Wind wave climate change: Impacts on the littoral processes at the Northern Buenos Aires Province Coast, Argentina

Walter C. Dragani, Paula B. Martin, Guadalupe Alonso, Jorge O. Codignotto, Bárbara E. Prario & Guido Bacino

Climatic Change
An Interdisciplinary, International Journal Devoted to the Description, Causes and Implications of Climatic Change

ISSN 0165-0009
Volume 121
Number 4

Climatic Change (2013) 121:649-660
DOI 10.1007/s10584-013-0928-8

Springer

Climatic Change (2013) 121:649–660
DOI 10.1007/s10584-013-0928-8

Wind wave climate change: Impacts on the littoral processes at the Northern Buenos Aires Province Coast, Argentina

Walter C. Dragani · Paula B. Martin · Guadalupe Alonso · Jorge O. Codignotto · Bárbara E. Prario · Guido Bacino

Received: 30 April 2013 / Accepted: 2 September 2013 / Published online: 19 September 2013

Abstract Several works reported wind-wave climate changes at Buenos Aires Province continental shelf. The aim of this work is to investigate the impact of these changes in the coastal processes of the region. This study is carried out by means of visual wave parameters gathered at the surf zone of Pinamar and by a conveniently implemented and validated numerical wave model (SWAN). Numerical results corresponding to a grid point located 30 km off Pinamar show a significant increase of wave heights from the S and SSE directions and in the frequency of occurrence of waves coming from the S, SSE and E. It is shown that these slight offshore appreciated trends would not have significant effects on the breaker heights observed at the surf zone at Pinamar. On the contrary, the slight positive trend observed offshore in the frequency of occurrence could be affecting the incidence of waves onshore, producing an increase in the number of cases of normal incidence at the surf zone and, consequently, a significant decrease in the alongshore wave energy flux assessed

W. C. Dragani · P. B. Martin · G. Alonso · B. E. Prario
Servicio de Hidrografía Naval y ESCM-INUN, Av. Montes de Oca 2124 (C1270ABV),
Ciudad Autónoma de Buenos Aires, Argentina

W. C. Dragani · P. B. Martin · G. Alonso · J. O. Codignotto · G. Bacino
CONICET, Consejo Nacional de Investigaciones Científicas y Técnicas,
Av. Rivadavia 1917. (C1033AAJ), Ciudad Autónoma de Buenos Aires, Argentina

W. C. Dragani · P. B. Martin · G. Alonso
Departamento de Ciencias de la Atmósfera y los Océanos, Facultad de Ciencias Exactas y Naturales,
UBA, Ciudad Universitaria, Pabellón II, 2do. Piso. (C1428EGA),
Ciudad Autónoma de Buenos Aires, Argentina

W. C. Dragani (✉)
Instituto Franco - Argentino para el Estudio del Clima y sus Impactos
(UMI IFAECI/CNRS - CONICET-UBA),
Ciudad Universitaria, Pabellón II, 2do. Piso. (C1428EGA), Ciudad Autónoma de Buenos Aires, Argentina
e-mail: dragani@hidro.gov.ar

J. O. Codignotto · G. Bacino
Servicio Geológico Minero Argentino (SEGEMAR),
Av. Julio A. Roca 651 10º P (C1067ABB), Ciudad Autónoma de Buenos Aires, Argentina

at Pinamar. This reduction in the alongshore wave energy flux could be responsible for some coastal changes detected in the region as, for instance, the remarkable shortening of Punta Rasa spit located 70 km northward Pinamar.

1 Introduction

The IPCC (Intergovernmental Panel on Climate Change) Working Group (WG) II stated that the analysis of risks to coastal population and ecosystems requires the inclusion of a broader range of coastal drivers of change. One of those drivers, which have received little attention to this date, is the change in the global wind-wave climate. In fact, impact studies of climate change, particularly in the coastal zone, have been hampered by the lack of assessment of potential changes in wave climate. Moreover, the IPCC WG I stated that more information on projected wave conditions are required to enable assessments of the effects of climate change on coastal erosion. Some particular beach resorts located along the Buenos Aires Province coast (Fig. 1) are suffering natural erosive processes, which are aggravated by human activities including urbanization, foredune degradation and/or sand mining. In this regard, Kokot (1997; 2010) reported an increase in the erosive processes at the coast of the Buenos Aires Province during the last three decades of the 20th Century. The author linked the enhanced erosion with changes in atmospheric and oceanic processes which seem to be a consequence of climate change.

A number of changes in atmospheric processes have been reported in the Southwestern Atlantic Ocean. Direct observations collected over the Patagonian continental shelf waters (Argentina) indicate that during the 90's, winds were 20 % stronger than during the 80's, and that their direction shifted towards the northwest (Gregg and Conkright, 2002). Barros et al.

