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Tidal and Subtidal Propagation in Two Atlantic Estuaries: Patos Lagoon (Brazil) and Ria de Aveiro Lagoon (Portugal)

J. M. Dias† and E. H. Fernandes‡

† Universidade de Aveiro, Departamento de Física, 3810-193, Aveiro, Portugal jdias@fis.ua.pt

‡ Departamento de Física, Fundação Universidade Federal do Rio Grande (FURG), CEP 96201-900, Rio Grande - RS, Brazil, dfsehf@furg.br

ABSTRACT

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Processes affecting the exchanges between lagoons and the adjacent inner continental shelf are controlled by tidal and subtidal oscillations. Patos and Ria de Aveiro are coastal lagoons located on the southeast coast of Brazil and northwest coast of Portugal, respectively. In the Patos Lagoon the tidal regime is micro-tidal and the local and non-local wind forcing dominate the hydrodynamics, while in the Ria de Aveiro lagoon tides are meso-tidal and represent the main forcing. The main purpose of this study is to compare the propagation of tidal and subtidal oscillations throughout the access channel of the Patos Lagoon and the main channels of Ria de Aveiro Lagoon. Predicted time series of sea surface elevation (SSE) were obtained through modelling experiments for Patos Lagoon, while measurements of SSE were carried out in several stations distributed along the main channels of the Ria de Aveiro Lagoon, providing the data for this comparative study. The SSE time series were high-pass/low-pass filtered and the propagation of tidal and subtidal oscillations was estimated for both lagoons by shifting from the time domain into the frequency domain and applying spectral and cross-spectral analysis to the filtered SSE time series. Results indicate that tidal and subtidal oscillations are differently attenuated in these lagoons due to the different local and non-local forcing and to the morphology of the lagoons. This study also indicates that the proposed method is an efficient and alternative way of estimating tidal and subtidal attenuation in both micro- and meso-tidal coastal lagoons.

ADITIONAL INDEX WORDS: *Spectral and cross-spectral analysis, local and non-local forcing, tidal attenuation.*

INTRODUCTION

Coastal lagoons experience forcing from tides, river discharge, wind stress, precipitation-evaporation balance, and surface heat balance (KJERFVE, 1994), and respond differently to these forcing actions. Exchanges between lagoons and the adjacent inner continental shelf are controlled by tidal and subtidal oscillations. Tidal exchanges are continuous and predictable as they are periodic, but subtidal processes are less predictable as they are generated by meteorological forcing over time scales on the order of days. Subtidal water level fluctuations can be produced by non-local forcing (which includes coastal sea-level changes due to changes in barometric pressure and non-local wind), and local forcing (which includes local wind stress and freshwater inflow). KJERFVE and MAGILL (1989) concluded that currents and water level fluctuations are naturally attenuated in coastal lagoons characterized by a single entrance channel.

The main purpose of this study is to estimate the attenuation of tidal and subtidal oscillations throughout the access channel of the Patos Lagoon and the main channels of Ria de Aveiro Lagoon, in order to compare the propagation of these oscillations in two coastal lagoons with different characteristics.

STUDY AREAS

Patos and Ria de Aveiro are coastal lagoons located on the southeast coast of Brazil (30-32°S, 50-52°W) and northwest coast of Portugal (40º38'N, 8º45'W), respectively, and sheltered from the Atlantic Ocean by complex coastal barrier systems (Figure 1).

Ria de Aveiro is the most extensive coastal lagoon in Portugal, and has a very irregular and complex geometry, characterized by narrow channels and large areas of mud flats and salt marshes. The morphology of the lagoon can be described as an arborescent system of channels with a single connection with the sea, which has a high longitudinal development organized in four main branches radiating from the sea entrance (Figure 1). The lagoon is 45 km long and 10 km wide, covering an area of 83 km^2 at high tide (spring tide), which is reduced to 66 km^2 at low tide. The average depth of the lagoon is about 1 m, except in the navigation channels. The only connection with the sea is through a 1.3 km long and 350 m wide channel. Freshwater contributions come from two rivers, Antuã (5 m^3s^{-1} average flow) and Vouga (50 m^3s^{-1}) (MOREIRA *et al.*, 1993; DIAS *et al.*, 1999). Tidal forcing controls the water exchange between the lagoon and the ocean. Tides are semi-diurnal with a small diurnal pattern and mean tidal range of about 2.0 m (DIAS *et al.*, 2000), reaching minimum and maximum tidal ranges of 0.6 and 3.2 m, respectively, during spring tide (DIAS, 2001). Thus, Ria de Aveiro is classified as a mesotidal lagoon (DAVIES, 1964).

