

Preliminary Analysis of Waves in the Coastal Zone of Monte Hermoso and Pehuén Co, Argentina

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ABSTRACT

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Coastal geomorphology is significantly influenced by waves because they are a major agent in removing and transporting sediments. Furthermore, any kind of human coastal activity is influenced by waves. Consequently, it is essential to know about the wave distribution of the coastal areas. The aim of this study was to analyze the waves at Monte Hermoso and Pehuén Co coastal zone, Buenos Aires, Argentina. The study was based on data obtained from an oceanographic tower located on the coast of the study area, between April 2007 and July 2009, analyzed annually and seasonally. The major occurrence and frequency of the significant wave heights (H_s) and the period of significant waves (T_s) were studied. The main percentages of H_s occurred between 0.25 and 1.5 m and were related to T_s between 0 and 16 seconds. The highest H_s rates were observed in spring, whereas the lowest ones in winter. Theoretical distribution probabilities were applied and the Weibull distribution was the most appropriate fit for the data, presenting a shape parameter of 0.82 and a scale parameter of 1.73. Joint probability analysis of H_s and T_s showed that summer and spring have similar patterns with larger probabilities of locally generated waves, whereas, contrary to what it is normally expected, winter has the larger percentage of swells because of the large number of calm-wind days. Finally, the Ursell number and the flux intensity parameter were obtained to demonstrate that the waves have been able to transport the typical sediments at the tower site toward the sea.

ADDITIONAL INDEX WORDS: Wave distribution, incidence wave analysis, Weibull, lognormal, Rayleigh, wave joint probability.

INTRODUCTION

Waves are an essential factor in the hydrodynamics of beaches because they play a major role in the on-offshore sediment-transport processes and those along the shore. Most of the geomorphology of beaches depends on the characteristics of the waves and the associated littoral currents. Furthermore, any kind of human activity on the coast is likely to be affected by waves or to affect wave and current dynamics. Coastal management strategies require, among other items, adequate information about wave climates and mechanisms to forecast wave conditions over long periods.

To establish such predictions, probability analyses have been developed based on the statistical study of long-term data provided by wave gages or numerical models. Longuet-Higgins (1952) provided the first theoretical analysis of wave probability, which initiated a number of studies worldwide that considered a diversity of probability distributions on wave

height and period, as well as joint probability distributions on both variables.

Some examples of these studies provide a general idea of the focus of the work being done in this area, especially in defining the most adequate distribution to represent specific wave conditions. For instance, a lognormal distribution was employed in the Spanish Mediterranean Sea (IMIDEA, 2009) because it was considered the most appropriate for describing the Balearic wave climate. On the other hand, Martínez-Díaz de León and Coria-Méndez (1993) compared the theoretical distributions of Fisher Tippet I, Weibull, and Rayleigh in Todos los Santos Bay, Mexico, where they found that the Fisher Tippet I was the most suitable for the area. Moreover, they characterized the seasonal regime of waves, applying the distributions to every season, which demonstrated that, depending on the time of the year, the distributions fit differently.

Probability distributions were also applied to parameterized laboratory data of waves in shallow foreshores and a composite of the Weibull distributions best generated a model of local wave distribution (Battjes and Groenendijk, 2000). In the Ebro River Delta (NW Spanish Mediterranean coast), Weibull was used to represent the long-term distribution of waves at three

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different coastal scales to demonstrate the implications of nearshore processes on the probability distribution of waves (González-Marco *et al.*, 2008). However, Rodríguez *et al.* (2002) proved that in mixed sea state, there was no distribution able to adequately characterize the cases of the bimodal sea states.

Although probability distributions for individual variables provide adequate information about wave climate for a region, joint probability of wave height (H) and period (T) give a complementary and integral view of the predominant conditions. Longuet-Higgins (1983) made a theoretical analysis of the joint probability functions. Other studies resulting in new parametric models of the joint probability density function were made by Haver (1985); Mathiesen and Bitner-Gregersen (1990); Moan, Gao, and Ayala-Uraga (2005); Cherneva *et al.* (2005); and Bitner-Gregersen and Guedes Soares (2007), among others. In most cases, the various authors analyzed the relationship between H and T , but there are also many examples of different correlations, such as H_s and characteristic surf parameter (Myrhaug and Fouques, 2010) and H and water level (Hawkes *et al.*, 2002).

Because of the lack of long-term wave data, these types of studies have not been done consistently along the coast of Argentina. The only previous study in the literature was by Martín *et al.* (2008) which applied the probability distribution to the data obtained from the Simulating Waves Nearshore (SWAN) model for the external area of Mar del Plata Harbour, Argentina. The results showed that Fisher Tippet I and Weibull were equally appropriate for representing the distribution of waves because there were no significant differences in the correlation coefficients.

Monte Hermoso and Pehuén Co are situated in the SW coast of Buenos Aires Province, Argentina ($38^{\circ}59'24''S$, $61^{\circ}17'28''W$ and $39^{\circ}00'13''S$, $61^{\circ}33'37''W$, respectively). Because little is known about the characteristics of the waves in this region, the aim of this study was to define the annual and seasonal wave distribution and to define the capability of the waves to transport sediments at the study area. Results were obtained by applying theoretical distributions to data corresponding to the 2007–2009 period. The parameters chosen for analysis were the significant wave height (H_s) and the significant wave period (T_s). This study was developed to define the dynamic conditions in the area before the installation of a set of oceanographic buoys and to study the effect of waves on the erosion processes occurring along the coasts at both resort localities.

STUDY AREA

Monte Hermoso and Pehuén Co are in an open bay, influenced by the Bahía Blanca Estuary (Figure 1). The coast between them is characterized by dissipative sandy beaches with a low slope and backed by extensive sand dunes. The area has a mesotidal regime with semidiurnal tides. The mean amplitude ranges between 2.32 and 3.35 m for neap and spring conditions, respectively, with a mean value of 3.10 m (Servicio de Hidrografía Naval, 2009).

