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# Maritime Climate in the Canary Islands and its Implications for the Construction of Coastal Infrastructures

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**Abstract**

Islands are isolated systems that depend on maritime trade for their subsistence. Efficient, durable and structurally reliable port infrastructures are essential for the economic and social development of islands. However, not all port infrastructures are designed in the same way. They can vary, depending on whether they are built on continental land, built on non-volcanic islands or built on volcanic oceanic islands (such as the Canary Islands, Spain). The latter islands are the subject of this study due to their specific features, construction difficulties and the importance of sound maritime infrastructures. The maritime climate of an area consists of the wave and storm regimes that affect it and, from these, the coastal dynamics and coastal formations of that area can be studied. For this reason, historical data were collated on significant directional wave heights from 1958 to 2015 from several WANA-SIMAR points in the virtual buoy network of State Ports of Spain located near the Canary Islands. These data have been studied to obtain the maximum directional wave heights (Hs) at each point. With this analysis, we have obtained useful summary tables to calculate wave height by a graphic method that transforms the distribution function into a line drawn on probabilistic paper, using reduced variables. This enables adjustments to be made by linear regression and minimum square methods to facilitate planning and design of maritime infrastructures in a reliable way.

*Keywords:* GNSS Network; Swell; Wave Height; Maritime Infrastructures.

## 1. Introduction

In the Atlantic zone, many socio-economic activities are affected in a significant way by weather events. This has generated the need to improve knowledge and prediction of such events, such as in the case of wave storms [1]. There are two types of waves that occur along the coast of the Canary Islands. One type is generated by disturbances or storms that circulate from west to east in the North Atlantic and spread to the islands in a south and southeast direction, called bottom sea or overflow [2]. These waves can reach heights of up to 8 metres and, in exceptional cases, up to 10 metres or more. The second type of swell is generated by the trade winds, whose direction is from the north and northeast [3]. This swell usually has a height of between 1.30 and 2 metres but can reach up to 4 metres in exceptional cases [4]. In continental maritime climates, a point on the coastline will be affected by a range of directions up to a maximum of 180 degrees. By contrast, in an archipelago, a point on a coastline could be affected by waves from any direction. This means that more directions must be considered to construct a port in the Canary Islands, than for a port on the continent. In

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addition, when sizing a structure subject to wave action, it is necessary to know or estimate the significant wave height associated with a certain probability of exceedance within the lifespan of the infrastructure [5]. To determine its design height, it is therefore necessary to model the statistical behaviour of values of significant wave height series that may put the structure at risk. This study collected all the historical data on significant directional wave heights from 1958 to 2015 from several WANA-SIMAR points of the Virtual Buoy Network of Spanish State Ports in the vicinity of the Canary Islands in order to obtain the maximum directional $Hs$ wave heights at each point. To make these estimations, the Canary island maritime climate must be analysed thoroughly. For better understanding, the influences on the maritime climate of the Canary Islands are described as follows:

### 1.1. Trade Winds

The trade winds are predominantly easterly winds blowing from areas of high subtropical pressure towards the low equatorial pressure belt, with a NE-SW direction in the Northern Hemisphere (NE or boreal trade winds) and SE-NW direction in the Southern Hemisphere (SE or southern trade winds) [6]. The contact between both trade winds occurs in the so-called intertropical convergence zone, a belt in which the air rises accompanied by clouds and precipitation and then falls in the tropical regions, where subsidence prevents the formation of clouds and the largest desert areas in the world are found [7]. This belt is sometimes interrupted by the presence of a zone of equatorial calms, characterized by light and variable winds, the so-called calms or doldrums. The trade winds sweep across approximately 30% of the globe's surface. Depending on their geographical location, a distinction can be made between oceanic and continental trade winds and those that cross the equator as monsoons [8]. Trade winds are felt more on oceanic masses than on continental masses and are characterized by their intensity (20 km/h on average) and constancy of direction. Thus, in the past, these winds were useful for commercial sailing ships sailing west, which is why they are known as trade winds. These winds are dry winds at their origin but they become loaded with moisture as they cross the ocean, causing heavy rains on the eastern coasts of the continents [9].

### 1.2. Autumn Calms

With the arrival of autumn, the well-known September calms appear throughout the archipelago. The duration of these lulls is variable (they can extend until December and even arrive before August) and are not always continuous. Sporadically, they are interrupted by frontal storms from the NW (from October onwards), waves from the NE, and/or waves produced by storms in the Canary Islands area of E, S and W components.

