records. The dynamics of the low frequency coastal sea level variability related to the local atmospheric driving forces was assessed using time-lag cross-correlation statistical (TLCCS) analysis, and multiple linear regression models (MLRM) in the time and frequency domain. The TLCCS analysis showed that response of the coastal sea level was maximized by local 12 N winds, which are locally long-shore oriented; with a 10-hour lag to the wind stress. The role of the cross-shore wind was negligible, and the isostatic effect of the atmospheric pressure was not observed. The MLRM in the time domain explained 56 % of the variance of the low frequency sea level oscillations, having as inputs the long-shore wind stress and the atmospheric pressure. The MLRM results indicated that the maximized response of the sea level was obtained with a 6-hour lag to the wind stress, and 37-hour lag to the atmospheric pressure. The MLRM in the frequency domain explained 84 % of the sea level oscillations for periods ranging from 6 to 9 days, maximized with a 10-hour lag to the long-shore wind stress, and a 37-hour lag to the atmospheric pressure. The MLRM results reinforce the findings obtained by TLCCS, where the main findings were (1) the cross-shore wind was negligible, (2) the isostatic effect of the atmospheric pressure was not observed, and (3) the long-shore wind was the main driving agent with a 6 to 10-hour lag over the sea level.

ADDITIONAL INDEX WORDS: *Low frequency sea level, multiple linear regression models, northern coast of Santa Catarina.*

INTRODUCTION

The sea level oscillations respond continually to astronomical, oceanography and atmospheric interactions over a wide range of periods (GILL, 1982). Indeed, all tide gauges records contain a whole spectrum of signatures, from the tide itself whose influence spans the entire spectrum but is primarily in the range of periods less than one day to secular and global eustatic changes which occur over periods of centuries (GORING, 1995). There is a small area of this spectrum, between 3 to 15 days, where combined variations of the atmospheric pressure and wind forcing affect the sea level. These meteorological influences produce low frequency oscillation on the sea level, known as meteorological tides. These oceanic fluctuations are generated mainly by meteorological conditions, where winds account for 90 % (GILL, 1982), and propagated along or towards the coastline.

Low frequency coastal sea level records have been widely used to study low frequency continental shelf dynamics and their relationship to the wind and atmospheric pressure. Most part of the low frequency rise and fall of the sea level is firstly driven by local long-shore wind stress through the Ekman mechanism. These oscillations cause a cross-shelf barotropic gradient, which is in geostrophic balance with long-shore current (THOMPSON, 1981; GARRET and TOULANY, 1982; CHUANG and WISEMAN JR, 1983; ALLEN and DENBO, 1984; PUGH, 1987; SCHWING, 1992; STECH and LORENZZETTI, 1992). However, there are some evidences of nonlocal wind effects on coastal sea level for South Brazil Bight region attributed to continental shelf waves (CASTRO and LEE, 1995).

The effect of atmospheric pressure is usually estimated using the inverse barometer (IB) approximation, where for an increase in 1 mbar of atmospheric pressure, the sea level is lowered by 1 cm. The IB implies to the isostatic response of sea level that responds to balance the applied barometric pressure gradients (PUGH, 1987; GORING, 1995). Some works reported good IB approximation (HAMON, 1966; WUNSCH, 1972), while other found nonisostatic response (PONTE, 1994; GORING, 1995). In addition, GORING and BELL (1993) found considerable seasonal variation of the IB approximation, being larger in the winter than the summer.

The low frequency sea level oscillations play an important role along the littoral zone of Santa Catarina State, in the Southern Brazil, as it is under a microtidal regime; the astronomical tides ranges between 0.4 to 1.2 m during neap and spring tide periods, respectively. Although, very few information is available in the scientific literature assessing this process, despite its importance in terms of coastal erosion, sediment dynamics and harbor activities, among many others (PEREIRA DA SILVA *et al.*, 1999; TRUCCOLO *et al.* 1996).

This study assessed the response of the low frequency coastal sea level to local meteorological forcing in the northern coast of Santa Catarina, using time-lag cross-correlation statistical (TLCCS) analysis and multiple linear regression models (MLRM) in time and frequency domain. The objectives were: (1) to determine the direction of the local wind stress that induces the maximum response of the coastal sea level; (2) to assess the effect of atmospheric pressure the IB approximation; and (3) to evaluate the interactions between weather data and low frequency coastal sea level records in order to used them in multiple linear regression models in time and frequency domain.

