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Sea-level Rise and Related Potential Hazards on the Argentine Coast

Néstor W. Lanfredi† Jorge L. Pousa,‡ and Enrique E. D'Onofrio

†Late Research Scientist,
Comisión de Investigaciones
Científicas de la Provincia
de Buenos Aires
y Facultad de Ciencias
Naturales, UNLP
La Plata
Argentina

‡Consejo Nacional de
Investigaciones Científicas y
Técnicas
y Facultad de Ciencias
Naturales, UNLP
Casilla de Correo 45-(1900)
La Plata
Argentina

Servicio de Hidrografía Naval
Departamento Oceanografía
Av. Montes de Oca 2124-
(1271) Buenos Aires
Argentina

ABSTRACT

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The potential consequences of an eventual acceleration in the rate of sea-level rise on the Argentine coast are considered in the light of the long-term trend in sea-level variation, the impacts that the Argentine coastal areas are undergoing from natural and anthropogenic processes, and the human activities that develop there. Water-level variations were determined from hourly tide height records for Buenos Aires, Mar del Plata, Quequén, and Puerto Madryn. The series used for Buenos Aires (1905–1992) and Quequén (1918–1981) presented no gaps. For Mar del Plata (1954–1992) there were gaps in April and June 1981, November and December 1986, and February and March 1987, while Puerto Madryn (1945–1983) showed a gap in May 1982. By suitably completing these gaps the corresponding series of annual levels, calculated as means of monthly mean values, were obtained. Symmetric, low-pass filters with Kaiser-Bessel windows were used to attenuate the contributions from periodic components ranging between 8 and 19 years. The filtered series were subjected to spectral analysis through the Fast Fourier Transform method, recolored in the frequency domain and antitransformed again. The results were used to perform linear regression analyses whose slopes indicated a long-term trend in water-level of +1.6 ± 0.1 mm/year for Buenos Aires, +1.4 ± 0.5 mm/year for Mar del Plata, +1.6 ± 0.2 mm/year for Quequén, and +3.5 ± 0.1 mm/year for Puerto Madryn. Examples of a rise in water level associated with a storm surge are given to show how this phenomenon affect the Argentine coast. Beach erosion from an accelerated rise in sea-level is quantified for a sector of the sandy shores of the Province of Buenos Aires using the well-known Bruun model. Other likely impacts, particularly on human activities, are also mentioned.

ADDITIONAL INDEX WORDS: *Spectral techniques, storm surges, impacts, coastal erosion.*

INTRODUCTION

As pointed out by KOMAR *et al.* (1991), some recent estimates of greenhouse-related sea-level rise by 2085 AD are about 2 to 4 times the 1 to 2 mm/year rise that has prevailed during the last 100 years. Predictions of this sort, though controversial, have led the scientific community to consider the potential consequences to the world's coastlines.

To see how an eventual acceleration in sea-level rise would affect the Argentine coast, it is important to determine the long-term trend in sea-level variation there, to give a look at the several impacts that the Argentine coastal areas are already undergoing from natural and anthropogenic processes, and to take account of the human activities that develop along the coastal fringe.

THE ARGENTINE COAST

The coastline of Argentina (not including the Malvinas and the Antarctic sector) is about 5,700 km long and spans from the Río de La Plata (34°11′ S) up to the south of Tierra del Fuego (55° S) (Figure 1). It can be divided into a temperate sector that spans from 35° S to 42° S, an arid sector from 42° S to 52° S, and a cold humid sector located on the Tierra del Fuego coast between 52° S and 55° S, approximately.

The major coastal landforms are deltaic-estuarine systems, marshes, cliffs and wave-cut terraces, and sandy and pebbly shores (SCHNACK, 1985). Sandy coastlines are typical along the strip extending from 36° S to 39° S, the northernmost part of the Argentine coast, where the shoreline shows dissipative characteristics with a significant littoral drift (between 400,000 and 1 million m^3/year).

Brackish and salt-water marshes are present all along the Argentine coast, the former mainly in the northeastern sector of the Province of Buenos Aires (Samborombón bay) and also in Mar Chiquita, Bahía Blanca and farther southward; the latter predominate in the Patagonia, where macrotidal environments prevail. The Patagonian coast is predominantly rocky and cliffy (Patagonian plateau), whereas the Buenos Aires (Pampean plains) coastline alternates between extensive low-lying and cliffy areas. The only typical tidal inlet along the Argentine coast is at the Mar Chiquita lagoon, located within a microtidal setting.

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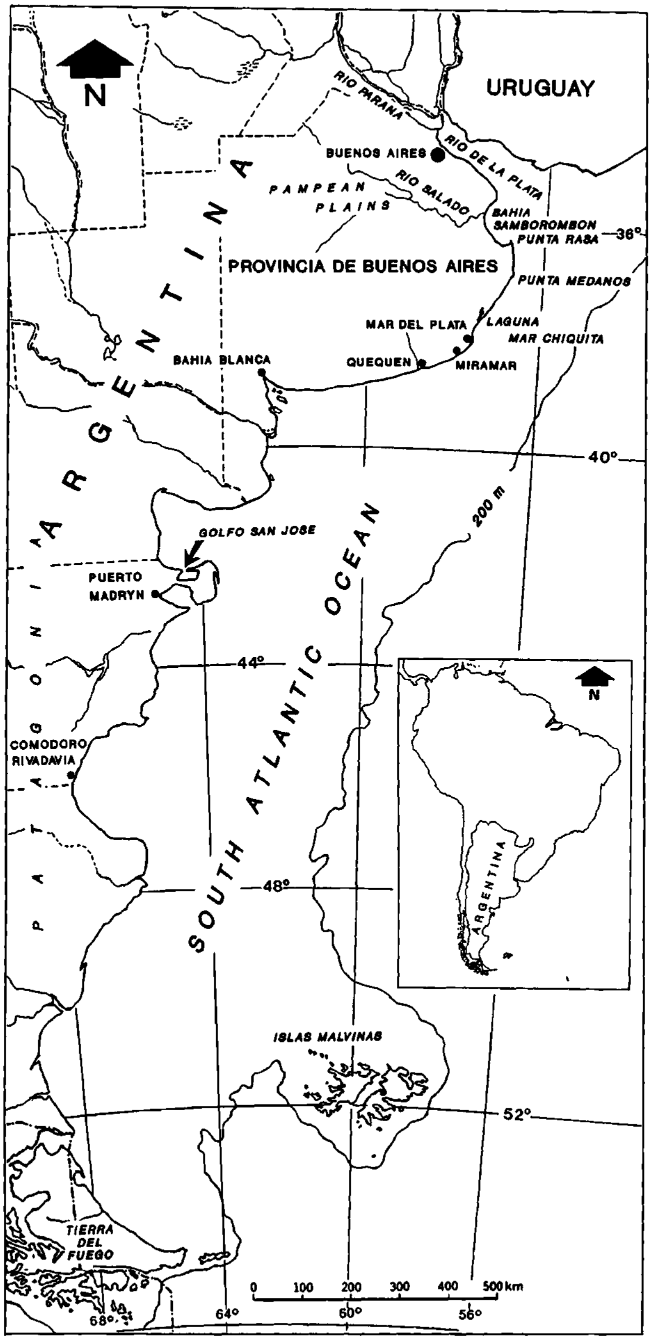

Figure 1. Map of the Argentine coast.

Wetlands are distributed all along the Argentine coast. The most typical and extense are those at Samborombón bay in the Salado basin depression where muddy, tidal flats develop along 100 km of coastline. Tidal flats and marshes are also present from Bahía Blanca southward. Wetlands along the Patagonian coast are more restricted to low-lying areas at the several embayments.

The Río de La Plata, a water body shared by Argentina and Uruguay, might be regarded as a complex deltaic-estuarine system which is the continuation of the Paraná river delta. It has a submerged deltaic front with several sand banks. The main body is freshwater, but the outer part is brackish.

Waves, Tides and Tidal Currents

Wave data is scarce in Argentina. The Province of Buenos Aires has the largest set of observational data. Generally, measurements have been undertaken only at those points where needed because of building purposes. Predominant wave directions for the Argentine coast are S, SE, and E. Wave heights in excess of 6 m have been recorded, while periods range mainly between 5 and 16 seconds, the latter corresponding to swell approaching from the south.

Tides along the Argentine coastline (and in the Río de La Plata) are basically semidiurnal. Figure 2 shows their ranges. Tidal currents are also of semidiurnal type. They can reach velocities of up to 400 cm/sec (San José gulf entrance), but mean values for most of the Patagonian coast range between 75 and 150 cm/sec. In the Río de La Plata tidal currents generally have velocities of about 30 cm/sec.