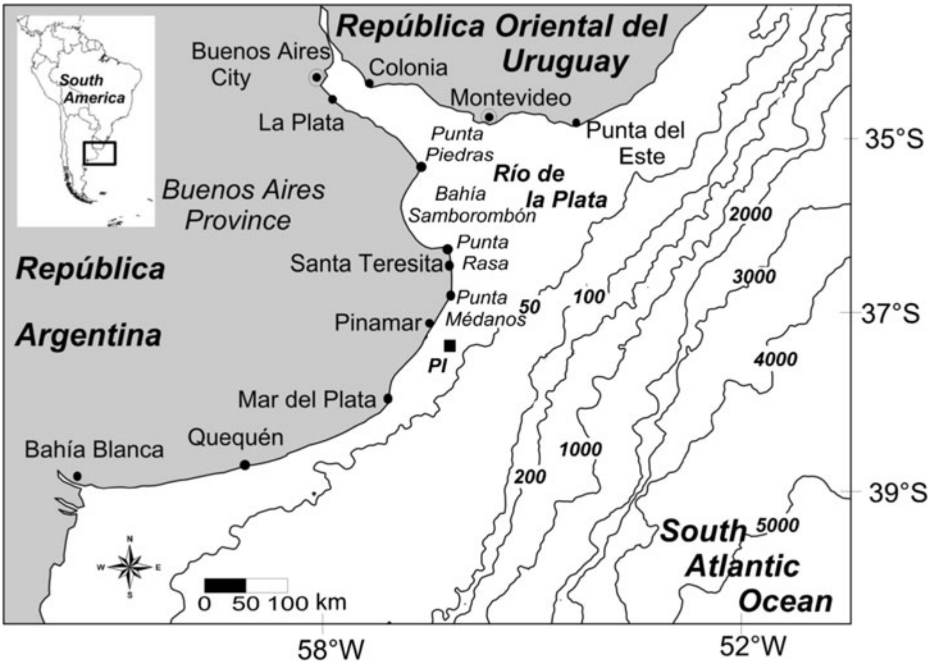

Fig. 1 Study area (computational domain where SWAN model was implemented). Depth contours in meters. PI: location where modelled wave heights was studied

(2000) found that the western border of the South Atlantic High and the atmospheric circulation over South-eastern South America have slowly shifted towards the south during the last decades. In addition, an enhancement of the easterly winds during summer and winter months over the Río de la Plata estuary and the adjacent shelf was reported by Simionato et al. (2005). Statistics of surface winds observed at the Jorge Newbery Airport (Buenos Aires City, Fig. 1) show a slight increase in the easterly winds' frequency and speed between 1981–1990 and 1991–2000. A comparison of the observations between both decades shows that the frequency of easterlies and north-easterlies has risen from 18.4 % to 22.0 % and from 11.5 % to 13.5 %, respectively. The mean speed of winds blowing from the east has risen from 4.4 m s^{-1} to 5.3 m s^{-1} (SMN, 1992; SMN, 2009).

The changes observed on winds have a direct effect on waves (see, for example, Zenkovich, 1967). Cox and Swail (2001) performed a global wave hindcast for the period 1958–1997 and obtained a slight but significant change in the annual mean and 99th percentile wind speeds and wave heights in the continental shelf offshore Buenos Aires Province (Plates 5 and 6 of their paper). Young et al. (2011) used a 23-year database of calibrated and validated satellite altimeter measurements to investigate global changes in oceanic wind speed and wave height. They estimated a general global trend of increasing values of wind speed and, to a lesser extent, wave height. Subsequently, Young et al. (2012) analyzed global altimeter data to determine whether there were measurable trends in extreme value return period estimates of wind speed and wave height. The trends indicated a positive trend in 100 year return period values of wind speed but no consistent trends for 100 year return period wave height. Recently Bertin et al. (2013) reported a significant increase in wave height in the North Atlantic Ocean over the 20th century and Hemer et al. (2013) found an increase in annual mean significant wave height over 7.1 % of the global ocean, predominantly in the Southern Ocean, which is greater during austral winter (July–September; 8.8 %). The spatial and temporal variability of extreme wave climate along the Central-South American continent was analyzed by Izaguirre et al. (2013). This study evaluates changes in the intensity of extreme significant wave height throughout the year over the 1980–2008 period, using a calibrated long-term wave reanalysis database forced with National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis. A higher increase of the extreme wave heights is found in the austral summer at Tierra de Fuego and the Falkland/Malvinas Islands, reaching 0.65 m per decade. Lately, Reguero et al. (2013) applied an extensively calibrated and validated wave reanalysis to describe the wave climatology in the region at different time scales and for scalar and directional wave parameters. Long-term changes are identified in the wave heights and mean direction of the energy flux show high spatial variability.

The possibility that wind wave heights are actually increasing in the South-eastern South American Continental Shelf was explored by Dragani et al. (2010). These authors analyzed time series of in situ (1996–2006) and Topex (1993–2001) annual mean significant wave heights gathered over the continental shelf and the adjacent ocean; even though the available series are too short to statistically assess changes, they display apparent positive trends. To further study the occurrence of a possible trend, the authors implemented SWAN wave model forced by the NCEP/NCAR surface winds in a regional domain, and performed a long term run for the period 1971–2005. The simulated wave heights showed significant positive trends at most of the inner continental shelf and the adjacent ocean. The most significant increase occurred between the 80's and the 90's, and the largest difference between both decades (0.20 m, 9 %) was observed around 34° S - 48° W. The wave height increase resulted slightly lower (7 %) over the Buenos Aires Province continental shelf. This study did not include the analysis of wave height trends considering different directions of propagation.

