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Are wind wave heights increasing in south-eastern south American continental shelf between 32°S and 40°S?

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ABSTRACT

In this paper, a possible increase in wind wave heights in the south-eastern south American continental shelf between 32°S and 40°S is investigated. Both time series of *in situ* (1996–2006) and topex (1993–2001) annual mean significant wave heights gathered at the continental shelf and adjacent ocean present apparent positive trends. Even though these trends are not statistically different from zero, it must be taken into account that the available *in situ* and satellite data have a short span and, moreover, *in situ* data present several gaps. Several papers presented evidence about a possible change on the low atmospheric circulation in this region of the southern hemisphere. Consequently, a weak increase in wave height might be occurring, which would be hard to quantify due to the shortness and the insufficiency of the available observations. In order to study a possible trend in mean annual wind wave heights simulating waves nearshore (swan) model forced with ncep/ncar surface wind was implemented in a regional domain for the period 1971–2005. The annual root-mean-square heights of the simulated wave show significant trends at several locations of the inner continental shelf and the adjacent ocean. The most significant increase is observed between 1991–2000 and 1981–1990 decades. The largest difference (0.20 m, 9%) occurs around 34°S–48°W. The wave height increase is somewhat lower, 7%, in the continental shelf and in the río de la plata estuary. The annual mean energy density (spatially averaged) also presents a significant positive trend (0.036 m^2/yr) and relatively high inter-annual variability. The possible link between this inter-annual variability and el niño–southern oscillation (enso) was investigated but no apparent relationship was found. A possible increase in the annual mean energy density of waves would be able to produce changes in the littoral processes and, consequently, in the erosion of the coast.

1. Introduction

Significant trends in the wind wave height in different seas around the globe, especially in the Northeast Atlantic and Northeast Pacific Oceans, reported by several authors, have been related to changes and variability of the wind regime. Carter and Draper (1988) studied ocean wave observations in the Northeast Atlantic and found a substantial increase in wave heights. The gradient of the regression line of the annual mean significant wave height for the period 1962–1983 was 0.034 m/yr. Bacon and Carter (1990) presented a review of all the available data, including both visual estimates and instrumental measurements, in the North Atlantic Ocean and the North Sea. They found an increase in the mean wave height over the whole North Atlantic of about 2% per year, which seems to have started around 1950. As pointed out by them, data were insufficient to assess whether maxima or extremes had also risen. Gulev and Hasse (1999) found significant wave height increases of 0.10–0.30 m/decade in the North Atlantic for the period 1964–1993, except for the western and central subtropics. Climatology of global waves obtained by Sterl et al. (1998) for the period 1979–1993 also showed trends in significant wave height. The largest trends were observed in the North Atlantic with an increase in more than 0.12 m/yr in January and in South of Africa where the positive trend exceeded 0.07 m/yr in July. Grevemeyer et al. (2000) detected a significant increase in the wave height over the last decades of their study (80 s and 90 s) in the Northeastern Atlantic. Wang and Swail (2001) assessed trends in the seasonal extremes of significant heights in the North Atlantic and North Pacific oceans, from a 40 yr global wave hindcast driven by the

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National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis (NCEP/NCAR) reanalysis wind fields. Using the NCEP/NCAR reanalysis and in situ data, Graham and Díaz (2001) found evidence of important changes in the winter (December–March) cyclone climatology of the North Pacific Ocean over the past 50 yr. The frequency and strength of extreme cyclones has markedly increased, with positive trends in the extreme surface winds between 25°N and 40°N and major changes in the cyclone-related circulation patterns in the Gulf of Alaska. The associated increase in extreme wave heights was inferred from both direct wave measurements and wave-model hindcasts. Cox and Swail (2001) described the first 40 yr global wave simulation derived from the NCEP/NCAR surface wind fields A global trend analysis showed well-defined statistically significant areas of increasing trend in the Northeast Atlantic and decreasing trend in the central North Atlantic for wind and waves. Consistent with previous studies, these areas were linked to the North Atlantic Oscillation. Simmonds and Keay (2002) used 6-hourly data from the NCEP/NCAR reanalysis set (1958–1997) to determine the winter and summer mean fluxes of momentum and mechanical energy into the Northern Hemisphere oceans. They found significant positive winter trends over the extratropical Pacific and in the Atlantic north of about 40°N which are broadly in line with those in observed significant wave height over the northern oceans in recent decades. Gower (2002) studied the inter-annual variability and trends from time series (1972–1999) of sea surface temperature, wind speed, and significant wave height gathered by 26 meteorological buoys off the west coast of Canada and the United States. Both the monthly wind speed and wave height means showed a positive trend. WoolfVariability and predictability of the North Atlantic wave climate et al. (2002) observed a substantial rise (up to 0.6 m) in the monthly mean wave heights on the Northeastern Atlantic during the latter part of the twentieth century, which showed a robust connection with the North Atlantic Oscillation. Gulev et al. (2003) described the development and validation of a global climatology (period 1958–1997) of basic wave parameters based on the voluntary observing ship (VOS) data from the Comprehensive Ocean–Atmosphere Data Set collection. The highest sampling biases were observed in the South Ocean, where wave height may be underestimated by 1–1.5 m because of poor sampling, primarily associated with a fair weather bias of ship routing and observation. Centennial time series of visually observed wave height demonstrate positive trends in significant wave height over the North Pacific with a maximum of 0.08–0.10 m/decade in the Northeast Pacific. In the North Atlantic and other basins significant upward changes (up to 0.14 m/decade) are observed only for the last 50 yr and not for centennial records (Gulev and Grigorieva, 2004). Méndez et al. (2006) estimated long-term positive trends in the frequency and intensity of severe storm waves applying a time-dependent statistical model to the Washington NOAA buoy (46005) significant wave height data set. Menéndez et al. (2008) studied the climatology and variability of extreme wave heights at 26 wave buoys in the Northeast Pacific over the 23 yr period 1985–2007. They showed seasonal long-term trends as well as the effect of inter-annual variability associated to the ENSO and mid-latitude climate patterns of extreme values of significant wave height at all buoys studied.