The SW–NE moving air masses flow across the southwestern part of the Buenos Aires Province throughout the year. This area has a temperate climate, characterized by warm summers

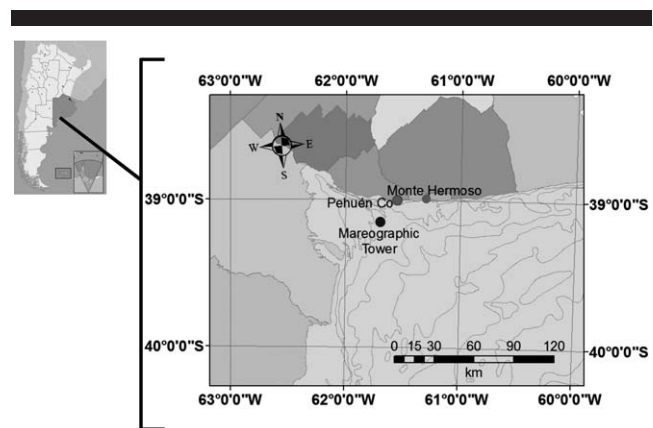


Figure 1. Geographic location of the study area. The oceanographic tower is at 21 and 39 km from the beaches of interest, respectively.

and cold winters and moderate springs and autumns. The average temperatures oscillate between 14 and 20°C and the mean annual precipitation is 650 mm (Campo de Ferreras *et al.*, 2004; Carbone, 2003).

The prevailing wind directions are from N, NW, and NE, whereas the strongest winds come from the S, SE, and SW, especially in spring and summer, with mean speeds that fluctuate between 22 and 24 km h⁻¹. Winter is the season of the year that presents more calm days and also has the lowest wind speeds (SMN, 1992) (Tables 1 and 2). There is an important regional, coastal phenomenon called *sudestada* (southeasterns), which usually occurs between April and November, with October being the month with the highest frequency. The *sudestada* is characterized by strong SE winds of greater than 35 km h⁻¹, persistent rains, and relatively low temperatures, for approximately 1 week. This phenomenon increases the increment of the wave heights, thus coastal structures are threatened and sometimes destroyed by them. Furthermore, natural beach erosion is intensified during these periods (Campo de Ferreras *et al.*, 2004).

However, recent studies at the Pehuén Co beach (Bustos, Piccolo, and Perillo, 2009) have demonstrated that the larger erosional events are observed during the SW winds. In some cases, the beach has lost more than 15 m³ of sand over the

Table 1. Monthly wind speed and directions (SMN, 1992).

| Month | Mean Speed (km h ⁻¹) | Direction | Calm Days (d) |
|-----------|-------------------------------------|-----------|---------------|
| January | 24.8 | E–N–S | 69 |
| February | 24.8 | N–E–NE | 90 |
| March | 23.5 | N–E–S | 124 |
| April | 21.3 | N–NW–W | 168 |
| May | 20.8 | N–W–NW | 216 |
| June | 20.1 | NW–W–N | 221 |
| July | 19.8 | N–NW–W | 233 |
| August | 20.2 | N–NW–W | 219 |
| September | 22.3 | N–NW–S | 131 |
| October | 22.8 | NW–N–E–S | 118 |
| November | 23.1 | N–E–S | 104 |
| December | 24.1 | E–N–S | 80 |

Table 2. Seasonal, mean wind speed and directions (SMN, 1992).

| Season | Mean speed (km h ⁻¹) | Direction | Calm Days (d) |
|--------|-------------------------------------|-----------|---------------|
| Summer | 24.6 | E-N-S | 239 |
| Autumn | 21.9 | N-NW-W | 508 |
| Winter | 20.0 | N-NW-W | 673 |
| Spring | 22.7 | N-E-S | 353 |

Table 3. Months considered in each season and number of data points included in each.

| Season | Months | No. of Data Points |
|----------|--------------------|--------------------|
| Summer | December–February | 6961 |
| Autumn | March–May | 9659 |
| Winter | June–August | 7363 |
| Spring | September–November | 7019 |
| All year | | 31,002 |

length of several profiles. It is, therefore, evident that local waves with short periods are a major factor in the beach dynamics and prediction and control of their occurrence is essential to any coastal management program

Another local phenomenon is the sea breeze. This is a local wind that blows from the sea caused by the difference of temperature between the sea and the land, which is why they occur especially in sunny, relatively calm, summer days (Simpson, 1994). They are also an important factor in sediment transport along the beach.

METHODOLOGY

The data were provided by an oceanographic tower (OT), located offshore to the southwest of the study area (38°0'95" S, 61°41' W) at 21 and 39 km, respectively, from Pehuén Co and Monte Hermoso, Argentina (Figure 1). A pressure sensor measured water level at a frequency of 10 Hz for a period of 2 minutes. Unfortunately, the sensor has no directional capability. The series are internally processed by a fast Fourier transform (FFT) algorithm, which estimates H_s and T_s centered in the time series. Data are transmitted in real time by radio to a central system located at the Consorcio de Gestión del Puerto de Bahía Blanca, Argentina, where they are stored. Because of memory restrictions in the tower computer, the original time series are not available for further analysis; therefore, it is not possible to detect the possibility of more than one wave train occurring at the site.

Table 4. Wave incidence.

| T_s (%) | 0–0.25 m | 0.25–0.5 m | 0.5–1 m | 1–1.5 m | 1.5–2 m | 2–4.5 m | Occurrence | Exceedance |
|------------|----------|------------|---------|---------|---------|---------|------------|------------|
| 0–4 s | 0.2 | 7.91 | 14.36 | 14.35 | 0.29 | 0 | 37.12 | 62.88 |
| 4–8 s | 0.17 | 5.53 | 14.05 | 0.02 | 3.21 | 0.09 | 23.07 | 39.81 |
| 8–12 s | 1.03 | 12.77 | 7.11 | 0.04 | 0.06 | 0.01 | 21.03 | 18.78 |
| 12–16 s | 2.23 | 10.69 | 3.79 | 0.05 | 0.07 | 0 | 16.83 | 1.95 |
| 16–20 s | 0.48 | 1.31 | 0.11 | 0 | 0 | 0 | 1.9 | 0.05 |
| 20–30 s | 0.03 | 0.02 | 0 | 0 | 0 | 0 | 0.05 | 0 |
| Occurrence | 4.15 | 38.23 | 39.41 | 14.46 | 3.64 | 0.11 | | |
| Exceedance | 95.85 | 57.62 | 18.21 | 3.75 | 0.11 | 0 | | |

A wave-incidence table was made, to observe the major occurrence and frequency of H_s and T_s . In addition, two graphs of exceedance were produced and analyzed. To characterize wave distribution, different theoretical probability distributions were applied to the total data and then to every season of the year. On the seasonal analysis, the H_s and T_s were compared and related to the wind speed of the study area. A similar analysis was made considering the joint probability of both variables.