### 1.3. The Equatorial Calm Belt

The so-called equatorial lulls are a region with mild winds, called calms, and some storms, which are located in the ocean near the equator and change position and size with the seasons [10]. These zones are located between the trade winds of the northern and southern hemispheres, between latitudes 10° S and 10° N. In these zones, the hot air from the earth's surface rises and flows towards the northwest and southwest at altitudes that vary between 800 and 6,000 meters to form anti-trade winds.

### 1.4. The Frontal Storms of the Atlantic to the NW of the Canary Islands

From October to May of each calendar year, the maritime climate of the Canary Islands is marked by storms from the NW and N. These storms are generated by the frontal storms that form to the NW of the Canary Islands around latitude 60º, in the area of low polar pressure, previously mentioned when commenting on global atmospheric circulation.

### 1.5. The Tropical Cyclones of the Western Canaries

The tropical cyclone season in the North Atlantic begins on June 1 (when the sea has already been warmed up by the sun to at least the 26.5 degrees that tropical cyclones need to form) and ends on November 30 of each calendar year (when the sea has cooled sufficiently to prevent cyclones from forming). Notwithstanding the above, hurricanes can occur all year round (except in March). Less commonly, they can form or turn into tropical or extra-tropical storms, generally in areas further away in the Caribbean and closer to the Canary Islands [11].

### 1.6. Squalls in the Canary Islands Area

Occasionally, and throughout the calendar year, low local pressures occur in the area of the Canary Islands, which are characterized by a core pressure over 1,000 millibars. This is what is known as a Canary Island squall. These squalls usually form to the west of the archipelago and move from west to east, passing through the south [12]. They generate winds of variable intensity and direction along their trajectory, depending on the pressure in their core. These winds give rise to local wind seas, not bottom seas, as there is not enough intensity for waves to develop.

The aim of maritime climate analysis of a coastal region is the prediction of waves and storms that could affect the region [13]. These predictions are necessary for coastal activities (ports, beaches, coastal defences, etc.) and for commercial and leisure navigation, as well as for the prevention of damage to coastal towns and maritime infrastructures [14]. The continuous measurement of waves is essential to obtain reliable results for the safe calculation and construction of maritime works. Wave measurement involves five characteristic parameters: climatic types, wave direction, periods, wave heights and wave duration [15].

The methodology section of this article describes the buoys selected to carry out the study of wave heights in all the directions that affect the islands that make up the Canary archipelago, as well as explaining the statistical method used in the document. In the results section, the maximum heights obtained for the years from 1958 to 2015 are presented. At the same time, the heights in the 16 directions studied in the Canary Islands are presented, for three different percentages. Finally, the conclusions of the study are presented.

## 2. Methodology

The Canary Islands are an outermost region that belongs to Spain. They are located 1,400 km from the nearest coasts of the European continent (the Iberian Peninsula) and 100 km off the western coast of the African continent (Western Sahara) (Figure 1).


**Figure 1. Location of the Canary Islands (in yellow) in relation to Spain, (Source: Google Maps)**

The process followed in the methodology of this paper is summarized in Figure 2 and is detailed below.

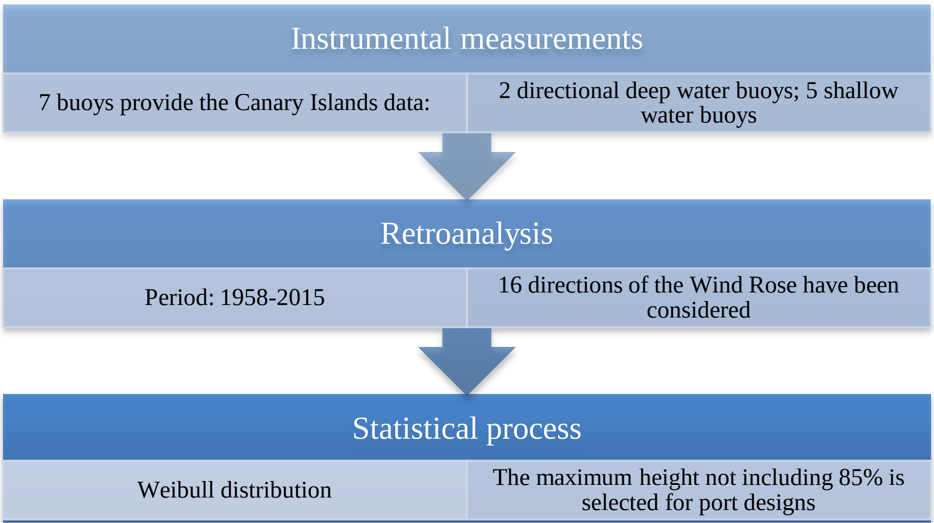


**Figure 2. Methodology followed in this paper**

Currently, wave data is available in the Canary Islands from the following sources:

