The relation between subtidal sea level fluctuations and atmospheric forcing in the Bahia Blanca Estuary, Argentina

MSc. Traineeship report

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Summary

This report deals with the results of a traineeship carried out as part of the MSc. program of Physical Geography at the Faculty of Geographical Sciences at Utrecht University.

In this report, a review is presented of the tidal characteristics in the Bahia Blanca Estuary, a mesotidal coastal plain estuary in the southwest of the Buenos Aires Province, Argentina. In the research, time series of sea level observations from three coastal stations in the Bahia Blanca Estuary, covering a full year time span, were examined. The tidal signal and the tidal constituents were calculated from the time series with the Godan program. It showed that M2 is the most important main constituent, and that the shallow water tides increase considerably from the mouth to the head of the estuary. Descriptive statistics applied to the sea level time series showed that the tidal wave is asymmetric, with asymmetry increasing from the mouth to the head of the estuary.

Also in this report, a review of the characteristics of the subtidal sea level fluctuations in the Bahia Blanca Estuary is presented. The subtidal sea level fluctuations were examined with harmonic analysis. It showed that fluctuations with large periods (>25 days) predominated in the subtidal sea level spectra, and that minor peaks occur at 0.08, 0.12 and 0.20 cycles per day. The subtidal sea level fluctuations at the three coastal stations coincide to a high degree, especially for the two stations that are located along the tidal channel.

The relation between subtidal sea level fluctuations and atmospheric forcing in the Bahia Blanca Estuary is further examined. To determine this relation, a wind stress time series was calculated from wind speed and wind direction data measured at a meteorological station in the Bahia Blanca Estuary during the same period. Next, the relation between subtidal sea level fluctuations and wind stress was quantified by cross spectrum analysis. It showed that the relation is significant with a confidence level of 95%. In terms of coherence, this relation is strongest for winds blowing from the NE, the direction in which the strongest winds were recorded. Southern cross-shore winds coming from the Bahia Blanca Estuary generally lead to a set up. Northern and northeastern cross-shore winds coming from the Pampas generally cause a set down.

Preview

As part of the MSc. program of Physical Geography at Utrecht University, a traineeship was carried out during the spring of 2001 at the IADO (Instituto Argentino de Oceanografia), Bahia Blanca, Argentina. The traineeship focussed on coastal processes and morphology. It was supervised by Prof.Dr. Piccolo (IADO) and Dr. P. Hoekstra (Utrecht University). During the traineeship, a database of sea level and meteorological observations covering a full year time span was examined. This report is the result of the analysis of this database.

Hereby I want to thank my supervisors, Dr. P. Hoekstra and Dr. M.C. Piccolo for their assistance. I welcome any further comments.

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1. Introduction

1.1 General Background

The Bahia Blanca Estuary is a mesotidal coastal plain estuary in the southwest of the Buenos Aires Province, Argentina (figure 1.1). The morphology of the northern part of the estuary is dominated by a large tidal channel, called Principal Channel. The Principal channel has a total length of 60 km from head (near Galván) to mouth (near Punta Tejada). Both depth and width increase considerably over this distance.

Three coastal stations are present in the Bahia Blanca Estuary (figure 1.1): Puerto Ingeniero White and Puerto Belgrano (located on the northern shore of the Principal Channel) and Oceanic Tower (located on the inner continental shelf, several kilometers offshore of the mouth of the Principal Channel). The latter coastal station represents open water conditions, while the former two show typical estuarine features.

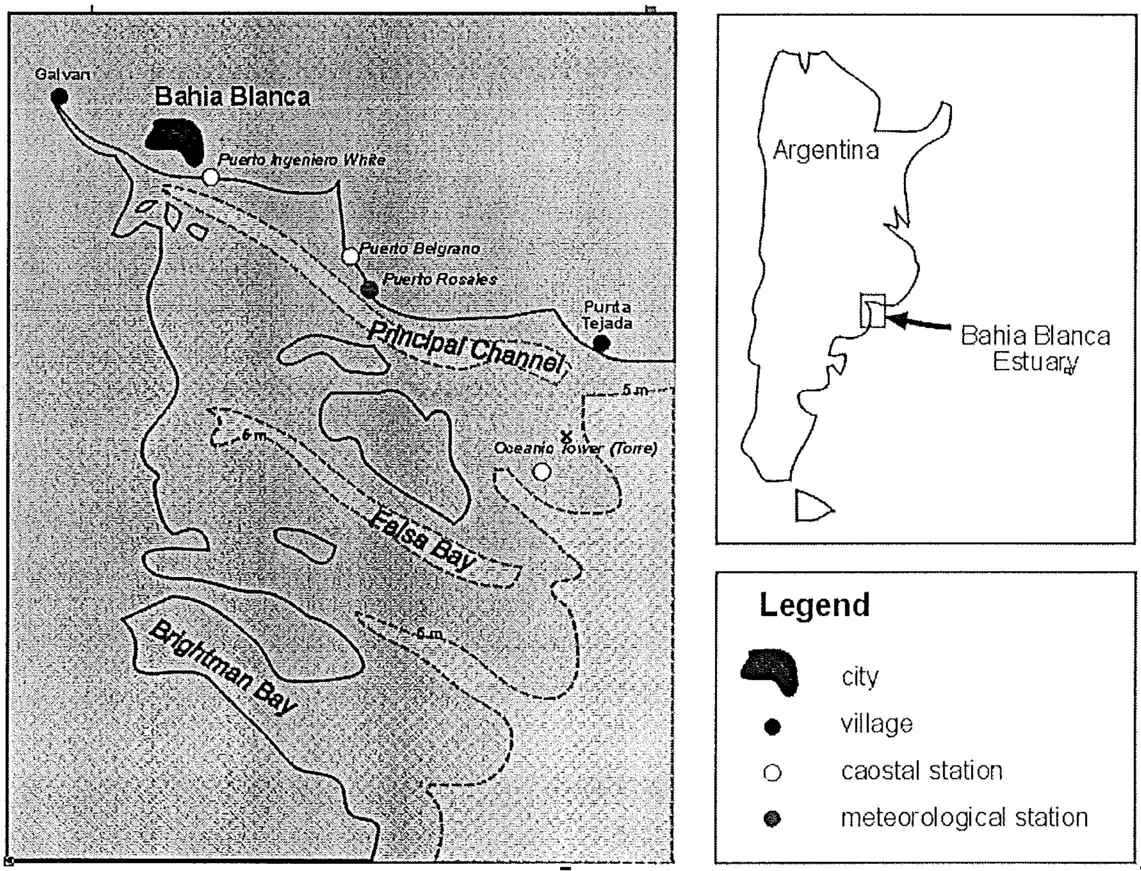

Figure 1.1: Location map of the Bahia Blanca Estuary. The three coastal stations are Puerto Ingeniero White, Puerto Belgrano and Oceanic Tower, the meteorological station is at Puerto Rosales.

The tides in the Bahia Blanca system are characterized by a standing, semidiurnal wave (Perillo et al, 2000). The prevailing winds and the geomorphology of the area play a major role in modifying the tidal wave (Perillo and Piccolo, 1991).

The significance of subtidal sea level fluctuations (periodic fluctuations with periods larger than those of the tides) have been extensively studied since the mid 70-ties (e.g. Brooks 1977, Chao and Pietrafesa 1980, Wang and Elliot 1978, Wong 1986 and Wong and Wilson 1984). In many cases atmospheric forcing, especially wind stress, is the major cause of these fluctuations.

1.2 Problem definition and relevance

Only few research has been carried out on the tides and non-tidal fluctuations in the Bahia Blanca Estuary. The most extensive study is Perillo and Piccolo (1991). This study showed that the maximum deviation from the tidal signal at the three coastal stations coincided with winds blowing from the NW (maximum set down) and SW (maximum set up). However, this research is biased since wind stress was not taken into consideration in the analysis. Furthermore, the relationship between winds and subtidal sea level fluctuations was determined by descriptive statistics. Only for one coastal station (Puerto Ingeniero White) it was quantified in terms of coherence.

In the study mentioned above, power spectra of subtidal sea level were calculated from sea level time series of only two coastal stations (Puerto Ingeniero White and Oceanic Tower). These time series consist of hourly observations for a period of four months. So far, long and continuous sea level time series with frequent observations were not available for research. Therefore, detailed research on the subtidal fluctuations in the Bahia Blanca Estuary (or any other location at the Argentine coast) has not yet been carried out. As a result, the relation between the subtidal sea level fluctuations and atmospheric forcing in the Bahia Blanca Estuary is still hardly known.

A detailed research of the subtidal variability in water level is quite important for understanding the circulation, transport and mixing processes in the Estuary. It is also important for understanding other low-frequency processes in the Bahia Blanca estuary. For example, subtidal motion is very important since it determines a large percentage of the long-term transport of suspended and dissolved matter. Furthermore, a better understanding of the tides and subtidal variability will certainly be useful in solving the pollution and dredging problems of the region.

Recently, a large dataset (sea chapter 3) of simultaneous sea level time series from *three* coastal stations (Puerto Ingeniero White, Puerto Belgrano and Oceanic Tower) together with a meteorological time series (from Puerto Rosales) is available. These time series cover a full year.