Storm Surges

Strong and persistent storm surges develop along the coast of the Province of Buenos Aires, from Bahía Blanca to the Río de La Plata, though some of them originate in the southern region of the Argentine continental shelf and reach the Río de La Plata after travelling northwards for hundreds of kilometers. Several cases of storm surges have been recorded along the Argentine coast simultaneously with the northwards travelling tidal wave (ALVAREZ and BALAY, 1970; VARA, 1974). The duration of these storm surges range from a few hours up to two or three days, producing a rise in water level that has sometimes been recorded as reaching 1.5 m over the astronomical tide. They can be of catastrophic effects, according to the oncoming direction, and give rise to strong currents whose effects on adjacent beaches are uncontrollable. Coastal plain flooding due to storm surges can be particularly destructive in areas such as the Río de La Plata shores and the Río Salado basin, where topographic gradients are extremely low. It has been guessed that the Coriolis effect could have its influence on this process. Floods due to storm surges are certainly very dramatic on the Río de La Plata shores, where the highest population densities in Argentina are found (included Buenos Aires, the country's capital). Here the water level rose 4.44 m over the chart datum in 1940, 3.81 m in 1958, and 4.06 m in 1989 (Argentine chart H-156) (see Figure 6). Every time this phenomenon has taken place very many inhabitants have suffered property losses and other damages.

On 21 March 1992, for example, the surface synoptic charts from the Servicio Meteorológico de la Armada Argentina (SMARA) (Figures 3 and 4) indicated that strong surface winds coming from the south and southwest had developed along the Argentine coast, producing a rise in water level over the astronomical tide. The storm surge was registered, among others, by the tide gauges at Puerto Madryn, Mar del

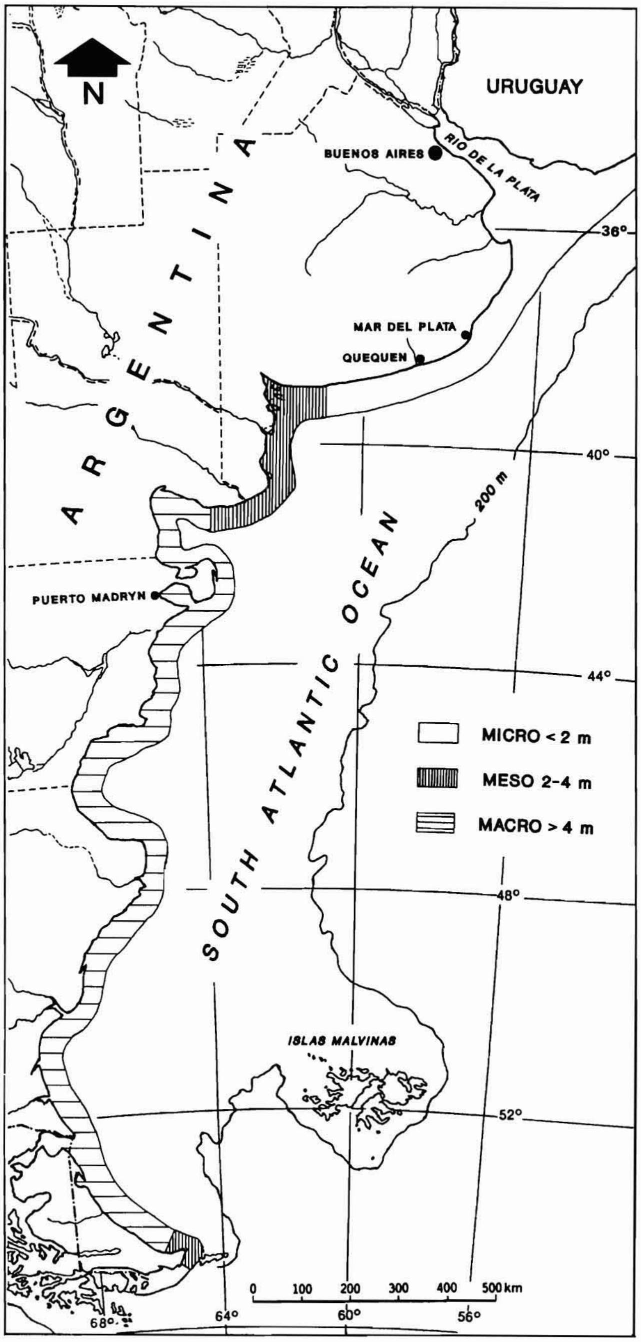

Figure 2. Tidal ranges along the Argentine coast.

Plata, San Clemente del Tuyú (Punta Rasa), Torre Oyarvide (within the Río de La Plata) and Buenos Aires (Figure 1). Due to this storm surge, two high waters of 6.86 and 6.68 m with respect to the chart datum (Argentine chart H-264) were measured at Puerto Madryn on March 21 (see Figure 9). These values became the largest for Puerto Madryn within the period July 1944–December 1992, exceeding the previous maximum of 6.64 m recorded in May 1981. The storm surge arrived at Mar del Plata in the night of 21 March and made the water level reach a height of 2.83 m with respect to the chart datum (Argentine chart H-251) (see Figure 7). On March 22 a high water of 2.91 m was recorded at Mar del Plata, a value exceeded only seven times during the period January 1954–December 1992, the maximum being 3.11 m in July 1962. Tide curves from San Clemente del Tuyú (Punta Rasa), Torre Oyarvide, and Buenos Aires indicated that the recorded heights were also very important.

Human Activities

Human activities along the coastal zones of Argentina include urban development and recreation, industry and commerce, port activities, fishing, military installations, research and conservation of natural resources. In certain areas, beach sand is mined for building purposes. Other activities include: mining of coastal gravels and shells, offshore oil exploration and extraction, and algae exploitation.

Out of the total population of Argentina (33 million people), over 41% inhabits the coastal zones. There is, however, a general gradient from north to south, with the greatest population numbers and densities in Buenos Aires and the surrounding urban centers. The lowest population concentrations and variety of activities are found in the Patagonia, where a few small urban centers support most of the regional population and activities.

SEA-LEVEL VARIATIONS

To determine sea-level variations on the Argentine coast hourly tide height records from Buenos Aires, Mar del Plata, Quequén and Puerto Madryn were analysed (Figures 1 and 2). Annual sea levels, calculated as means of monthly mean values, were determined from these records. While the information concerning Buenos Aires, Mar del Plata and Puerto Madryn was actually worked out for this paper, that of Quequén was taken from LANFREDI *et al.* (1988).

Tide Measurements and Data Background

In the beginning all tide measurements along the Argentine coast were made with standard automatic analog tide gauges similar to those appearing in the U.S. Department of Commerce Manual of Tide Observations (1974). Towards the middle of the seventies they were replaced by Leupold Stevens Type A, Model 71, analog gauges. The gauges were driven by winding clocks because there was not a reliable electric power supply at the piers. Continuous rolls were used on which the operator made one or two daily annotations of the hour and the water level observed on a tide staff whose zero was the same as the gauge zero. Comparing the readings on the continuous roll with those from the tide staff it was possible to check the movement of the clock graphically, and to determine if the position of the pen was correct. Rough observations were neglected (D'ONOFRIO, 1984). The rolls were read mostly manually with special rules, estimating 0.1 or 0.5 mm, according to the thickness of the trace and the scale used, so that measurements were accurate to within 1 cm. Since the speed of the rolls were 2.5 cm per hour, errors in