- ***Instrumental Measurements***

There are seven buoys and coastal radar installed in the Canary Islands, which are located as follows: two directional deep water buoys, (*Boya Gran Canaria*, anchored off *Galdar* at 780 m depth and *Boya Tenerife Sur*, anchored off *Punta Rasca* at 710 m depth); five shallow water buoys at variable depths between 40 and 60 m, two of which are off *Santa Cruz*, both directional, one off the *Granadilla Port* and two in *Las Palmas*, *Cebadal* (West coast) and *Puerto* (East coast). These last three are scalar buoys. In addition, there is coastal radar in the Port of *Las Palmas de Gran Canaria* that currently has no data available to the public. The four directional buoys measure four of the five parameters (they do not distinguish between sea and swell) and the three scalar buoys only measure three parameters (they do not measure either direction or weather type). All data generated by the seven buoys and the radar are affected by wave deformation and should not be used in marine climate analyses directly.

In order to be used correctly, they need to be unblocked down to deep water. The shallow water buoys, for obvious reasons, and the two deep water buoys, because they are in sheltered island areas, are therefore affected by diffraction during the storms they must measure. It is surprising that this fact is often ignored by the institution that operates the buoys, as well as by most of the consultants, especially foreign consultants, who analyse the maritime climate of the Canary Islands. Frequently, one can see analyses carried out by taking the data directly from the buoys or the use of these data to rectify, erroneously and downwards, results obtained by other more reliable methods.

About the retroanalysis, this technique generates wave data using numerical wind and wave models from current or past surface weather charts. Its reliability has been improved with the models that feed the system. Historically, three series of data have been produced, supported by three node meshes: the WASA nodes (1972-1994) that have become obsolete due to the age of the models used; the WANA nodes (1995 onwards) [16]; and the SIMAR-44 nodes (1958-2001) (superimposed on the WANA) both fully operational. SIMAR-44s were obtained in the year 2000 by the European HIPOCAS project [17] using historical weather charts dating back to 1958. In a direct way, they measure the five wave parameters in addition to the wave height/period ratios so important for these calculations.

Accessing the historical data of the website of the organization State Ports of Spain*, a statistical analysis of the data has been carried out with a yearly sample from 1958 to 2015. The results obtained predict the storm calculation for a maritime infrastructure in the study area, the Canary Islands. In this analysis, a maximum of 16 directions of the Wind Rose have been considered [18], covering a sector of 11.25º on each side of the direction of study.

The WANA-SIMAR44 points of the State Ports network have been considered. The SIMAR data set is formed by time series of wind and wave parameters from numerical modelling. They are, therefore, simulated data and do not come from direct measurements. The WANA series come from the sea state prediction system that State Ports developed in collaboration with the State Agency of Meteorology (AEMET). They are not predicted data but diagnostic or analytical data. This means that, for each instant, the model provides wind and pressure fields consistent with the previous evolution of the modelled parameters and consistent with the observations made. The SIMAR series arises from the union of two large sets of simulated wave data which the State Ports have available: SIMAR-44 and WANA. Ten WANA-SIMAR44 points have been chosen for the study of the Canary Island archipelago's waves in deep waters, with the intention of not being points that could be affected by the shelter provided by other islands. The points chosen in this project have been marked with a red dot (Figure 3).