The Patos Lagoon is the largest choked coastal lagoon in the world (KJERFVE, 1986). With a length of 250 km and average width of 40 km, the lagoon has a surface area of 10,360 km^2, and can be classified as a shallow lagoon since it has an average depth of 5 m. Cells limited by shallow sand spits mark the morphology of the lagoon, connected to the South Atlantic Ocean through a 20 km long and less then 1 km wide single inlet. The rivers that flow into the lagoon have a catchment area of 201,626 km^2. They exhibit a typical mid-latitude flow pattern (high discharge in late winter and early spring, and low to moderate discharge through summer and autumn), with mean annual freshwater contribution of 2000 $m^3 s^{-1}$. The lagoon is microtidal and tides are mixed, mainly of the diurnal type, with mean tidal amplitude of 0.47 m. The principal tidal constituent O_1 (period 25.8h) has amplitude of 10.8 cm. Several hydrodynamic studies carried out in the lagoon and in its estuarine area during the last decade present a thorough investigation of the main forces controlling the dynamics of the system (FERNANDES et al., 2001; 2002; in press; MOLLER *et al.*,

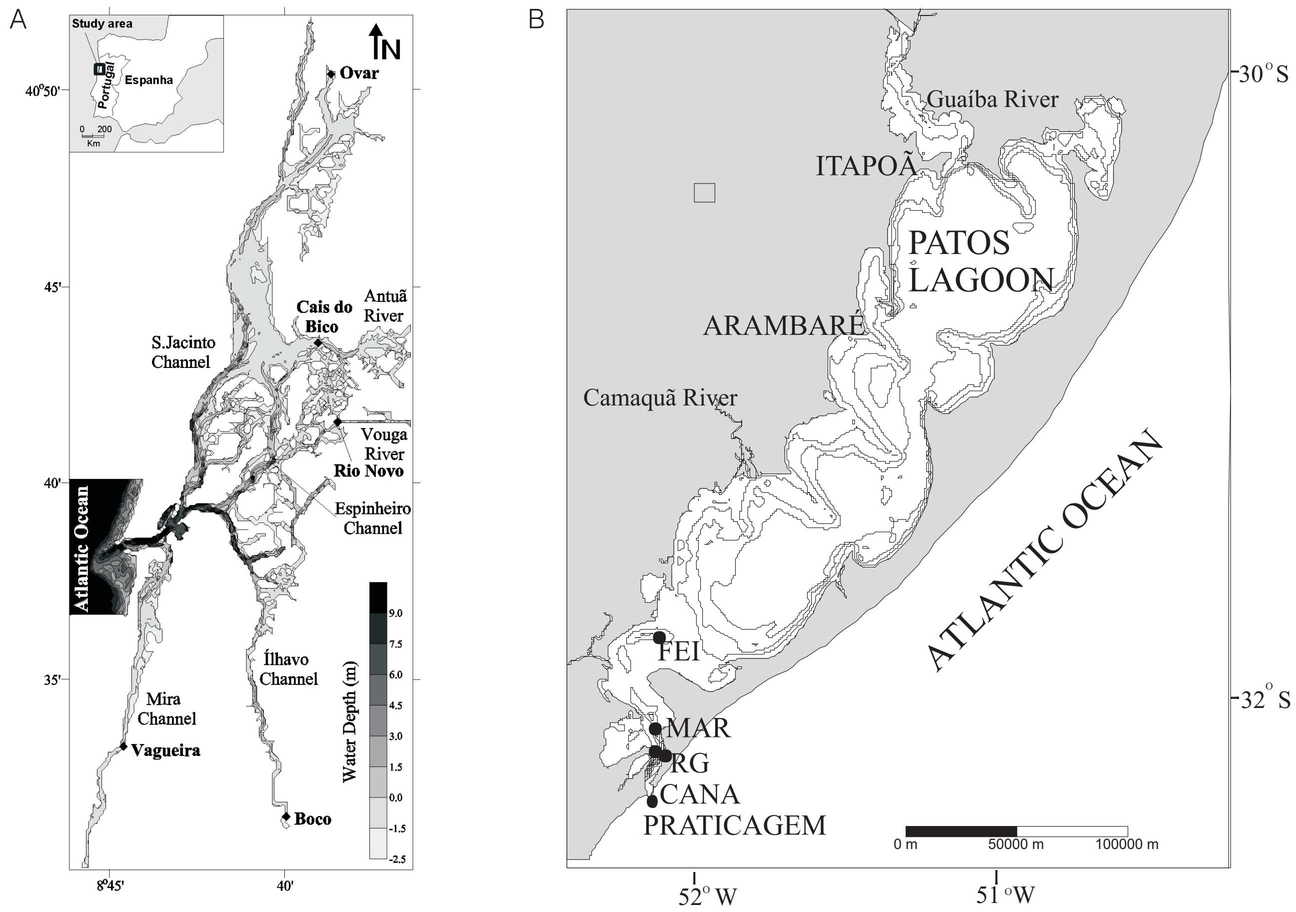

Figure 1. The Ria de Aveiro Lagoon (A) and Patos Lagoon (B), with the location of sea surface elevation stations used in this work.

1996; 2001). They observed that the dynamics of the system is essentially dependent on the wind and on the freshwater discharge.

METHODS

The SSE data used for this comparative study of the attenuation of tidal and subtidal oscillations in Patos and Ria de Aveiro lagoons was obtained from modelling and field experiments, respectively. Modelling experiments used to study the attenuation of tidal and subtidal signals in the Patos Lagoon estuary are presented in FERNANDES *et al.* (In press). Hourly SSE time series for Ria de Aveiro were measured throughout the main channels in 1987 and 1988 by the Instituto Hidrográfico, using temporary tide gauge stations (INSTITUTO HIDROGRÁFICO, 1991).