The effect of interannual climate variability and change on the historic, directional wave climate of the Southern Hemisphere was studied by Hemer et al. (2010). They found that significant wave heights in the Southern Ocean showed a strong positive correlation with the Southern Annular Mode (SAM), particularly during Austral autumn and winter months. In addition, the directional variability of the wave energy flux of the Southern Ocean associated with the SAM was expected to be of importance to the wave-driven currents responsible for the transport of sand along coastal margins in the Southern Hemisphere. Codignotto et al. (2012) analyzed a long term wind wave simulation with the aim of providing clues to understand the observed erosive processes which are affecting Samborombón Bay, located at the Río de la Plata estuary (Fig. 1). The analysis of the 35 year-long simulation shows a significant increment of the frequency (10 and 7 cases decade^{-1}) and height (0.04 and 0.02 m decade^{-1}) of the waves propagating from the E and ESE directions towards the bay. In agreement with Hemer et al. (2010) Codignotto et al. (2012) also reported that the increase in the frequency and height of the easterly and southeasterly waves would increment the long shore energy flux factor (*Pls*), enhancing the capability of transporting sediments along the coast, particularly at the southern sector of the bay.

Southward Samborombón Bay (Fig. 1), several hundreds of kilometers of sandy beaches are widely exposed to environmental forcings (for instance, wind wave climate, storm surges and mean sea level). The motivation of the present work is to investigate whether changes in the heights and frequencies of occurrence of wind waves, reported by Dragani et al. (2010) at Buenos Aires Province inner continental shelf, would might be actually affecting the coastal processes in the region, according to Kokot (1997; 2010). This study, although mainly supported by visual wave parameters gathered at the surf zone of Pinamar (Fig. 1), is also carried out by means of a conveniently implemented numerical model.

2 Study area

Between Punta Rasa and Punta Médanos (Fig. 1) the orientation of the coast is typically N-S but, precisely at Punta Médanos, the coastline abruptly changes 35° its direction presenting a predominant NNE-SSW orientation. Punta Médanos is located about 70 km south of Punta Rasa and about 160 km north-northeast of Mar del Plata (Fig. 1). The beaches are sandy, practically straight, with a variable width (from 60 to 140 m) and with slopes lower than 2°. Sediment (mainly quartz sand) is predominantly transported toward the N in huge rates, 0.3–1.0 10^6 m^3 year^{-1}, estimated by Caviglia et al. (1991) using the wave flux energy method (CERC, 1984). Northward Mar del Plata there is no significant structures that could affect the natural littoral drift. Tides in the northern region of the Buenos Aires Province continental shelf (Fig. 1) present a mixed and primarily semidiurnal regime. Tides have a spring range of 1.70 and 1.67 m at Mar del Plata and Santa Teresita, respectively (SHN, 2013). The coincidence of large or even moderate high tides and large meteorologically induced surges has historically caused catastrophic floods in many coastal areas of the Buenos Aires Province (Fiore et al., 2009; Pousa et al., 2012).

3 Data

Surface wind data from NCEP/NCAR Reanalysis I were used to drive the simulation. A discussions about the quality of NCEP/NCAR over the Southern Hemisphere can be found in Simmonds and Keay (2000), among others. NCEP/NCAR reanalysis has been successfully utilized as forcing in several numerical regional studies in the area (see, for instance, Dragani et al., 2010; Codignotto, et al., 2012). The period adopted for the numerical simulations was 1971–2005, in agreement with Codignotto et al. (2012) who studied the erosive processes in the Buenos Aires Province in connection with a possible wind-wave climate change in the region. A bilinear (linear) interpolation was used to generate appropriate wind fields to match the spatial (temporal) resolution of SWAN wave model.

The model domain includes regions as dissimilar as the very shallow Río de la Plata, the Uruguayan continental shelf, part of the adjacent Argentinean and Brazilian continental shelves, the continental shelf break and a portion of the South-western Atlantic Ocean. Bathymetric data for the model were obtained as a combination of 1′×1′ resolution depth data set coming from GEBCO (2003) for the continental shelf break and the deep ocean, and from digitalized nautical charts from the SHN (Servicio de Hidrografía Naval of Argentina) for the continental shelf and coastal areas. Those depths were interpolated to the model grid applying the inverse square-distance method.

4 Wave modeling

SWAN is a numerical wave model that provides realistic estimates of wave parameters in coastal areas (Booij et al., 1999; Ris et al., 1999). The particular implementation of the model to the study region spans the area between 30° S and 42° S, and 40° W and 65.5° W (computational domain can be seen in Dragani et al., 2008, Fig. 1), with a grid spacing of 22.7 km×20.0 km (100×70 grid points). A complete validation of SWAN wave model in this computational domain was presented by Dragani et al. (2008), who showed that the described domain is large enough to generate realistic wind wave fields (sea and swell) at the Río de la Plata adjacent continental shelf.

To study the evolution of the wave heights in the region, it was decided to analyze the annual root-mean-square of the significant wave height (Hs) instead of the annual mean significant height (Hs is the variable provided by the simulations), because it gives proper weight to the larger wave conditions and, therefore, will probably be a more sensitive discriminator of changes (Dragani et al., 2010). Time series of the simulated annual root-mean-square of the significant wave height (Hrms) were obtained for 16 directions, 22.5° apart (N, NNE, NE and so on) at 37° 15′ S–56° 30′ W, a representative point (grid node) located 30 km offshore Pinamar (denoted as PI in Fig. 1). 95 % confidence intervals for Hrms values are less than ±0.02 m (adopting Student's distribution) and, therefore, are not shown in the figures. Least-square regression lines for the period 1971–2005 were fitted to every series. The computed gradients only resulted statistically different of zero at a 95 % of confidence for two propagation directions: S and SSE. The calculated gradients of the best fit lines and the corresponding 95 % confidence limits were 0.06±0.05 and 0.09±0.08 m/decade, respectively (Figs. 2). For the frequency of occurrence of waves from the different directions, the computed gradients resulted statistically different from zero at a 95 % of confidence level for the S, SSE and E directions. The calculated gradients of the best fit lines and the corresponding 95 % confidence limits were 7±6, 7±5 and 13±7 cases/decade (Figs. 3).