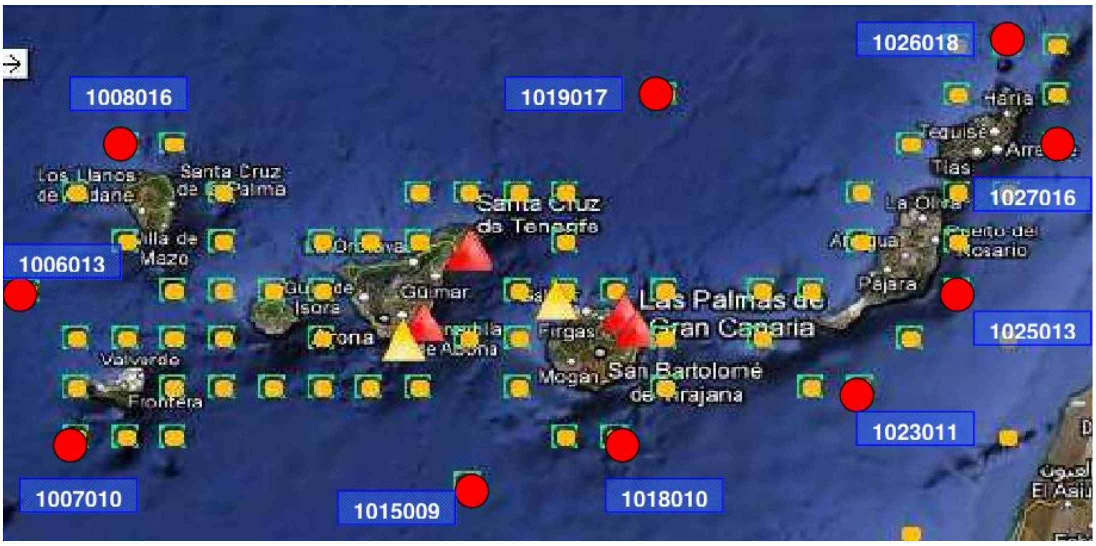


**Figure 3. SIMAR points chosen in 2008, the year the study started**

* *www.puertos.es*

Every point provides data over 58 years, thus analysing maximum wave heights in 12 months, and they provide 696 values for each of them, obtaining a sample of 6,960 values from the 10 points considered. For the purposes of this study, minimum heights in the same direction in the same year have been discarded and the maximum has been selected. Once maximum directional heights are obtained [19], the general method of calculating the average regimes is applied, following the recommendations for marine infrastructures ROM 03.91 [20]. This results in the probability that a certain wave height will not be exceeded in the average calendar year, i.e., the probability of not exceeding in deep waters in the study area. This probability is obtained from the number of observations in each interval, with respect to the total number of observations available. The data obtained have been adjusted with the *Weibull* distribution function, as this is the best adjustment that has been observed.

As mentioned above, ten SIMAR points have been studied for the 58 years for which information is available. For each year, there is data on the maximum monthly height, i.e., 12 months, which corresponds to 12 different wave heights. These heights are the maximum heights that have occurred within this 58-year sample, and dimensioning a maritime work for this height leads to an unnecessary over-dimensioning for a wave that has been generated once in 58 years. This is why these data are taken and fitted to a *Weibull* distribution, to obtain the line followed by the points and, consequently, the wave height by means of the probability of not exceeding. The procedure followed for the northern direction is explained as an example:

1. Once the maximum values for each year in the same direction have been obtained (in this case we take the data from N direction), they are ordered from highest to lowest and an order number is assigned (1,2,3,4...).
2. With this order number and the total data number, we calculate F ($Hs$) by applying Weibull.
3. The data $Hs$ (m) is represented against $F$ ($Hs$) on probabilistic paper and fitted to the corresponding line by the method of least squares.
4. This straight line defines the wave height to estimate the dimensions required for coastal structures with a probability of not exceeding.
5. To determine the wave height in the northern direction that does not exceed 85%, substitutions must be made in the formula $Hs$ (m) provided after representing the data graphically.
6. If it is desired to know the wave height in the northern direction that does not exceed 85%, the formula obtained in Figure 4 after adjustment must be substituted into the formula obtained in Figure 4.

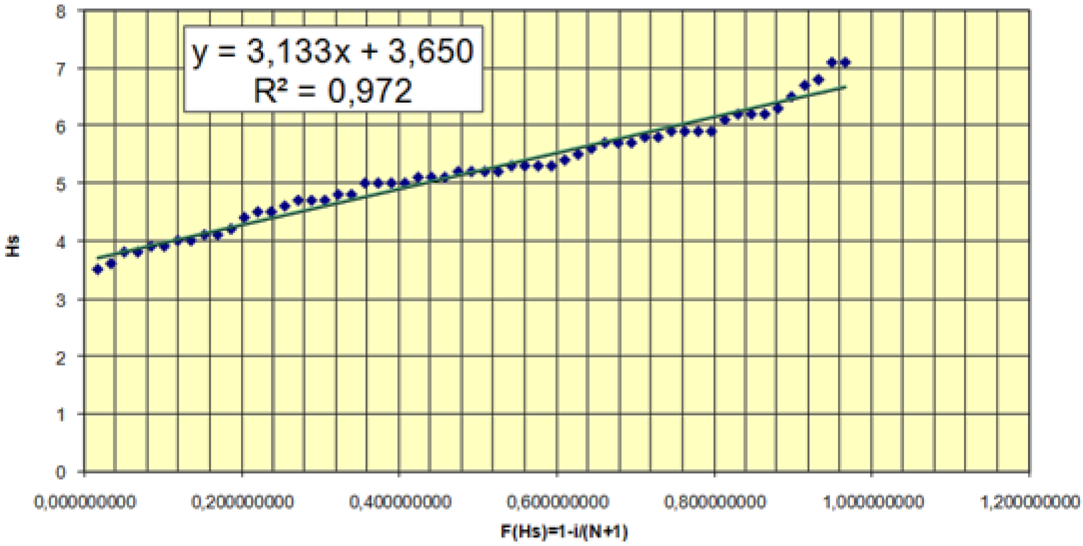


**Figure 4. Equation obtained to find the height not exceeding 85% in the northern direction, after the Weibull adjustment**

This result is for the northern direction and, depending on the area of the coast in particular, it will be necessary to study the directions in which it is affected and to keep the most unfavourable direction, i.e., the maximum. It is this wave height that is taken as a starting point and with which the maritime climate, propagation and stability of the structure in the project of a maritime work is started.