Several atmospheric changes have also been reported in the Southwestern Atlantic, even though no studies about wind wave changes in this hemisphere can be found in specialized literature. For instance, Gibson (1992) showed a poleward shift of 3° in the maximum wind at 500 hPa during the period 1976–1991. Van Loon et al. (1993) calculated the latitude of the zonal average of the subtropical ridge over the Southern Hemisphere, finding a 2° change in the period 1976–1990. Local observations over the Patagonian continental shelf waters indicated that during the 90 s, winds were 20% stronger than during the 80's, and that their direction shifted northwesterly (Gregg and Conkright, 2002). Escobar et al. (2003) showed that the western border of the South Atlantic high has slowly shifted southward during the last decades. This displacement has produced a larger frequency of easterly winds over the Río de la Plata region (Fig. 1). Other studies seem to confirm this result. The southward shift of the South Atlantic high was also investigated by Camilloni (1999), Camilloni (2005) and Camilloni et al. (2005), a southward displacement of the regional atmospheric circulation over south-eastern south America was inferred by Barros et al. (2000) and an enhancement of the easterly winds during summer and winter months over the Río de la Plata estuary was reported by Simionato et al. (2005a). Moreover, surface wind statistics corresponding to periods 1981–1990 and 1991–2000 show a slight increase in the easterly wind frequency and speed at the Jorge Newbery Airport (Buenos Aires City). A comparison of the observations between both decades indicates that the frequency of easterlies and north-easterlies increased from 18.4% to 22.0% and from 11.5% to 13.5%, respectively. The easterly mean wind speed has risen from 4.4 to 5.3 m/s. (SMN, 1992, 2009).

The aforementioned wind variability seems to have impacted on the sea level, the frequency and height of positive and negative storm surges in the Río de la Plata and the adjacent continental shelf. Escobar et al. (2004) studied the annual mean frequency of "sudestadas" (positive storm surges over 1.60 m) during the last five decades of 20th century. A positive trend in the absolute frequency was observed during the last decades, rising from 44 cases in the 60 s to 79 cases in the 90 s. D'Onofrio et al. (2008) studied the changes in frequency, duration and height of storm surges in the Río de la Plata over the period 1905–2003 from statistical analysis of hourly water levels. Their results show that the decadal averages of both frequency and duration of positive surges have increased during the last three decades.

With regards to the impact of wind changes on waves in the region, Cox and Swail (2001) inferred a slight but significant change in annual mean and 99th percentile wind speed and wave height in the Buenos Aires Continental Shelf, offshore the Río de la Plata mouth. Nevertheless, they highlighted the difficulty in separating some inhomogeneities in the NCEP/NCAR winds from real climate change. Dragani and Romero (2004) studied the impact on mean wave parameters in the upper Río de la Plata, associated to a possible future scenario in which wind frequencies and intensities for the easterly directions would be respectively 30% and 10% higher than the present values. The results for the upper Río de la Plata

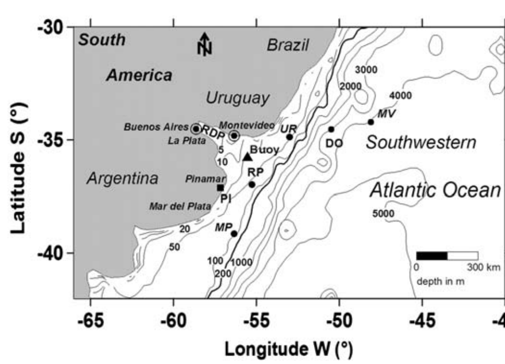

Fig. 1. Study area (computational domain where SWAN model was implemented). RDP: Río de la Plata. Depth contours in meters; the 200 m depth contour is highlighted with a heavy line. The locations where modeled wave heights were studied are MP: "Mar del Plata continental shelf", RP: "Río de la Plata mouth", UR: "Uruguayan continental shelf", DO: "deep ocean" and MV: "maximum variation". Datawell buoy position is pointed out with a triangle.

show that mean easterly wave heights would be increased by 0.12 m (13%) relative to present values (0.90 m) and their frequencies would be increased by 30% (from 18.4 to 23.9%), producing larger total heights. The mean period for easterly waves would not change significantly (less than 4%, from 5.3 to 5.5 s). The results obtained are a first approximation to the problem, suggesting that within the upper Río de la Plata the wave climate is very sensitive to possible changes in the wind patterns. Dragani et al. (2008) and Campos (2008) implemented Simulating Waves Nearshore model (SWAN) in the Río de la Plata and adjacent continental shelf in order to study maximum wave heights associated to meteorological extreme events between 1971 and 2000. A slight and significant positive trend (slope equal to 0.30 m/decade) was found in the series of simulated maximum annual wave height. It is important to note that changes in the wave regime in this area can have a large impact not only on the ocean properties through variations of the depth of the mixed layer but also in the sedimentary regime, affecting some of the most important ports and beaches of South America. According to this, Cuchiara et al. (2009) made a characterization of the wave climate in the Southern Brazilian Shelf based on a thorough review of existing field data and on numerical modeling experiments with SWAN model. This study was carried out to understand the mechanisms driving episodic mud bank attachments to the sandy shore, and the interaction of these banks with the flow and waves.

In the light of the above mentioned studies the motivation for this work has been to investigate whether a possible change in wind wave heights might be occurring in the South Western Atlantic Ocean off the Río de la Plata estuary. Unfortunately long wind wave data records are extremely scarce in this region; consequently such an investigation can only be faced by complementing the few observations available with an appropriate numerical study, using a validated numerical model forced with wind from a reliable dataset. Wave models provide a tool to study impacts of various climate change scenarios and investigate physical explanations of statistical results. Wolf and Woolf (2006) used a wave model of the NE Atlantic using synthetic wind fields, varying the strength of the prevailing westerly winds and the frequency and intensity of storms, the location of storm tracks and the storm propagation speed. These results indicated that there is not a simple relationship between wind speed and wave height. The direction and persistence of the wind and size and speed of cyclones may be as important as the actual wind speed. This paper is focused on studying the trends in the annual mean and maxima wind wave heights in the Southeastern South American Continental Shelf between 32°S and 40°S from *in situ* and remote observations available and a numerical simulation carried out with SWAN model forced by the NCEP/NCAR reanalysis.