5 Visual observations at Pinamar

Breaker heights at Pinamar (Fig. 1) have been visually observed from the shore twice a day, without large gaps (less than 6 %), since 1989. After a rigorous quality control the period

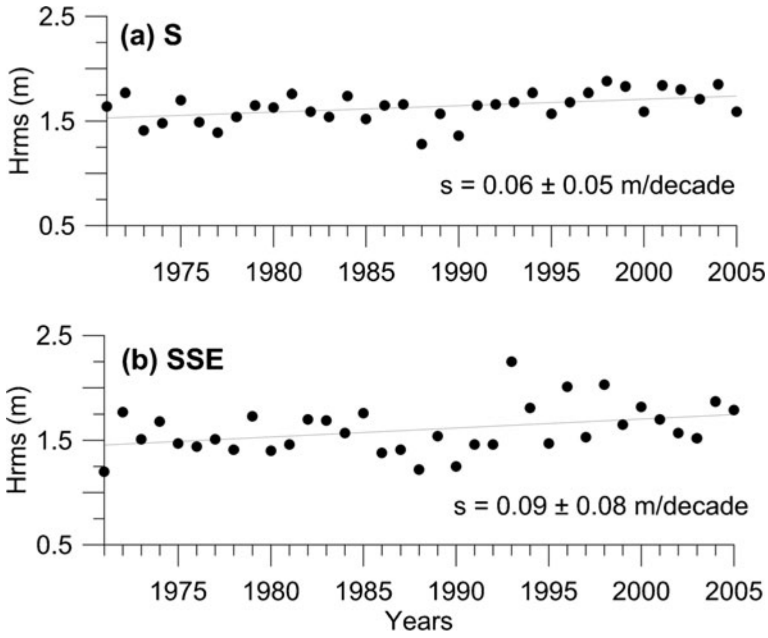

Fig. 2 Modeled (SWAN) annual root-mean-square of the significant wave heights (Hrms) for wind waves propagating from (**a**) the S and (**b**) the SSE (1971–2005 period) at PI point (Fig. 1). Corresponding least-square regression line is also included

spans from 1989 to 2007 (19 years) was selected because it presents the best performance of data acquisition. These breaker heights are estimated following the guidelines given by the Littoral Environment Observation (LEO) Data Collection Program (Schneider, 1981). The observer estimates the breaker height of the most seaward line of breakers which are generally the largest breakers. Typically the breakers are low (~ 1 m) and relatively close to the shore and breaker heights are fairly easy to estimate. However, when the breakers are high and the surf zone is wide (especially during storms) it is considerably more complicated. In some cases, during storms or high windy conditions, is not possible to estimate the breaker heights because the waves are too large and too far from the shore. Therefore, visual breaker heights are frequently used to give a realistic estimation of the mean wave parameters in the surf zone, but they are rather inappropriate to establish, for example, the annual maximum breaker height.

The angle of wave approach at breaking (θ_b) is determined by using a protractor which must be held horizontally with its base oriented parallel with the shoreline. The observer then sights along the direction from which the breaking waves are approaching shore and records the appropriate angle from the protractor. When waves come normally respect to the coast the angle of wave approach is taken like 0°, if they come from the left (right) hand of the observer, a negative (positive) value for the angle is taken. In general, the greatest uncertainties occur when waves approach obliquely respect to the shoreline. In these cases the error of the observations can reach some degrees (in general, less than 3°). However, when the incidence of the waves is practically normal respect to the shoreline, the error in the wave approach angle become quite lower (no more than 1°) and consequently, the observed values are highly reliable.

The annual amount of normal incidences at Pinamar is presented in Fig. 4a. In this figure, a slight but significant positive trend (17±10 cases decade^{-1}) can be clearly appreciated in the analyzed period. Consistently with this fact, negative trends are appreciated in the annual