## 3. Results and Discussion

All the historical data of significant directional wave heights from 1958 to 2015 from several WANASIMAR points of the *Puertos del Estado* virtual buoy network, located in the vicinity of the Canary Islands, have been studied to obtain the maximum directional wave heights (Hs) at each point. With this analysis, very useful summary tables are obtained to calculate the wave height *"on site"* by a graphic method that transforms the distribution function into a straight line drawn on probabilistic paper by using reduced variables, being able to make the adjustment by means of linear regression by the least squares method and thus be able to design the maritime work. In the data used, for directional significant height (representing the average height of the highest third of waves), the direction variable is already taken into account due to the prevailing wind and with respect to the peak period in seconds, the swell is composed of a superposition of groups of waves of different periods, and the period of the group of waves with the most energy has been taken into account, i.e. the peak period $Tp$, so that any other variable would not be on the safety side. No other parameters have been experimented with, as these are the two necessary to perform the probabilistic adjustment; applying Weibull and with a sample of 58 years it is considered quite reliable. Analyzing the values of maximum directional wave heights, the probability that a certain wave height will not be exceeded in a period equal to one year was obtained using the Weibull function. Table 1 summarizes the maximum significant directional wave heights from 1958 to 2015. It is with these data that the statistical analysis is conducted to obtain the wave prediction in the area where a coastal infrastructure is to be designed, in the case of the Canary Islands.