A probability distribution is defined as the fraction of events that a particular event is not exceeded. Probability density was used and considered as the fraction of events that a particular event is expected to occur, and it represents the rate of change of a distribution (U.S. Army Corps of Engineers, 2001). In this study, the theoretical probability distributions lognormal, Rayleigh, and Weibull were applied (Battjes and Groenendijk, 2000; Institut Mediterrani de Estudis Avançats, 2009; Martin *et al.*, 2008; Matínez-Díaz de León and Coria-Méndez, 1993). These distributions were selected because they are used in coastal wave characterization and, in most cases, they properly describe wave heights.

The lognormal density function distribution is given by Equation (1):

$$fx(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}} \quad (1)$$

where the μ and σ are the mean and standard deviation of the $\ln(x)$, and x represents the variable being analyzed. The cumulative distribution function is defined by Equation (2):

$$Fx(x; \mu, \sigma) = \frac{1}{2} \operatorname{erfc} \left[-\frac{\ln x - \mu}{\sigma\sqrt{2}} \right] = \Phi \left(\frac{\ln x - \mu}{\sigma} \right) \quad (2)$$

where erfc is the complementary error function, and Φ is the standard-normal cumulative distribution function.

The Rayleigh distribution, which is also commonly used to characterize wave parameters, is defined by Equation 3:

$$f(x; \sigma) = \frac{x}{\sigma^2} \exp \left(-\frac{x^2}{2\sigma^2} \right) \quad (3)$$

The Weibull distribution was also employed, and defined by Equation 4:

$$f(x; \lambda, k) = \frac{k}{\lambda} \left(\frac{x}{\lambda} \right)^{k-1} e^{-(x/\lambda)^k} \quad (4)$$

where k is the shape parameter, and λ is the scale parameter.

In addition, joint probability distributions of H_s and T_s were applied. The joint probability refers to two or more parameters

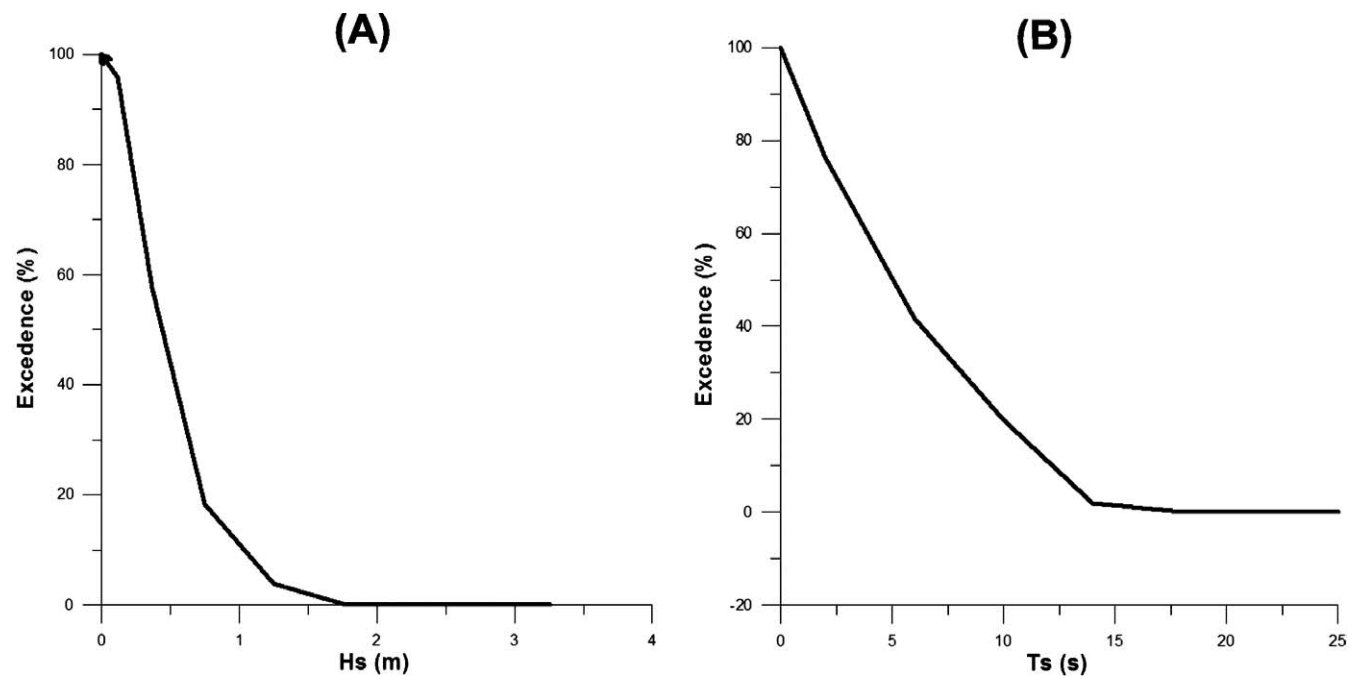


Figure 2. Exceedance percentage graphs of (A) significant wave height, and (B) significant wave periods.

occurring simultaneously to produce a response of interest (Hawkes *et al.*, 2002). The distribution of H_s and T_s proposed by Mathiesen and Bitner-Gregersen (1990) is based in the combination of the three-parameter Weibull distribution for $f(H_s)$ and the lognormal distribution for $f(T_s|H_s)$ presented by Ochi (1998):

$$f(H_s, T_s)(H_s, T_s) = f(H_s)f(T_s|H_s) \quad (5)$$

To characterize the seasonal distribution of waves, the data were classified by season (Matínez-Díaz de León and Coria-Méndez, 1993). Table 3 represents the months that define each

season, as well as the number of H_s and T_s included in each. The difference in the amount of data is because erroneous values were deleted, independent of the month of the year.