1.3 Goal and research questions

The aim of this study is to examine the characteristics of sea level fluctuations (tidal and non-tidal) at the northern shore of the Principal Channel in the Bahia Blanca Estuary, and to document the forcing mechanisms responsible for the subtidal variability. The research questions are:

1. What are the characteristics of the tidal wave in the Bahia Blanca Estuary, in terms of tidal range, asymmetry, duration of flood and ebb and phase lag, and what are the amplitudes and (Greenwich) phase lags of the tidal constituents?
2. What are the monthly fluctuations in mean sea level, mean high tide and mean low tide? What are the spectral peaks of the subtidal sea level fluctuations? How is the relation between the subtidal sea level fluctuations between the different coastal stations, and how can the differences be explained?
3. What are the characteristics of the winds in Bahia Blanca Estuary, in terms of dominate and strongest wind direction? What are the spectral peaks of the wind stress fluctuations, and which wind direction causes the largest part of the wind stress variance?
4. Can one define the relation between the subtidal sea level fluctuations and the meteorological data (wind speed and direction)?

2. Literature review

2.1 Tidal signal

The tidal signal is the so called predicted astronomical tide. It is the sum or composite result of tidal astronomical components, called tide generating constituents or tidal constituents. The periods of the tidal constituents are constants, but the amplitude (A) and Greenwich phase lag (ϕ) are variable. The Greenwich phase lag (ϕ) is the difference between the astronomical argument for Greenwich (UK) and the phase of the observed constituent signal.

There are over 300 tidal constituents, with M2, S2, N2, K2, K1 and O1 often being the most important. Two types of tidal constituents can be distinguished: main constituents and shallow water tides. The main constituents directly correspond with one of the relative astronomical motions between earth, sun and moon. In deep ocean waters they make up for almost 100% of the tidal signal. However, in shallow water the tidal wave will show a deformation. Because the speed of propagation of a progressive wave is approximately proportional to the square root of the depth of water in which it is traveling, shallow water has the effect of retarding the trough of a wave more than the crest. This results in tidal asymmetry. The deformations can be expressed as a Fourier series by adding higher harmonic tides, known as partial tides or shallow water tides (Foreman, 1977).

2.2 Non-tidal sea level fluctuations

Non-tidal sea level fluctuations are the deviations in the recorded/observed sea level from the predicted astronomical tide. The non-tidal fluctuations in an estuary can be locally induced by five factors: morphology, atmospheric and meteorological forcing, river runoff, salinity gradients and higher order, non-local phenomena through a coupling with a coastal ocean (Wang and Elliot, 1978).

A) Morphology

The propagation of the tidal wave though an estuary is affected by the geometry of the channels and tidal flats. The effects of geomorphology on the tidal wave include reflection, convergence and bed friction. Bed friction drains energy from the tidal wave and leads to a reduction in amplitude and phase shift between the horizontal and vertical tide (and thus tidal asymmetry). Convergence produces an increase or decrease of the amplitude. Reflection of the tidal wave on the channel flanks and the head of the estuary may lead to resonance, and converts the original progressive form to a standing wave. Theoretically this occurs when the length of the channel is at least one fourth of the wavelength of the tide.

B) Atmospheric and meteorological forcing

Atmospheric and meteorological effect include atmospheric pressure and winds. Changes in atmospheric pressure generally produce a set up or set down in sea level. The inverse barometer effect is 1.01 cm of water height per millibar of atmospheric pressure (Chao and Pietrafesa, 1980). Winds produce waves (supratidal sea level fluctuations) and a set up/set down in mean water levels (subtidal sea level variations). Supratidal sea level fluctuations are periodic fluctuations with much periods smaller than those of the tides, and subtidal sea level fluctuation have larger periods than those of the tides.

C) River runoff

River runoff generally produces a phase shift between the horizontal and vertical tide, causing tidal asymmetry. Furthermore, input of fresh water also effects the salinity.

D) Higher order, non-local phenomena through a coupling with the coastal ocean

Higher order, non-local phenomena include seasonal variations in the strength of offshore currents, upwelling and water temperature.

2.3 Spectral analysis

Spectral analysis can be applied to decompose the sea level time series into underlying sine and cosine functions of different frequencies, in order to determine those that appear particularly strong or important. The computational problem of fitting sine and cosine functions of different frequency (f) to the time series can be considered in terms of multiple linear regression. Here the dependent variable is the time series (the observed sea level), and the independent variables are the sine and cosine functions of all possible (discrete) frequencies. Such a linear multiple regression model may be written as:

$$x_t = a_0 + \Sigma\,(a_k\cos(2\pi ft) + b_k\sin(2\pi ft)), \qquad \text{for } k=1 \text{ to } q$$

Here x_t is the amplitude of the sea level time series and f is the frequency. a_k and b_k are the cosine and sine parameters, that tell us the degree to which the respective functions are correlated with the data. There are as many sinusoidal waves as there are data points. The periodogram and spectral density are measures for the degree that a certain frequency is present in the time series.

The periodogram values can be computed as the product of the squared sine and cosine parameters and the number of cases divided by two. If the periodogram value (p_k) is large, one can conclude that there is a strong periodicity of the respective frequency in the time series. The periodogram values can be interpreted in terms of variance (sums of squares) of the data at the respective frequency or period.

The spectral density estimates are computed by smoothing the periodogram values with a weighted moving average. By doing this, one may identify the general frequency "regions" that significantly contribute to the cyclic behaviour of the time series.

2.4 Physical characteristics of the Bahia Blanca estuary

The Bahia Blanca Estuary is a mesotidal coastal plain estuary in the southwest of the Buenos Aires Province, Argentina (figure 1.1). The area extends over 2300 km^2, and comprises several NW-SE orientated tidal channels, extensive intertidal flats and some islands. The morphology of the northern part of the estuary is dominated by a large tidal channel, called Principal Channel (figure 1.1). The Principal channel has a total length of 60 km from head (near Galván) to mouth (near Punta Tejada). Both depth and width increase considerably over this distance. The depth of the Principal Channel increases from about 3 to 22 m, and width from about 0.2 to 3-4 km (Perillo et al, 2000). At the sea side, the Principal Channel ends in a modified ebb tidal delta (Cuadrado and Perillo, 1997).

The tides in the Bahia Blanca system are characterized by a standing, semidiurnal wave (Perillo et al, 2000), respectively. The mean tidal amplitude varies between 3.5 and 2.2 m at the head and mouth of the estuary (Perillo and Piccolo, 1990). This corresponds with a meso-tidal regime (Davies, 1964). The Bahia Blanca estuary is a hypersynchronous-type estuary, as the tidal amplitude increases from mouth to head. This indicates that convergence is dominant over friction. The original progressive form of the tidal wave is converted into a standing wave as a result of reflection on the channel flanks and the head (Perillo and Piccolo, 1990). The factors river runoff and salinity can be considered negligible to explain the non-tidal sea level fluctuations in the BB estuary, because of the low discharges of tributaries to the Bahia Blanca estuary (Perillo and Piccolo, 1990) and the well-mixed characteristics of the outer region of the estuary (Piccolo et al., 1987). Kelvin waves have not been observed in the Bahia Blanca estuary. The estuary is probably to small and there are to many tidal flats for Kelvin waves to develop (personal communication with Perillo).

The typical weather pattern of the region is dominated by mid-latitude westerly winds and the influence of the Subtropical South Atlantic High. The resulting circulation induces strong NW and N winds with a mean velocity of 24 km h^{-1} during 40% of the year, with gusts of over 100 km h^{-1} during storms (Piccolo, 1987).

Previous research on the tides and non-tidal fluctuations in the Bahia Blanca estuary has been carried out by Garcia (1983), Piccolo and Perillo (1989) and Perillo and Piccolo (1991). The latter one is the most extensive study.

Perillo and Piccolo (1991) give a general description of the tidal characteristics of the Bahia Blanca estuary. This study comprises a two year period (October 1983 to 1985), with hourly tidal and wind direction records of three coastal stations, Puerto Ingeniero White, Puerto Belgrano and Oceanic Tower. Perillo and Piccolo (1991) computed the tidal constituents for the three coastal stations. It was found that M_2 is the most important main constituent, and that the semidiurnal main tidal constituents increase from the mouth to the head of the estuary. Furthermore, it was found that the tide is predominantly mixed diurnal at Oceanic Tower, but purely semidiurnal at Puerto Ingeniero White and Puerto Belgrano.

Perillo and Piccolo (1991) also examined the influence of wind direction of the sea level by means of descriptive statistics. The study showed that the maximum negative deviations coincided with winds blowing from the NW and maximum positive ones with SW winds. However, this research is biased since wind stress was not taken into consideration in the analysis. Furthermore, the relation between wind and sea level was not quantified in terms of coherence.

3. Data set and data analysis

3.1 Description of the data set

Sea level data were obtained from three coastal stations at Puerto Ingeniero White, Puerto Belgrano and Oceanic Tower, hereafter noted as respectively Pto IW, Pto B and OT/Torre in graphs and tables. Sea level gauges at the three coastal stations measured the sea level over a full year, starting at the 3rd of January 2000. This gave three time series. The observations were made every 10 minutes, taking the ten-minutes average. By doing so, high frequency fluctuations (wind waves) were already filtered from the time series.