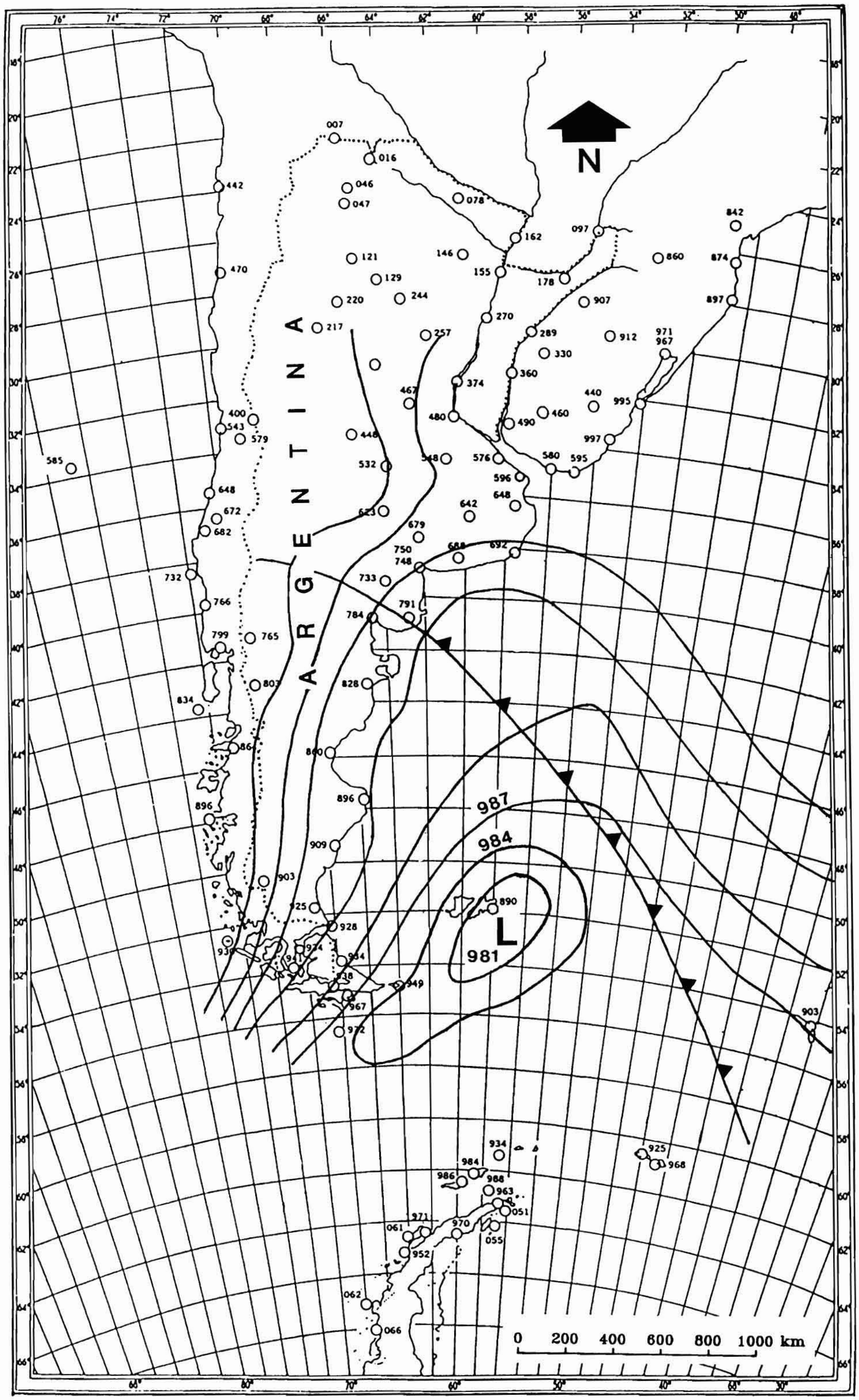

Figure 3. Surface synoptic chart of the Argentine coast. Date: 21 March 1992. Hour: 03:00 GMT. Δp = 3 hPa.

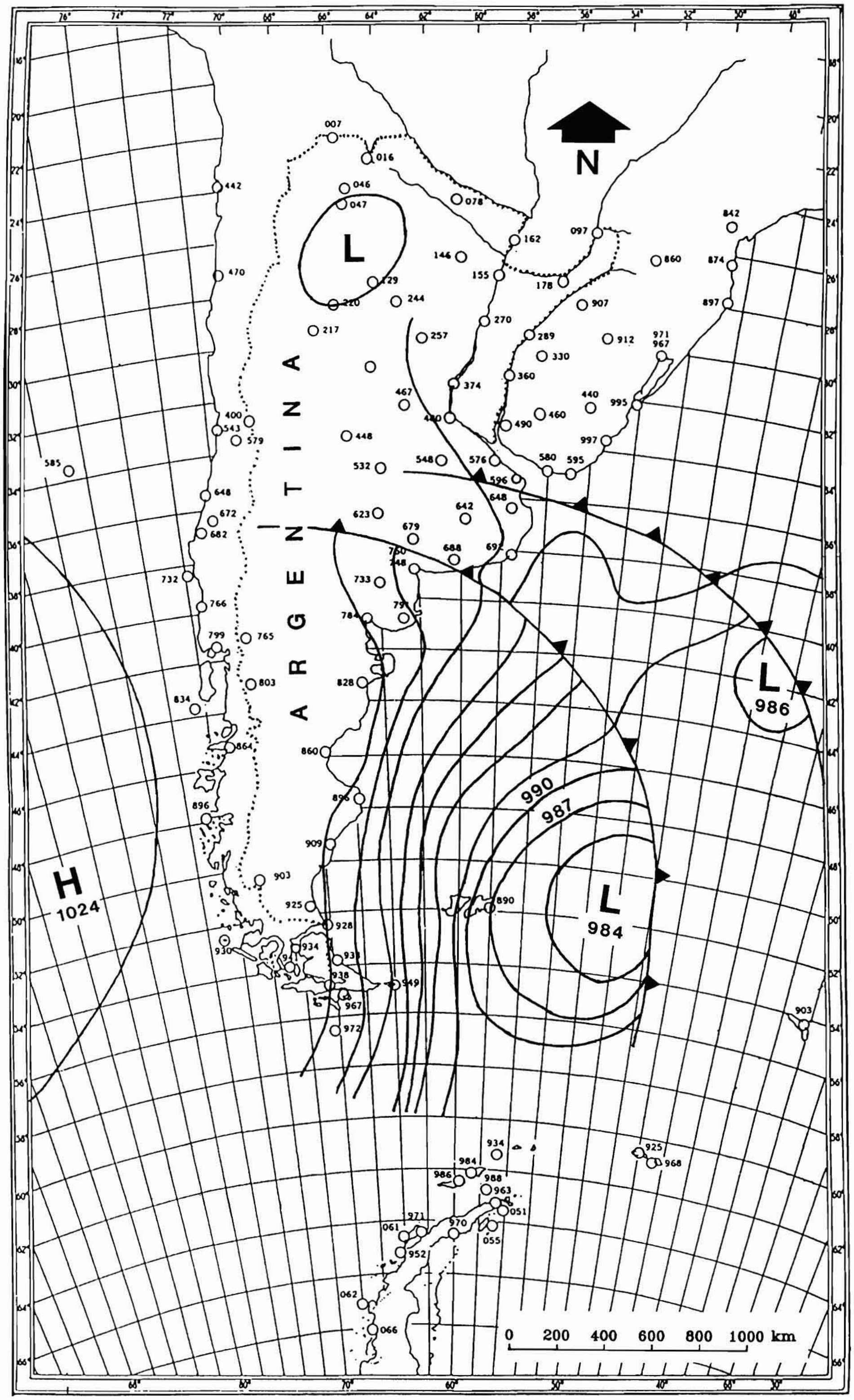

Figure 4. Surface synoptic chart of the Argentine coast. Date: 21 March 1992. Hour: 15:00 GMT. Δp = 3 hPa.

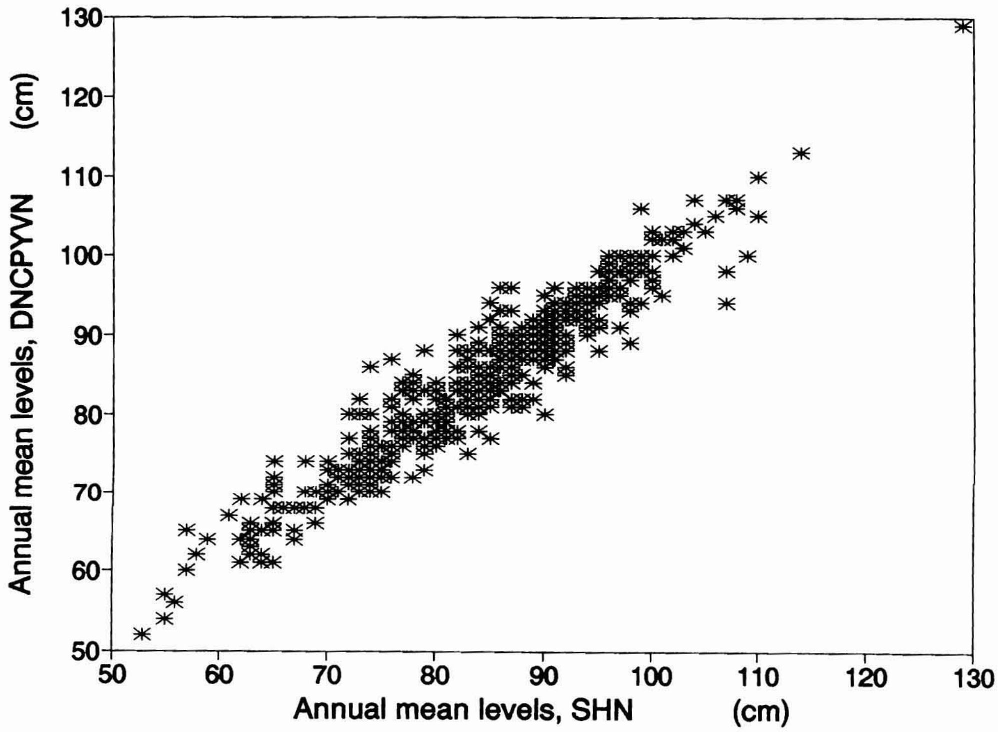

Figure 5. Correlation diagram of monthly mean levels (1950–1991) for the Buenos Aires SHN and DNCPYVN tide stations (r = 0.95).