2. Wave height trends observed on remote and *in situ* data

The single *in situ* long-term observations of directional waves available for the region were collected between 1996 and 2006, using a Datawell Waverider (DW) directional wave recorder (Datawell, 1997) moored in the outer Río de la Plata estuary at 35°40′S and 55°50′W (Fig. 1). The instrument was programmed to measure 20 min sea level records with a 0.5 s sampling interval, every 2 h and 40 min. This record presents several gaps, one of them longer than 1 yr (from October 2003 to November 2004), two of them eight months long (March 1998 to October 1998; November 1998 to June 1999) and three of them seven, four and three months long. The annual mean significant wave height presents a small positive trend but it was statistically not different from zero. Consequently, this single, short and incomplete *in situ* wave data does not show evidence of a possible trend in wave height.

Significant wave heights obtained from the Ocean Topography Experiment were also explored. Available wave data (1993–2001) gathered on $0.4^\circ \times 0.4^\circ$ areas located on the crossing of the satellite tracks (one cycle every ten days, 17 points on the tracks and, approximately, 570 observations per year) at the Uruguayan continental shelf (34.8°S, 53.8°W, crossing of tracks 087 and 178), Río de la Plata mouth (37.1°S, 55.2°W, crossing of tracks 087 and 102), Mar del Plata continental shelf (39.15°S, 56.65°W, crossing of tracks 087 and 026) and deep ocean (35°S, 51°W, crossing of tracks 061 and 163), UR, RP, MP and DO (Fig. 1), were selected. Crossing of satellite tracks areas were chosen in order to have a better sampling (two values every cycle). It should be pointed out that significant wave heights derived from altimeters in general show biases when compared to buoy data (Durrant et al., 2009). Errors in the source of satellite altimeter data, especially instrumental or methodological causes of false trends, must be carefully eliminated. Cotton and Carter (1994) proposed a method of calibrating estimates of significant wave height from satellite altimeters (Geosat, ERS-1 and TOPEX).

Significant wave data were obtained from World Wave Atlas version 2.07 (Fugro Oceanor AS, 2006). World Wave Atlas contains quality controlled data from Topex (1993–2001), available buoy data and global wave model data, which are carefully validated in order to ensure the data homogeneity. Time series of TOPEX annual mean height and 95% confidence interval at UR, MP, DO, can be observed in Fig. 2. RP time series was not included in the figure because it presents very similar features to MP time series. Large inter-annual variability can be observed in the figure. The maximum inter-annual variation occurred between 1994 and 1995 where annual mean wave height increased 9% (from 1.58 to 1.73 m) at UR, 8% (from 1.79 to 1.93 m) at MP and 13% (from 2.32 to 2.60 m) between 1999 and 2000 at DO. A positive trend is also apparent, particularly at DO. Least-square regression lines were fitted in each case. The calculated slopes (and corresponding 95% confidence limits) of the best fit lines were 0.16 ± 0.30, 0.12 ± 0.20 and 0.03 ± 0.30 m/decade and the determination coefficients were 0.12, 0.13 and 0.01 for DO, MP and UR, respectively. Thus it can be seen that none of the computed slopes resulted significantly different to zero at a 95% of confidence.

Breaker heights at Pinamar (located approximately 150 km westward of RP, Fig. 1) have been visually observed from the shore twice a day, without large gaps, since 1989. 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 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 difficult. In some cases, during storms or high windy conditions, it is not possible to estimate the breaker heights because the waves are too large and too far from the shore. Thus, visual breaker heights are frequently used to give a realistic estimation of the mean breaker height in the surf zone, but they are rather inappropriate to establish the annual maximum breaker height. Annual mean breaker heights gathered at Pinamar (Fig. 3b) were analyzed and compared with simulated mean heights (Section 3.2).

3. Wave height trend from a regional simulation with swan

Our results, based on the scarce and short span *in situ* measurements and satellite observations, show visual but not statistically significant trends in the annual mean wave height. It

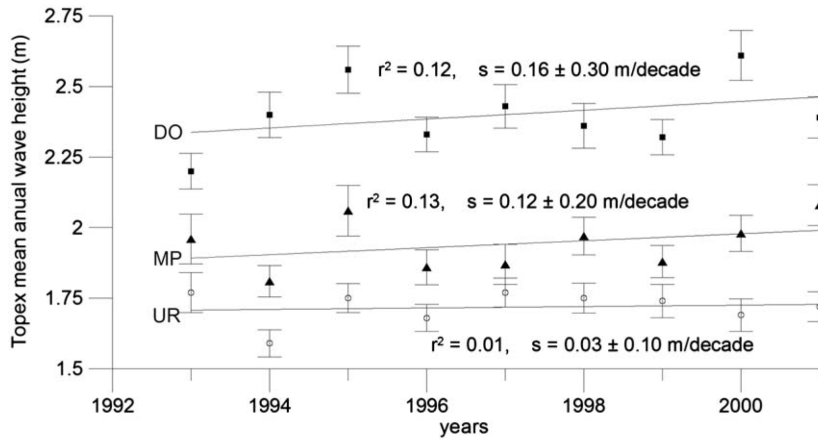

Fig. 2. Topex annual mean significant wave heights (1993–2002 period) at UR, MP and DO. Corresponding least-square regression lines are also included.