The sea level time series of Puerto Ingeniero White and Puerto Belgrano are continuous records, but the time series of Oceanic Tower/Torre show some gaps. Sea level data at Oceanic Tower/Torre were not recorded from 03/03/2000 to 10/03/2000, 18/04/2000 to 22/04/2000 and 20/09/2000 to 30/09/2000. The time series of Puerto Ingeniero White and Puerto Belgrano encompass 708 low tides and 709 high tides, while the time series of Torres encompasses only 667 low tides and 668 high tides.

In Argentina, coastal stations do not use a fixed ordnance datum. Each coastal station has its own and unique reference level. Most often, this reference is calculated as the lowest sea level of a one-year time series, minus 1 standard deviation. In this way the actual sea level will always be above the reference level.

Atmospheric variables, including atmospheric pressure, wind speed and wind direction (at 10 m above the surface) were obtained for the same period as the sea level time series from a meteorological station at Puerto Rosales. This station is located along the Principal Channel, about 5 km east (headward) of coastal station Puerto Belgrano (figure 1.1). Observations were made every 30 minutes (by taking the thirty-minutes average) from 15/01 to 31/12 2000.

There are 6 gaps in the meteorological time series from Peurto Rosales. The largest gap spans almost two months, from 06/09 to 31/10 2000. For this period, data from the meteorological station at Puerto Ingeniero White was used. The meteorological time series of Puerto Ingeniero White shows a high resemblance with that of Puerto Rosales; wind speed at the two stations simultaneously rises and falls. The remaining gaps are from 22/06 to 08/07, from 14/07 to 15/07, from 21/08 to 22/08, from 01/09 to 03/09, at 04/09 and from 06/09 to 07/09 2000.

3.2 Methods

Descriptive statistics: characteristics of the sea level fluctuations

First, high and low tides (sea level and time) were calculated from the original sea level time series of the three coastal stations. The results were subjected to a detailed descriptive statistical research. Hereby the annual mean sea level, mean high tide, mean low tide and mean tidal range were calculated, together with the monthly variations in sea level, high and low tide. Furthermore, the mean duration of the ebb and flood were calculated and the phase lags between the different stations were determined.

Descriptive statistics: the characteristics of the atmospheric variables

For each wind direction, average wind speed and related wind stress were calculated from the meteorological time series of Puerto Rosales. Wind stresses were calculated using the bulk formula (Nelson, 1977):

$$\tau_x = \rho_a C_D (W_{10}, U_{10})$$
$$\tau_y = \rho_a C_D (W_{10}, V_{10})$$

Where τ_x and τ_y denote the E-W and N-S components of the stress (with positive values for winds blowing from respectively the east and north, and negative values for wind blowing from respectively the west and south), ρ_a is the density of air, C_D the empirical drag coefficient, W_{10} is the observed wind speed, and U_{10} and V_{10} are the eastward and northward components of the wind velocity measured at a height of 10m. The density of air ρ_a was given a constant value of 1.22 kg m $^{-3}$, and the empirical drag coefficient C_d, has a constant value of 0.0013 (Kraus, 1972).

By using the bulk formula a wind stress time series, with wind stresses decomposed in N-S and E-W direction, was calculated from the wind speed and wind direction of the meteorological time series of Puerto Rosales. As winds blowing from the NW are dominant in the Bahia Blanca estuary (Piccolo, 1987, see also figure 5.4), also a wind stress time series was calculated with wind stresses decomposed in NW-SE and NE-SW direction. Hereby τ_x' and τ_y' denote the NE-SW and NW-SE components of the stress (with positive values for winds blowing from respectively the northeast and northwest, and negative values for wind blowing from respectively the southwest and southeast).

Harmonic analysis: the tidal signal

Amplitudes and Greenwich phase lags of 69 possible tidal constituents (26 main constituents and 43 shallow water tides) are calculated with the Godan program (Foreman, 1977). This program calculates the amplitudes and phase lags via a least squares fit method, as explained in chapter 2. Gaps in sea level time series (like in that of the OT/Torre sea level time series) are easily handled in the Godin program, because it is not necessary that the observation times are evenly spaced. However, the Godin program is able to analyse hourly data only, so the time interval of the sea level timeseries had to be reduced prior to the analysis. With the same time series the astronomical tide was calculated for the period from 03/01 2000 to 31/12 2000.

The Formzahl coefficient is computed at each coastal station for the classification of the tidal types according to the formula defined by Defant (1961): $F = (K_1 + O_1) / (M_2 + S_2)$. Where F is less than 0.25 the tide is considered to be of the semidiurnal type, and where F is between 0.25 and 1.25 the tide is considered to be of the mixed type.

Harmonic analysis: the subtidal sea level fluctuations

Since the main interest of this study is the subtidal variability along the Principal Channel, the calculated astronomical tide was subtracted from the sea level time series of the three coastal stations. By doing this, the variability of diurnal, semidiurnal and higher tidal frequency fluctuations was removed. The result, the residual time series, is the sea level variation (set up and set down) due to wind forcing and the inverse barometric effect. As atmospheric pressure causes fluctuations smaller than 0.02 m (personal communication with Cintia Piccolo), its effect is considered negligible in this study.

With the Fast Fourier Transformation module of the program Statistica, the power spectra of the subtidal sea level fluctuations were computed from the residual time series. Hereby the residual time series is decomposed into sine and cosine functions of different frequencies, in order to determine which frequencies account for large amounts of non-tidal sea level variation.

Next, cross spectral analysis was carried out to determine the correlation of the subtidal sea level fluctuations at the three coastal stations. The correlation of the three power spectra was determined by calculating the coherence squared (γ^2) between each of the coastal station pairs.

Harmonic analysis: wind stress fluctuations

With the program Statistica, the power spectra of the different components of the wind stress fluctuations were also computed from the wind stress time series in order to determine which frequencies account for large amounts of variation.

Relation between subtidal sea level fluctuations and wind stress

The non-tidal sea level fluctuations of the three coastal stations were examined in conjunction with the different components of the wind stress for evidence of wind-forced subtidal variations. The relation between non-tidal sea level and wind stress was quantified by calculating the coherence squared between the wind stress time series of Puerto Rosales and the residual sea level time series of the three coastal stations. The coherence squared was calculated with the cross spectral analysis module of the program Statistica.

Furthermore, for every wind direction the mean set up/set down was calculated using descriptive statistics.

4. Results

4.1 Statistical characteristics of the sea level fluctuations

4.1.1 Annual mean sea level

The annual mean sea level at each coastal station is shown in table 4.1. As all three coastal stations use a difference reference level, the annual means of the time series are not the same.

	Pto IW	Pto B	OT/Torre
Mean sea level [m]	2.60	2.44	1.86

Table .1: Annual mean sea level for the three coastal stations, from January 3rd 2000 to January 3rd 2001.

The time series of the coastal stations were standardized by distracting the annual means. By doing this, comparisons can be made between the different stations. Hereafter, only the standardized time series are used. When sea level elevations are presented (single observations as well as monthly means, high tides, low tides etc) they concern deviations from the annual mean.

4.1.2 Monthly variations in the sea level

The monthly mean sea level showed fluctuations up to 15 cm from the annual mean (figure 4.1). A set up occurred at Puerto Ingeniero White from January to May 2000, at Puerto Belgrano from March to July 2000 and at Oceanic Tower from January to February and from November to December 2000. The highest set down occurred in September and October 2000, when the monthly mean see level was more than 10 cm below the yearly mean at each coastal station. The deviation of the monthly mean sea level from the yearly mean is comparable at all coastal stations from January to April and from August to December 2000, although the monthly mean sea level at Puerto Belgrano was about 5 cm lower than at the other stations during this period. From May to July 2000 though, monthly mean sea level at Puerto Belgrano was more than 10cm higher than at Puerto Ingeniero White and Oceanic Tower.

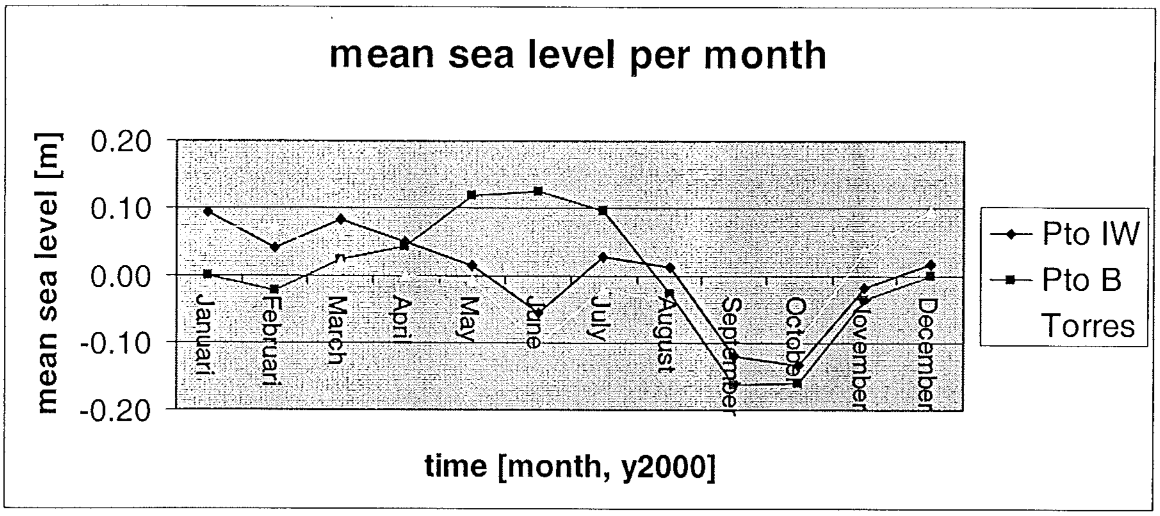

Figure 4.1: Mean monthly deviation from the annual mean sea level for the three coastal stations, from January to December 2000.