RESULTS AND DISCUSSION

Annual Analysis

To characterize the Monte Hermoso and Pehuén Co waves, their distributions are presented in a wave incidence table (Table 4). Most significant wave heights occurred between 0.25 and 1.5 m and were related with significant wave periods

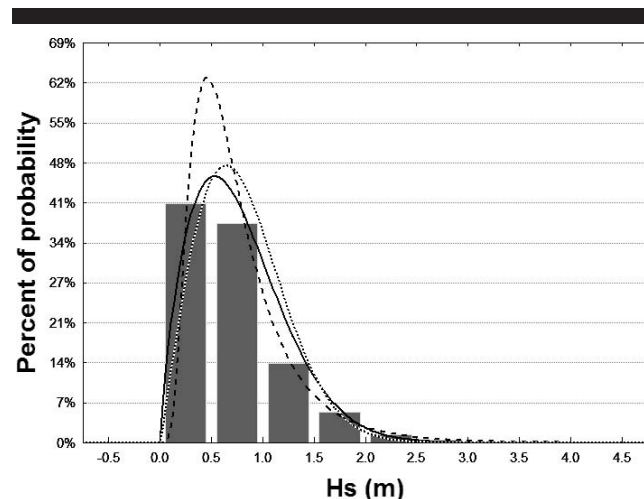


Figure 3. Probability distributions of H_s .

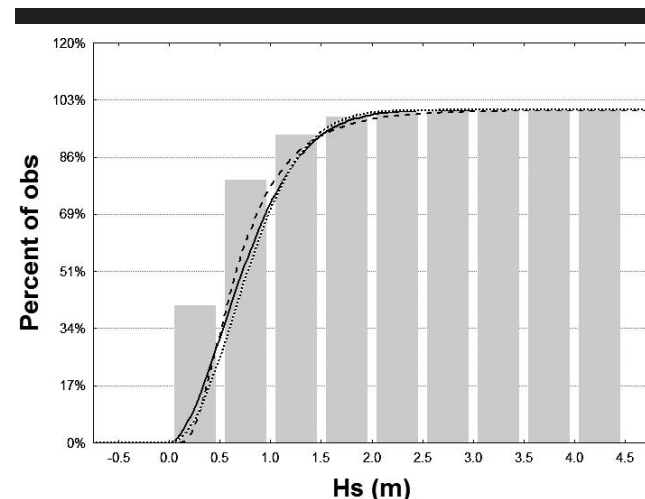


Figure 4. Weibull cumulative distribution of H_s .

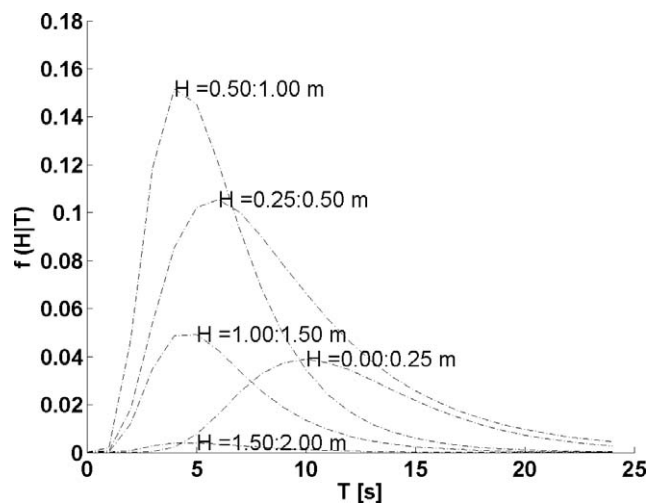


Figure 5. Annual wave joint probability.

between 0 and 16 seconds. The H_s between 0.25 and 0.5 m represent 38% of the total, and the heights between 0.5 and 1 m correspond to 39%. Meanwhile, 37% of the waves present a period of up to 4 seconds, whereas 44% of them have periods of between 4 and 12 seconds. Waves with heights greater than 1.5 m and periods greater than 16 seconds were not been observed during the study. The local waves, which are smaller than 0.25 m, only represent 4% of the total. Assuming linear wave theory and the depth at the wave gage of 8 m at low water

and a mean tidal range of 3.1 m, most waves can be considered to be in shallow or intermediate waters. Even the smallest-period waves, estimated by the instrument method, are steep enough to break.

Figure 2 shows the exceedance percentages of H_s and T_s . More than 97% of the waves had an H_s less than 1 m and 57% of them were less than 0.5 m. For the T_s , 80% of the waves had values up to 12 seconds, with almost 40% of the waves between 0 and 4 seconds.

Different theoretical probability distributions were applied to determine which one best fit the data. In all of them, the mean and the standard deviation were equal, $\mu = 0.76$ and $\sigma = 0.47$, respectively (Figure 3). Neither the lognormal or Rayleigh distribution fit the data because they consistently overestimated the wave heights (Figure 3); in particular, the latter tended to overestimate the number of the larger wave heights. The Rayleigh distribution was generally adequate, except for near coastal wave records because the model did not show the larger waves breaking in the shallow waters (Figure 3) (U.S. Army Corps of Engineers, 2001).

Application of the Weibull distribution resulted in the best fit. The scale parameter was 1.73, whereas the shape parameter was 0.82. The shape parameter indicates the mean value of the probability density; in other words, values larger than this number have a 50% chance of occurrence (Vitale, 2010). In our case, heights are greater than 0.82 m. Moreover, the mean H_s was lower than that parameter and H_s larger than the mean height (0.76 m) were more frequent. The scale parameter is relatively high because, being a coastal zone, there was wide data dispersion.