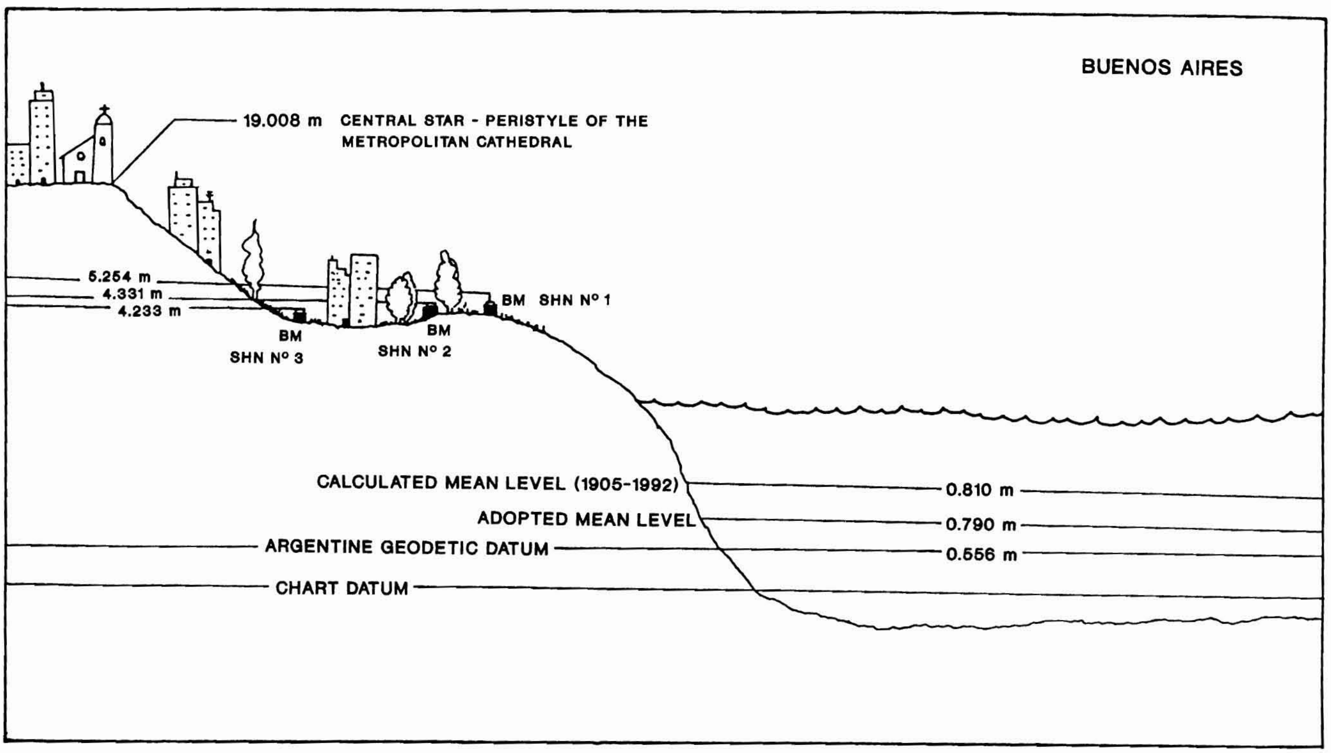

Figure 6. Schematic view of the coast of Buenos Aires (Argentine chart H-156).

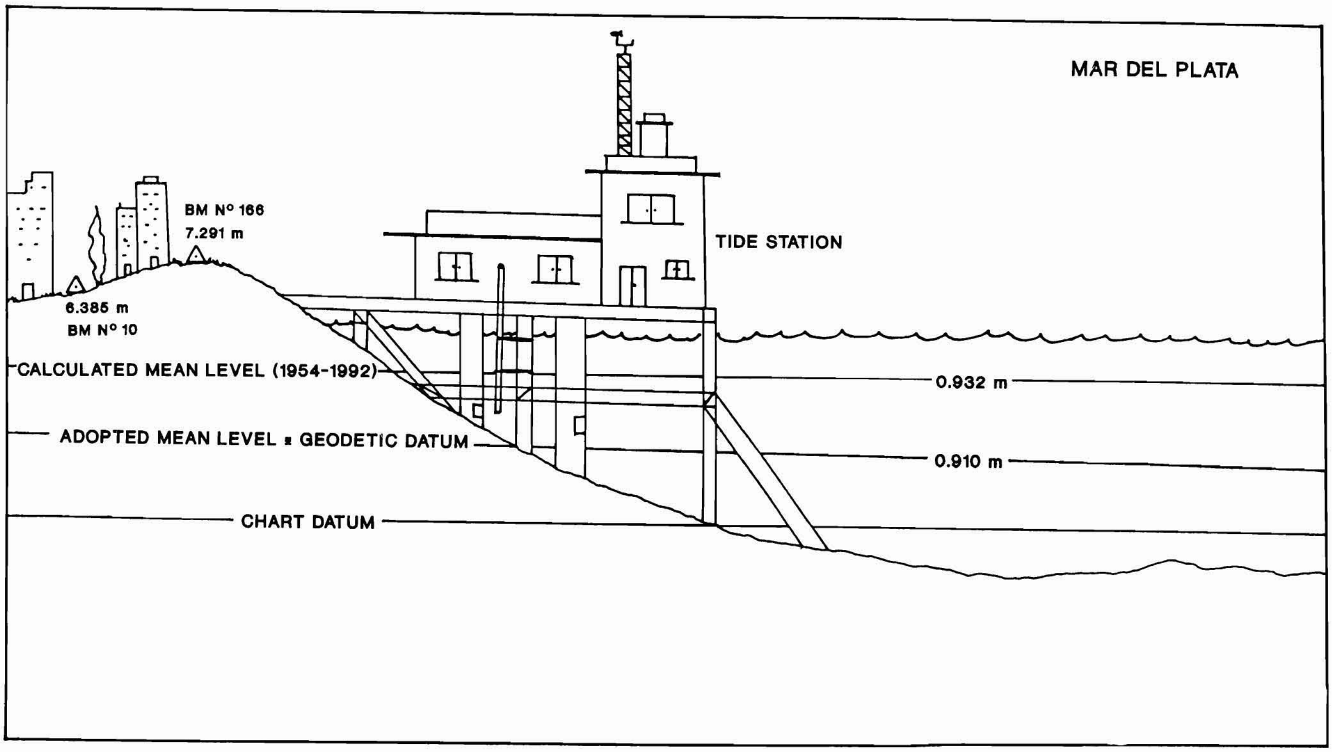

Figure 7. Schematic view of the coast of Mar del Plata (Argentine chart H-251).

time keeping were never larger than 1 minute. The zero of each gauge was carefully verified to avoid any systematic error in the time series. The operation and maintenance of the gauges were performed following the recommendations of UNESCO (1985). Yet, in order that old and new annual mean levels should match they were calculated as arithmetic means of hourly heights without applying any of the filters mentioned by UNESCO (1985). Undesired contributions were removed by spectral techniques (see below).

The two original series for Buenos Aires were taken from the tide stations of the Dirección Nacional de Construcciones Portuarias y Vías Navegables (DNCPYVN) and the Servicio de Hidrografía Naval (SHN). The former spanned from 1905 to 1991, and the latter from 1950 to 1992. Since both stations are only 9 km apart, their monthly mean levels from 1950 to 1991 were highly correlated, with a correlation coefficient r = 0.95 and a y-intercept close to zero (Figure 5). This made it possible to complete the DNCPYVN series with the 1992 value from the SHN station, allowing for the fact that both series were referred to the same geodetic datum.