**Table 1. Summary of maximum directional Hs of the points studied**

| **RANGE** | 11,25 | 348,75 | 326,25 | 303,75 | 281,25 | 258,75 | 236,25 | 213,75 | 191,25 | 168,75 | 146,25 | 123,75 | 101,25 | 78,75 | 56,25 | 33,75 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ± 11,25º | 348,75 | 326,25 | 303,75 | 281,25 | 258,75 | 236,25 | 213,75 | 191,25 | 168,75 | 146,25 | 123,75 | 101,25 | 78,75 | 56,25 | 33,75 | 11,25 |
| years | N | NNW | NW | WNW | W | WSW | SW | SSW | S | SSE | SE | ESE | E | ENE | NE | NNE |
| 1958 | 3,5 | 7,4 | 7,9 | 0 | 4,7 | 5,2 | 4,1 | 0 | 0 | 0 | 2 | 3 | 0 | 3,3 | 3,3 | 5,8 |
| 1959 | 4,7 | 5,7 | 5,3 | 5,7 | 5,2 | 5,1 | 3,7 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 4,6 | 5,2 |
| 1960 | 7,1 | 4,9 | 6,8 | 4,1 | 6,7 | 10,1 | 2,9 | 0 | 0 | 0 | 0 | 0 | 0 | 2,2 | 2,9 | 4 |
| 1961 | 5,7 | 5,6 | 5,6 | 3,9 | 3,4 | 4,3 | 5,5 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4,1 | 6 |
| 1962 | 6,2 | 7 | 6,2 | 5,1 | 5 | 6,1 | 6,3 | 5,3 | 0 | 0 | 0 | 0 | 2 | 0 | 5,8 | 6,1 |
| 1963 | 4,6 | 6,5 | 6,8 | 5,7 | 5,6 | 4,8 | 5,6 | 0 | 0 | 0 | 0 | 1 | 2 | 2 | 3,5 | 4,4 |
| 1964 | 5,1 | 5,4 | 6,5 | 7,2 | 6,4 | 6,1 | 2,8 | 2 | 0 | 0 | 0 | 0 | 3,2 | 0 | 3,6 | 3,3 |
| 1965 | 5,3 | 4,4 | 4,7 | 4,3 | 6 | 4,3 | 3,5 | 3,3 | 0 | 0 | 0 | 0 | 0 | 0 | 4,3 | 5,3 |
| 1966 | 3,9 | 7,5 | 9,1 | 5,1 | 2,5 | 5 | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 0 | 4,3 | 5 |
| 1967 | 5,1 | 5,2 | 4,7 | 0 | 0 | 0 | 2,8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3,5 | 5 |
| 1968 | 5 | 3,8 | 8,8 | 5,5 | 4,6 | 4,1 | 3,2 | 2 | 2 | 2 | 0 | 0 | 2 | 2,3 | 3,5 | 4,7 |
| 1969 | 3,6 | 4,4 | 6,8 | 7,3 | 5 | 4,7 | 3,5 | 4,1 | 2 | 2 | 2 | 2 | 2 | 0 | 4,3 | 4,7 |
| 1970 | 6,1 | 5,2 | 2,8 | 7,2 | 4,5 | 7,3 | 3,6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5,5 | 5,7 |
| 1971 | 5,3 | 5,4 | 2,1 | 3,4 | 2,8 | 2,9 | 2,9 | 2 | 3 | 3 | 3 | 3 | 0 | 0 | 3,8 | 3,8 |
| 1972 | 5,7 | 7,9 | 8,3 | 6,1 | 6,4 | 2,7 | 1,8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4,3 | 5,1 |
| 1973 | 7,1 | 7,8 | 4,1 | 4,2 | 3,5 | 3,8 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 3,6 | 4,8 |
| 1974 | 5,2 | 6,5 | 6,2 | 4,7 | 4,5 | 2,4 | 0 | 0 | 0 | 0 | 0 | 2 | 3 | 2,5 | 4,4 | 4 |
| 1975 | 5,3 | 3,2 | 5,5 | 3,9 | 4,5 | 2,7 | 0 | 2 | 2 | 2 | 2 | 1 | 2 | 0 | 3,7 | 5,4 |
| 1976 | 5,5 | 6,2 | 8,5 | 6 | 4,4 | 5,5 | 1,9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3,2 | 3,8 |
| 1977 | 4,2 | 7,2 | 6,8 | 4,1 | 3,1 | 4,6 | 0 | 3 | 3 | 3 | 3 | 2,2 | 0 | 0 | 3,6 | 4,7 |
| 1978 | 5,9 | 5,3 | 6,9 | 4,1 | 3,3 | 1,7 | 0 | 0 | 1 | 0 | 1 | 1 | 2 | 0 | 3,7 | 4,2 |
| 1979 | 5,8 | 6,3 | 5,7 | 3,4 | 7,1 | 7,1 | 3,9 | 4 | 3 | 3 | 3 | 0 | 2 | 0 | 3,7 | 6,3 |
| 1980 | 5,3 | 5,3 | 4,4 | 3,7 | 2,8 | 5,1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 6,5 | 7,2 |
