TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 19
Number 1
March 2025
DOI: 10.12716/1001.19.01.32

# Hindcasting of Extreme Wave Events in the Fairway of Port of Santos (Brazil) over the Last Eighty Years

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ABSTRACT: Port of Santos is responsible for 29.0% Brazil's trade flow. A concern arisen due to climate changes has been the increase in the frequency and severity of extreme wave events on the fairway. The limit established by the Maritime Authority's Pilotage Regulations for the total suspension of traffic on the fairway regarding waves is when significant heights greater than 3.0 m occur. A summary of the hindcasting of extreme wave events in Santos Bay since 1940 has been presented. The findings of the statistical assessment since that time identified an increase of more than 6 times in environmental downtime due to extreme wave events and the analysis of extreme wave height values for return periods of 50, 75 and 100 years revealed increases of 3.8% to 9.9%, depending on the statistical distribution used and the return period considered.

## 1 INTRODUCTION

In 2024 Port of Santos (Brazil) had a throughput of 179.8 million tons and 5.4 million TEUs, 29.0% of the Brazilian trade flow (or US$ 174.43 billion) and received the traffic of 5,557 vessels in its fairway [1], including New-Panamax (LOA = 366 m, B = 51.0 m). According to [2] it is the first in container handling in Latin America (see Fig. 1). It is the most significant in the Southern Hemisphere for all types of cargo and holds strategic importance for Brazil.

In this era of climate change, the awareness of more frequent and severe extreme events impacting port operations motivated by this quantitative analysis of historical trends. Previous studies are not known in this concern. The port's environmental downtime rate is increased by the probability of total traffic suspension when waves exceed 3.0 m, the limit of significant height on the fairway established by the Maritime Authority's Pilotage Regulations.

This paper presents the main results of the hindcasting of extreme wave heights in Santos Bay since 1940. Utilizing wave measurements obtained from an oceanographic buoy, extreme wave events were identified with the objective of calibrating the series in an oceanographic model. The series, covering 1940 to 2023, received this adjustment. The correlation between offshore and nearshore wave heights was determined using a coastal buoy managed by Santos Pilots. Nearshore records from other periods were employed to validate this correlation, with the aim of making it more realistic.

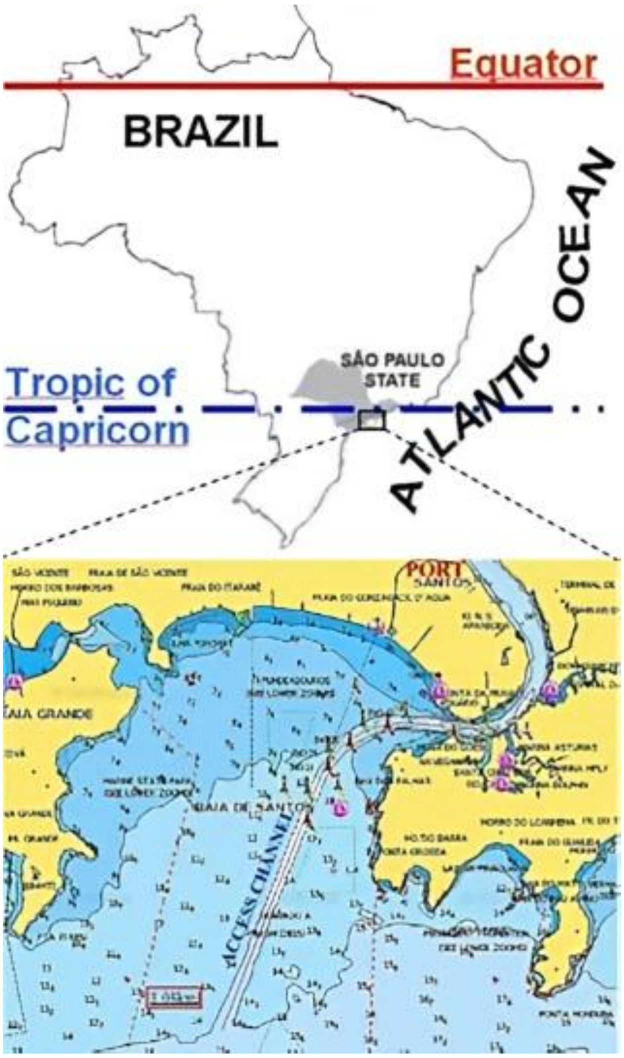


Figure 1. Santos Bay and its 8 km of fairway. The Port is located inside the Estuary of Santos. The fairway is maintained by permanent dredging at level -15.0 m (Chart Datum) and is 8 km long, facing SSW, from where the swell responsible for most extreme wave events comes.