4.1.3 Annual mean tidal range, high tide and low tide

At every coastal station, the mean low tide is larger than the mean high tide, compared to the annual mean sea level (table 4.2A and B). At Oceanic Tower, the mean low tide (compared to the annual mean sea level) is about 1.1 times the mean high tide. At Puerto Belgrano this is about 1.2, and at Puerto Ingeniero White even about 1.25. The annual mean tidal range is also different for the three stations. It increases from 2.41 m at Oceanic Tower (near the mouth of the estuary) to 3.60 m at Puerto Ingeniero White (near the head of the estuary, table 4.2C).

Both the mean high tide and the mean low tide increase from Oceanic Tower (near the mouth of the estuary) to Puerto Ingeniero White (near the head of the estuary, table 4.2A and B). However, the rates of increase are not the same. While the mean low tide increases by about 60% from Oceanic Tower to Puerto Ingeniero White, the mean high tide increases only about 35%.

		Pto IW	Pto B	OT/Torre
A) high tides	Mean	1.54	1.40	1.16
	Standard deviation	0.27	0.27	0.24
B) low tides	Mean	-2.06	-1.79	-1.25
	Standard deviation	0.40	0.42	0.36
C) tidal range	Mean	3.60	3.19	2.41
	Standard deviation	0.49	0.50	0.43

Table 4.2A: mean high tides, *B*: mean low tides, and *C*: tidal range for the three coastal stations, from January 3rd 2000 to January 3rd 2001.

4.1.4 Monthly variations in the high and low tides

Figure 4.2 and 4.3 show the monthly variations in respectively mean high tide and mean low tide. It can be seen that the set up of about 10 cm that occurred at Puerto Belgrano from May to July 2000, was associated by higher high tides as well as higher low tides. For the rest of the year though, the high and low tides are quite coherent at the three coastal stations. At all stations, lower high tides as well as low tides were recorded in September and October 2000.

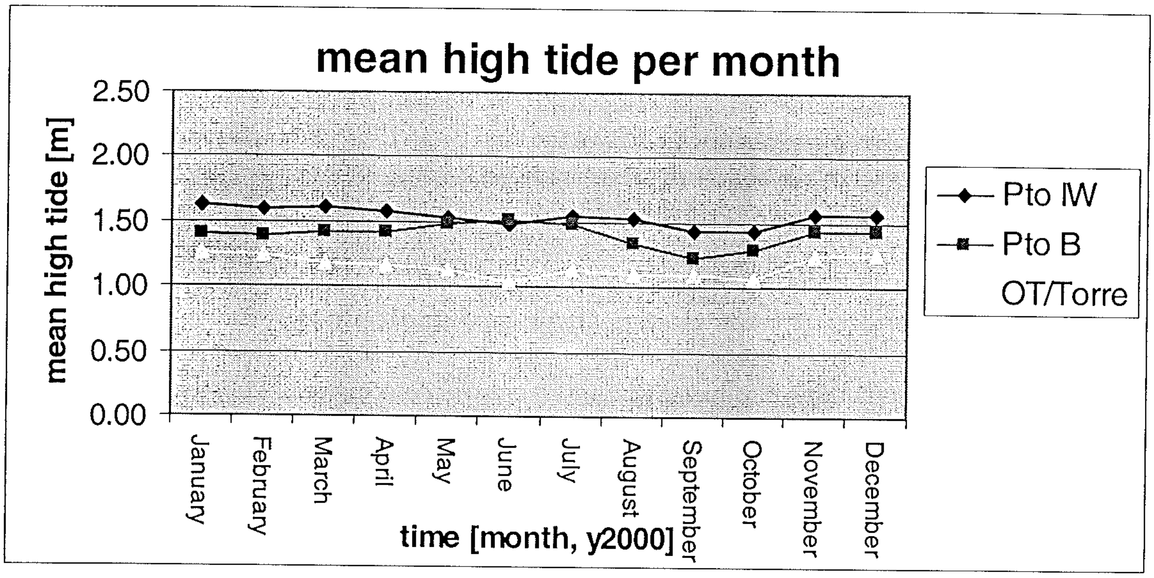

Figure 4.2: mean high tides for the three coastal stations, from January to December 2000

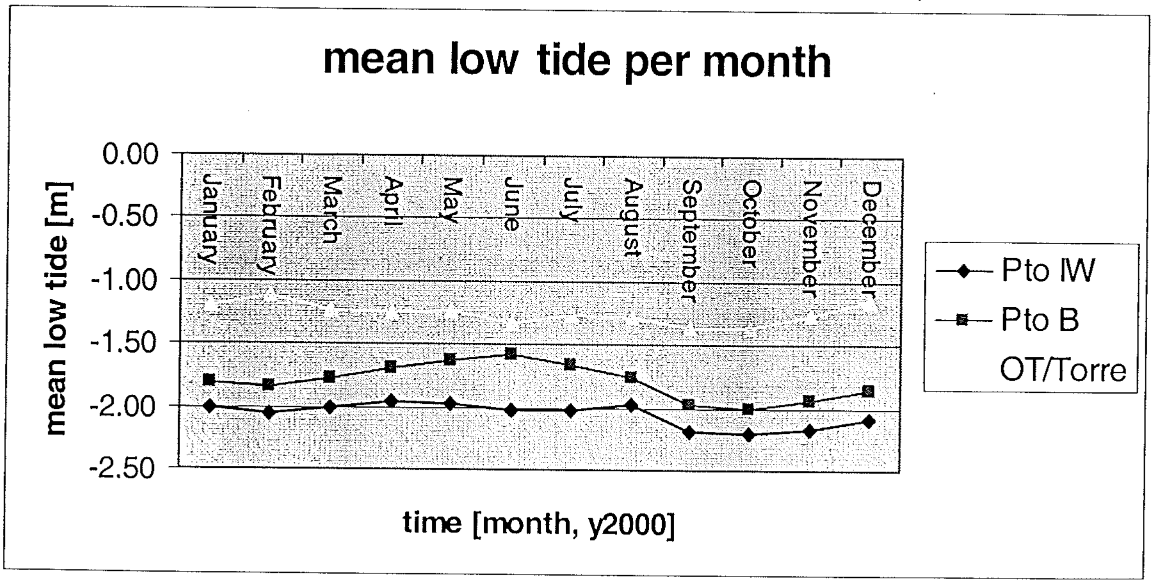

Figure 4.3: mean low tides for the three coastal stations, from January to December 2000

4.1.5 Highest and lowest high and low tides

The highest as well as the lowest sea level of the three time series were recorded at Puerto Ingeniero White (table 4.3) Here a maximum sea level of 2.53 m was recorded in the morning of March 27, and a minimum sea level of –3.12 m in the evening of November 5.

The high tide range is calculated as the highest high tide minus the lowest high tide of the time series, the low tide range as the highest low tide minus the lowest low tide. Table 4.3 shows that the range of the low tides is about 50% larger than that of the high tides. For example, the highest high tide recorded at Oceanic Tower was about 2 meters higher than the lowest high tide, while the highest low tide was almost 3 meters higher than the lowest low tide. This means that there is a lot more variation in the low tides than in the high tides. Some of the highest low tides recorded at Puerto Belgrano and Oceanic Tower are even above the annual mean sea level.