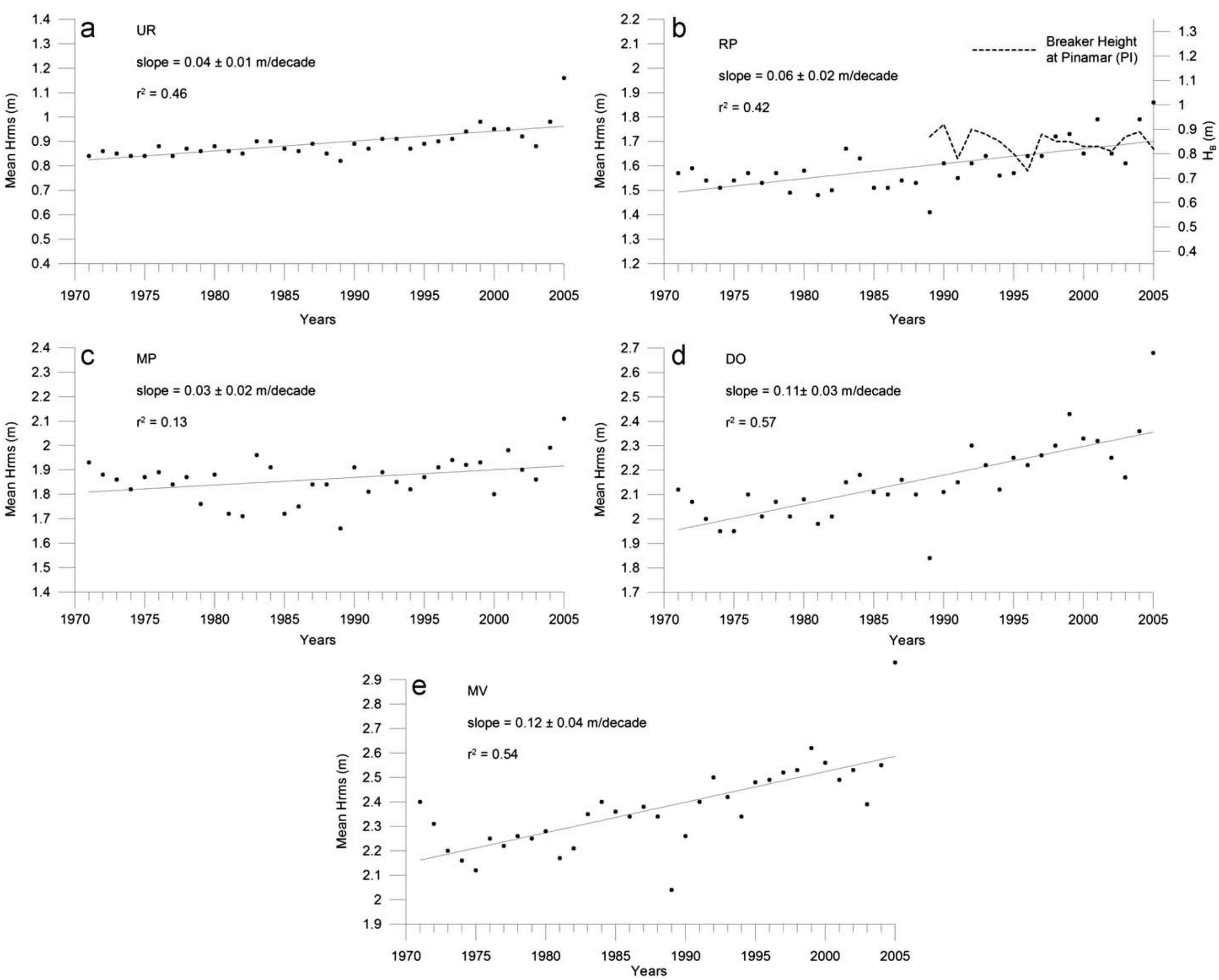

Fig. 3. Modeled (SWAN) annual root-mean-square of the significant wave heights (1971–2005 period) at UR (a), RP (b), MP (c), DO (d) and MV (e). Annual mean breaker heights at Pinamar (dashed lines) are incorporated in Fig. 3b. Corresponding least-square regression lines are also included.

is necessary to highlight, nevertheless, that for the above mentioned reasons and considering the large gaps, none of the data available are sufficient to detect a weak hypothetical trend, if it were occurring. As mentioned in the introduction, there are several evidences of changes in the low atmospheric circulation in this region of the Southern Hemisphere, including the impact on the oceans. Consequently, a weak increase in wave height might be occurring in the area of study, which would be difficult to quantify in short time series. To further study possible changes in the mean and maxima annual wind wave heights in the area a regional application of SWAN model was implemented, which was run forced by the NCEP/NCAR surface wind for the period 1971 and 2005. In this section, this application is described and the results, discussed.

3.1. Simulation description

SWAN is a numerical wave model that provides realistic estimates of wave parameters in coastal areas (Booij et al., 1999, Ris et al., 1999). Even though the model was specifically designed for coastal applications, it can be applied to generate wind surface gravity waves on any scale (Holthuijsen et al., 2004). The model is based on the wave action balance equation. It considers the action density spectrum rather than the energy density spectrum since, in presence of currents, action density is conserved whereas energy density is not (Whitham, 1974). The frequency space generated in the numerical experiments presented in this paper has 20 frequencies, between 0.05 and 1.00 Hz.

The model domain spans the area between 30°S and 42°S, and 40°W and 65.5°W (Fig. 1), with a grid spacing of 22.7 km × 20.0 km (100 × 70 grid points). The numerical simulation was carried out for the period December 1st, 1970, to December 31st, 2005; significant wave heights, periods and directions were computed at each node of the computational domain. SWAN model was run in non-stationary mode, with time step equal to 1 h and initialized at rest (wave parameters set zero at every grid point). Using this initial condition the first wave parameter fields can be quite misleading, so, the first month of the numerical simulations (December 1970) was considered as spin up and, therefore, disregarded. A complete validation of SWAN model in the described computational domain was presented by Dragani et al. (2008). No incoming wave was imposed as boundary condition at the open boundaries of the computational domain. The aim of this study is to assess changes in sea (wind waves generated in the computational domain) therefore swell coming from outside this domain, although probably significant, has not been considered.