ENVIRONMENTAL SETTING

Study Site

The northern coast of Santa Catarina State (Figure 1) is located in the South Brazil Bight (SBB), which is a major geomorphologic feature of the Brazilian Continental Shelf (BCS). The along-coast length of the SBB is approximately 1,100 km, and the bathymetry is generally smooth, with isobaths paralleling the coastline (STECH and LORENZZETTI, 1992; CASTRO and LEE, 1995). The BCS width off the study area is about 120 km, where the near shore isobaths following the local variations of coastline, which orientation is approximately 20° N, although it is 45° N for the entire SBB.

Sea Level Fluctuations

The local astronomical tides range from 0.4 to 1.2 m along the spring/neap lunar cycle, with mean range about 0.7 m (TRUCCOLO and MELO FILHO, 1997). The relative importance of diurnal and semidiurnal constituents of astronomical tides, given by the Form Number ($FN=(A_{K1}+A_{01})/(A_{M2}+A_{S2})$, PUGH, 1987), is 0.3. This means that the tidal regime is mixed with predominance of semidiurnal tides, with inequalities of height (TRUCCOLO and SCHETTINI, 1999). Considering the fact that the tidal regime along the northern coast of Santa Catarina State is micro-tidal, changes due to atmospheric forcing, rather being small, presents considerable importance. TRUCCOLO *et al.* (1996) related one event when the sea level was 1.0 m above the predicted astronomical tide in this coastal area. Events like this synoptic with spring tide high water causes floods in several shore cities like Itajaí and Balneário (TRUCCOLO *et al.*, 2000).

Atmospheric Circulation

The predominant atmospheric circulation pattern is characterized by a semi-fixed high-pressure atmospheric system, the South Atlantic Anticyclone (SAA). The SAA is characterized by tropical air masses and anticlockwise gyre. However, the weather conditions change during the winter when Polar Anticyclone (PA) migrates from southwest to northeast along South America. The PA is characterized by dry and cold air masses. The limit between the air masses originated the Wintertime Cold Fronts (WCF), which divide both air masses and promote variation of atmospheric pressure as they move. The track, direction, and intensity of the WCF are variable. In most cases they are severe, featuring extremely low central pressures called Extra-tropical Cyclones (EC), with clockwise gyre, strong winds, and high precipitation rate. Associated with WCF and EC occurs the wind field rotation, with anticlockwise change of wind direction, changing from northeast to northwest- southwest.

The WCF passage occurs 3 to 5 times per month, with 6 to 10-day interval, and averaged displacement of 500 km/day (STECH and LORENZZETTI, 1992). These meteorological forcing actuates on the SBB likely most other continental shelves at the same latitude, and is an important source of energy for coastal hydrodynamics at 2 to 15-day period (STECH and LORENZZETTI, 1992; MARONE and CAMARGO, 1994; CASTRO and LEE, 1995; TRUCCOLO *et al.*, 1996; TRUCCOLO and FRANCO, 1999).

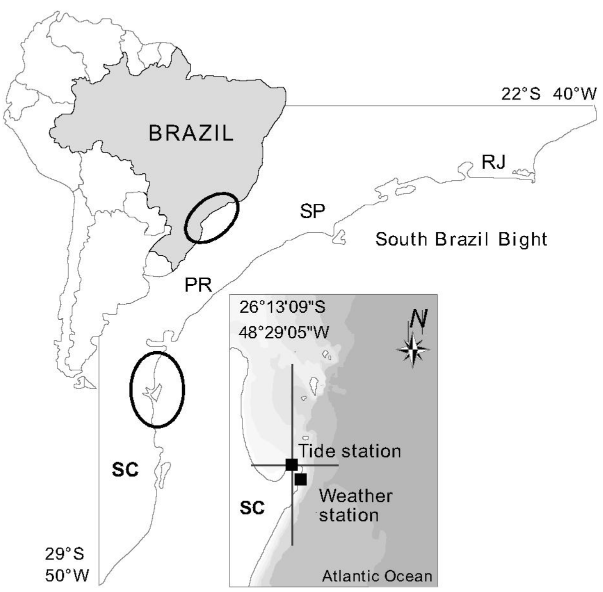

Figure 1. Locations of the study site at São Francisco do Sul Island, northern coast of the Santa Catarina State. Position of the tide and weather station are indicated.