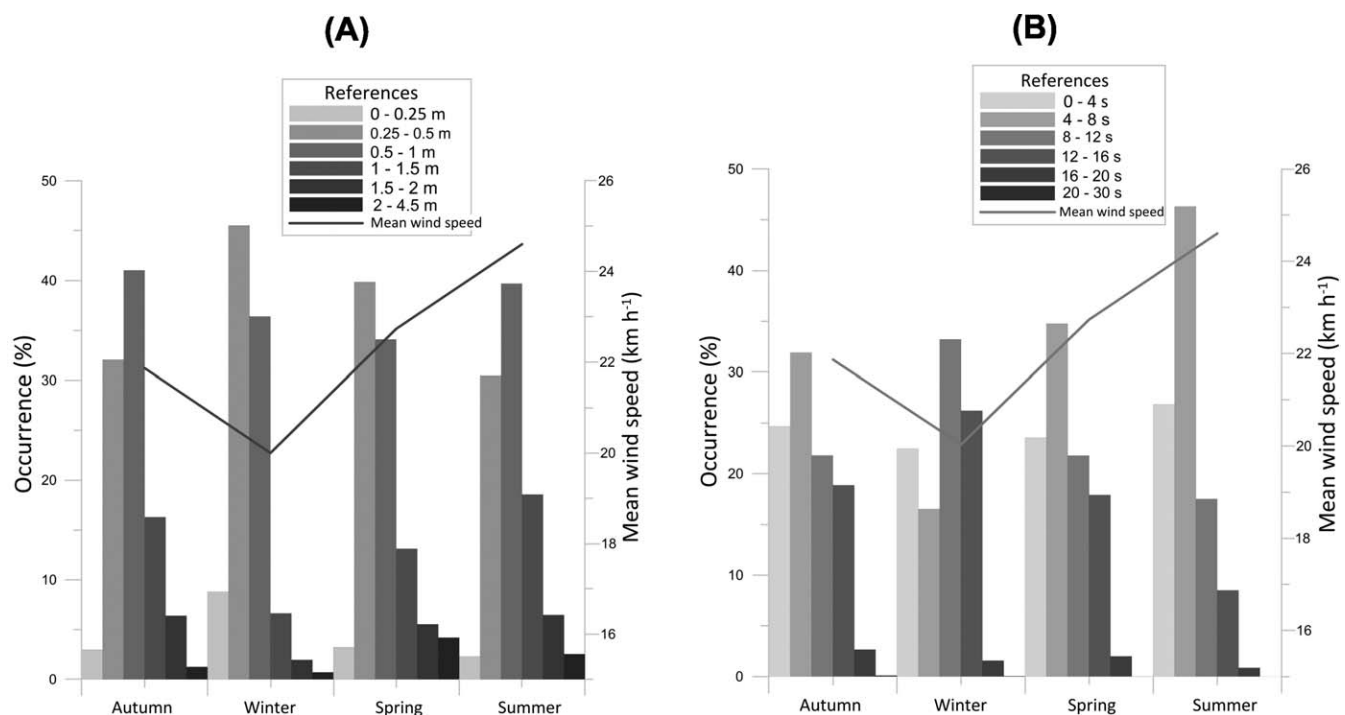
Figure 6. Relationship between seasonal distributions of wave parameters and mean wind speed: (A) H_s , and (B) T_s .

Table 5. Wave incidence at spring.

| T_s (%) | H_s (%) | | | | | | Occurrence | Exceedance |
|------------|-----------|------------|---------|---------|---------|---------|------------|------------|
| | 0–0.25 m | 0.25–0.5 m | 0.5–1 m | 1–1.5 m | 1.5–2 m | 2–4.5 m | | |
| 0–4 s | 0.06 | 8.01 | 12.99 | 2.28 | 0.2 | 0.03 | 23.56 | 76.44 |
| 4–8 s | 0.1 | 6.21 | 14.17 | 8.41 | 3.77 | 2.09 | 34.75 | 41.68 |
| 8–12 s | 0.79 | 12.34 | 5 | 1.54 | 0.81 | 1.3 | 21.78 | 19.9 |
| 12–16 s | 1.57 | 12.06 | 1.9 | 0.88 | 0.72 | 0.78 | 17.9 | 2 |
| 16–20 s | 0.72 | 1.21 | 0.01 | 0.01 | 0.03 | 0 | 1.99 | 0.01 |
| 20–30 s | 0 | 0.01 | 0 | 0 | 0 | 0 | 0.01 | 0 |
| Occurrence | 3.24 | 39.84 | 34.08 | 13.12 | 5.53 | 4.19 | | |
| Exceedance | 96.76 | 56.92 | 22.84 | 9.72 | 4.19 | 0 | | |

Table 6. Wave incidence at summer.

| T_s (%) | H_s (%) | | | | | | Occurrence | Exceedance |
|------------|-----------|------------|---------|---------|---------|---------|------------|------------|
| | 0–0.25 m | 0.25–0.5 m | 0.5–1 m | 1–1.5 m | 1.5–2 m | 2–4.5 m | | |
| 0–4 s | 0.07 | 7.87 | 14.49 | 3.83 | 0.51 | 0.07 | 26.83 | 73.17 |
| 4–8 s | 0.3 | 8.52 | 18.61 | 12.12 | 4.97 | 1.79 | 46.3 | 26.86 |
| 8–12 s | 0.74 | 8.88 | 4.91 | 1.7 | 0.68 | 0.61 | 17.51 | 9.35 |
| 12–16 s | 1.17 | 4.58 | 1.46 | 0.91 | 0.32 | 0.07 | 8.5 | 0.85 |
| 16–20 s | 0.03 | 0.61 | 0.22 | 0 | 0 | 0 | 0.85 | 0 |
| 20–30 s | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Occurrence | 2.31 | 30.44 | 39.68 | 18.56 | 6.47 | 2.54 | | |
| Exceedance | 97.69 | 67.25 | 27.57 | 9.01 | 2.54 | 0 | | |

The cumulative Weibull distribution (Figure 4) shows that waves of less than 0.5 m have a 41% probability of occurrence, whereas waves with heights lower than 1.5 m have a 93% probability of occurrence. In comparison, the probability of waves higher than 2 m is only 1%.

Finally, joint probability wave density results were obtained (Figure 5). Heights between 0.5 and 1 m with 3 to 6 seconds of period had the highest occurrence probability. Waves that oscillate between 0.25 and 0.5 m with a T_s of 4 to 7 seconds were also representative but with 28% less probability of occurring. The waves that were most improbable were the ones that presented with heights between 1.5 and 2 m with periods of 3 to 8 seconds.

Seasonal Analysis

The seasonal analysis of waves was related to the wind mean speed in the study area (Figure 6). It was observed that, in each season, the H_s and T_s had a strong relationship with the

intensity of winds. The highest waves occurred in spring, represented by the 4.19% with an H_s of more than 2 m. The T_s is regularly distributed, with 58.31% of less than 8 seconds, and the rest between 8 and 16 seconds (Table 5). Spring is also the season with the highest probability of the sudestada climatic phenomenon occurring, so one of the predominant wind directions is SE, which it is believed to generate the highest H_s of the year.

Most of the highest H_s results occurred in the summer, when 27.6% of H_s results were greater than 1.5 m. In fact, there were an important number of waves that exceeded 1.5 m (9%). This phenomenon was related to short periods and 73.1% of them had values of less than 8 seconds (Table 6). Most of the waves with high H_s and short T_s were associated with the most elevated wind speeds of the year (24.6 km h^{-1}). Because the sea breeze is a common feature during summer in this area, we assumed that this phenomenon could be their cause.