Surface wind data from NCEP/NCAR reanalysis I were used to drive the simulation. This reanalysis uses the same climate model, which it was initialized with, a wide variety of weather observations: ships, planes, RAOBS, station data and satellite observations. By using the same model, climate/weather statistics and dynamic processes can be examined without the complication that model changes can produce. The result of this analysis is a set of gridded data (spatial resolution: 1.875° in longitude, 1.905° in latitude) with a temporal resolution of 6 h. The main advantages of the reanalyzes are their physical consistency and relatively high temporal coverage (since 1/1/1948 to the present) but, on the other hand, it should be mentioned that some possible inhomogeneities in the NCEP/NCAR winds are difficult to separate from real climate change (Cox and Swail, 2001). Full details of NCEP/NCAR project and the dataset are given in Kalnay et al. (1996) and discussions about product quality over the Southern Hemisphere can be found in Simmonds and Keay (2000a), among others. Bilinear (linear) interpolation was used to generate appropriate wind fields to match the spatial (temporal) resolution of the SWAN model. NCEP/NCAR reanalysis has been successfully implemented as forcing in several regional studies (see, for instance, Simionato et al., 2005, 2006a, b, 2007).

The study area (Fig. 1) 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 (Fig. 1). Bathymetric data for the model were obtained as a combination of $1' \times 1'$ resolution depth data set coming from GEBCO (2003) for the continental break and the deep ocean and from digitalized nautical charts for the Río de la Plata (SHN, 1986, 1992, 1993, 1999a, b) for the continental shelf and coastal areas. These data were interpolated to model grid applying the inverse square-distance method.

3.2. Simulation results

In order to study a possible wave height increase in the region, annual root-mean-square of the significant wave height was analyzed instead of annual mean significant height because it gives proper weight to the larger wave conditions, and will probably be a more sensitive discriminator of changes. The time series of simulated annual root-mean-square of the significant wave height (H_{rms}) at UR, RP, MP, DO and MV can be observed in Fig. 3. As will be discussed later, MV is the point of the computational domain that presents maximum variation in annual mean heights and DO is an intermediate point between MV and UR. 95% confidence intervals for annual mean values are less than ± 0.02 m and, therefore, were not included in the figure. Least-square regression lines (1971–2005 period) were fitted to the data at each location and are shown in Fig. 3. The calculated gradients of the best fit lines (and the corresponding 95% confidence limits) were 0.04 ± 0.01, 0.06 ± 0.02, 0.03 ± 0.02, 0.11 ± 0.03 and 0.12 ± 0.04 m/decade and the determination coefficients were 0.46, 0.42, 0.13, 0.57 and 0.54 for UR, RP, MP, DO and MV, respectively (Fig. 3a–e). All the computed gradients are significant at 95% of confidence level. It is interesting to note that even though the trend results are significant for the entire period of simulation, it was not significant during the first decade (1971 to 1980) but seems to start during the '80 s. The maximum positive (+0.42m) and negative (-0.30) inter-annual variation at MV (Fig. 3e) occurs between 2004 and 2005 and between 1988 and 1989, respectively. Maximum inter-annual variations can also be observed at the other selected locations (UR, RP, MP and DO) for the same years, but were slightly smaller than for MV. At this last location, simulated annual root-mean-square heights ranged from 2.04 m (in 1989) to 2.97 m (in 2005). It is important to highlight that the last year represented here (2005) has the largest values of wave heights at all stations.

Annual mean breaker heights (H_b) gathered at Pinamar were compared with simulated mean heights at RP (Fig. 3b). Even though both parameters are rather different, both data series present some similarities, for example, they show a relative minimum at 1991 between two relative maxima at 1990 and 1992, a decrease from 1992 to 1994, an increase from 1996 to 1998 and a very low variation from 1997 to 2000. In contrast, the trend in annual mean breakers at PI resulted significantly not different to zero.

The time series of simulated annual maximum significant heights at UR, RP, MP, DO and MV can be observed in Fig. 4. Least-square regression lines (1971–2005 period) were fitted for each location. Calculated gradients of the best fit lines (and corresponding 95% confidence limits) were 0.08 ± 0.05, 0.20 ± 0.20, 0.20 ± 0.30, 0.35 ± 0.25 and 0.12 ± 0.28 m/decade and the determination coefficients were 0.20, 0.09, 0.05, 0.19 and 0.02 for UR, RP, MP, DO and MV, respectively (Fig. 4a–e). Computed gradients at UR, RP and DO were significant at a 95% level but at MP and MV they were not statistically different from zero.

All wave parameter fields described in this work (Figs. 5–8) are presented in a sub-domain spanning from 32°S to 40°S and from 45°W to the coast since results near open boundaries of the