MEASUREMENTS AND TREATMENT OF THE DATA

Sea Level and Weather Data

Hourly sea level data were recorded with an Aanderaa™ WLR7® tide gauge deployed at the Enseada Beach, São Francisco do Sul (Figure 1). Hourly wind speed and direction, and atmospheric pressure, were monitored with a Campbell™ automatic weather station deployed at 10 m high at Grande Beach, São Francisco do Sul. The wind direction was magnetic declination corrected by subtracting 17°, and decomposed into long-shore (north - south) and cross-shore (east - west) components. The wind shear stress (τ_W) was calculated by the quadratic stress law (WU, 1969):

$$\tau_W = \rho_{AIR} C_W |U_{10}| U_{10} \qquad (1)$$

Where ρ_{AIR} is the air density, C_W is the drag coefficient given by $C_w = 0.001(1.1 + 0.053|U_{10}|)$ (STECH and LORENZZETTI, 1992), and U_{10} is the wind speed measured at 10 m high.

The time series were recorded from July 14th to December 15th, 1996, resulting in 3,692 values (154 days). The time series were filtered using a low-pass Lanczos square filter in order to eliminate diurnal and higher frequency oscillations. Oscillations longer than 55 hours were all preserved. The linear trend of the remaining time series was removed.

Statistics of the Time Series

The statistics analyses of the sea level time series indicated that 74% of the total signal variance can be attributed to the astronomical tides, and 24% of signal variance was accounted to the low frequency oscillations. This result shows that the sea level signal is dominated by high frequency oscillations, but the low frequency cannot be neglected.

In order to better evaluate the importance of low frequency oscillations, high and low limits around the time series mean sea level were stated as 0.5 and 0.8 m. The 0.5 m limit was chose as it is the mean amplitude of spring tidal, and the 0.8 m was chose as it exceed the maximum amplitude of astronomical tide in 25%. Considering the non-filtered data, the sea level exceeded the limit of ± 0.5 m in 19.4% of the time, meanwhile the above limits values for the low frequency signal was 6.4%, meaning 32%. Considering the ± 0.8 m limits, only 2.2% of the raw observations exceeded it, and 2% were at the low frequency component, or 91%. In early July was observed the higher low frequency sea level oscillation during the study period, where the sea level was 0.9 m above to predicted astronomical tide.

The surface atmospheric pressure was highly dominated by low frequency oscillations, which accounted for 68% of the total signal variance. The wind stress statistics were performed on the long-shore and cross-shore components. The low frequency oscillations accounted for 54% of long-shore component, mainly related with the stronger southerly winds, and the high frequency accounted for 41%. The high and low frequency oscillations of the cross-shore wind component accounted for 44% and 47%, respectively. Such behavior can be explained by the sea breeze phenomena, and also by the coastline orientation, which is approximately north-south oriented.

TIME-LAG CROSS-CORRELATION (TLCC) ANALYSIS

According GARRET and TOULANY (1982), the basic technique to look for how the sea level is related to the local atmospheric pressure and wind stress is applying cross-spectral analysis. Nevertheless, a number of different approaches are possible, such as Time-Lag Cross-Correlation (TLCC) analysis. The TLCC analysis was firtly used to relate the atmospheric pressure and wind stress, and after that, to relate the relationship between these weather forcing to the sea level.The TLCC was also used between atmospheric pressure and sea level to assess how the IB approximation actuates for the present case, and was also used between wind stress and sea level to find out what wind direction causes maximum response in the low frequency band.

Atmospheric Pressure and Wind Stress

As the wind stress is a vector variable, the TLCC coefficient between atmospheric pressure p and the wind stress $\tau(\theta)$ for a given direction θ with respect to North and a given time lag κ, is $\rho_{p\tau(\theta)}(\kappa)$. It must consider all possible directions, which for the present case is -90° N ≤ θ ≤ 90° N. The maximum cross-correlation coefficient between atmospheric pressure and wind stress (Figure 2a) was -0.41 for a wind orientation of 37° and 16-hour lag. Despite the cross-correlation coefficient showed poor linear relationship, the obtained wind direction was pretty close of the WCT displacement direction, of about 45°.