For Mar del Plata (SHN Mar del Plata Club tide station) the series spanned the period 1954–1992, with gaps in April and June 1981, November and December 1986, and February and March 1987. These values were drawn from the DNCPYVN tide station, which is next to the SHN station and related to it through geometric levelling.

At Quequén the DNCPYVN tide station made sea-level measurements from 1918 up to 1950. In 1951 a new tide gauge, tied to the same geodetic datum, was set up by the SHN to replace the old one. The analysis of LANFREDI *et al.* (1988) used 64 years of registered hourly heights (1918–1981).

Finally, for Puerto Madryn (SHN tide station) the whole series spanned the period 1945–1983, with a gap in May 1982. This value was completed through the maximum entropy method (MEM) (BURG, 1968; ULRYCH and BISHOP, 1975). To cover the gap, both parts of the series were extended with a MEM filter and the obtained values averaged.

For illustration purposes Figures 6 to 9 depict schematic views (not to scale) of the coast of Buenos Aires, Mar del Plata, Quequén, and Puerto Madryn, respectively. Calculated and adopted mean levels, geodetic datum and bench marks relative to the chart datum are shown.

Data Analysis

The spectra of annual mean levels of hourly registered heights contain periodic contributions from the astronomical tide that have to be removed, as otherwise they might mask the secular mean sea-level trend looked for. These contributions have periods that range between 8 and 19 years (GODIN, 1972). Two low-pass numerical filters were used here for attenuating them. The filters were designed from the Kaiser-Bessel window (HAMMING, 1977) following the recommendations of HARRIS (1978), who pointed out the advantages of this window after having performed a comparative analysis

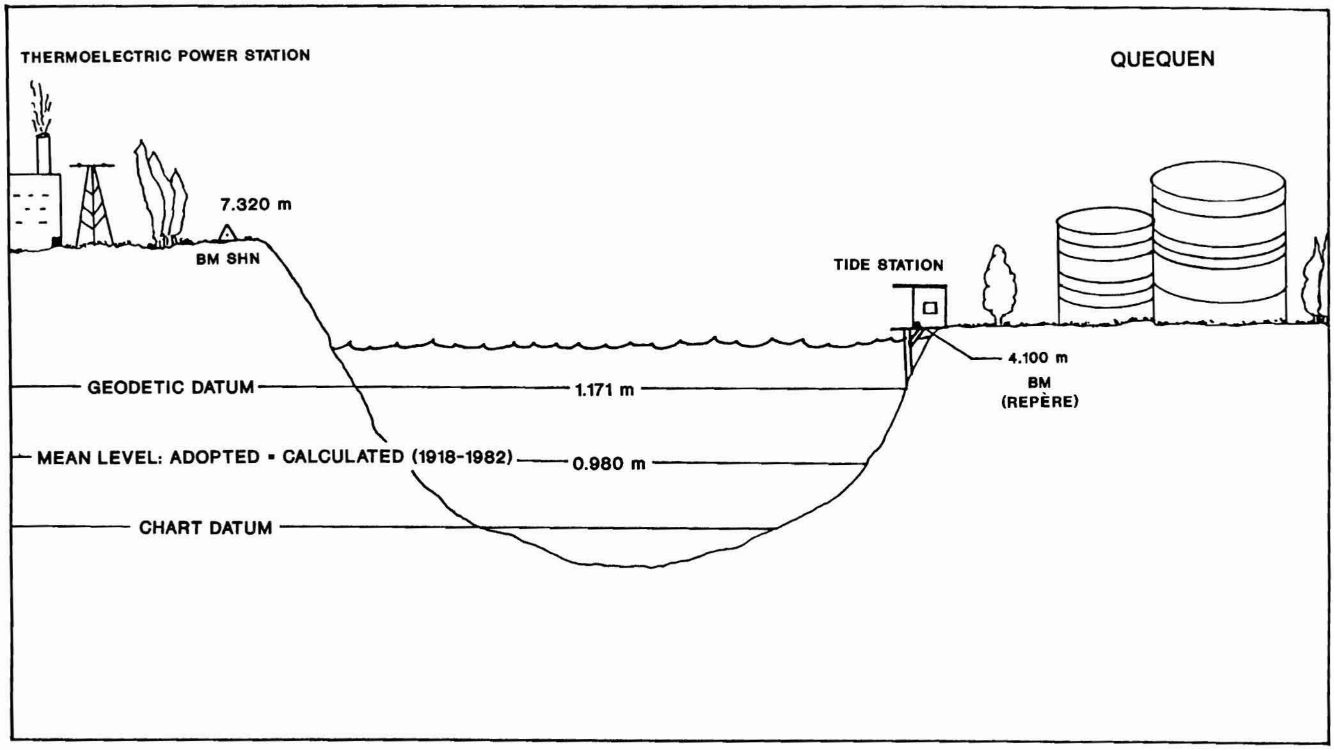

Figure 8. Schematic view of the coast of Quequén (as seen from the sea towards the mouth of the Quequén Grande river) (Argentine chart H-253).

of a set of 22 different windows. Kaiser suggested that in order to reduce the well-known Gibbs phenomenon the Fourier coefficients should be assigned suitable weights. According to HARRIS (1978), the weights should have the following mathematical form

$$w(k) = \begin{cases} \dfrac{I_0(\alpha\sqrt{1 - (k/N)^2})}{I_0(\alpha)}, & |k| \leq N \\ 0, & |k| > N \end{cases}$$

where

$$I_0(x) = 1 + \sum_{n=1}^{\infty} \left[\frac{(x/2)^n}{n!}\right]^2$$

is a modified Bessel function of the first kind and zero order. The Kaiser weights are symmetrical with respect to k = 0, *i.e.*, w(k) = w(−k), and have two parameters, N and α. N is the half width of the window where 2N + 1 coefficients are kept, whereas α determines the "shape" of the window as well as the size of the ripples. The parameters N and α can be calculated through the empirical formulae derived by Kaiser (HAMMING, 1977):

$$\alpha = \begin{cases} 0.1102(A - 8.7), & A > 50 \\ 0.5842(A-21)^{0.4} + 0.07886(A-21), & 21 < A \leq 50 \\ 0, & A \leq 21 \end{cases}$$

where $A = -20 \log_{10}\delta$ is the attenuation in decibels, δ being the size of the maximum ripple, and

$$N = \frac{A - 7.95}{28.72\Delta F}$$

where ΔF is the width of the transition band.

The main variable taken into account in devising the filters was the number of data in the series. This is because in performing the convolution of the primary data with the synthesized filter, 2N annual mean levels are lost for a 2N + 1 element filter (N annual mean levels at each end of the series). Two low-pass, 17 element filters were devised whose cutoff frequencies were 0.112 1/year and 0.076 1/year. The former was used to deal with the data from Quequén (LANFREDI *et al.*, 1988), and the latter with the data from Buenos Aires, Mar del Plata and Puerto Madryn. Figures 10 and 11 show the weights assigned to each element of both filters and their transfer function, or frequency response, respectively.

Since the filters had to have a reduced number of elements, their transition bands made some spectral contributions to be unduly attenuated while others became insufficiently weakened. To overcome these difficulties the filtered series were subjected to a spectral analysis through the Fast Fourier Transform (FFT) method with a rectangular window. Then they were recolored in the frequency domain, as the filter response was known, and antitransformed again. The results obtained were used to perform linear regression analyses whose slopes are the sea-level trends searched for.