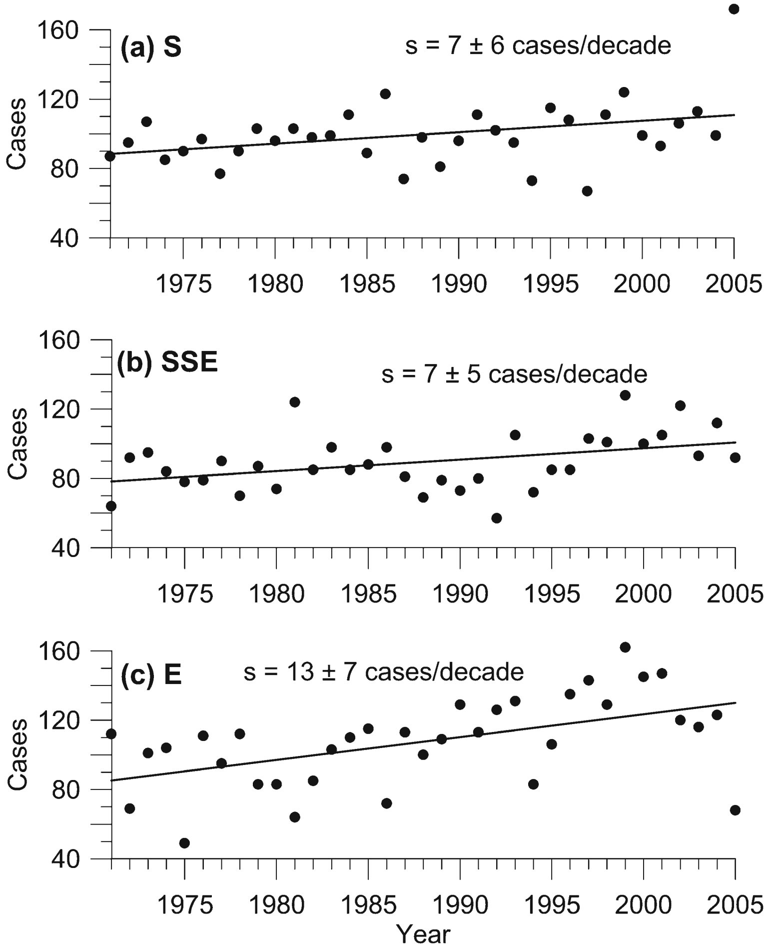

Fig. 3 Modeled (SWAN) annual frequency of occurrence for wind waves propagating from (**a**) the S, (**b**) the SSE and (**c**) the E (1971–2005 period) at PI point (Fig. 1). Corresponding least-square regression line is also included

amount of waves approaching obliquely respect to the coast, from the left or the right respect to an observer looking the sea (figures not included in this paper). On the other hand, annual mean breaker heights (H_b) gathered at Pinamar are presented in Fig. 4b. A very slight decreasing of the annual breaker heights can be observed in this figure. Statistically, this decreasing is not significant different to zero. The annual root-mean-square of the breaker height at Pinamar (period: 1989–2007) is 0.91 m and the mean wave period is 9 s.

6 Estimated alongshore wave energy flux at Pinamar

Sediment is predominantly transported toward the north-northeast at a variable rate (0.3–1.0×10^6 m^3 $year^{-1}$) as estimated by Caviglia et al. (1991) using the wave energy flux method (CERC, 1984; Dean and Dalrymple 2004) and Kokot (1997) using geomorphological techniques. Historically, the total amount of material moved along the shoreline has been

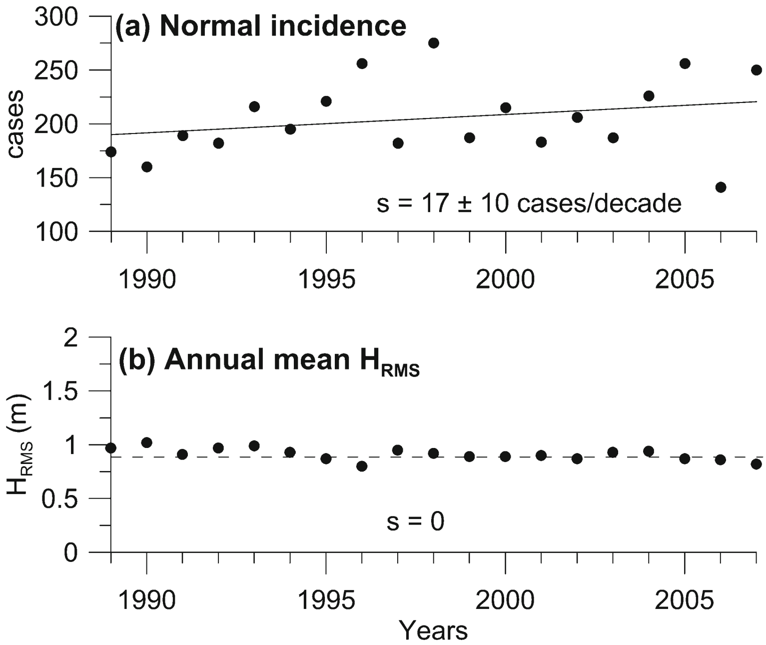

Fig. 4 (**a**) Observed annual amount of normal incidence of waves (cases) at Pinamar. Least-square regression line is also included (95 % confidence interval is indicated) and (**b**) annual root-mean-square of observed heights at Pinamar

assumed proportional to the wave energy flux per unit crest (*Pls*). This quantity is usually estimated by means of a simple formulation which is proportional to $\rho g^{3/2} H_b^{5/2}$ (sin 2 θ_b) (CERC, 1984), where ρ is the seawater density, g is the acceleration due to gravity, and H_b and θ_b are the observed wave height and the angle between the wave crest and the shoreline, respectively. It can be easily observed that greater values of H_b and θ_b, lead to higher values of *Pls* (considering that θ_b is, in general, lower than 45° in the surf zone). The annual flux was assessed using the observed wave parameters at Pinamar. Our results indicate that the net annual Pls is, in general, directed towards the north-northeast which is in good agreement with the results obtained by Caviglia et al. (1991). Taking into account the obtained positive trend in the annual amount of normal incidences at Pinamar (Fig. 4a) it seems reasonably to suppose that the alongshore wave energy flux factor (*Pls*) might also present a variation during the study period. Computed *Pls* (Fig. 5) displays a marked decrease of −155 KJ m^{-1} per decade (1 KJ=10^3 J) in the north-northeastward wave energy flux (Fig. 5a), −63 KJ m^{-1} per decade in the south-southwestward direction (Fig. 5b) and −92 KJ m^{-1} per decade in the net flux (difference between the two values aforementioned) in the north-northeastward direction (Fig. 5c). These trends can be easily explained considering the observed increase in the number of cases of normal incidence at Pinamar, which would produce a significant decrease in the long shore energy wave flux at this sector of the coast.