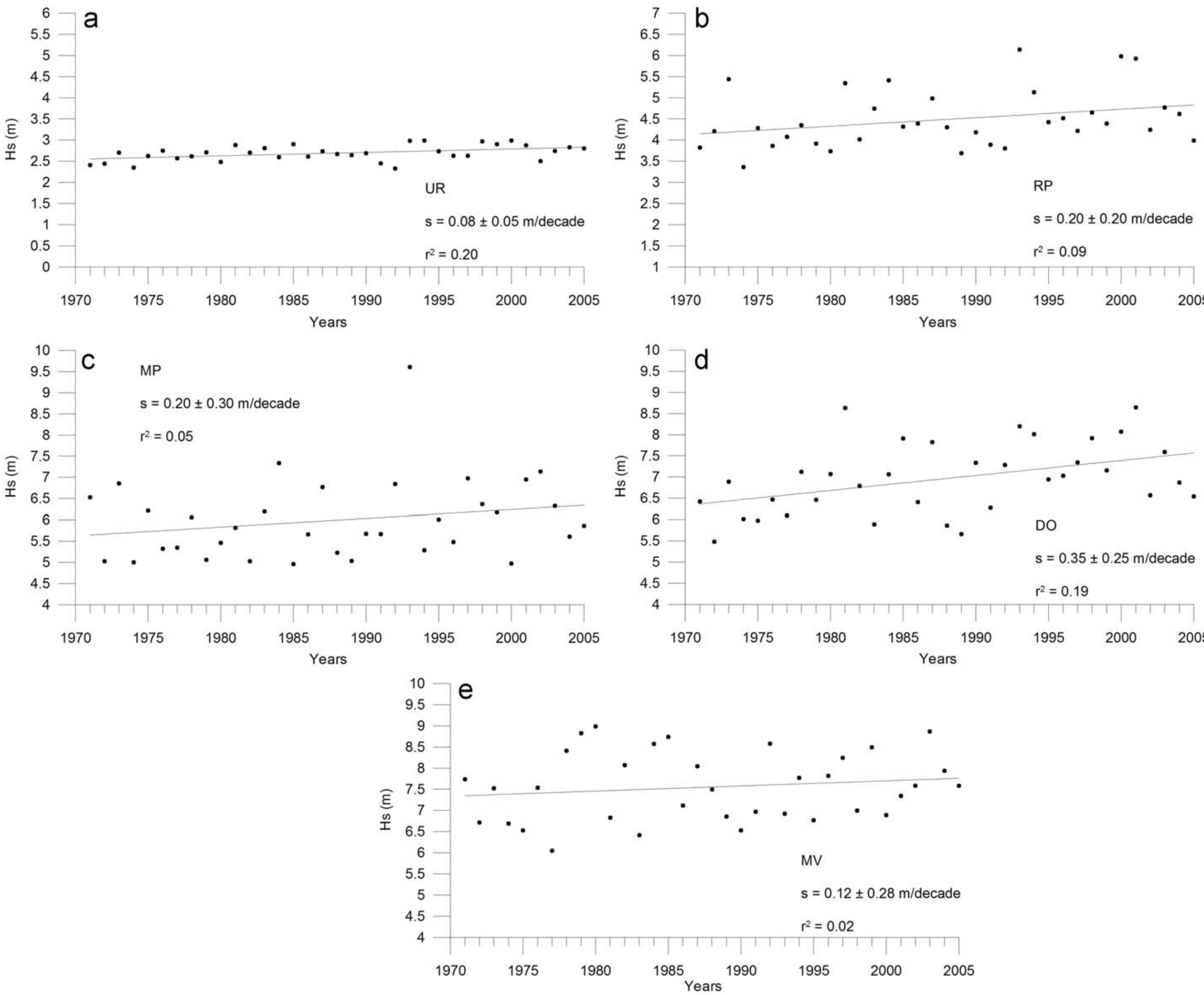

Fig. 4. Modeled (SWAN) annual maximum significant wave heights (1971–2005 period) at UR (a), RP (b), MP (c), DO (d) and MV (e). Corresponding least-square regression lines are also included.

computational domain cannot be trusted. It must be noticed that MP is located relatively close to the southern edge of the computational domain and, consequently, results obtained for this location (presented in Figs. 3c and 4) could be quantitatively misleading.

Root-mean-square wave height, period and direction fields over the period 1971–2005 were obtained from the simulation with SWAN model. The mean field of H_{rms} is shown in Fig. 5a. It can be observed that heights gradually decrease towards the coast, from approximately 2.5 m at the most southeastern portion of the domain, to less than 1.0 m in the upper Río de la Plata estuary. Mean period and direction fields can be observed in Fig. 5b. Wave directions are predominately westward, except at the southernmost part of the region where propagation is in general northwestward. Wave periods display a similar pattern to wave heights, that is, values decrease gradually towards the coast and minimum periods are found at the upper Río de la Plata. It must be kept in mind that the wave parameters shown in Fig. 5 only represent the sea condition since swell (entering from open boundaries) is not considered in our simulations.

Decadal H_{rms} fields over the periods 1981–1990 and 1991–2000 are shown in Fig. 6a and b, respectively. An increase in heights, over the whole area, during the last decade is evident, especially at the north-easternmost portion of the domain. Decadal mean period and direction fields (not shown) do not exhibit significant variations, the maximum differences being less than +0.2 s for periods and +4° (clockwise) for directions. For this reason in what follows we will concentrate on the analysis of the wave height variability. The difference in mean height between decades 1991–2000 and 1981–1990 is displayed in Fig. 7. Positive values are observed over the whole model domain and the highest differences, more than 0.20 m, occur at around 34°S–48°W (MV). Consequently, a notable increase in wave height, from the 80's to 90's decade, seems to have occurred in the whole region of study. Fig. 8 displays the standard deviation of the H_{rms} field over the period 1981–2000. In general, the standard deviation decreases towards the coast and the largest values occur at the same position where the wave height maximum difference (MV) was observed (Fig. 7). At this location the increase in H_{rms} between the 80's and 90's was almost 9% and, in the continental shelf and in

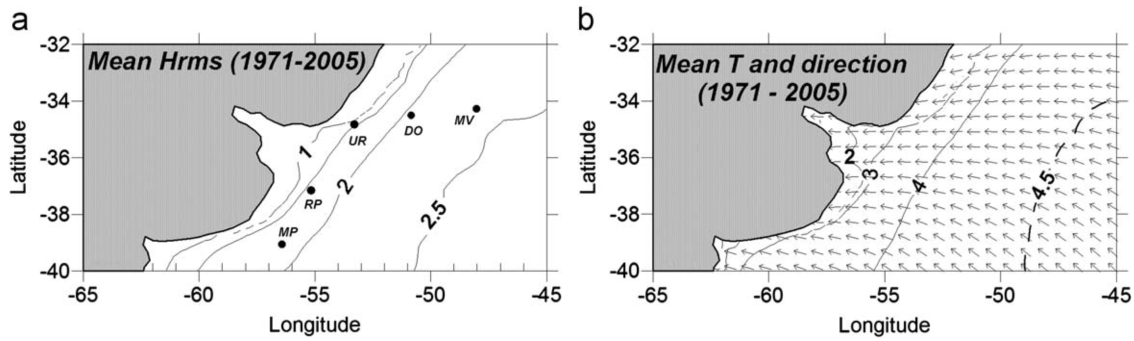

Fig. 5. (a) Simulated root-mean-square of the significant wave heights (m) and (b) mean periods (s) and wave propagation directions (arrows, not scaled), for 1971–2005 period.