Results

The filtered series of annual mean levels for Buenos Aires ranged from 1913 to 1984. The linear regression analysis

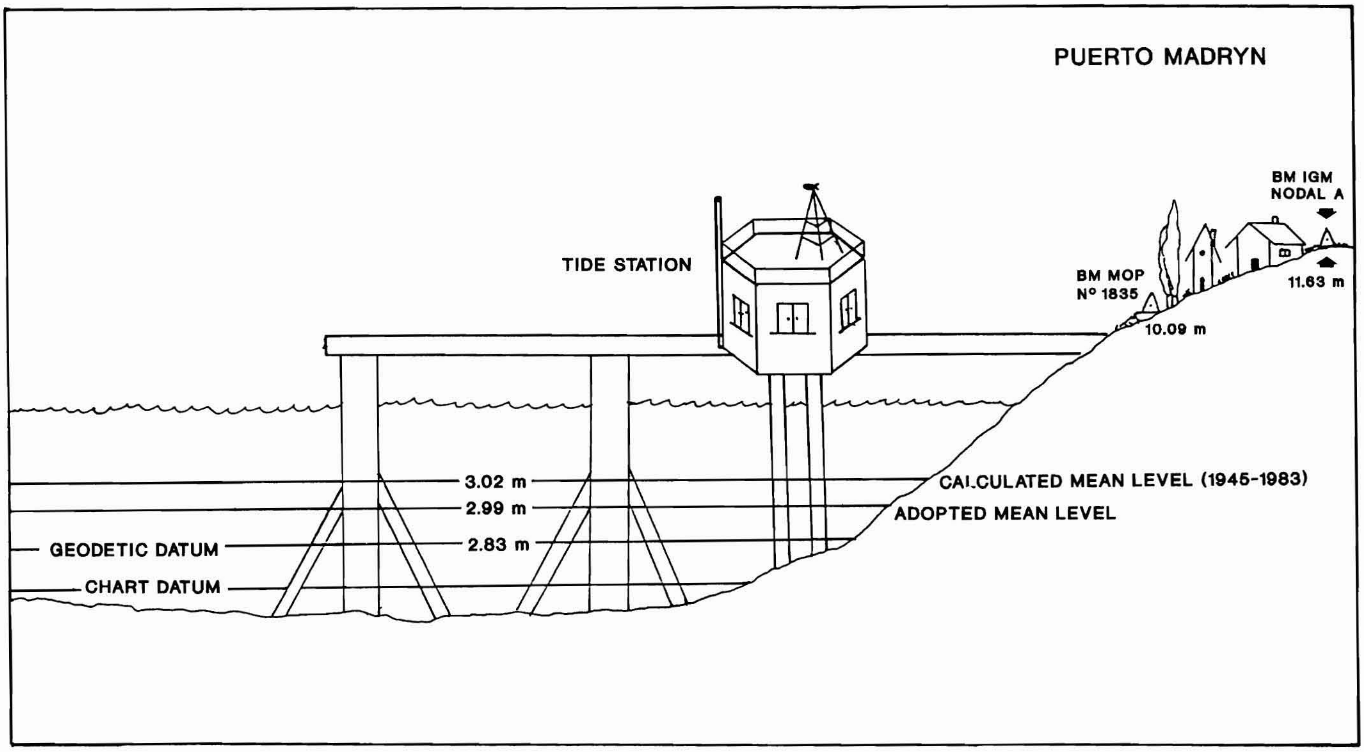

Figure 9. Schematic view of the coast of Puerto Madryn (Argentine chart H-264).

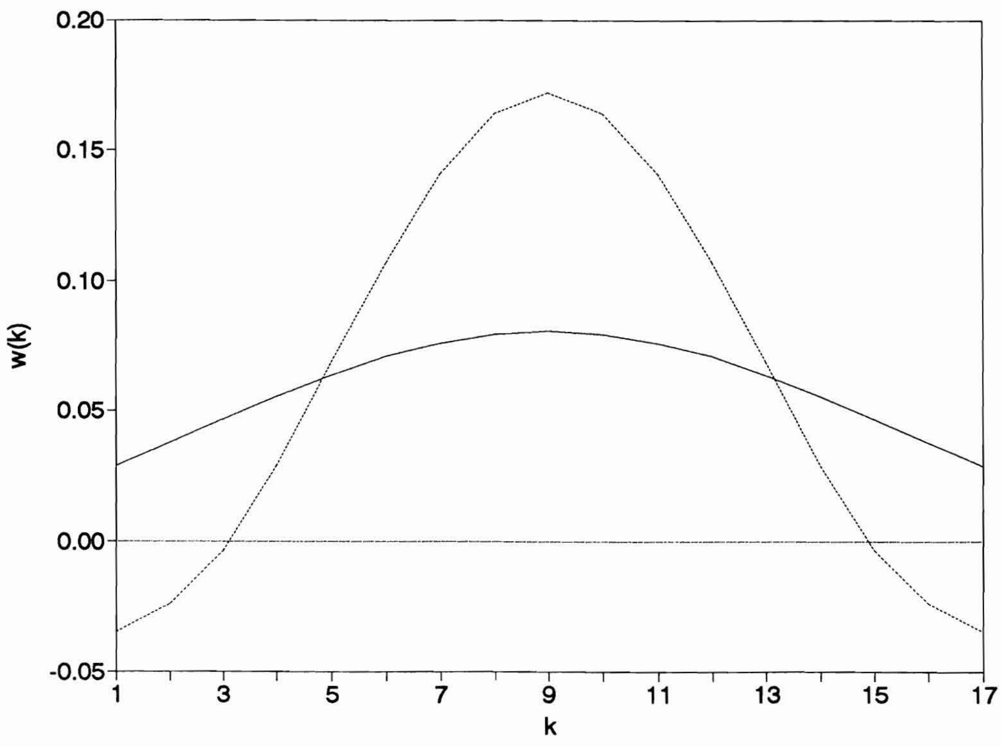

Figure 10. Weights assigned to the filters used for Buenos Aires, Mar del Plata and Puerto Madryn (solid line), and for Quequén (dashed line).

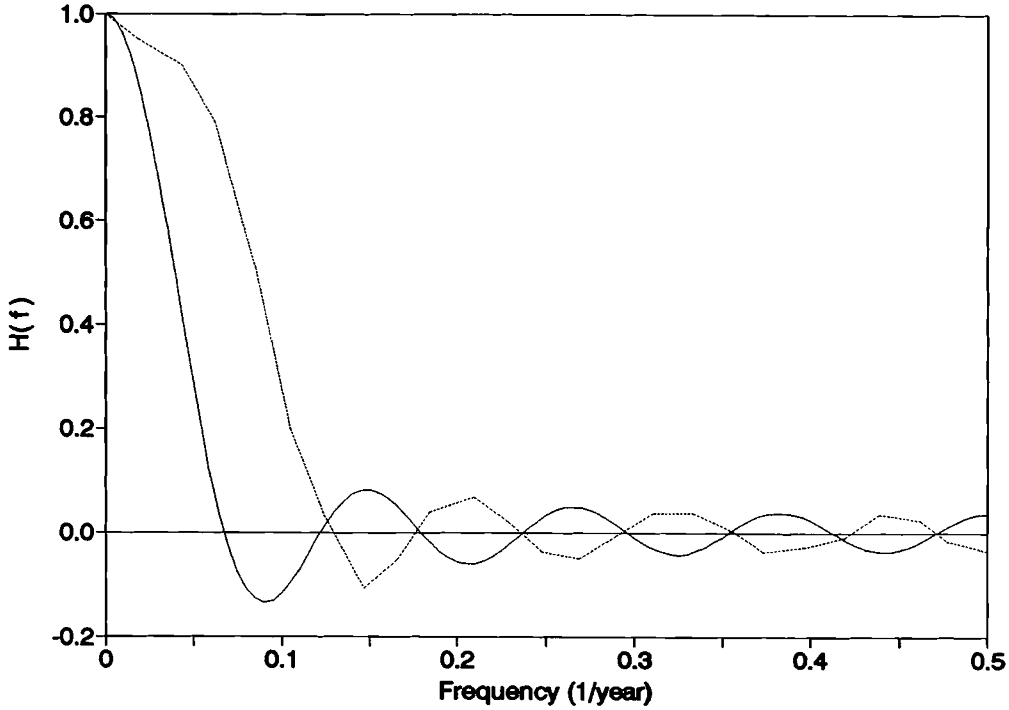

Figure 11. Frequency response of the filters used for Buenos Aires, Mar del Plata and Puerto Madryn (solid line), and for Quequén (dashed line).