A) high tides	**Pto IW**		**Pto B**		**OT/Torre**	
Highest	*sea level [m]*	*day*	*sea level [m]*	*Day*	*sea level [m]*	*day*
1 (maximum)	2.53	Mar 27 (mo)	2.36	Jun 06 (an)	2.06	Jul 18 (ev)
2	2.52	Mar 29 (ni)	2.31	Jul 18 (ev)	2.06	Nov 13 (en)
3	2.35	Jun 06 (an)	2.29	Mar 29 (ni)	2.01	Mar 29 (ni)
lowest	*sea level [m]*	*day*	*sea level [m]*	*Day*	*sea level [m]*	*day*
1	0.47	Jul 31 (ni)	0.46	Jul 17 (mo)	0.10	Jul 17 (mo)
2	0.54	Jul 17 (mo)	0.47	Jul 31 (ni)	0.16	Sep 11 (an)
3	0.56	Sep 11 (an)	0.54	Jul 2 (ni)	0.21	Jul 2 (ni)
high tide range	*range [m]*		*range [m]*		*range [m]*	
	2.06		1.90		1.96	

B) low tides	**Pto IW**		**Pto B**		**OT/Torre**	
lowest	*sea level [m]*	*day*	*sea level [m]*	*day*	*sea level [m]*	*Day*
1 (minimum)	-3.12	Nov 5 (en)	-2.66	Nov 5 (en)	-2.37	Jul 17 (ni)
2	-2.95	Jul 17 (ni)	-2.65	Nov 3 (en)	-2.12	Nov 5 (en)
3	-2.91	Nov 3 (en)	-2.64	Nov 4 (en)	-2.05	Jun 21 (ni)
highest	*sea level [m]*	*day*	*sea level [m]*	*Day*	*sea level [m]*	*day*
1	-0.33	Jul 18 (an)	0.19	Jul 18 (an)	0.54	Jul 18 (an)
2	-0.46	Nov 14 (ni)	-0.03	Nov 14 (ni)	0.46	Nov 14 (ni)
3	-0.60	May 22 (an)	-0.39	May 15 (an)	0.11	May 22 (an)
low tide range	*range [m]*		*range [m]*		*range [m]*	
	2.79		2.85		2.91	

Table 4.3: Amplitudes of the *A:* three highest and three lowest high tides, together with the high tide range, *B:* three lowest and three highest low tides, together with the low tide range at the three coastal stations, and the days that they occurred between January 3rd 2000 and January 3rd 2001. mo = morning, an = afternoon, ev = evening and ni = night.

4.1.6 Ebb and flood

At every coastal station, the mean period of the tidal wave is around 12h 25' (table 4.4A). This is standard for a semidiurnal tidal wave. At Oceanic Tower, deviations from the mean period are larger than at Puerto Ingeniero White and Puerto Belgrano. At the former coastal station, the standard deviation is about 33 minutes, while for the latter two it is only about 25 minutes.

Table 4.4B and 4.4C show that the average duration of the ebb and flood is not the same at each coastal station. At Puerto Belgrano, flood and ebb have a more or less equal duration, about 6h 10'. However, at Oceanic Tower, average duration of ebb is about 40 minutes longer than flood. At Puerto Ingeniero White, the situation is reverse. Here the average duration of flood is about 30 minutes longer than ebb. This means that the duration of flood increases from Oceanic Tower (near the mouth of the estuary) to Puerto Ingeniero White (near the head of the estuary), while the duration of ebb decreases.

A) period of the tidal wave	**Pto IW** *Flood [min]*	**Pto B** *flood [min]*	**OT/Torre** *flood [min]*
Mean	745.11	745.10	744.97
Standard deviation	24.87	24.62	33.30

B) flood	**Pto IW** *Flood [min]*	**Pto B** *flood [min]*	**OT/Torre** *flood [min]*
Mean	387.98	367.6	352.12
Standard deviation	25.7	23.67	27.16

C) ebb	**Pto IW** *ebb [min]*	**Pto B** *ebb [min]*	**OT/Torre** *ebb [min]*
Mean	357.16	377.54	392.97
Standard deviation	24.74	23.97	35.74

Table 4.4A: Period of the tidal wave, *B:* duration of flood, and *C:* duration of ebb, at the three coastal stations.

4.1.7 Phase lags between the coastal stations

The time series of the three stations showed that the high and low tides occur progressively later from Oceanic Tower to Puerto Ingeniero White (table 4.5). This means that there is a phase lag between the stations, which increases progressively from the mouth to the head of the estuary. The phase lag is higher for the high tides (on average more than 1h 30') than for the low tides (on average less than 1h).

A) Phase lag between high tides	OT/Torre *Time of high tide compared to Torres [min]*	Pto B *Time of high tide compared to Torres [min]*	Pto IW *Time of high tide Compared to Torres [min]*
Mean	0	60.12	91.96
Standard deviation	0	21.37	23.17

B) Phase lag between low tides	OT/Torre *Time of low tide compared to Torres [min]*	Pto B *Time of low tide compared to Torres [min]*	Pto IW *Time of low tide compared to Torres [min]*
Mean	0	44.77	56.30
Standard deviation	0	19.36	21.69

Table 4.5A: Phase lag between the high tide, and *B:* phase lag between the low tide at the three coastal stations. Coastal station Oceanic Tower (OT/Torre) is used as a reference.

4.2 Statistical characteristics of the wind climate

The meteorological time series of Puerto Rosales shows that the prevailing wind direction is from the NW and NNW (figure 4.4). The average wind speed for these directions is around 6 m/s (figure 4.5). However, the winds with the highest average wind speed are those blowing from the W to SW, with average velocity of 7 m/s. Maximum wind speeds were also recorded from this direction (table 4.6). NNE to E winds are generally not that strong and mean velocities are around 4 m/s in these directions.

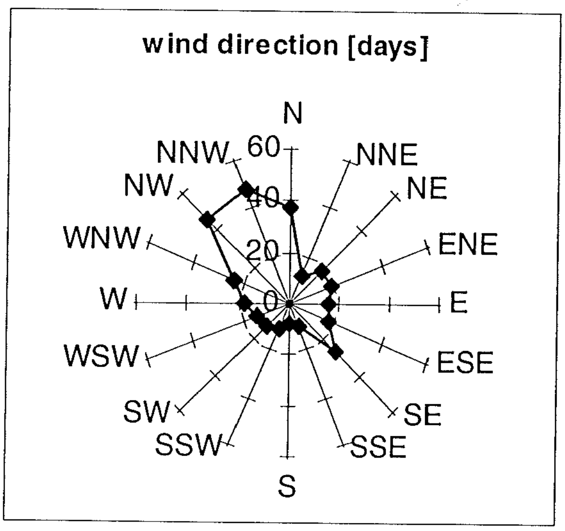

Figure 4.4: Wind direction at Puerto Rosales (frequency in number of days) from 15/01 to 31/12 2000.

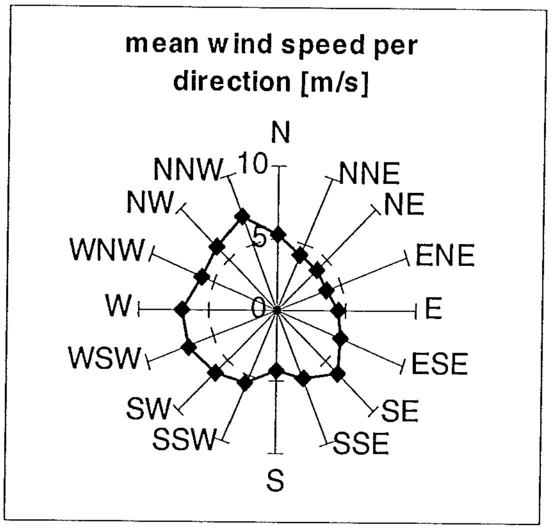

Figure 4.5: Mean wind speed per direction at in Puerto Rosales, from 15/01 to 31/12 2000.

	Date	Direction	wind speed [m/s]
1 (max)	13/11/00	SW	20.1
2	01/02/00	SW	19.7
3	15/12/00	SW	19.7
4	19/11/00	SSW	18.8
5	07/02/00	SSE	18.3

Table 4.6: The five highest observed wind speeds at Puerto Rosales, between 15/01 and 31/12 2000.

4.3 Tidal signal

Table 4.7 summarizes the values of the most important tidal constituents at the three coastal stations. M2 is the most important mean constituent at all three stations, followed by S2, N2, L2 and K1 at Puerto Ingeniero White and Puerto Belgrano, and K1, S2 and O1 at Oceanic Tower. The shallow water tides/partial tides increase considerably from Oceanic Tower (near the mouth of the estuary) to Puerto Ingeniero White (near the head of the estuary), some by more than 400%.

			Pto IW		Pto B		OT/Torre	
type of component	**symbol**	**T** *[h]*	**A** *[m]*	ϕ *[degrees]*	**A** *[m]*	ϕ *[degrees]*	**A** *[m]*	ϕ *[degrees]*
semi-diurnal	**M2**	12.42	1.66	262.35	1.36	176.84	1.03	152.88
	S2	12.00	0.20	337.23	0.17	292.01	0.15	270.97
	N2	12.66	0.20	209.84	0.17	93.97	0.12	77.58
	K2	11.97	0.06	333.87	0.05	339.13	0.04	279.93
	L2	12.19	0.20	299.69	0.17	246.51	0.11	215.02
	2N2	12.91	0.07	175.16	0.05	9.68	0.05	357.36
	v2	12.63	0.10	232.33	0.09	132.04	0.06	105.93
	labda2	12.22	0.08	294.31	0.06	222.70	0.05	185.28
	mu2	12.87	0.14	53.99	0.13	282.16	0.11	269.30
	others		<0.05		<0.05		<0.05	
Diurnal	**K1**	23.93	0.19	68.71	0.16	49.64	0.19	38.74
	O1	25.82	0.15	64.24	0.15	347.12	0.13	342.50
	P1	24.07	0.05	47.90	0.06	11.31	0.04	35.74
	Q1	26.87	0.04	75.05	0.04	314.31	0.04	334.70
	others		<0.03		<0.03		<0.03	
long-period	**all**		<0.03		<0.03		<0.03	
shallow water tides (partial tides)	**M4**		0.22	333.56	0.17	179.66	0.06	167.55
	MS4		0.06	61.49	0.05	330.92	0.02	258.78
	MN4		0.05	284.77	0.02	140.46	0.02	113.07
	others		<0.03		<0.03		<0.03	
Formzahl coefficient	**F**		0.18		0.20		0.27	

Table: 4.7: The amplitudes (A) and Greenwich phase angles (ϕ) of the most important tidal constituents and the Formzahl (F) coefficient at the three coastal stations in the Bahia Blanca Estuary.