Wave H_s distribution in autumn was similar to that of summer, with an increment in the waves under 1 m of height

Table 7. Wave incidence at autumn.

| T_s (%) | H_s (%) | | | | | | Occurrence | Exceedance |
|------------|-----------|------------|---------|---------|---------|---------|------------|------------|
| | 0–0.25 m | 0.25–0.5 m | 0.5–1 m | 1–1.5 m | 1.5–2 m | 2–4.5 m | | |
| 0–4 s | 0.08 | 6.73 | 15.15 | 2.47 | 0.22 | 0.01 | 24.67 | 75.33 |
| 4–8 s | 0.04 | 4.05 | 13.84 | 9.02 | 4.34 | 0.61 | 31.9 | 43.43 |
| 8–12 s | 0.92 | 9.01 | 7.28 | 2.76 | 1.21 | 0.61 | 21.8 | 21.63 |
| 12–16 s | 1.53 | 10.02 | 4.66 | 2.03 | 0.61 | 0.02 | 18.87 | 2.76 |
| 16–20 s | 0.37 | 2.19 | 0.09 | 0.01 | 0 | 0 | 2.66 | 0.1 |
| 20–30 s | 0.06 | 0.04 | 0 | 0 | 0 | 0 | 0.1 | 0 |
| Occurrence | 2.99 | 32.05 | 41.02 | 16.29 | 6.39 | 1.26 | | |
| Exceedance | 97.01 | 64.96 | 23.93 | 7.65 | 1.26 | 0 | | |

Table 8. Wave incidence at winter.

| T_s (%) | H_s (%) | | | | | | Occurrence | Exceedance |
|------------|-----------|------------|---------|---------|---------|---------|------------|------------|
| | 0–0.25 m | 0.25–0.5 m | 0.5–1 m | 1–1.5 m | 1.5–2 m | 2–4.5 m | | |
| 0–4 s | 0.5 | 7.77 | 12.12 | 1.87 | 0.18 | 0.03 | 22.47 | 77.53 |
| 4–8 s | 0.28 | 3.5 | 8.43 | 2.8 | 1.25 | 0.26 | 16.52 | 61.02 |
| 8–12 s | 2.51 | 19.06 | 9.9 | 1.09 | 0.47 | 0.17 | 33.2 | 27.82 |
| 12–16 s | 4.85 | 14.34 | 5.84 | 0.87 | 0.06 | 0.26 | 26.21 | 1.61 |
| 16–20 s | 0.63 | 0.85 | 0.08 | 0 | 0 | 0 | 1.57 | 0.04 |
| 20–30 s | 0.04 | 0 | 0 | 0 | 0 | 0 | 0.04 | 0 |
| Occurrence | 8.8 | 45.52 | 36.38 | 6.63 | 1.96 | 0.72 | | |
| Exceedance | 91.2 | 45.67 | 9.3 | 2.67 | 0.72 | 0 | | |

and a small percentage of larger waves. On the other hand, the distribution of the period was closer to that of spring than summer, but with an increase in the percentages of long periods between 12 and 20 seconds (Table 7).

On the other hand, winter had the least wave intensity, being the season with more of the calm days of the year. The lowest H_s

and the longest T_s occurred during this season as well. The waves of this season had a 50% of probability of being less than 0.5 m in height, whereas waves between 0.5 and 1 m were also important and waves that exceeded 1 m had a null distribution. In fact, they only represent the 9.3% of the total, whereas the other seasons oscillate between 22% and 27%. This is