The time series of SSE from stations located at the ocean boundaries and at several stations throughout the Patos Lagoon access channel and Ria de Aveiro main channels were high-pass/low-pass filtered (Fast Fourier Transformation technique FFT), considering a cut-off frequency of 0.0000093 Hz (30h), in order to separate the high frequency signal (tidal oscillations) and the low frequency signal (subtidal oscillations). Spectral analysis (8 Hanning windows) was applied in time series of SSE. The energy spectrum obtained with data from the ocean boundary was used as a reference to compare with the energy spectrum obtained throughout different stations. This comparison provides an alternative way of estimating the attenuation of the tidal and subtidal signals in different frequencies as progressing landwards. The coherence and phase between the signal at the ocean boundary and at different stations inside the lagoon was studied by applying cross-spectral analysis (8 Hanning windows) at the obtained high and low frequency time series of SSE. This procedure was applied in data from both lagoons, providing the base for the proposed comparative study. FERNANDES *Et al*. (In press) present more details about this alternative method.

RESULTS AND DISCUSSION

Figure 2 presents results from the spectral analysis carried out with data from the station located at the mouth (column 1) and throughout the main channels of the Ria de Aveiro lagoon for concurrent periods (column 2), and the cross-spectrum, coherence and phase spectra for the same data set decomposed into tidal (column 3) and subtidal frequencies (column 4). The overall results from the spectral analysis indicate that processes at the semi-diurnal (SD) frequency dominate the tidal forcing at the mouth of the lagoon (column 1), although diurnal (D) and quarter-diurnal (QD) tidal frequencies also have to be considered. The energy spectrum for stations located throughout the main channels (column 2) present similar patterns, although the energy associated with D and SD frequencies is lower than at the mouth, showing that these tidal oscillations are progressively attenuated as they propagate landwards (this attenuation is quantified in Table 1). The energy on QD frequencies for the stations is always higher than at the mouth, indicating that these frequencies are amplified inside the lagoon.