At Oceanic Tower the tide is predominantly mixed semidiurnal. Here the Formzahl coefficient (see chapter 4) is somewhat larger than 0.25 (table 4.7). At the other two coastal stations the tide is purely semidiurnal, and the Formzahl coefficient is less than 0.25.

4.4 Subtidal sea level fluctuations

Long term changes, with frequencies lower than 0.04 cycles per day (periods >25 days) predominate in the subtidal sea level spectra (figure 4.6), especially at the Oceanic Tower. This means that the subtidal sea level fluctuations with large periods are very strong, and account for a large percentage of the subtidal sea level variance. For shorter time scales, the spectra of the three coastal stations have common energy peaks at 0.08 and 0.12 cycles per day. Puerto Ingeniero White and Puerto Belgrano also have a minor peak at 0.2 cycles per day, while this is absent at Oceanic Tower. The amplitudes of the energy peaks are comparable in magnitude for each coastal station, but are slightly larger for low frequency scales and slightly smaller for high frequencies at Oceanic Tower.

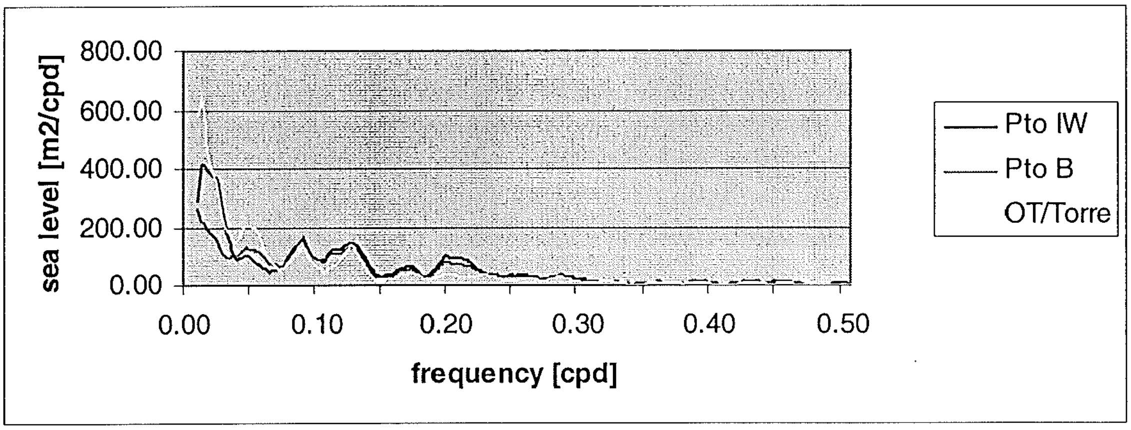

Figure 4.6: Power spectra for sea level at Puerto Ingeniero White (Pto IW), Puerto Belgrano (Pto B) and Oceanic Tower/Torre (OT/Torre), calculated from the residual sea level time series from 03/01 2000 to 31/12 2000.

The coherence squared (γ^2), a measure of the correlation of the subtidal sea level fluctuations between different coastal stations, is very large for the Puerto Ingeniero White – Puerto Belgrano coastal station pair (figure 4.7). It is generally above 0.98 for frequencies larger than 0.08 cycles a day, and between 0.8 and 0.98 for frequencies smaller than 0.08 cycles a day. This means that the subtidal sea level fluctuations at Puerto Ingeniero White and Puerto Belgrano coincide to a high degree, especially for fluctuations with periods between 2 and 10 days.

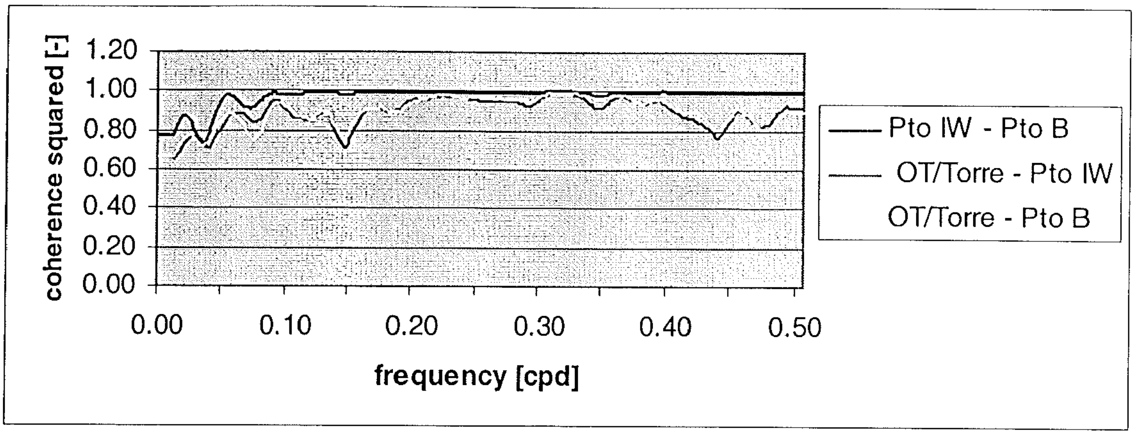

Figure 4.7: Coherence squared (γ^2) of non-tidal sea level, Puerto Ingeniero White vs. Puerto Belgrano, Puerto Ingeniero White vs. Oceanic Tower and Puerto Belgrano vs. Oceanic Tower, calculated from the residual sea level time series from 03/01 2000 to 03/01 2001.

The coherence squared of the Oceanic Tower - Puerto Ingeniero White coastal station pair and that of the Oceanic Tower - Puerto Belgrano coastal station pair is lower than that of the Ingeniero White – Puerto Belgrano coastal station pair (figure 4.7). This is especially the case for frequencies between 0.05 and 0.20 cycles a day and for frequencies between 0.4 and 0.5 cycles a day. This means that the subtidal sea level fluctuations at Oceanic Tower, the coastal station located on the inner continental shelf, do not coincide to the same degree with Puerto Ingeniero White and Puerto Belgrano, the two coastal stations located along the Principal Channel.

4.5 Wind stress fluctuations

As with the subtidal sea level spectra, long term changes with frequencies lower than 0.04 cycles per day (periods >25 days) also predominate in the wind stress spectra (figure 4.8 and 4.9). This means that the wind stress fluctuations with large periods are very strong. Winds in the NW-SE direction account for the largest part of the wind stress variance. For example, wind stress variance in the NW-SE direction reaches values of 8 N^2/m^4cpd for periods larger than 25 days, while the variance in the NE-SW direction is only about 2 N^2/m^4cpd. For shorter scales, the spectrum of the wind stress in the NW-SE direction has a smaller energy peak at 0.08 cycles a day.

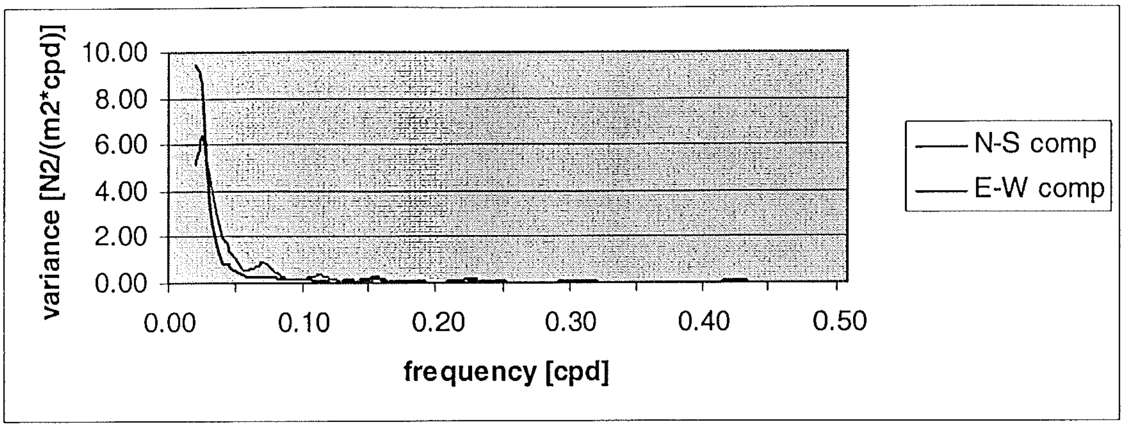

Figure 4.8: Power spectra for N-S and E-W components of the wind stress (respectively τ_y and τ_x) at Puerto Rosales, calculated from the meteorological time series from 15/01 to 31/12 2000.