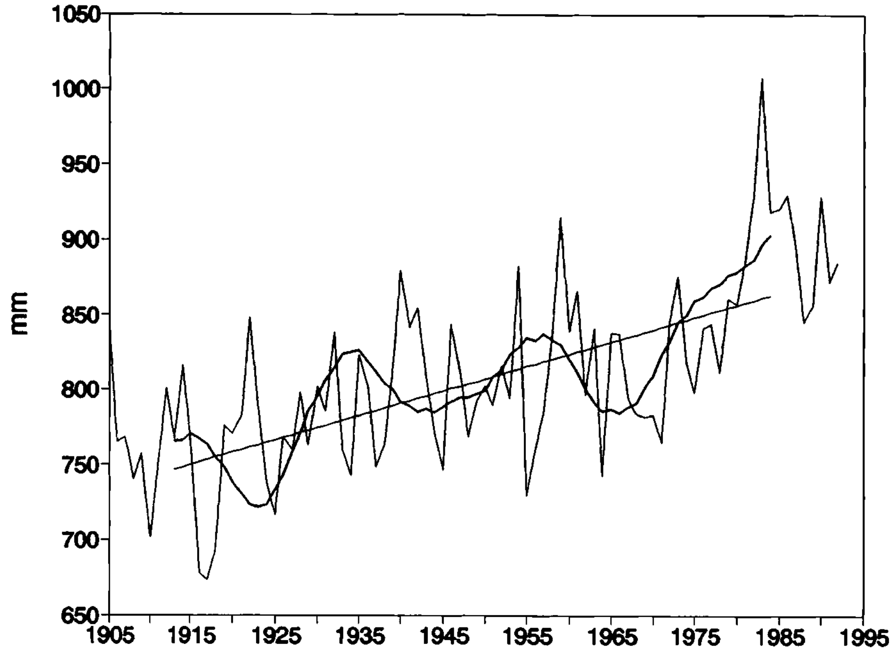

Figure 12. Linear regression calculated from filtered data (heavy solid line) of the annual mean levels for Buenos Aires.

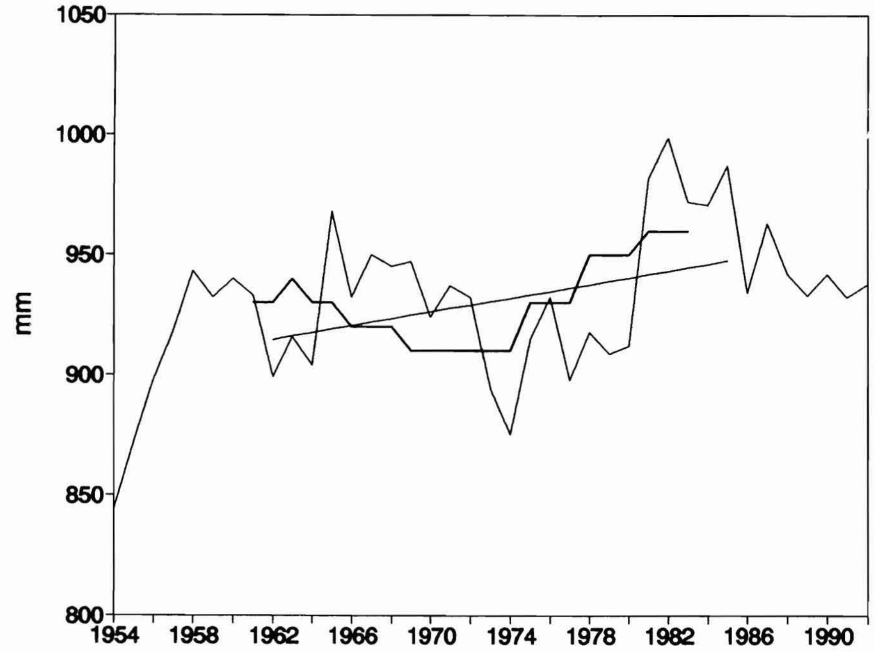

Figure 13. Linear regression calculated from filtered data (heavy solid line) of the annual mean levels for Mar del Plata.

throwed a long-term trend in water-level of +1.6 ± 0.1 mm/year, with a correlation coefficient r = 0.81 (Figure 12).

For Mar del Plata the filtered series of annual mean sea levels spanned the period 1962–1984. The obtained trend was +1.4 ± 0.5 mm/year with r = 0.56 (Figure 13).

For Quequén LANFREDI *et al.* (1988) carried out the linear regression with a filtered series of 48 annual mean sea levels (1926–1973). The trend was +1.6 ± 0.2 mm/year with r = 0.52 (Figure 14).

Finally, for Puerto Madryn the resultant filtered series of

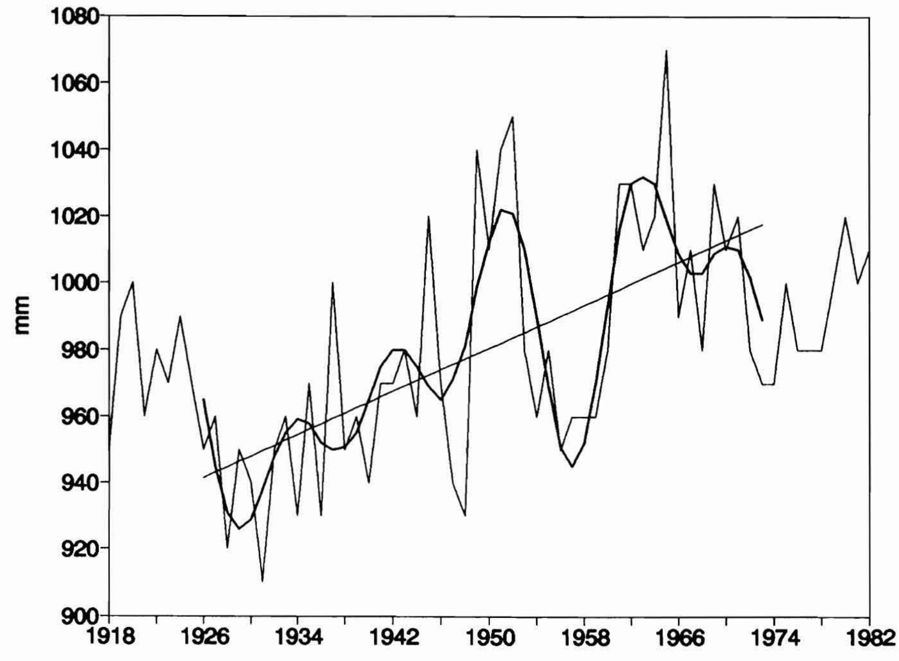

Figure 14. Linear regression calculated from filtered data (heavy solid line) of the annual mean levels for Quequén.

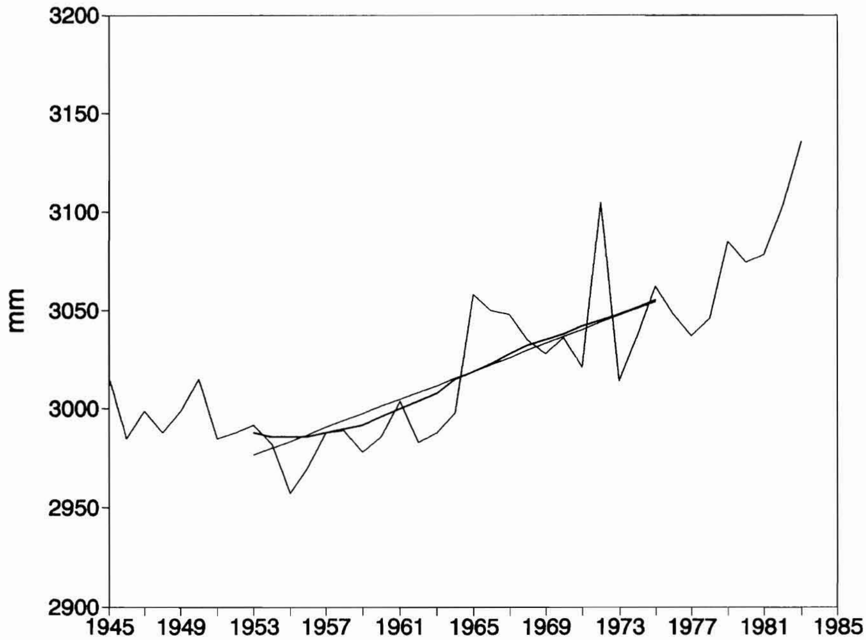

Figure 15. Linear regression calculated with filtered data (heavy solid line) of the annual mean levels for Puerto Madryn.

annual mean sea levels reduced to the period 1953–1975, with a trend of +3.5 ± 0.1 mm/year and a correlation coefficient of 0.98 (Figure 15).

SEA-LEVEL RISE AND POTENTIAL HAZARDS

From the viewpoint of present and future potential hazards, low-lying coastal lands must be considered, especially those found in the Province of Buenos Aires. DENNIS *et al.* (1995) have stated that a one-meter rise in sea level could affect at least 3,400 km^2 of land, mainly comprising the northern sector of the Río de La Plata (particularly Buenos Aires and its surroundings), and that this threatens land and buildings valued at U$S 5,100 to 5,500 million (about 8% of Argentina's 1991 GNP).