Results also indicate that subtidal processes are usually less energetic than the tidal oscillations, except in situations of extreme weather events, when the subtidal frequencies are amplified along the channels. The data from Ovar and Cais do Bico stations, for example, present high energy values at the low frequencies because it was obtained during the occurrence of a rare storm surge event observed at the Portuguese coast, which had an amplitude of approximately 0.80 m. The high subtidal energy observed at Rio Novo is explained by the rainy season.

The co-spectrum, coherence and phase spectra show that the time series of water elevation measured at the mouth and at

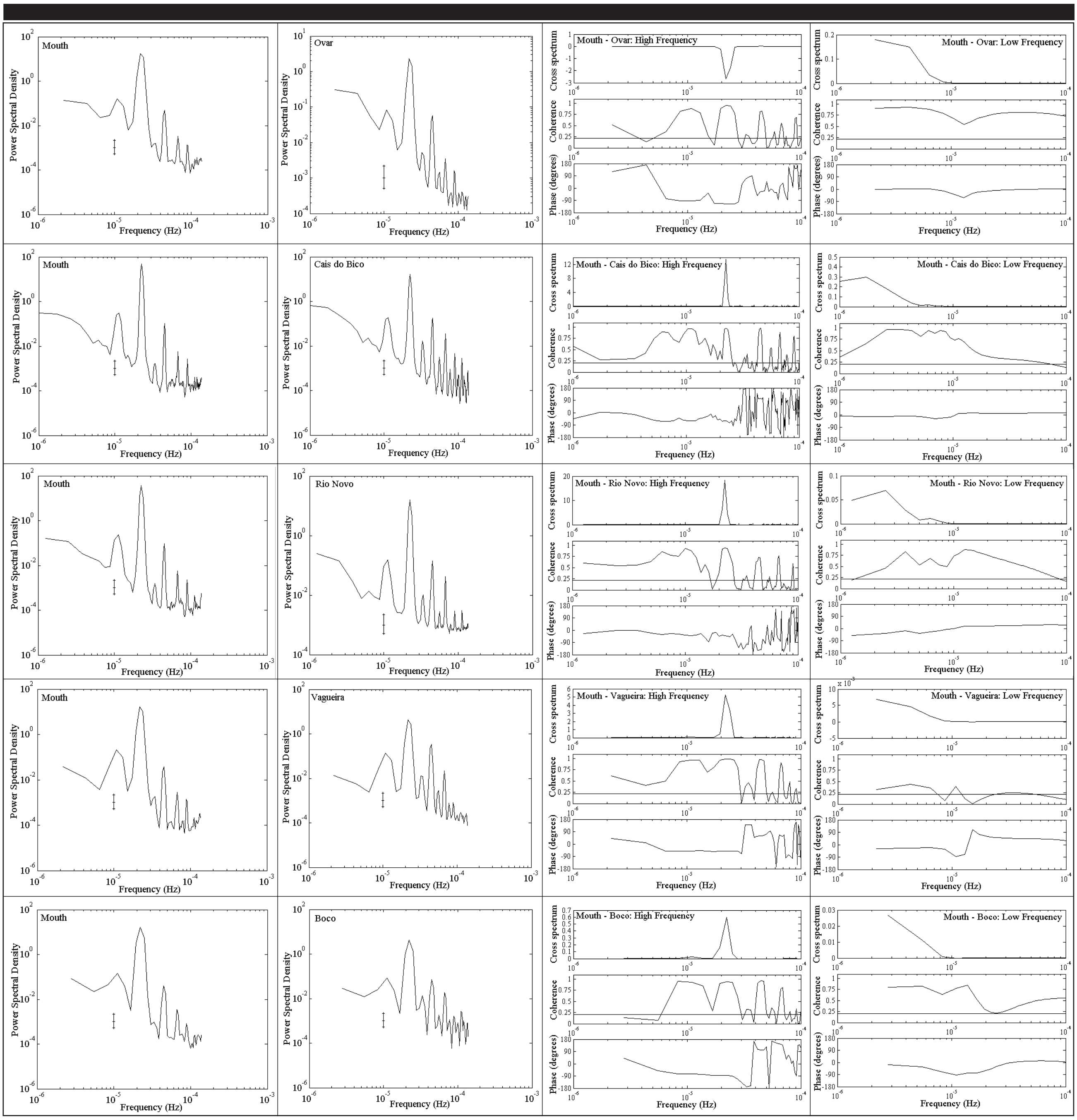

Figure 2. Spectrum and cross spectrum results for the Ria de Aveiro experiment. The vertical error bar in the spectrum indicates a 95 % confidence level and the horizontal line in the coherence spectra indicates the 95% significance level.