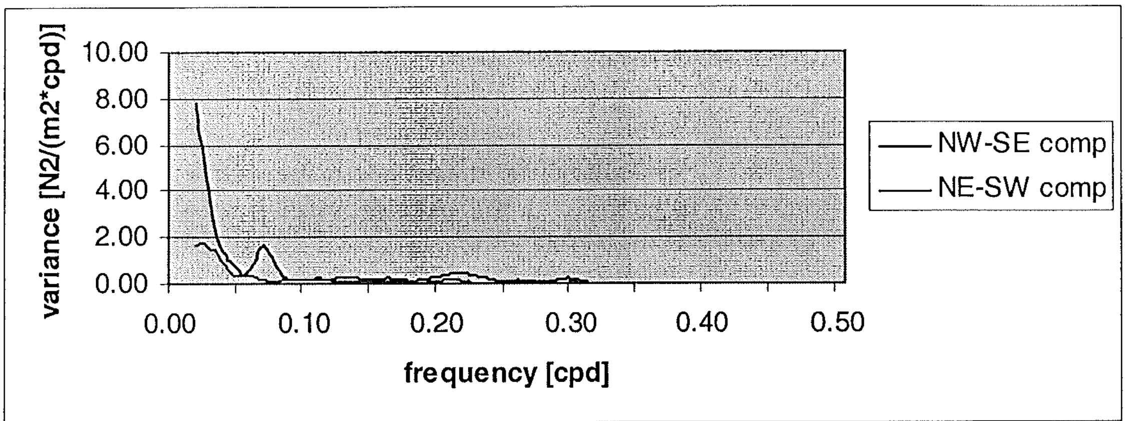

Figure 4.9: Power spectra for NW-SE and NE-SW wind stress (respectively τ_y' and τ_x') at Puerto Rosales, calculated from the meteorological time series from 15/01 to 31/12 2000.

4.6 Relation between subtidal sea level fluctuations and wind stress

Winds blowing from the south (cross-shore winds coming from the Bahia Blanca estuary), lead to a high set up (high positive non-tidal sea levels), 12 to 15 cm on average (figure 4.10). Smaller set ups occur when winds are blowing from the west and east. Wind blowing from the north and northeast (cross-shore winds coming from the Pampas) cause a large set down (high negative non-tidal sea level) of 10 to 12 cm on average. Most remarkable is that the prevailing northwestern winds do not cause much of a set up or set down. The average non-tidal sea level is around zero for wind blowing from this direction.

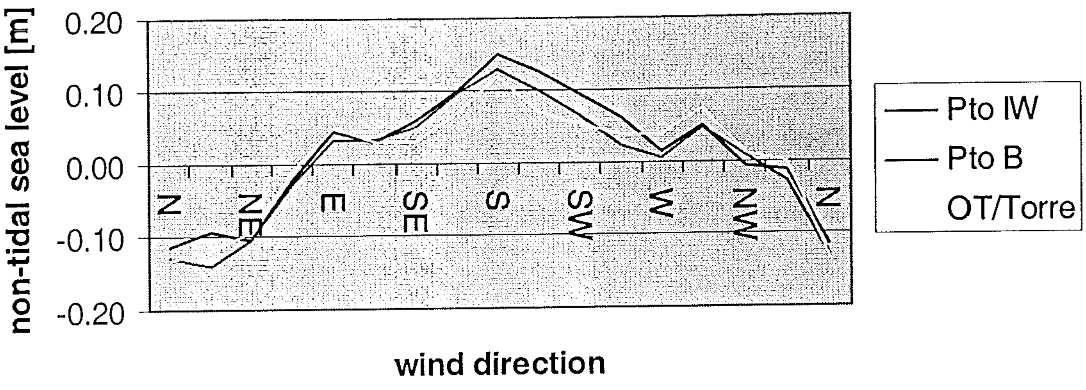

Figure 4.10: Averaged non-tidal sea level (set up/set down) at the three coastal stations per wind direction, calculated from the wind stress time series of Puerto Rosales and the residual sea level time series at Puerto Ingeniero White, Puerto Belgrano and Oceanic Tower, from January 15th to December 31th 2000.

The three highest set ups and lowest set downs (the maximums respectively minimums of the residual sea level time series) at the three coastal stations are shown in table 4.8. Both maximum set up and maximum set down at Puerto Ingeniero White are more than 25% larger than at the other two coastal stations. Non-tidal set up was more than two meters above the tidal sea level at a northern storm in the night of november 14th. The lowest set down at Puerto Ingeniero White was measured at December 16th, when SSE winds caused a set down of –1.46 m. It is highly remarkable that some of the highest set ups occurred at northern, cross shore winds coming from the Pampas. Also, some of the lowest set downs occurred at southeastern winds coming from the ocean.

Pto IW max set ups			Pto IW max set downs		
Date	set up [m]	wind dir	date	set down [m]	wind dir
14/11/00 00:10	2.11	N	16/12/00 12:10	-1.46	SSE
08/09/00 18:10	1.90	WSW	24/12/00 07:10	-1.43	WSW
19/08/00 13:10	1.80	SE	11/09/00 14:10	-1.32	SE

Pto B max set ups			Pto B max set downs		
Date	set up [m]	wind dir	date	set down [m]	wind dir
14/11/00 00:10	1.56	N	16/07/00 23:10	-1.07	SW
08/09/00 19:10	1.54	WSW	16/12/00 13:10	-1.12	SSE
12/09/00 01:10	1.49	E	24/12/00 07:10	-1.15	WSW

OT/Torre max set ups			OT/Torre max set downs		
Date	set up [m]	wind dir	date	set down [m]	wind dir
18/07/00 14:10	1.54	WNW	17/07/00 01:10	-1.07	SW
12/09/00 01:10	1.40	E	24/12/00 02:10	-0.98	WSW
14/11/00 02:10	1.34	N	15/09/00 15:10	-0.95	N

Table 4.8: The three highest non-tidal set ups and the three lowest set downs at the Puerto Ingeniero White, Puerto Belgrano and Oceanic Tower, calculated from the residual sea level time series at Puerto Ingeniero White, Puerto Belgrano and Oceanic Tower, from January 15th to December 31th 2000.

The coherence squared (γ^2) is used as a measure to quantify the correlation between subtidal sea level and wind stress. The average coherence squared between the different components of the wind stress and the subtidal sea level at the three coastal stations is shown in table 4.9. The average coherence squared is largest if the wind stress is decomposed in NW-SE and NE-SW components, according to the respectively prevailing and strongest wind directions (see paragraph 4.2). The highest average coherence squared, with values between 0.62 and 0.64, are found for cross shore winds blowing in NE-SW direction. This is the direction in which the strongest winds were recorded, which coincides with the highest set ups and set downs.

Averaged coherence squared	**subtidal sea level**		
	Pto IW	**Pto B**	**OT/Torre**
wind stress (N-S comp)	0.63	0.62	0.60
wind stress (E-W comp)	0.49	0.49	0.51
wind stress (NW-SE comp)	0.56	0.55	0.54
wind stress (NE-SW comp)	0.62	0.62	0.64

Table 5.9: Averaged coherence squared (γ^2) between four components of wind stress (N-S, E-W, NW-SE and NE-SW) and the subtidal sea level at the three coastal stations (Puerto Ingeniero White, Puerto Belgrano and Oceanic Tower).

Figure 4.11, 4.12 and 4.13 show the coherence squared (γ^2) between wind stress in NW-SE and NE-SW direction at Puerto Rosales and subtidal sea level at respectively Puerto Ingeniero White, Puerto Belgrano and Oceanic Tower. As the coherence squared is generally larger for the NW-SE and NE-SW components of the wind stress, only the graphs of the coherence squared between subtidal sea level and these components of the wind stress are presented.

The correlation between wind stress and subtidal sea level is significant at each coastal station for all frequencies between 0 and 0.5 cycles per day, as the coherence squared is above 0.22 (the 95% significance level). The values of the coherence squared generally vary between 0.6 and 0.8, though local minima, with values below 0.4 occur at 0.04, 0.18 and 0.26 cycles for the NW-SE wind stress component and at 0.44 and 0.48 cycles a day for the NE-SW component of wind stress. At Puerto Belgrano and Oceanic Tower there is also a minimum in the coherence between subtidal sea level and the NE-SW component of wind stress at 0.04 cycles a day.