Atmospheric Pressure and Sea Level

The maximum cross-correlation coefficient between atmospheric pressure and sea level was -0.64 for a 38-hour lag (Figure 2b). In the case of good agreement with the IB approximation, the best correlation coefficient should be about 1 and near of the zero-lag. In the present case, the zero-lag correlation coefficient was -0.14. In other words, the IB aproximation is not valid for the present case.

Wind Stress and Sea Level

The maximum cross-correlation coefficient between wind stress and sea level was 0.53 for a wind orientation of 12° and 10-hour lag (Figure 2c). This result show good agreement of the obtained wind direction with the local coastline orientation, about 20°, and suggest the direct response of the local low frequency oscillation to the Ekman mechanism: northerly winds lowering the sea level, and southerly winds rising it.

MULTIPLE LINEAR REGRESSION MODEL (MLRM) ANALYSIS

TLCC analysis evaluates only the linear relationship between pairs of variables. It does not allow the separation of the individual effect of each meteorological forcing, since atmospheric pressure and wind present inherent relationship between each other, and both play a role on the low frequency sea level oscillation. The application of Multiple Linear Regression Models (MLRM) is an improved method to estimate the linear relationships between wind and atmospheric pressure to the sea level in low frequency. This method allows to eliminate the interdependence of the time series (WUNSCH, 1972; GARRET and TOULANY, 1982; SCHWING *et al.*, 1988; TSIMPLIS and VLAHAKIS, 1994; GORING, 1995; TSIMPLIS, 1995; TSIMPLIS and SPENCER, 1997; BELL and GORING, 1998). This analysis was performed for the time and frequency domains.

Time Domain Analysis

The sea level response, $\eta(t)$, to atmospheric pressure, $P_a(t)$, and wind stress, $\tau_W(t)$, forcing can be estimated by a MLRM analysis in the time domain. In this analysis, $\eta(t)$ is assumed as the dependent variable, varying as function of cross-shore, τ_X, and long-shore, τ_Y, wind stress components, and atmospheric pressure, P_a, as:

$$\eta(t) = \beta_x \,.\, \tau_x(t-k_\tau) + \beta_y \,.\, \tau_y(t-k_\tau) + \beta_p \,.\, P_a(t-k_p) \qquad (2)$$

where k_τ and k_p are the wind stress and atmospheric pressure time lags, respectively, and β_x, β_y, and β_p are linear regression coefficients (GARRETT and TOULANY, 1982). The wind direction that is most effective inducing sea level changes can be obtained by:

$$\theta = \tan^{-1}\left(\beta_y / \beta_x \right) \qquad (3)$$

This angle maximizes the model response. For convenience, the wind stress given in N/m^2 was converted to 10^2 N/m^2 by multiplying by 100, since 1 mbar = 10^{2}N/m^2 or 10^{2}Pa.

Figure 3a shows the total variance explained by the models changing the lag of wind stress and atmospheric pressure. The best coefficients for the MLRM were extracted from the resulting matrix. The best sea level reconstruction was obtained with a 37-hour and 6-hour lags for atmospheric pressure and wind stress, respectively. The wind stress direction that maximizes the low frequency sea level explained variance was of about 0° N, which is close to the local coastline orientation. The obtained optimized model was:

$$\eta(t) = -0.0.\tau_x(t-6) + 1.6.\tau_y(t-6) - 1.9.P_a(t-37) \qquad (4)$$

The model could reproduce 56% of the low frequency variability of the sea level. According equation 4, a sea level rise of 1.9 cm could be expected after a 37-hour lag from a decrease