7 Discussion

Even though, at the present, this sector of the Buenos Aires Province coast has presented a very weak scientific attention, paradoxically, it has a huge economic interest because along

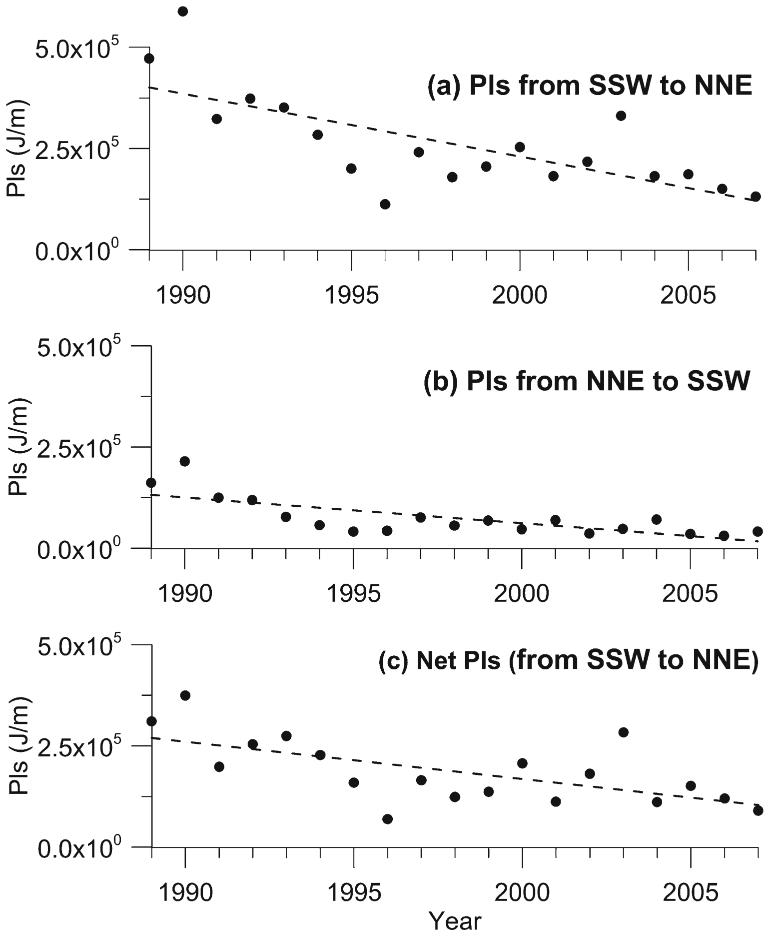

Fig. 5 Computed alongshore wave energy flux per unit crest (Pls in Jm^{-1}) at Pinamar (**a**) from SSW, (**b**) from NNE and (**c**) annual net flux

their coast there are emplaced a lot of seaside resorts visited by millions of tourist every summer. Almost no systematic measurements of coastal or environmental parameters are available at the studied zone; in consequence, there is not any comprehensive study about alongshore currents, nearshore circulation, onshore-offshore and alongshore sediment transport and their temporal and spatial variability. In general, such data or studies constitute the cornerstone to understand or, at least, to give a possible explanation about the evident long-term variability of some coastal processes in the region. The single, relatively long and systematic data series gathered in the area correspond to wave parameters visually observed at the surf zone at Pinamar (Fig. 1). This lack of field information logically constitutes a clear explanation about the scarce amount of scientists articles, published in the peer reviewed literature, on littoral dynamics or coastal processes at the Buenos Aires Province coast.

Numerical results showed a significant increase of waves heights propagating from the S and SSE (Fig. 2) and an increase in the number of cases of waves coming from the S, SSE and E (Fig. 3) at a grid point *PI* located 30 km offshore Pinamar (Fig. 1). Apparently, this slight increase appreciated offshore in the simulated wave height has not an effect on the breaker heights observed at the surf zone at Pinamar (mean annual H_b presents a practically constant value). On the contrary, the slight positive trend in frequencies of waves coming from the S, SSE and E (Fig. 3) at PI in combination with possible bathymetric changes at the coastal waters of the inner continental shelf could be affecting the incidence of waves at the surf zone producing an increase in the amount of normal propagation of waves. A possible reduction in the angle of wave approach at breaking (θ_b) would be responsible of the significant decrease in *Pls* detected at the surf zone at Pinamar (Fig. 5) and then, could be responsible of some coastal changes observed in the area.