each station have a coherence level of almost 1 at the tidal frequencies. At these frequencies the co-spectral density function indicates that the oscillations at the mouth and at each station are well correlated, in particular at the SD frequencies. The coherence for Ovar, Cais do Bico and Rio Novo are also almost 1 at the frequencies of interest. Results for Boco, and particularly for Vagueira, however, show lower coherence, although it is still above the 95% significant level.

Table 1 presents a summary of the tidal and subtidal attenuation/amplification determined from spectral analysis and the phase delay between the mouth and landward stations obtained from cross-spectral analysis. Results show that the SD and D frequencies are strongly attenuated from the mouth to the far end of the channels, and that there is a significant phase delay between the mouth and each station. These results are in agreement with numerical results presented by DIAS *et al.* (2000) and DIAS (2001). They observed that the tidal amplitude decreases and the phase lag increases from the mouth towards the far end of the channels. Ria de Aveiro is a very shallow lagoon with a very complex geometry and by these reasons distortion occurs as the tidal wave propagates along the shallow channels. The strong currents that develop in the shallow water face resistance due to bottom friction, a process that removes much of the propagating tidal energy, and reduces the wave amplitude. Irregular channel lines and varying depths impose multiple wave reflections and interactions that generate multiple frequencies.

Results for the QD frequencies show that these frequencies are highly amplified as the tide propagates along the Ria de Aveiro channels and that there is a significant delay between the mouth and each station. These results are consequence of the complex geometry and shallowness of this lagoon. In these conditions the tidal wave progression is modified by bottom friction and multiple wave interactions due to reflection. The resulting distortions are proportional to the square of the tidal water level, determined by the SD and D dominating frequencies, and are expressed as simple harmonic constituents with frequencies corresponding to the fourth-diurnal species (PUGH, 1987).

At subtidal frequencies, the pattern obtained for Ria de

Table 1. *Tidal and subtidal attenuation / amplification (negative values) and phase delay throughout the Patos Lagoon (summer period) and Ria de Aveiro Lagoon. D diurnal, SD semi-diurnal, QD quarter diurnal and LP long period frequencies. The calculated % is determined from the ratio between the spectral density function at the mouth and at each station, and the phase delay was obtained through cross-spectral analysis.*

	Attenuation / Amplification (%)				Phase Delay (º)			
	D	SD	QD	LP	D	SD	QD	LP
CANA	7.0	13.0	25.0	0	-2	-3	-7	0
CANB	14.0	20.0	38.0	0	-6	-3	-10	0
RG	15.0	20.0	40.0	0	-7	2	-12	0
MAR	75.0	100.0	100.0	23	No significance	No significance	No significance	-160º
FEI	83.0	100.0	100.0	64	No significance	No significance	No significance	-150º
Ovar	49.4	86.8	-17.8	-128.2	35	115	28	4
Cais do Bico	40.9	65.4	-75.6	-110.7	45	60	257	12
Rio Novo	26.1	52.8	-66.7	-36.4	38	39	148	35
Vagueira	36.2	74.1	9.4	63.0	50	50	305	27
Boco	42.1	73.9	-75.0	67.1	75	85	257	18

Aveiro is dictated by weather events. Standard conditions in the lagoon present small river discharge and no effect of the non-local wind on the behaviour of sea surface elevation. Thus, small subtidal energy is observed at the mouth, being attenuated along the lagoon channels, as shown for Vagueira and Boco. In events of high river discharge, as observed for Rio Novo station, the subtidal energy at the places located under the direct influence of freshwater discharge (from Vouga river in this case) is high. This subtidal energy is attenuated along Espinheiro Channel, although presenting higher values at the mouth than in standard conditions. Results for Ovar and Cais do Bico, on the other hand, were obtained during the occurrence of a rare storm surge at the Portuguese coast, and by this reason the subtidal energy at the mouth is abnormally high. This long period oscillation also propagates along Ria de Aveiro, being largely amplified.