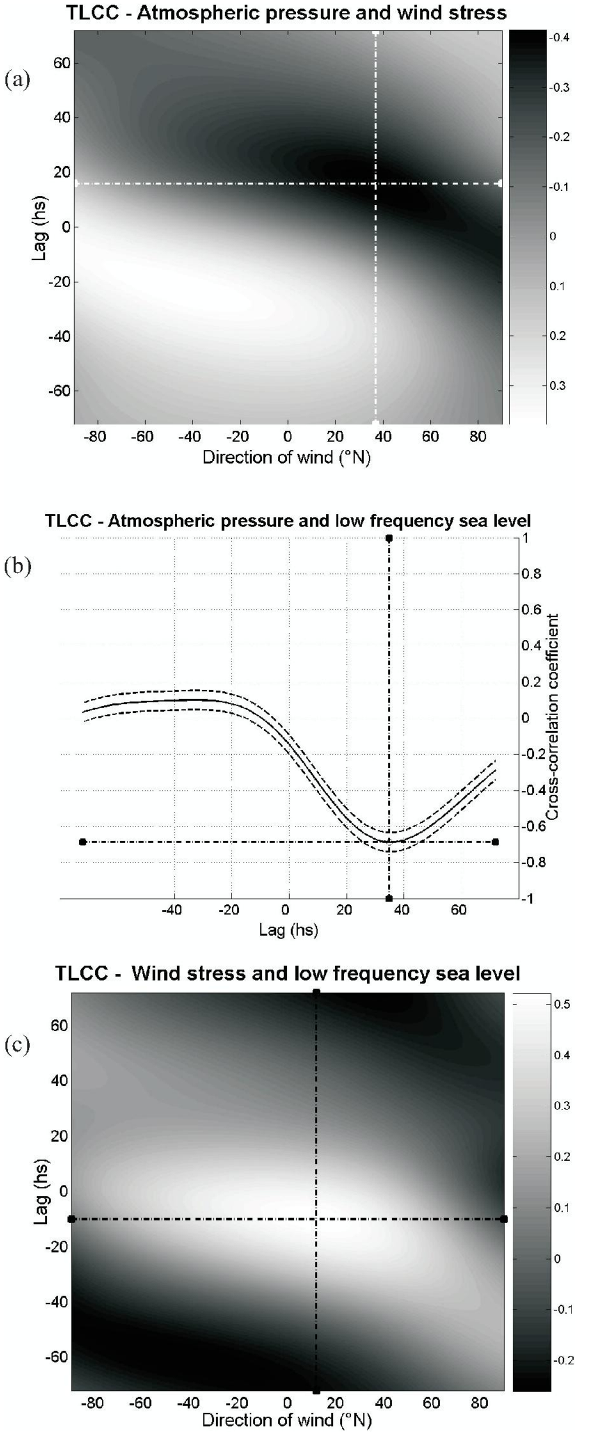

Figure 2. Time-Lag Cross-Correlation results of: (a) atmospheric pressure and wind stress; (b) atmospheric pressure and low frequency sea level; and (c) wind stress and low frequency sea level.

in 1 mbar of the atmospheric pressure. Similarly, the sea level could rise of 1.6 cm after a 6-hour lag from an increase in 10^2 Pa of the long-shore wind stress. The Figure 3b illustrates the predictive capability of the MLRM in the time domain. The model was more effective to reproduce positive oscillations, suggesting that the negative oscillations could be resulting of nonlocal meteorological and/or oceanographic effects. The inclusion of the IB approximation did no improve the model, which reinforce the findings using the TLCC analysis.

Frequency Domain Analysis

The linear relationship between a given frequency ω of sea level, $\eta(\omega)$,with the same frequency of the independent variables is given by:

$$\eta(\omega)=\beta_{\tau x}(\omega).\tau_x(\omega)+\beta_{\tau y}(\omega).\tau_y(\omega)+\beta_p(\omega).P_a(\omega)+\varepsilon \qquad (5)$$

The coefficients $\beta_{\tau x}$, $\beta_{\tau y}$ and β_p are now complex functions dependent of the frequency, with amplitude and phase that represent the magnitude and the lag of the sea level response to a specific meteorological forcing. The coefficients are obtained for any frequency by the solution of the system of equations:

$$\begin{aligned}
&\Phi_{\tau x,\tau x}.\beta_{\tau x}+\Phi_{\tau x,\tau y}.\beta_{\tau y}+\Phi_{\tau x,p}.\beta_p=\Phi_{\tau x,\eta}\\
&\Phi_{\tau y,\tau x}.\beta_{\tau x}+\Phi_{\tau y,\tau y}.\beta_{\tau y}+\Phi_{\tau y,p}.\beta_p=\Phi_{\tau y,\eta} \qquad (6)\\
&\Phi_{p,\tau x}.\beta_{\tau x}+\Phi_{p,\tau y}.\beta_{\tau y}+\Phi_{p,p}.\beta_p=\Phi_{p,\eta}
\end{aligned}$$