In the Salado basin, another low-lying land largely devoted to agriculture and cattle raising, the recurrence of historic floods have made human activities somewhat restricted, and have led the Public Works authorities to construct drainage canals towards the Samborombón bay in the beginning of this century, but the results have not been optimal (SCHNACK *et al.*, 1991).

Beach Erosion and Other Impacts

Beach erosion is an ongoing process, even at the present rate of sea-level rise. The coastline between Punta Rasa and Mar del Plata is undergoing severe erosion, partly due to natural causes (*e.g.*, lack of fluvial sediment input, storm surges, and wave action), but mainly because beach-sand mining and urbanization in the dune zone take place without any planning or environmental assessment. Engineering structures have been installed to protect the shore (*e.g.*, in Mar del Plata), but in many cases they operate locally and cause downdrift erosion by reducing littoral sediment transport.

The first and best-known model relating shoreline retreat to an increase in local sea level is that proposed by Bruun in 1962. This model assumes that with a rise in sea level the beach profile moves upward and landward, though retaining its original shape. The landward shift constitutes the shoreline retreat. The model is illustrated in Figure 16 for a two-dimensional analysis (KOMAR *et al.*, 1991). Bruun derived a relationship for the shoreline retreat rate, R, due to an increase in sea level, S:

$$R = \frac{L}{B + h} S$$

where L is the cross-shore distance to the water depth h taken by Bruun as the depth to which nearshore sediments exist (closure depth). The vertical dimension B represents the berm height or other elevation estimate of the eroded area.

WEGGEL (1979) proposed an interesting method to evaluate shoreline retreat from Bruun's concept. He uses an exponential decay equation to fit the actual profile data in a series of steps until only small changes in the fitting process are obtained between successive approximations. The equation is of the form,

$$y - y_0 = he^{-\alpha x}$$

where y is the vertical coordinate of the profile, x is the horizontal coordinate, y_0 is a datum adjustment factor (to be determined by trial and error), h is the above-mentioned closure depth, and α is an empirical coefficient that describes the rate of increase in water depth with distance offshore.

Application of this procedure to the sandy shoreline of Pun-

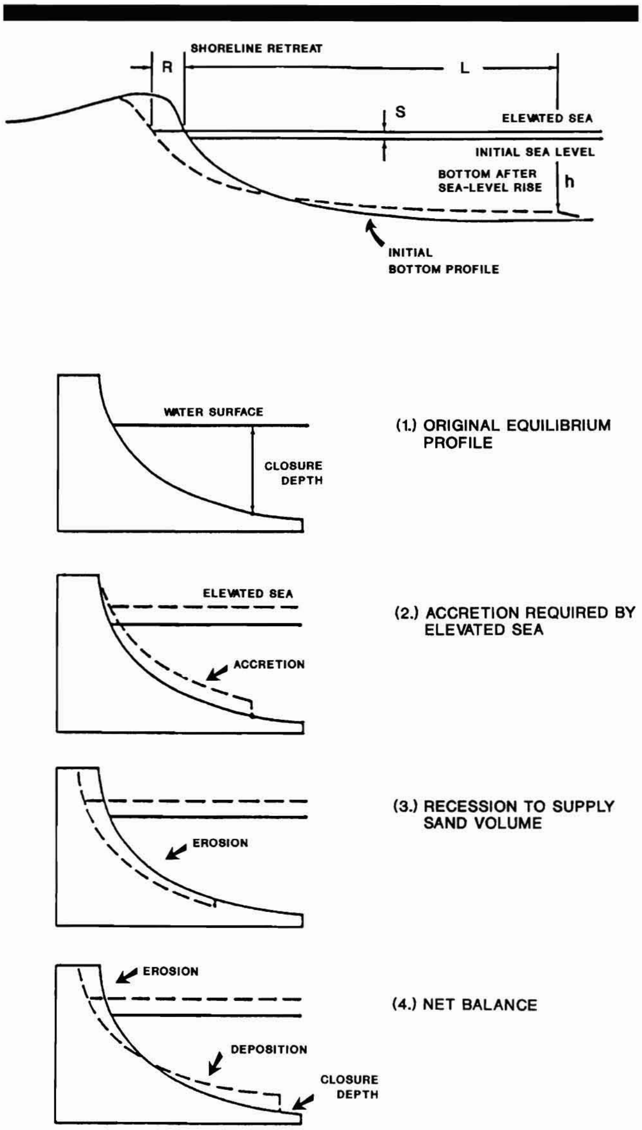

Figure 16. The net change in beach profile position due to a rise in sea level, according to the Bruun model. (From Komar *et al.*, 1991).

ta Médanos gave a shoreline recession of 0.31 m/year. This rate was obtained using the long-term trend in sea-level rise from Quequén, +1.6 ± 0.2 mm/year (LANFREDI *et al.*, 1988).

Considering the scenarios of 0.2, 0.5 and 1.0 m increases in sea level by the year 2100 proposed by DENNIS *et al.* (1995), a beach profile at Punta Médanos would undergo a retreat of 0.39, 0.97 and 1.94 m/year respectively. These estimates suggest dramatic impacts from such a rapid sea-level rise. Natural beaches, however, do not respond exactly to this idealized model. Therefore, straightforward application of Bruun's rule must be cautiously considered, but it can be used as a guiding approach for evaluation purposes.

Impact on harbours in any of the predicted scenarios would probably be high in the Buenos Aires and Bahía Blanca because of the flat, low-lying terrain of the surrounding areas where very important economic activities take place. At Mar del Plata, Quequén, Puerto Madryn, and Comodoro Rivadavia the impact would be moderate and the affected areas would be those next to the shoreline. To the south the impact would be low.

Salt-water encroachment of coastal aquifers and inland transportation of pollutants should also be mentioned as possible impacts. Wetlands would be affected, either by migration and recolonization or by disappearance when migration is restricted by highlands or hard substrates (SCHNACK *et al.*, 1991).

FINAL COMMENTS

As described above, even with the present rates in sea-level rise the Argentine coastal areas are undergoing several kinds of impacts in response to both natural and anthropogenic processes. The accelerated rate in sea-level rise predicted for the next century will exacerbate these impacts, and the need for expertise, sufficient available data, suitable policies and management regulations will be rendered inescapable if proper use and protection of the coastal zone are to be achieved.

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□ RESUMEN □

Se consideran las consecuencias que un acelerado ascenso del nivel del mar podría acarrear a la costa argentina a la luz de la tendencia a largo plazo en el cambio del nivel del mar, de los impactos naturales y antropogénicos que la franja costera argentina sufre actualmente y de las actividades humanas que allí se desarrollan. Las variaciones del nivel de las aguas fueron determinadas a partir de registros de alturas horarias de marea para Buenos Aires, Mar del Plata, Quequén y Puerto Madryn. Las series usadas para Buenos Aires (1905–1992) y Quequén (1918–1981) no presentaron interrupciones. La de Mar del Plata (1954–1992) tenía interrupciones en abril y junio de 1981, noviembre y diciembre de 1986, y febrero y marzo de 1987, mientras que la de Puerto Madryn (1945–1983) presentaba una interrupción en mayo de 1982. Una vez completadas convenientemente estas interrupciones se obtuvieron las correspondientes series de niveles medios anuales, calculadas como promedios de valores medios mensuales. Se utilizaron filtros pasabajos, simétricos, con ventanas de Kaiser-Bessel para atenuar las contribuciones de componentes periódicas de entre 8 y 19 años. Las series filtradas fueron analizadas con la transformada rápida de Fourier, recoloreadas en el dominio de la frecuencia y antitransformadas de nuevo. Los resultados se usaron para construir rectas de regresión cuyas pendientes indicaron una tendencia a largo plazo en la variación del nivel de las aguas de $+1.6 \pm 0.1$ mm/año para Buenos Aires, $+1.4 \pm 0.5$ mm/año para Mar del Plata, $+1.6 \pm 0.2$ mm/año para Quequén, y $+3.5 \pm 0.1$ mm/año para Puerto Madryn. Se presentan ejemplos del aumento del nivel de las aguas asociado con una onda de tormenta para mostrar cómo este fenómeno afecta a la costa argentina. Utilizando el modelo de Bruun se cuantifica la erosión que sufriría una playa del sector arenoso de la costa de la Provincia de Buenos Aires debido a un aumento acelerado del nivel del mar. Se mencionan también otros impactos probables, especialmente sobre las actividades humanas.