| 1981 | 5,4 | 6,8 | 6,7 | 5,1 | 5 | 0 | 2,8 | 2 | 2 | 0 | 0 | 1,7 | 0 | 2,3 | 4,4 | 5,2 |
| 1982 | 5,9 | 9,6 | 6 | 6,2 | 5,6 | 4 | 2,6 | 2 | 2 | 0 | 0 | 0 | 2 | 3,5 | 4,1 | 4,7 |
| 1983 | 5 | 6,3 | 0 | 5,9 | 3,6 | 5,2 | 2,9 | 0 | 2 | 2 | 3 | 3 | 3 | 2,4 | 3,2 | 4,9 |
| 1984 | 6,5 | 5,8 | 3,6 | 4,5 | 5 | 4,5 | 4,9 | 0 | 0 | 0 | 1 | 1 | 2 | 0 | 4,5 | 6,2 |
| 1985 | 4,5 | 6,4 | 7,1 | 7,8 | 3,2 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 1,9 | 4 | 5 |
| 1986 | 6,2 | 6,7 | 4 | 2,4 | 1,7 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 3 | 2,5 | 3,4 | 4,2 |
| 1987 | 4,4 | 7,6 | 7,3 | 6,5 | 4,9 | 3,5 | 0 | 2 | 2 | 0 | 0 | 0 | 2 | 4,8 | 4,9 | 5,4 |
| 1988 | 6,2 | 5,5 | 5,2 | 4,9 | 4,5 | 3,2 | 2,7 | 3,3 | 3 | 2 | 3,7 | 3 | 3 | 0 | 4,4 | 5,7 |
| 1989 | 5,9 | 8,6 | 6,9 | 3,4 | 2,7 | 5,1 | 6,5 | 4,9 | 0 | 0 | 3 | 3 | 2 | 0 | 4 | 5,9 |
| 1990 | 6,3 | 6,3 | 5,8 | 4,6 | 4,4 | 3,7 | 4,2 | 0 | 0 | 2 | 3 | 3 | 3 | 2,8 | 3 | 4 |
| 1991 | 6,7 | 6,4 | 7,8 | 5,4 | 5,1 | 4,4 | 4,5 | 3,4 | 0 | 0 | 0 | 0 | 2 | 2,1 | 2,9 | 5,1 |
| 1992 | 5,2 | 5,4 | 4,4 | 0 | 0 | 0 | 0 | 0 | 0 | 2,7 | 3,1 | 2 | 2 | 0 | 3,4 | 4,8 |
| 1993 | 5,2 | 6,2 | 5,7 | 6,4 | 5,4 | 0 | 5,3 | 0 | 0 | 0 | 3 | 3 | 3 | 3 | 3,2 | 4,1 |
| 1994 | 5,7 | 6,1 | 4,4 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 3 | 0 | 5,5 | 6,9 |
| 1995 | 5,6 | 6,4 | 6,1 | 4,3 | 0 | 4,1 | 3,6 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 4,7 | 4,7 |
| 1996 | 4,1 | 6,5 | 8,1 | 7,8 | 5,2 | 5 | 3,4 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 3,8 | 5,9 |
| 1997 | 4,1 | 7,3 | 7,7 | 4,2 | 3,9 | 0 | 2,5 | 3 | 3 | 3 | 0 | 0 | 3 | 2,1 | 2,7 | 3,6 |
| 1998 | 5,8 | 7,1 | 7 | 5,7 | 4,9 | 2,6 | 0 | 3 | 2 | 2 | 3 | 2 | 2 | 2,2 | 4,2 | 4,9 |
| 1999 | 9,7 | 6,7 | 6,2 | 0 | 0 | 0 | 0 | 3 | 3 | 2 | 3 | 4 | 4 | 4,6 | 5,3 | 4,3 |
| 2000 | 5,2 | 5,2 | 6 | 5,7 | 4 | 0 | 2,1 | 0 | 2 | 2 | 2 | 2 | 3 | 0 | 4 | 4,8 |
| 2001 | 4,8 | 6 | 6,4 | 4 | 4,5 | 5 | 0 | 3 | 2 | 2,3 | 0 | 3 | 3 | 2,1 | 4,1 | 4,9 |
| 2002 | 4,7 | 6,8 | 7,2 | 5 | 3,8 | 3,2 | 4 | 4 | 2 | 0 | 0 | 3,3 | 4 | 4,9 | 4,6 | 5,2 |
| 2003 | 6,8 | 7,4 | 9,4 | 3,9 | 4,2 | 1,9 | 0 | 0 | 1,7 | 0 | 0 | 2 | 1 | 2,6 | 4,3 | 5,3 |
| 2004 | 4,8 | 4,5 | 4,2 | 4,1 | 4,3 | 3 | 2,4 | 1,8 | 1 | 1 | 2 | 2 | 2 | 1,2 | 3,1 | 4,4 |
| 2005 | 5 | 5,3 | 5 | 5,2 | 4,8 | 4,5 | 2,3 | 1 | 1 | 1 | 1 | 2 | 2 | 1,9 | 2,1 | 3,9 |
| 2006 | 3,9 | 4,7 | 6,8 | 5,9 | 3,3 | 0 | 0 | 3 | 2 | 2 | 0 | 2 | 3 | 2,4 | 2,8 | 3,8 |
| 2007 | 3,8 | 4,4 | 4,7 | 0 | 2,7 | 2,2 | 0 | 1,9 | 0 | 0 | 3 | 3 | 3,8 | 0 | 4,7 | 5,1 |
| 2008 | 5 | 5,7 | 4,2 | 0 | 3,7 | 4,6 | 1,6 | 0 | 1 | 2 | 2 | 3 | 3 | 0 | 4,3 | 4,3 |
| 2009 | 4,5 | 5,3 | 5,8 | 4,3 | 2,5 | 2,7 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 1,8 | 3,1 | 4,5 |
| Hsmax | 9,7 | 9,6 | 9,4 | 7,8 | 7,1 | 10,1 | 6,5 | 5,3 | 3 | 3 | 3,7 | 4 | 4 | 4,9 | 6,5 | 7,2 |