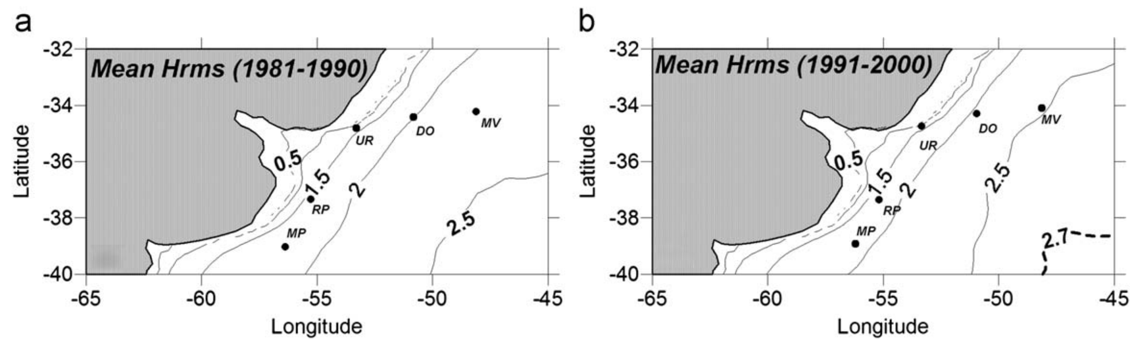

Fig. 6. Simulated root-mean-square of the significant wave heights (m) for (a) 1981–1990 period and (b) 1991–2000 period. The 2.7 m contour is added in Fig. 6b (dashed heavy line).

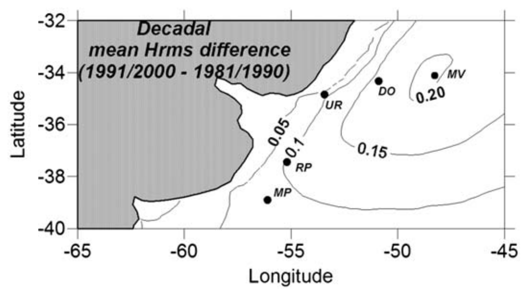

Fig. 7. Difference between simulated decadal root-mean-square of the significant wave heights (1991–2000 decade minus 1981–1990 decade).

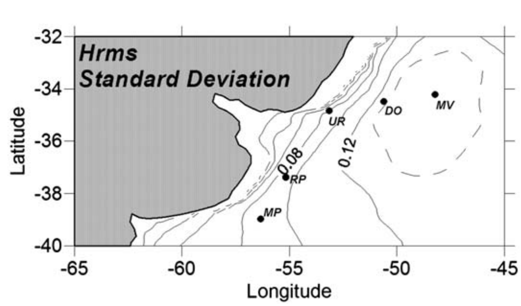

Fig. 8. Standard deviation of simulated root-mean-square of the significant wave heights, 1981–2000 period.

the Río de la Plata estuary, the increase of H_{rms} is a little less (approximately 7%). The composite difference between 1981–90 and 1991–2000 was tested against a null hypothesis of no change (95% confidence level) and it was rejected for the whole computational domain. Consequently, our results suggest that the decadal mean heights could have been significantly increased from the 80's to the 90's.

Time series of annual mean $H_{rms}{}^2$, spatially averaged in the sub-domain from 1971 to 2005, are presented in Fig. 9. It should be noticed that $H_{rms}{}^2$ is proportional to the spatially averaged annual mean energy density E ($E=\rho g H_{rms}{}^2/8$, where ρ is the sea water density, g the acceleration due to gravity). In general, the time series of the simulated H_{rms} at every location of the computational domain (Fig. 3) matches very well with $H_{rms}{}^2$ (or E). The least-square regression line was fitted and the gradient of the best fit line resulted of 0.036 m^2/yr, which is significant at a 95% of confidence.

4. Discussion and conclusions

Several studies have suggested the possible occurrence of changes in the low atmospheric circulation in the southwestern Atlantic Ocean (Gibson, 1992; Van Loon et al.; 1993; Gregg and Conkright, 2002; Camilloni, 1999, 2005; Barros et al., 2000; Escobar et al., 2003; Camilloni et al., 2005; Simionato et al., 2005), which seem to be impacting the ocean. Simmonds and Keay (2000b) presented an analysis of the variability and trends exhibited by many aspects of Southern Hemisphere mean sea level extratropical cyclones during the period 1958–97. Across the 40-yr period the annual and seasonal mean cyclone densities have undergone reductions at most locations south of about 40°S (with the greatest reductions near 60°S), and increases to the north. It is shown that the mean radius of Southern Hemisphere extratropical cyclones displays almost everywhere a significant positive trend, and there are also increases in annual mean cyclone "depth" (i.e., the pressure difference between the center and the "edge" of a cyclone). In March 2004 the first-ever reported

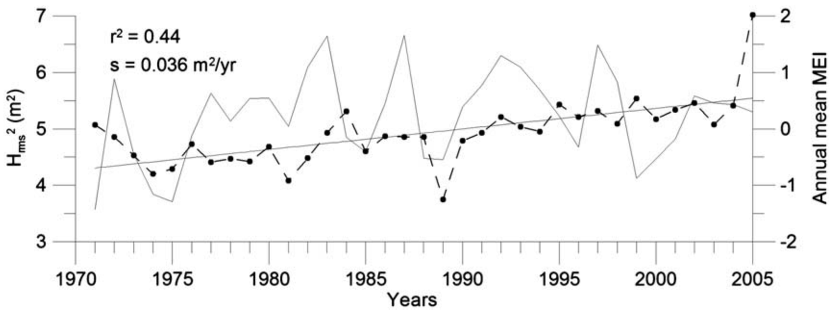

Fig. 9. Spatially averaged annual mean $H_{rms}{}^2$ (dashed line), 1971–2005 period (corresponding least-square regression lines are also included) and annual mean Multivariate ENSO Index (MEI) values (solid line).

hurricane in the South Atlantic hit southern Brazil (Pezza and Simmonds, 2005). A mid-to-high latitude-blocking index showed that the five days before the genesis were in the 0.6% first percentile of intensity considered over the last 25 yr, followed by an unprecedented combination with low shear. The observed and predicted trends towards an increasingly positive phase of the Southern Annular Mode in global warming scenarios could favor similar conditions, increasing the probability of more Tropical Cyclones in the South Atlantic.