FERNANDES *et al*. (in press) discuss in detail the attenuation of tidal and subtidal oscillations throughout the Patos Lagoon estuary. Figure 3 illustrates the attenuation of the tidal signal in the area during the summer (1992) obtained using spectral and cross-spectral analysis.

The attenuation of the tidal signal is estimated based on the comparison between the energy spectra obtained for the ocean boundary (used as a reference, where the power spectral density were 0.22, 0.075, 0.077, 0.325 at the diurnal, semi-diurnal, quarter-diurnal, and long period frequencies, respectively) with the energy spectrum obtained for the stations located throughout the estuary. The overall results from the spectral analysis (Figure 3, first column) indicate progressive attenuation of the tidal signal in the lower estuary (until RG, Figure 1), with the predominance of processes at the diurnal (D) frequency. The tidal signal becomes negligible at MAR station (Figure 1). The indication of a new pick in a higher frequency confirms that the dynamics of the middle estuary is mainly driven by the local forcing generated by the freshwater discharge from the main lagoon and the local wind effect, being fairly affected by the remote forcing.

Results also indicate that QD and SD oscillations are more attenuated than the D oscillations. Table 1 illustrates this pattern by presenting the calculated % of attenuation based on the ratio between the spectral density function at the mouth and at several stations throughout the Patos Lagoon estuary.

Results from the cross-spectral analysis presented in Figure 3 indicate that the time series of water elevation prescribed at the mouth and the calculated elevations at CANA, and RG are in phase and have a coherence level of almost 1 at all frequencies of interest. Cross-spectral results for MAR presented very small values of the co-spectrum with coherence values well below the 95 % significance level, indicating that the SSE time series at the mouth is essentially uncorrelated to the modelled time series at MAR (as indicated by the spectral results for this station).

Results for the subtidal frequency presented in Table 1 also indicate a high correlation between the prescribed subtidal signal at the mouth and the water elevation calculated for CANA, CANB and RG, where the subtidal oscillations travel without attenuation. On the landward stations (MAR and FEI) however, the coherence decreases significantly (not shown), indicating that the influence of the prescribed low frequency oscillations in these areas is small. The phase spectra indicate that the low frequency oscillations at the ocean boundary are out of phase by 160 and 150 degrees from those at MAR and FEI, suggesting the existence of a node in that area. MOLLER *et al.* (2001) also observed that the upper estuary behaves as a nodal point where the pressure gradient conditioned by the wind has its sign changed, and the water elevation reaches its maximum and minimum values.

The overall results for the Patos Lagoon clearly indicate that the attenuation of the tidal and subtidal oscillations is strongly related to the geomorphology of the system. The tidal and subtidal signals are progressively attenuated in the lower estuary, but once the system becomes wider and shallower, the energy of the propagating tidal and subtidal signals are significantly dissipated due to friction.

CONCLUSIONS

Tidal and subtidal oscillations are differently attenuated in the Patos and Ria de Aveiro lagoons due to differences in the local and non-local forcing and in the morphology of each system. In the Patos Lagoon the tidal signals are progressively attenuated throughout the access channel, and the subtidal energy prescribed at the ocean boundary is stronger and propagates further than the tidal energy. For Ria de Aveiro Lagoon the tidal energy is stronger than the subtidal energy, propagating into the far end of the channels, and the semi-diurnal and diurnal tidal signals are similarly attenuated whereas the quarter-diurnal signal is essentially generated inside the lagoon. The subtidal energy is usually very low, however the energy associated with sporadic extreme weather events connected with coastal sea-level changes or high river discharge is amplified along the lagoon channels.

This study indicates that the method proposed by FERNANDES *et al*. (In press) for estimating the propagation of tidal and subtidal oscillations throughout the access channel of a micro-tidal choked coastal lagoon dominated by wind forcing is also an alternative way of estimating such attenuation in a meso-tidal coastal lagoon. Moreover, it is clear that this method can be applied on both modelling predictions and measurements of SSE carried out throughout the access channel of coastal lagoons.