## 2 SOURCES OF DATA OF SIGNIFICANT WAVE HEIGHT OF THE EXTREME EVENTS

Hourly offshore wave heights were taken from Santos Buoy, which uses directional measurements with accelerometers and angular sensors ([3]). The Brazilian Navy Hydrography Centre's National Buoy Program - PNBOIA maintained the meteoceanographic anchoring buoy from May 2011 to November 2018. Fig. 2 shows the coordinates of the buoy positioned in deep waters at a depth of approximately 200 meters.

Hourly wave height data from the deep-sea oceanographic model were extracted at the grid point nearer to the Santos buoy from the oceanographic hindcasting global model ERA5 model (provided by the European Centre for Medium-Range Weather Forecasts - ECMWF [4]), from 1940 to 2023 (see the location in Fig. 2).

Hourly wave height data in the nearshore region were collected using an Acoustic Doppler Current Profiler (ADCP) positioned at level – 11,0 m (Chart Datum), near Santos Port Fairway in Santos Bay (refer to Fig. 2), maintained since 2015 by Santos Pilots [5]. The period evaluated was from April 2015 to July 2023.

Two other series of nearshore wave records were used to validate the correlation between offshore and nearshore wave heights: the campaign from February 1982 to September 1984 [6], with a waverider (of one accelerometer) record every 3 hours at the location marked as UNA in Fig. 2, at level – 16,0 m (Chart Datum); the campaign from October 1972 to November 1973 [7], with an ultrasonic wave gauge record two times of day located in the central region of Santos Bay, between 24° 00′ 00″ S, 46° 21′ 18″ W (level – 10,0 m, Chart Datum) and 24° 02′ 40″ S, 46° 21′ 32″ W (level – 14,0, Chart Datum, nearby the fairway mouth).


Figure 2. Coordinates of the locations employed in the extreme wave events height assessment. The assessment of the offshore wave climate (deep water from the waves) used data from the PNBOIA Santos Buoy, located at the edge of the Continental Shelf (approximately 200 m deep), and from the nearest grid point of the oceanographic hindcasting global ERA5 model (approximately 1,000 m deep). For the assessment of nearshore waves, the most extensive wave series were those from the ADCP located near the fairway to the Port of Santos (11 m deep) and from the UNA WAVE RIDER, which operated in 16 m deep at a location approximately 68 nautical miles SW of the fairway.

## 3 METHODS

### 3.1 *Statistical analysis of the significant wave height of the extreme events offshore*

According to [8], the theory of statistics requires that individual data points employed in statistical analysis are statistically independents, and to produce independent data points we need to think of extreme events, rather than individual hourly storms (or with another sampling time) wave heights. The most employed method to separate wave heights in extreme events is called Peak Over Threshold (POT) analysis. It involves choosing a wave height threshold arbitrarily. The only data points used in the POT statistics are the peaks (maximum wave heights) occurring during each extreme event. Thus, when threshold selection is appropriate, the values of extreme events will be very representative.

Extensive studies have been conducted on the wave climate in Santos Bay and offshore. A 4.0 m wave height threshold was used to apply the POT to ERA5 and PNBOIA offshore data. This value matches the highest significant wave heights recorded in Santos Bay near the fairway (nearshore), therefore it represents a known rare limit for extreme wave events nearshore, obviously making it a practical threshold to adopt. Therefore, the independence of wave peaks was ensured by empirical observations along time.

With this procedure, it was possible to identify 89 significant wave heights pairs of extreme events, obtained from ERA5 and PNBOIA, in which at least one height of the pair exceeded 4.0 m, during the period from May 2011 to November 2018.