Punta Rasa spit, located at the northernmost border of Buenos Aires Province Atlantic coast approximately 100 km northward Pinamar (Fig. 1) is a dynamic sandy natural feature which has shown significant, evident and obvious natural transformations in a relatively short time scale. Since the first topographic surveys carried out during the emplacement of San Antonio lighthouse in the last decade of the 19th century, Punta Rasa spit grew quasi-monotonic towards the north-west in a delicate equilibrium between wind wave climate, littoral processes and storms (Kokot, 1997). But, since approximately a decade ago, the spit has shown a significant and accelerated retrogression. Two pictures of Punta Rasa spit, one of them taken from an aircraft in 1964 by the SHN and another taken from the INPE in 2009 (Instituto Nacional de Pesquisas Espaciaes of Brazil) were analyzed by Dragani et al. (2012). The comparison of both figures evidences that the sand spit has disappeared in the image of 2009, which is in agreement with Kokot (2010). As a result of this complex transformation, the northwest extreme of Punta Rasa retreated around 560 m in less than 50 years. This change of the spit could be associated with a gradual reduction of the alongshore sand transport, which comes predominantly from the south, which would be in good agreement with the decrease in the northward alongshore wave energy flux detected at Pinamar (Kokot, 1997 and 2010). It is important to highlight that the aeolian sand transport and some anthropogenic effects should also be analyzed as possible drivers of the significant and accelerated retrogression of Punta Rasa sand spit.

A possible relationship between the Southern Hemisphere Annular Mode (SAM) index, defined as the difference in the normalized monthly zonal-mean sea level pressure (SLP) between 40°S and 70°S, with the modeled (SWAN) annual root-mean-square of the Hrms for wind waves propagating from the S and the SSE (1971–2005 period) at PI point (Fig. 2) was analyzed in the present work. Even though the SAM index also presents a positive trend in the period of analysis (http://www.lasg.ac.cn/staff/ljp/data-NAM-SAM-NAO/SAM(AAO).htm) it is important to highlight that correlation between annual the SAM index and annual Hrms, for wind waves propagating from the S and the SSE, is less than 0.2. Although it is well known that the SAM index reflects changes in the main belt of sub-polar westerly winds (enhanced Southern Ocean westerlies occur in the positive phase of the SAM, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch3s3-6-5.html) preliminary results obtained in this work shows that the SAM index would be weakly associated with long-term changes in wave climate at the Buenos Aires Province inner continental shelf.

In addition to the above discussed changes in the wave climate and in the alongshore wave energy flux is important to highlight other changes associated to the storm surge and to the mean sea level which securely contributes to the observed changes in the littoral processes in the region. Water level observations (Escobar et al., 2004; D'Onofrio et al., 2008) reveal changes in the frequency and height of positive and negative storm surges in the Río de la Plata. Escobar et al. (2004) studied the annual mean frequency of "sudestadas", defined as the positive storm surges over +1.60 m, during the last five decades of the 20th century, and observed a positive trend in the absolute frequency during the last decades, rising from 44 cases in the 60's to 79 cases in the 90's. Fiore et al. (2009) and Pousa et al.

(2012) studied the storm surges at the coast of the Buenos Aires Province and reported a 7 % increase in the number of positive storm surges in the last decade. The decadal frequency trend for positive storm surges obtained was +0.19±0.10 events per year. On the other hand, sea level has been slowly but monotonically increasing in the study area. Lanfredi et al. (1998), reported a long term trend in the water level of +1.6±0.1 mm yr^{-1} for Buenos Aires city (analyzed period: 1905–1992) and +1.4±0.5 mm yr^{-1} for Mar del Plata (analyzed period: 1954–1992). In addition, recently Losada et al. (2013) reported long-term changes in sea-level components in Latin America and the Caribbean.

8 Conclusion

Several studies have suggested the possible occurrence of changes in the low atmospheric circulation in the Southwestern Atlantic Ocean which seem to be impacting the ocean. Indeed several papers reported changes the wind waves at the Western South Atlantic Ocean. In this work, numerical results showed a significant increase of wave heights propagating from the S and SSE and an increase in the number of cases of waves coming from the S, SSE and E at the inner Buenos Aires Province continental shelf. The slight positive trend in frequencies of waves in combination with possible bathymetric changes could be producing an increase in the amount of normal incidences at Pinamar. Consequently, a possible reduction in the angle of wave approach at breaking would be responsible of the significant decrease in the alongshore wave energy flux detected at the surf zone at Pinamar. This fact could be trigger of different changes in the littoral processes in the regions. Northward Pinamar, Punta Rasa spit has shown significant, evident and obvious natural retrogression in a relatively few years. Apparently, this shortening could be associated with a gradual reduction of the alongshore sand transport, which comes predominantly from the south. This fact is highly consistent with the decrease of the northward alongshore wave energy flux detected at Pinamar, which is a consequence of the reported wind wave clime change at the Buenos Aires continental shelf.

Acknowledgments This paper is a contribution to the CONICET PIP 112-200801-02599 and 112-201101-00176 projects.

References

Barros V, Castañeda ME, Doyle M (2000) Recent precipitation trends in Southern South America to the East of the Andes: an indication of a mode of climatic variability. In: Smolka P, Wolkheimer W (eds) Southern Hemisphere Paleo and Neoclimates Concepts, Methods, Problems. Springer, Berlin, pp 187–206

Bertin X, Prouteau E, Letetrel C (2013) A significant increase in wave height in the North Atlantic Ocean over the 20th century. Glob Planet Chang 106:77–83

Booij N, Ris RC, Holthuijsen LH (1999) A third-generation wave model for coastal regions. 1. Model description and validation. J Geophys Res 104(C4):7649–7666

Caviglia F, Pousa J, Lanfredi W (1991) A determination of the energy flux constrant from the dredge records. J Coast Res 7(2):543–549

CERC (1984) Littoral Processes. In Shore Protection Manual, Ch. 4, vol. 1. US Government Printing Office, Washington, pp 1–214

Codignotto J, Dragani WC, Martin PB, Simionato CG, Medina RA, Alonso G (2012) Wind-wave climate change and increasing erosion observed in the outer Río de la Plata, Argentina. Cont Shelf Res 38:110–116. doi:10.1016/j.csr.2012.03.013

Cox A, Swail V (2001) A global wave hindcast over the period 1958–1997: validation and climate assessment. J Geophys Res 106(C2):2313–2329

Dean, R. and Dalrymple, R., 2004. Coastal Processes with Engineering Applications, Cambridge University Press.