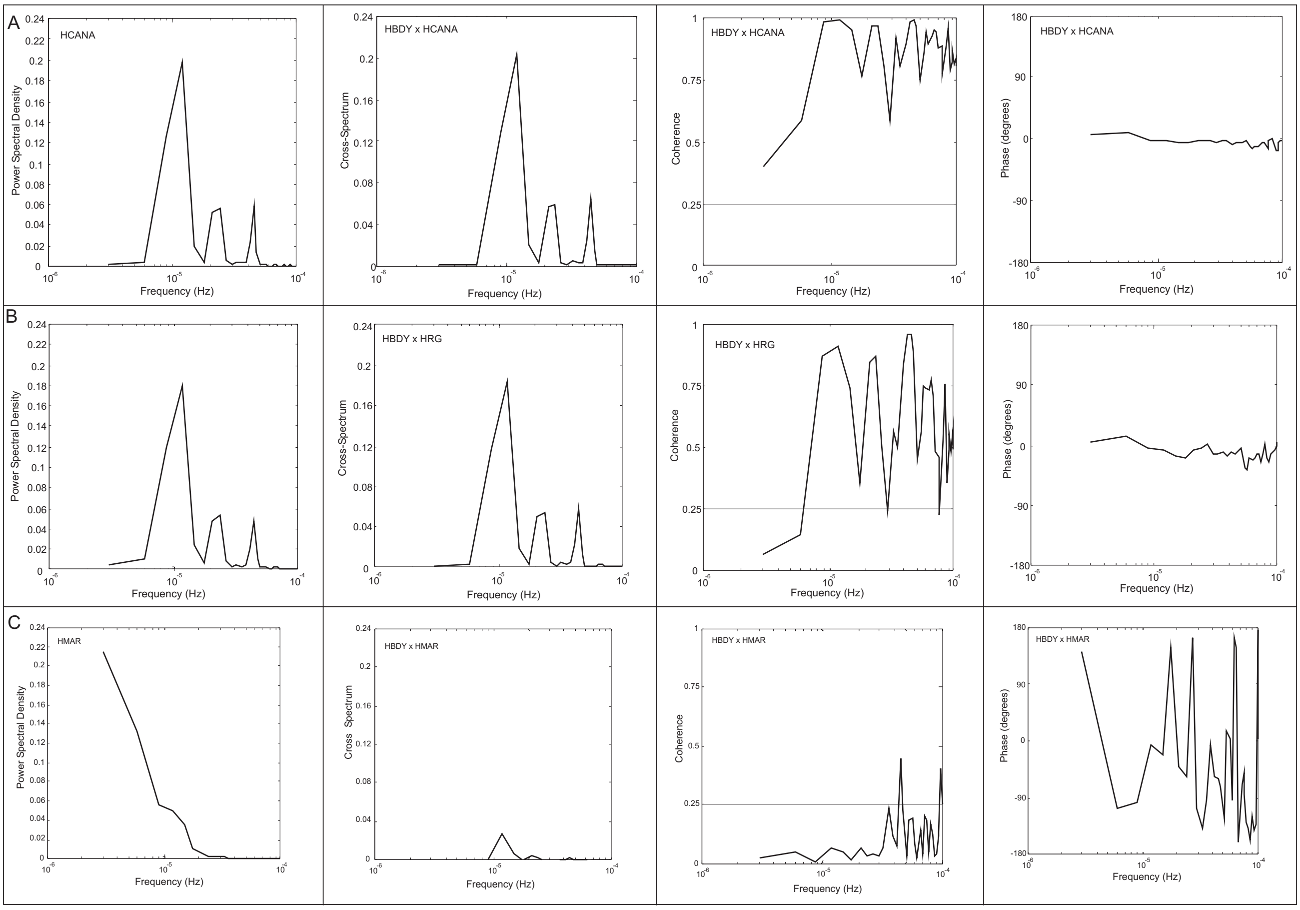

Figure 2. Spectrum and cross spectrum results for the Ria de Aveiro experiment. The vertical error bar in the spectrum indicates a 95 % confidence level and the horizontal line in the coherence spectra indicates the 95% significance level.

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