where $\Phi_{xy}(\omega)$ is the cross-spectrum between the variables (GARRET and TOULANY, 1982; SCHWING *et al.*, 1988; SCHWING, 1992; TSIMPLIS and VLAHAKIS, 1994; GORING, 1995). The spectral analysis was calculated using Welch method. Spectral results were averaged over 6 blocks of data with 23 days each, with overlap of 2 days, giving 12 effective degrees of freedom, or 21 independent frequencies with resolution of 0.023 cycles per day.

The atmospheric pressure, long-shore wind stress and sea level spectra showed that the most of variance were concentrated in the 5 to 10-day period. The coherence between them was maximized for the same periods (Figure 4ab). The model in the frequency domain could reproduce 84% of the low frequency sea level variance (Figure 4g). The residual variance accounted for up to 70% of the sea level variability in higher frequencies and less than 10% for the low frequency sea level variations as it was considered in this study (Figure 4h). Such results pointed out that the frequency domain model had great capability to reproduce the sea level only using local weather data.

The response of the sea level to the long-shore wind stress and atmospheric pressure can be analyzed by the amplitude and phase of $\beta_{\tau x}(\omega)$, $\beta_{\tau y}(\omega)$ and $\beta_p(\omega)$ coefficients, respectively (Figure 4cdef, $\beta_{\tau x}(\omega)$ not showed). The former indicated that the sea level could rise about 3 to 4 cm to an increase in 10^2 Pa of the wind shear stress after 10 to 12-hour lag. The latter indicated that the sea level could rise about 1.8 to 3.5 cm to a decrease in 1 mbar of the atmospheric pressure after 27 to 35-hour lag.