D'Onofrio E, Fiore M, Pousa JL (2008) Changes in the regime of storm surges at Buenos Aires, Argentina. J Coast Res 24:260–265

Dragani W, Garavento E, Simionato C, Nuñez M, Martín P, Campos MI (2008) Wave simulation in the outer Río de la Plata estuary: an evaluation of SWAN model. J Waterw Port Coast Ocean Eng 134(5):299–305

Dragani WC, Martín P, Campos MI, Simionato C (2010) Are wind wave heights increasing in South-eastern South American continental shelf between 32S and 40S? Cont Shelf Res. doi:10.1016/j.csr.2010.01.002

Dragani, W. C., Codignotto, J.O., Martin, P. B., Campos, M. I., Alonso, G., Simionato, C. G. and Medina, R., 2012. Some coastal impacts related to wind wave changes in south-eastern South American continental shelf. Editors: B. Veress and J. Szigethy, in "Horizons in Earth Science Research", Nova Science Publishers, 6, 161–177.

Escobar G, Vargas W, Bischoff S (2004) Wind tides in the Río de la Plata estuary: meteorological conditions. Int J Climatol 24:1159–1169

Fiore M, D'Onofrio E, Pousa JL, Schnack E, Bértola G (2009) Storm surges and coastal impacts at Mar del Plata, Argentina. Cont Shelf Res 29(14):1643–1649. doi:10.1016/j.csr.2009.05.004

GEBCO, 2003. User guide to the centenary edition of the GEBCO Digital Atlas and its data sets. Ed. Jones MT, Natural Environment Research Council.

Gregg, W.W. and Conkright, M.E, 2002. Decadal changes in global ocean chlorophyll. Geophys Res Lett 29(15):doi:10.1029/2002GL014689

Hemer M, Church J, Hunter J (2010) Variability and trends in the directional wave climate the Southern Hemisphere. Int J Climatol 30:475–491

Hemer M, Fan Y, Mori N, Semedo A, Wang X (2013) Projected Changes in wave climate from a multi-model ensemble. Nat Clim Chang. doi:10.1038/nclimate1791

Izaguirre C, Méndez FJ, Espejo A, Losada IJ, Reguero BG (2013) Extreme wave climate changes in Central-South America. Clim Chang. doi:10.1007/s10584-013-0712-9

Kokot RR (1997) Littoral drift evolution and management in Punta Médanos, Argentina. J Coast Res 13(1):192–197

Kokot RR (2010) Espigas indicadoras de proveniencia de olas en la costa Argentina. Rev Asoc Geol Argent 67(1):19–26

Lanfredi N, Pousa J, D'Onofrio E (1998) Sea level rise and related potential hazards on the Argentine coast. J Coast Res 14(1):47–60

Losada I, Reguero B, Méndez F, Castanedo S, Abascal A, Mínguez R (2013) Long-term changes in sea-level components in Latin America and the Caribbean. Glob Planet Chang 104:34–50

Pousa JL, D'Onofrio E, Fiore M, Kruse E (2012) Environmental impacts and simultaneity of positive and negative storm surges on the coast of the Province of Buenos Aires, Argentina. Environ Earth Sci 24(1A):260–265

Reguero B, Méndez F, Losada I (2013) Variability of multivariate wave climate in Latin America and the Caribbean. Glob Planet Chang 100:70–84

Ris RC, Holthuijsen LH, Booij N (1999) A third-generation wave model for coastal regions. 2. Verification. J Geophys Res 104(C4):7667–7681

Schneider, C., 1981. The littoral environment observation (LEO) data collection program. Coastal Engineering Technical Aid 81–5. Coastal Engineering Research Center, US Army, Corps of Engineers, Virginia, 23 p.

SHN (2013) Tablas de Marea. Servicio de Hidrografía Naval. Ministerio de Defensa, Buenos Aires

Simionato, C., Vera, C. and Siegismund, F., 2005. Surface wind variability on seasonal and interannual scales over Río de la Plata. J. Coast. Res (21):770-783

Simmonds, I., Keay, K., 2000. Mean Southern Hemisphere extratropical cyclone behavior in the 40-year NCEP-NCAR reanalysis. J. Climate (13):873–885

SMN, 1992. Estadisticas Climatológicas 1981–1990. Serie B - N° 37. Fuerza Aérea Argentina, Comando de Regiones Aéreas, Servicio Metorológico Nacional. 710 p.

SMN, 2009 Estadisticas Climatológicas 1991–2000. Fuerza Aérea Argentina, Servicio Metorológico Nacional. CD-rom.

Young IR, Zieger S, Babanin AB (2011) Global Trends in Wind Speed and Wave Height. Science 332:451–455

Young IR, Vinoth J, Zieger S, Babanin AV (2012) Investigation of trends in extreme value wave height and wind speed. J Geophys Res 117:C00J06

Zenkovich VP (1967) Processes of coastal development. Steers Oliver and Boyd, Londres, 738 pp