It should be noted that the scientific community has been warning for years that climate change is driving sea level rises due to the melting of the poles. This aspect should be considered when planning coastal works, especially in areas that have suffered periodic flooding episodes, as in the case of *San Andrés*, on the island of Tenerife. In this context, the probable future increase in storms on the north coast of the Canary Islands and the hourly rotation of wave directions in the south because of climate change poses another uncertainty regarding processes that could trigger coastal flooding [21]. Furthermore, ocean wind waves are also affected by climate change [13]. Indeed, a Portuguese study [22] states that the wave climate over the northeast Atlantic has undergone considerable changes, not only in terms of wave height but also in terms of direction and period.

Although long periods of time are required for wave studies, since there are no data prior to the 1950s, studies have been conducted with the data from the years available. With these data, studies have shown that wave heights have increased over the years, with the effect being more noticeable in northerly directions because this direction corresponds to the heights of larger waves in the Atlantic [23]. Other studies [24] have also shown that, over the years, episodes of extreme waves have become more frequent in the Atlantic Ocean, and therefore studies such as ours are very necessary when designing a maritime infrastructure. A study of wave heights in the Atlantic Ocean [25], covering the period from 1982 to 2017, studies the seasonal prediction in all areas of the Atlantic. In its conclusions it states that, especially in the mid-Atlantic ridge (where the Canary Islands are located), the prediction of heights has improved greatly over the years and that the data currently provided are very accurate for marine designs. Regarding studies conducted specifically in the Canary Islands, a similar study has been carried out, studying 23 points between the Canary Islands and Morocco [26], with the aim of knowing the wave energy potential, obtaining wave heights similar to those shown in this article.

As a conclusion to this statistical study, the values indicated in Table 2 for the 16 directions are obtained. These wave heights are substituted in the straight line obtained for percentages not exceeding 85, 50 and 20% of wave height. In the north direction, a 6.31 m wave height of 85% non-exceedance percentage has been calculated with the maximum height registered in the 58 years by the SIMAR points being 9.7 m. Obviously, a maritime structure cannot be projected for a wave height of 9.7 m since it would be over-sized, which is why the 6.31 m wave height is taken as the starting point for the rest of the calculations.

**Table 2. Wave heights for the 16 directions calculated to improve the reliability of maritime works in the Canary Islands**

| Hs (m) | N | NNW | NW | WNW | W | WSW | SW | SSW | S | SSE | SE | ESE | E | ENE | NE | NNE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 85% | 6.31 | 7.48 | 7.92 | 6.48 | 4.39 | 6.07 | 4.86 | 4.06 | 2.75 | 2.73 | 3.32 | 3.19 | 3.29 | 3.77 | 5.08 | 5.98 |
| 50% | 5.22 | 5.97 | 5.81 | 4.97 | 5.79 | 4.33 | 3.45 | 2.86 | 2.07 | 2.09 | 2.38 | 2.31 | 2.53 | 2.71 | 4.02 | 4.95 |
| 20% | 4.28 | 4.66 | 4.00 | 3.67 | 3.18 | 2.84 | 2.23 | 1.82 | 1.48 | 1.54 | 1.58 | 1.55 | 1.89 | 1.80 | 3.10 | 4.07 |
| Hs max | 9.7 | 9.6 | 9.4 | 7.8 | 7.1 | 10.1 | 6.5 | 5.3 | 3 | 3 | 3.7 | 4 | 4 | 4.9 | 6.5 | 7.2 |

## 4. Conclusion

The highest wave heights obtained correspond to the north to southwest directions, since the Canary Islands are affected by a greater fetch length (straight length by which the mass of water is affected by the force and direction of the wind). The fetch measured from the American continent (north to southwest directions) is greater than the fetch measured from the African or European continents (northeast-southeast directions).

These results are the starting point to estimate the dimensions required for coastal structures in the Canary Islands, hence the importance of the present study. Once these significant wave heights in each direction are obtained, they are multiplied by the directionality coefficients. The most accepted way to determine these coefficients is proposed by the ROM 03.91 by means of propagation with computer programs or making wave plans, in the Canary Islands K(directionality) = 0.85-1, depending on the return period taken. With this wave height (Table 2) multiplied by the coefficients of directionality, diffraction (deviation of the waves when encountering an obstacle), refraction (wave that is reflected, that is to say it bounces off an obstacle) and shoaling (phenomenon of assertion that is the effect produced in the wave, when the height of the seafloor is notably reduced on its arrival at the coast), the breakage at the point of study is analysed. In other words, it is determined whether the wave breaks before or after arriving at the projected structure.

## 5. Declarations

### 5.1. Author Contributions

Conceptualization, J.C.S.; methodology, J.R.M.; software, J.R.M. and N.C.P.; validation, J.C.S.; investigation, J.R.M.; resources, J.C.S.; writing—original draft preparation, N.C.P. All authors have read and agreed to the published version of the manuscript.

### 5.2. Data Availability Statement

The data presented in this study are openly available in *https://dialnet.unirioja.es/servlet/tesis?codigo=221998*.

### 5.3. Funding

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### 5.4. Conflicts of Interest

The authors declare no conflict of interest.

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