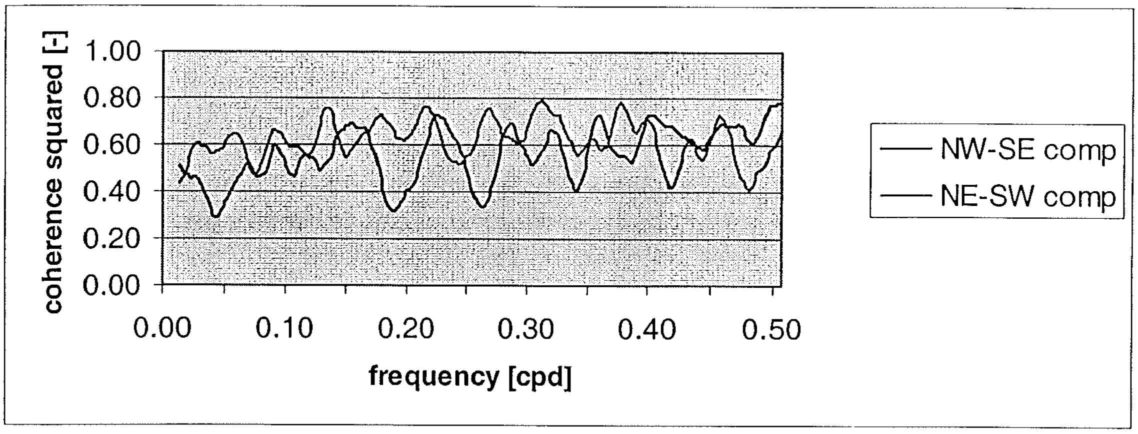

Figure 4.11: Coherence squared (γ^2) between the NW-SE and NE-SW component of the wind stress and the subtidal sea level at Puerto Ingeniero White

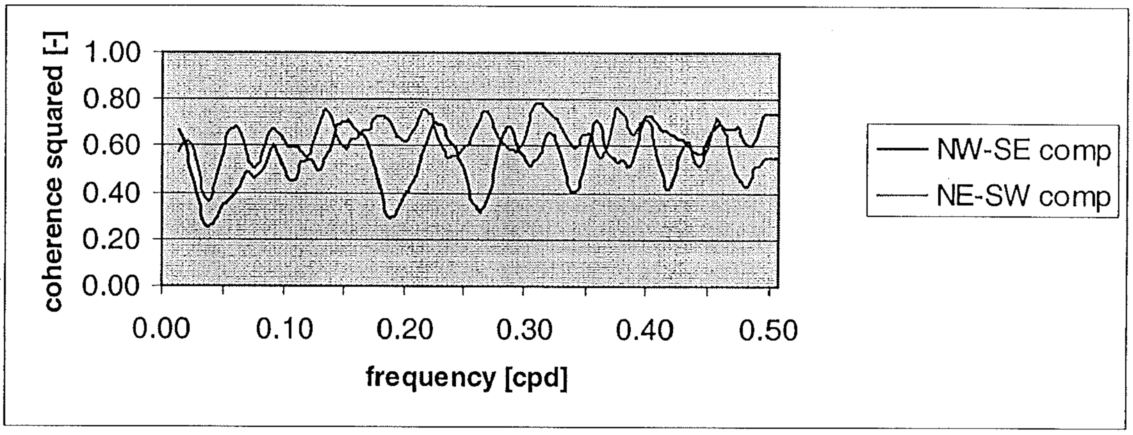

Figure 4.12: Coherence squared (γ^2) between the NW-SE and NE-SW component of the wind stress and the subtidal sea level at Puerto Belgrano

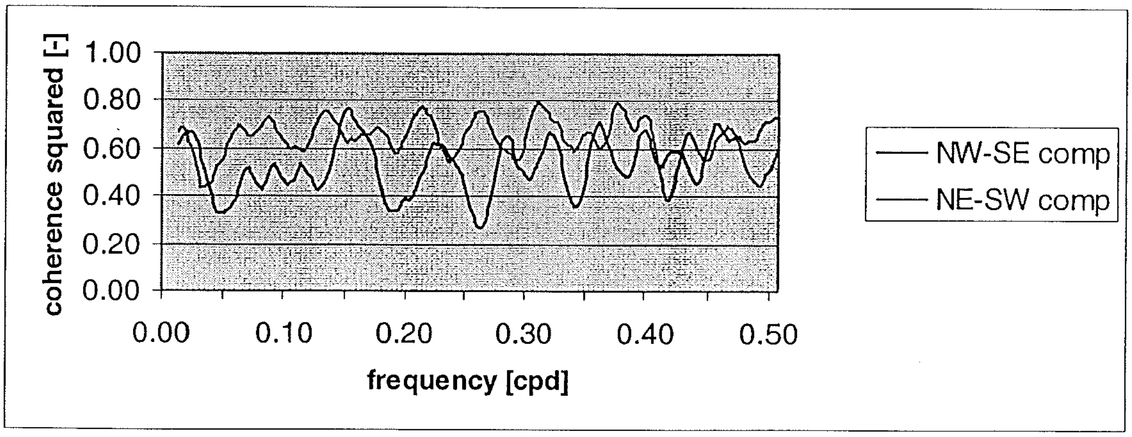

Figure 4.13: Coherence squared (γ^2) between the NW-SE and NE-SW component of the wind stress and the subtidal sea level at Oceanic Tower

5. Discussion

One aspect of this research deserves some more attention: the relation between subtidal sea level and wind stress. Perillo and Piccolo (1991) showed that the maximum set downs in the Bahia Blanca Estuary coincide with winds blowing from the northwest, and maximum set ups with southwestern winds. However, this research shows that highest average set ups are caused by southern winds, and that highest set downs are caused by northern and northeastern winds (see figure 4.10). As the conclusions of Perillo and Piccolo (1991) are based on hourly observations with lots of gaps, the results presented in this report (based on observations taken every ten minutes) are probably far more accurate

The correlation between wind stress and subtidal sea level in the Bahia Blanca Estuary proves to be significant with a 95% confidence level at each coastal station for all frequencies between 0 and 0.5 cycles per day. However, the coherence is far less than in other publications on the relation between wind stress and subtidal sea level. For instance, the average coherence between wind stress and subtidal sea level in the Bahia Blanca Estuary is on average around 0.55, while Chao and Pietrafesa (1980) found values around 0.75 in the Carolina Capes (USA), Wong and Wilson (1984) observed values around 0.80 in Great South Bay (USA) and Wong (1986) values around 0.80 in Delaware's Inland Bays (USA). The lower coherence in the Bahia Blanca Estuary is probably the result of the lack in meteorological data. For this study, wind speed and wind stress data from only one meteorological station were used, and this meteorological station did not coincide with any of the coastal stations. Chao and Pietrafesa (1980), Wong and Wilson (1948) and Wong (1986) used wind speed and wind stress data from a number of meteorological stations, each at the same location as their coastal tidal stations.

6. Conclusions

Descriptive statistical research and spectral analysis of the three sea level time series and the meteorological time series resulted in the following conclusions:

1. The tidal wave is asymmetric. This is demonstrated by:

- inequality of the high and low tide amplitudes. The mean low tide amplitudes are larger than the mean high tide amplitudes
- inequality of the duration of flood and ebb. On the inner continental shelf near the mouth of the Principal Channel, the duration of ebb is larger than flood, while near the head of the Principal Channel the situation is reverse

2. The asymmetry of the tidal wave increases from the mouth to the head of the Principal Channel. Over this distance, the amplitude of the low tide increases much more than that of the high tide, and the duration of flood increases in disadvantage of ebb.

3. The mean tidal range increases from 2.41 m near the mouth to 3.60 near the head of the Principal channel.

4. The tides show a progressively increasing phase lag from the mouth to the head of the Principal Channel. The phase lag is highest for the high tides (over 90 minutes).

5. M2 is the most important mean constituent of the tides in the Bahia Blanca Estuary, followed by S2, N2, L2 and K1 at the coastal stations along the northern shore of the Principal Channel, and K1, S2 and O1 at the coastal station near the mouth of the Principal Channel. The shallow water tides/partial tides increase considerably from the coastal station at the mouth of the estuary to the coastal station near the head of the estuary, some by more than 400%.

6. The prevailing wind direction in the Bahia Blanca Estuary is from the NW and NNW. The average wind speed for these directions is around 6 m/s. However, the winds with the highest average wind speed are those blowing from the W to SW, with average velocity of 7 m/s. Fluctuations with large periods (>25 days) predominated in the wind stress energy spectra. Winds in the NW-SE direction account for the largest part of the wind stress variance in the Bahia Blanca Estuary.

7. Fluctuations with large periods (>25 days) also predominated in the subtidal sea level spectra. Minor peaks of subtidal sea level variance occur at 0.08, 0.12 and 0.20 cycles per day. The subtidal sea level fluctuations at the two coastal stations located along the Principal Channel coincide to a high degree, especially for fluctuations with periods between 2 and 10 days. The subtidal sea level fluctuations at the coastal station on the inner continental shelf near the mouth of the Principal Channel, do not coincide to the same degree, but are still significant with 95% confidence level.

8. Southern cross-shore winds coming from the Bahia Blanca Estuary, generally lead to a set up, with an average amplitude of 12 to 15 cm. Smaller set ups occur for winds blowing from the west and east. Northern and northeastern cross-shore winds coming from the Pampas generally cause a set down, with an average amplitude of 10 to 12 cm. However, some of the highest set ups occurred at northern winds, and some of the lowest set ups occurred at southeastern winds.

9. The relation between subtidal sea level fluctuations and wind stress is significant with a confidence level of 95%. In terms of coherence, this relation is strongest for winds blowing in NE-SW direction, the direction in which the strongest winds were recorded.

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