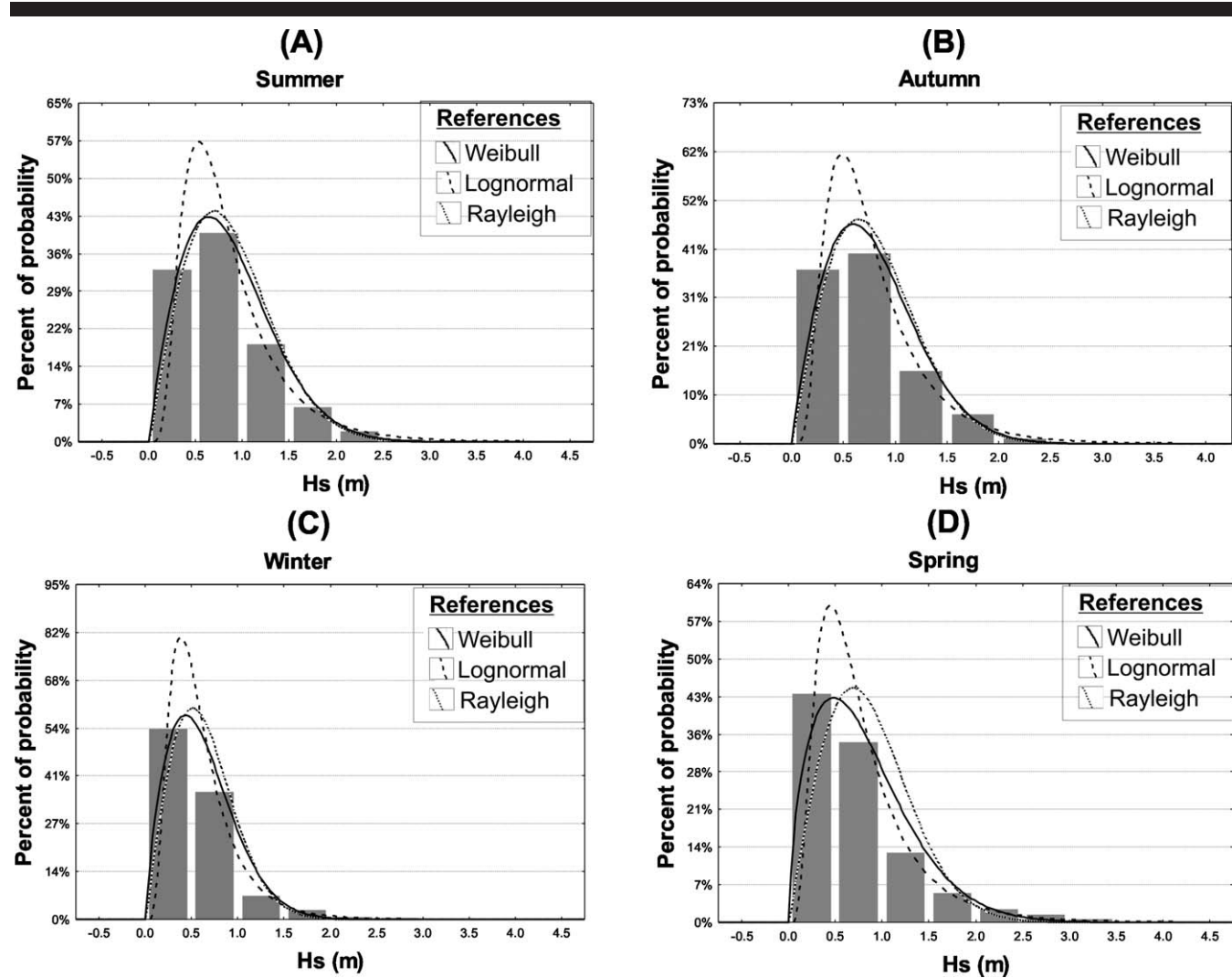


Figure 7. Lognormal, Rayleigh, and Weibull probability distributions for seasons: (A) summer, (B) autumn, (C) winter, and (D) spring.

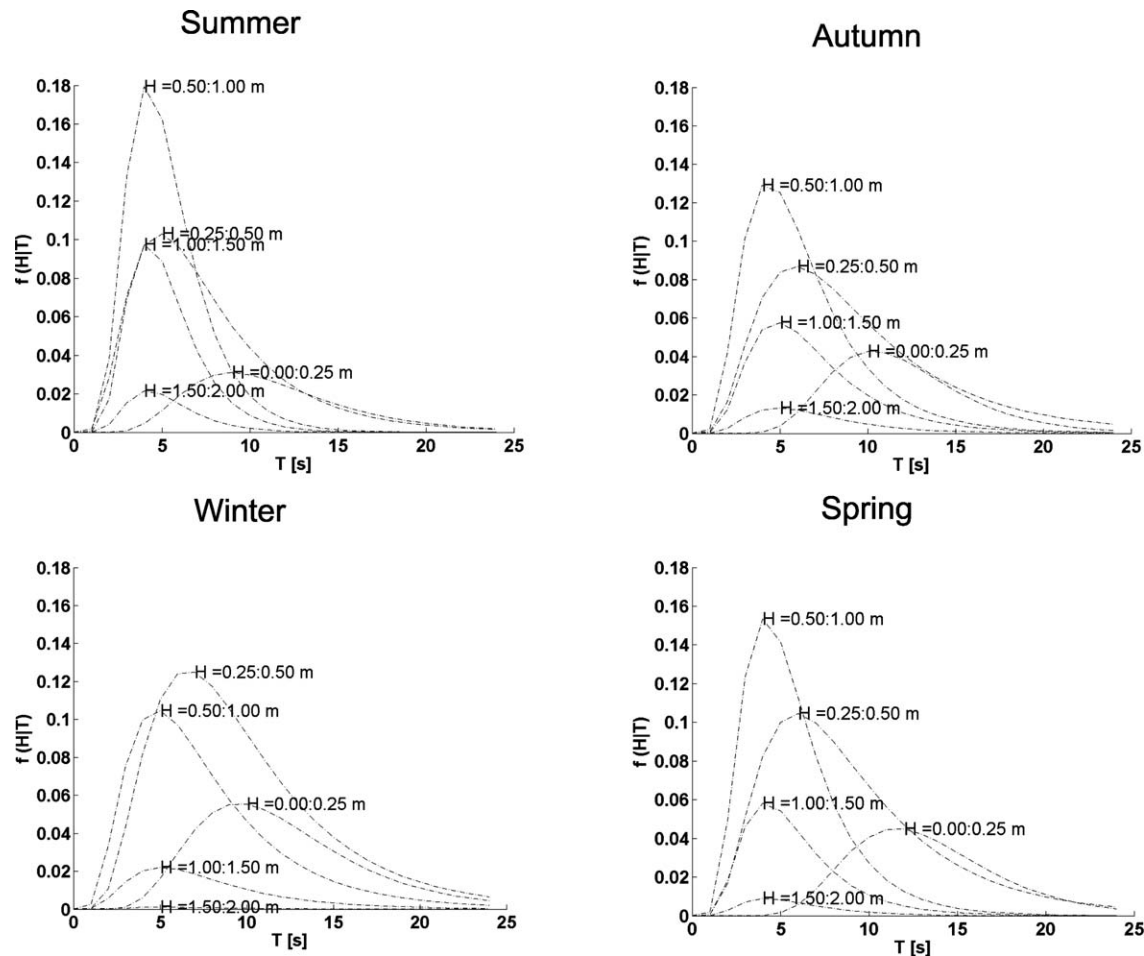


Figure 8. Seasonal wave joint probability.

associated to long T_s periods, with 70% of the periods greater than 8 seconds (Table 8). Therefore, because there was little local generation, these waves are distinctly generated, likely from the passage of cyclonic fronts that are initiated near Antarctica and move along the continental slope before moving toward Africa.

The probability distributions applied to all data yielded the same results (Figure 7). The distribution that best fit the data in all cases was Weibull distribution, whereas lognormal and Rayleigh distributions overestimated the H_s because the study area is located in shallow waters.

Finally, the joint probability of wave data was also applied to each season. Summer and spring had similar distributions of H_s and T_s because the waves most likely to occur had H_s height of 0.5–1 m with a T_s period between 3 and 7 seconds. Waves that continue in importance are the ones that had an H_s of 0.25–0.5 m and T_s of 5 to 6 seconds (Figure 8). The main difference between both distributions is that summer waves presented shorter periods, represented by the pronounced slope of the curves of the distributions, which mostly ranged from 3 to 7 seconds, because the generating winds came from

the north with high speeds producing local waves. On the other hand, spring had an important number of waves, with periods oscillating between 10 and 14 seconds because the winds had an important SE component, so the wave generation was not necessarily local.

Autumn also had the greatest probability of waves of 0.5 to 1 m heights, but with shorter periods oscillating between 4 and 5 seconds. Waves that ranged from 0.25 to 0.5 m with 5 to 6 seconds of T_s were second in probability. Winter showed a different behavior from the other seasons because it was more probable that the waves in the area had an H_s of 0.25 to 0.5 m and a T_s of 5 to 7 seconds. Also in winter, there was an important probability of waves from 0.5 to 1 m with 4 to 6 seconds of T_s . Winter had the most regular distribution of waves with curves with soft slopes.