Indeed several papers reported trends in the storm surge (Escobar et al., 2004; D'Onofrio et al., 2008) and the wind wave height (Cox and Swail, 2001) regimes in the Río de la Plata estuary and adjacent continental shelf. In this paper, a possible increment in the annual mean wave height was investigated from the few observations available and numerical simulations. The apparent trends observed in annual mean height calculated from data collected at the Río de la Plata mouth (1996–2006) and from T/P data (1993–2002) were not significantly different to zero. Nevertheless, the occurrence of a possible trend is difficult to assess from the short span and scarce available observations. This study was carried out by the application of a numerical model. Annual mean wave heights of sea (wind waves generated in the computational domain without considering swell) modeled with SWAN and forced with NCEP/NCAR reanalysis showed significant trend at all the selected coastal locations of Buenos Aires inner continental shelf (MP, RP and UR) and adjacent deep ocean (DO and MV) in the simulated period. On the other hand, annual maximum wave heights showed significant trend at UR, RP and DO but the computed slopes are not statistically different to zero at MP and MV. These results are in good agreement with Cox and Swail (2001), who inferred a slight but significant change in annual mean and 99th percentile wave height in the Buenos Aires continental shelf, offshore the Río de la Plata mouth. However, Cox and Swail (2001) found clearer trends in the annual maximum wave height series than in the annual mean series.

The difference in the mean height between 1991–2000 and 1981–1990 decades showed positive values over the entire model domain. The highest difference, more than 0.20 m, occurs at around 34°S–48°W. Annual mean height standard deviation decreases towards the coast and the largest values occur at the same position (MV) where the wave height maximum difference was observed. At this location, the increase in the significant wave height between the 80's and 90's was around 9%. The increase in wave height is around 7% in the continental shelf and in the Río de la Plata. Consequently, the numerical simulation supports the hypothesis that a possible increase in wave height from the 80's to the 90's might have occurred in the whole region of study as a consequence of the slight southward trend in the western border of the South Atlantic semi-permanent high-pressure system. In addition to this idea, Pezza et al. (2009) introduced a South Atlantic index as a useful diagnostic of potential conditions leading to tropical transition in the area, where large-scale indices indicate trends towards more favourable atmospheric conditions for tropical cyclone formation.

Accordingly to the increase in wave height, time series of the spatially averaged annual mean $H_{rms}{}^2$ (proportional to annual mean energy density) also presented a significant positive trend (0.036 m^2/yr) and a relatively high inter-annual variability. The possible link between this inter-annual variability and El Niño-Southern Oscillation (ENSO) was investigated. Annual mean values calculated from the bimonthly Multivariate ENSO Index (MEI) values (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/table.html) and annual mean $H_{rms}{}^2$ time series are compared in Fig. 9. No apparent relationship between both signals is observed. The coefficient of determination calculated between both data series was no different from zero, indicating that the inter-annual wave energy variability in the area of study does not seem to be connected with the ENSO. Nevertheless this relevant issue should be further explored in a separate paper.

A possible increase in the mean wave height raises two important points to be considered. Firstly, if a possible increase in the mean wave height were associated to a change in the wind pattern in the region, then it is natural to think that an increase in the mean depth of the mixed layer of the ocean could have occurred as well. Huang et al. (2006) studied the decadal variability of wind-energy input to the world ocean and found that this energy varied greatly on inter-annual to decadal time scales. In particular, they showed that it has increased 12% over the past 25 yr, and that the inter-annual variability mainly occurs in the latitude bands between 40° and 60°S and around the equator. If that is the case, the deepening of the mixed layer would have produced a larger mixing of surface water and, consequently, a slight reduction of the sea surface temperature in this region of the South Atlantic Ocean. Secondly, an increment in frequency and speed of wind and in the wave heights (and, consequently, in the wave density energy) might be able to affect littoral processes. This would especially produce variations in the alongshore transport of sand and an increase in wind and wave set-up and consequently, in the erosion of the coast. Therefore, the Buenos Aires coast would be more frequently exposed to wave effects, giving rise to intensified associated littoral processes. In this sense, an increase in the erosive processes along the sandy coast of Buenos Aires province (Fig. 1) during the last 30 yr has been reported by Kokot (1997) and Nicholls et al. (2007). It is generally accepted that one of the main causes of increased erosion processes is the mean sea level rise. The potential consequences of an eventual acceleration in the rate of sea level rise on the Argentine coast were studied by Lanfredi et al. (1998) from hourly tide height records, finding a long term trend in water level of +1.6 ± 0.1 mm/yr for Buenos Aires city (analyzed period:

1905–1992) and $+1.4 \pm 0.5$ mm/yr for Mar del Plata (analyzed period: 1954–1992). Considering this last value of increasing rate for Mar del Plata, the sea level rise produced in the last 30 yr would be lower than 0.05 m, which is too small to be responsible for the reported erosive situation. In addition, a possible variation of the swell in the region (not analyzed in this paper) could contribute in the deepening of the mixed layer as well as in the littoral processes and should be particularly analyzed in a future study.

The European project WASA (Waves and Storms in the North Atlantic) has been set up to verify or disprove hypotheses of a worsening storm and wave climate in the northeast Atlantic and its adjacent seas in the last century (WASA Group, 1998). Its main conclusion is that the storm and wave climate in most of the northeast Atlantic and in the North Sea has undergone significant variations on timescales of decades; it has indeed roughened in recent decades, but the intensity of the storm and wave climate seems to be comparable with that at the beginning of last century. Consequently they highlighted the risks of using short records in the studies of trends. It should be remarked that most of the mentioned analyses have considered periods corresponding to the last decades when there was an increasing trend in wave climates.

Finally, it must be noted that the abovementioned discussion has been supported by numerical simulations carried out with SWAN model forced with NCEP/NCAR reanalysis. In this sense, the difficulty in separating some possible inhomogeneities in the NCEP/NCAR winds from real climate change must be highlighted. This last remark clearly illustrates the need to face a data acquisition program to gather homogeneous and long *in situ* observations in order to further investigate the possible trends inferred from our numerical study.

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