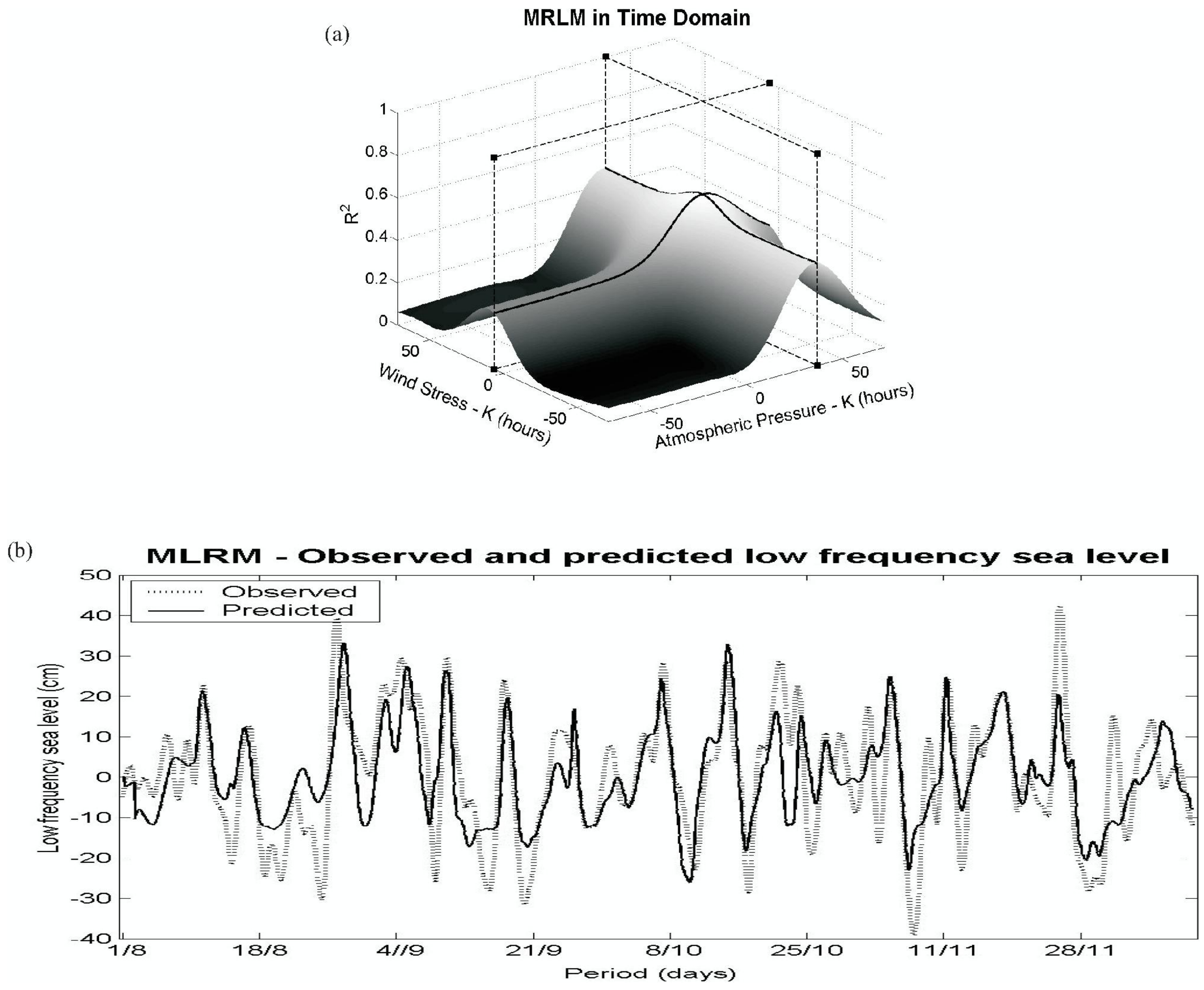

Figure 3. Results of MLRM in time domain: (a) statistical model; (b) observed and predicted low frequency sea level.