Sediment Transport

The waves that characterized the area of the buoy were related to the sedimentological features and were used to establish whether those were capable of transporting the

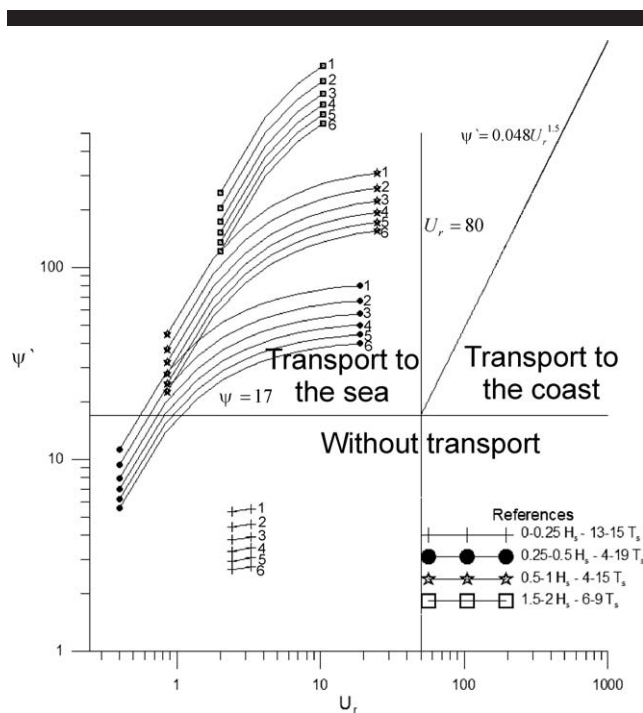


Figure 9. Net normal transport scheme based on the correlation between the Ursell number and the flux intensity parameter (Perillo, 2003; Sunamura, 1982). For each joint H_s and T_s , a family of sediment-size curves is plotted: 1 = 0.125 mm; 2 = 0.15 mm; 3 = 0.175 mm; 4 = 0.2 mm; 5 = 0.225; and 6 = 0.25.

material at the tower site. Gómez and Perillo (1992) made the only study describing the sediment characteristics in the area, and they described the sediments as mostly fine to very fine sands, between 1.9 and 3 ϕ (0.268 to 0.125 mm).

Sunamura (1982) and Horikawa (1988) established a correlation between the Ursell number ($U_r = HL^2/d^3$) and the flux intensity parameter (ψ'):

$$\psi' = \frac{(d_0 \sigma)^2 \rho}{(\rho_s - \rho) g D} \quad (6)$$

$$d_0 = \frac{H}{sh(kd)} \quad (7)$$

where $\sigma = 2\pi/T$, ρ is the water density, ρ_s is the sediment density, g is gravity, D is the diameter of the sediment, $k = 2\pi/L$, and d is the depth. Both parameters were calculated to determine whether there was a net transport and its potential direction (Perillo, 2003; Sunamura, 1982) (Figure 9). Only shallow and intermediate water waves were taken into account, and waves that occurred less than 2% of the time were not considered. The analysis was made for the whole suite of sediment sizes found in the area near the OT produced a family of curves for each joint H_s and T_s .

The waves for which H_s was less than 0.25 m were not able to transport sediment. The ones for which H_s ranged between 0.25 and 0.5 m and associated with a T_s of 4 to 19 seconds could move all sand sizes as long as the T_s were larger than 5 seconds.

Finally, those waves that were larger than 0.5 m were able to transport all sediments independent of the T_s . When sediment transport was possible, based on the Ursell number, the wave's transport direction was seaward. For fixed values of H_s and T_s , depth was the controlling factor in defining transport direction. At 8 m depth, basically all sediment was transported offshore. To reverse that situation, the depth should be at least 5 m for the larger waves.

CONCLUSIONS

Wave data were analyzed between April 2007 and July 2009 offshore of the southern coast of Buenos Aires Province (Argentina). The aim of this work was to obtain the long-term probabilities of wave parameters for the coastal zone of Monte Hermoso and Pehuén Co, Argentina. An incidence table was analyzed and theoretical probability distributions were applied to the data.

Waves in the study area had heights between 0.25 and 1 m, with periods of less than 8 seconds. Heights greater than 2 m and periods greater than 12 seconds had only a 1% chance of occurring. High waves were the ones that removed the greatest quantity of sediment because they carried a lot of energy and should, therefore, be considered when marine structures are made.

The season of the year with the highest H_s was spring, with 4.19% of the waves having values that exceeded 2 m. Similarly, summer was characterized by the largest percentage of waves that exceed 1.5 m in height (27.6%) and were related to short periods of less than 8 seconds. Winter had the smallest H_s values, with more the 50% of the waves less than 0.5 m in height and with long periods of more than 8 seconds. The analysis showed there was a strong relationship between local winds and the H_s of the waves. In spring and summer, the H_s tended to be higher because the winds were stronger, produced by the regularity of the coastal breeze, and there were fewer calm days. On the other hand, winter had the lowest H_s , related to the lessened intensity of the winds because those waves had a distinct area of generation.

The lognormal and Rayleigh distributions did not represent the wave distribution of the study area because those models are more appropriate for deep waters. The scale parameter of Weibull is relatively high and can be used for coastal areas, where waves are influenced by the bathymetry. Therefore, the Weibull distribution represented the data properly.

General joint-probability analysis indicated that heights between 0.5 and 1 m with 3 to 6 seconds of period had the greatest probability of occurrence. Waves with heights between 0.25 and 0.5 m with T_s of 4 to 7 seconds were also representative but had a 28% lower probability of occurring. Summer and spring had similar distributions of H_s and T_s because the waves most likely to occur were between 0.5 and 1 m with periods between 3 and 7 seconds, with summer waves having shorter periods because the generation winds came from the north, with high speeds producing local waves. Winter, on the other hand, was different from the other seasons because most of the waves were oceanic with few local waves because of the large number of calm days, contrary to what is normally expected.

Almost 40% of the analyzed waves were able to move the sediment in the study area, with waves that had an H_s between 0.25 and 1 m and a T_s of greater than 5 seconds, the most likely to move the sediment. In all cases, sediment was transported seaward.

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