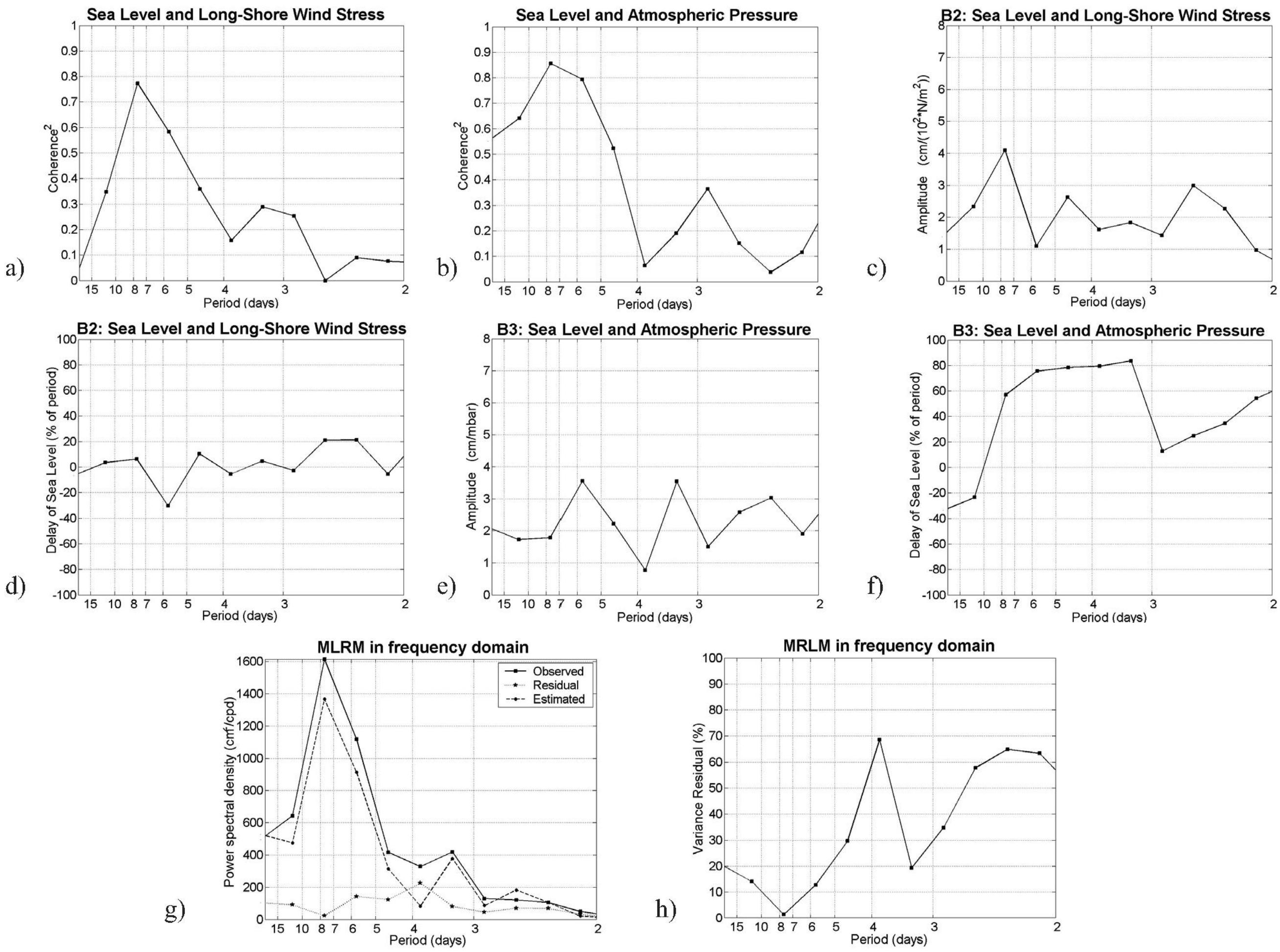

Figure 4. Spectral analysis and results of MLRM in frequency domain: (a,b) coherence between sea level and long-shore wind stress, and atmospheric pressure; (c,d,e,f) amplitudes and phases of $\beta_{\tau x}(\omega)$ and $\beta_p(\omega)$ coefficients, respectively; (g) power spectral density of observed, residual and estimated coastal sea level; and (h) residual variance.

CONCLUSIONS

In spite of limited observations in space and time, it was possible to assess the importance of low frequency sea level oscillations in the northern coast of Santa Catarina State, Southern Brazil, with considerable degree of confidence. It was demonstrated that in the case when high positive low frequency oscillations, which can be as high as 1 m, coincides with spring tide high water, extreme sea level heights can be expect representing potential flood hazards for nearshore areas. The main findings are summarized bellow:

(i) The low frequency oscillations during 1996 winter-spring season showed that the main atmospheric forcing that promotes the rise and fall of coastal sea level was the long-shore component of the wind stress at the coast, with the atmospheric pressure playing a secondary role.

(ii) The TLCC results pointed out that:

- the maximum response of the sea level was induced by local winds with orientation of 12°, nearly long-shore oriented to the coastline. The response of the sea level presented 10-hour lag to the wind stress. The cross-shore wind effect was negligible,
- the relationship between long-shore wind stress and sea level (12° and 10-hour lag, with the wind anticipating the sea level), and between the former and atmospheric pressure (37° and 16-hour lag, with the atmospheric pressure anticipating the wind), can be attributed to different scale processes. The former can be satisfactorily related to the Ekman mechanism, as it is well correlated to the coastline locally. The latter is better understood if attributed to the WCF displacement direction, which agree with the regional scale of the coastline.

(iii) The MLRM in time and frequency domain improved the understanding of the complex relationships between the variables as they allow to weigth the effects of each one. The main findings were that:

- the MLRM in time domain explained about 60% of the sea level variability, meanwhile the MLRM in the frequency domain explained 84%,
- the time domain model best fitted the observations with 37-hour lag to the atmospheric pressure and 6-hour lag to the long-shore wind stress. The most effective wind stress direction, that induced sea level oscillation was nearly 0°, corroborating with the TLCC results,
- the frequency domain model gave the best results about the sea level response with 10 to 12-hour lag to the long-shore wind stress and 27 to 35-hour lag to the atmospheric pressure.

(iv) The IB approximation was not observed in the data set. THOMPSON (1981) and PUGH (1987) suggested that when wind and atmospheric pressure relationship are significant locally, as it is in the present case, the IB could not be visible in the time series, or simply do not exist. On the other hand, the data set used in this study was representative only for winter and spring seasons, and the absence of IB approximation can be a matter of seasonality (GORING and BELL, 1993). The TLCC and MLRM results all indicated that the atmospheric pressure effect was higher than the expected from the isostatic value.

(v) The general results pointed out that the models had great capability to reproduce the low frequency sea level variability using only local weather data

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