### 3.2 *Adjustment of the ERA5 significant wave height data to PNBOIA*

Adjusting ERA5 significant wave height data to match PNBOIA records at Santos Buoy yielded an adjusted coefficient based on the 89 extreme wave events. This adjustment was made using a linear regression based on a scatter plot. This coefficient was considered valid for the entire ERA5 model series (from 1940 to 2023) in deep water offshore.

The quality of the regression can be assessed by r-Squared ($r^2$ or the coefficient of determination), which is a statistical measure that determines the proportion of variance in the dependent variable that can be explained by the independent variable. In other words, r-squared shows how well the data fits the regression model (the goodness of fit).

### 3.3 *Correlation between nearshore and offshore significant wave heights*

Employing 58 extreme wave events from April 2015 to July 2023, identified by the POT, a linear regression based on a scatter plot was obtained between the wave heights recorded in the Santos Pilots ADCP nearshore and the wave heights of the ERA5 in deep water offshore.

### 3.4 *Validation of the correlation nearshore x offshore significant wave heights*

The coefficient of correlation obtained according to explained in item 3.3 was validated with more nearshore data of 8 extreme wave events comprised from July 1982 to September 1984 and more 2 extreme wave events that occurred in May and July 1973.

### 3.5 *Final correlation of the nearshore fairway waves with the ERA5*

A final weighted coefficient, based on correlation coefficients from items 3.3 and 3.4, was used for the entire ERA5 series to estimate the nearshore waves.

### 3.6 *Nearshore waves hindcasting from ERA5 with final correlation coefficient*

Two 19-year periods were considered in the hindcasting analysis, one called remote, from 01/01/1940 to 31/12/1958, and another called present, from 08/08/2005 to 08/08/2023. The justification for choosing this 19-year period was that it corresponded approximately to the lunar nodal period of 18.61 years, which we have used for the simultaneous study of the rise in mean sea level on the Brazilian coast. For each of these very distant periods, the correlation coefficient previously determined was applied to the ERA5 series offshore to obtain the estimate of the nearshore wave height series. In this way, it was possible to perform a statistical analysis of the frequency of extreme nearshore waves and compare significant heights and the number of extreme wave events.

### 3.7 *Extreme value analysis from ordered nearshore significant wave heights*

The Cumulative Distribution Function (CDF) is considered the most robust relationship for both interpolation and extrapolation due to its straight-line structure, as stated in [8]. The probability that any wave height (H) exceeds a specified value (P(H)) can be converted into a straight line by transforming the probability into reduced variates on the ordinates, and wave heights on the abscissas. The coefficients of the slope and the intercept of the straight-line relationship are determined by linear regression analysis. The most common distributions employed for analysis of extreme values of ordered statistical in descending order of significant wave height are the Log-Normal, Gumbel and Weibull. The reduced variates employed by these distributions are known as Z, G and W.

For the Log-Normal Distribution, the Z value is derived from the Standard Normal Probability Tables. It is calculated using an equation that considers the mean and standard deviation of ln H (see [8]). The scatter diagram with linear correlation is given by Z x ln H. The coefficients of the slope and the intercept of the straight-line relationship determined by linear regression analysis are correlated with the mean and standard deviation of ln H.

For the Gumbel Distribution, the G value is obtained reducing P(H) according to logarithmic functions (see [8]). The scatter diagram with linear correlation is given by G x H. The coefficients of the slope and the intercept of the straight-line relationship determined by linear regression analysis are correlated with G.

For the Weibull Distribution, the W value is obtained reducing P(H) according to logarithmic functions (see [8]). The scatter diagram with linear correlation is given by G x H. The coefficients of the slope and the intercept of the straight-line relationship determined by linear regression analysis are correlated with W. The Weibull Distribution has three parameters, in addition to slope and intercept coefficients a third coefficient ($\alpha$) will require some trial and error to obtain the best straight line in the scatter plot.

## 4 RESULTS

### 4.1 *Adjusting ERA5 wave eights data to match PNBOIA*

Fig. 3 shows the linear regression based on a scatter plot between significant wave height of PNBOIA and ERA5. It was observed, according to [9], that ERA5 underestimates the actual values, that is necessary to correct them by multiplying per 1.300. Under these conditions, a real significant height in deep water of 4.0 m corresponds to ERA5 3.08 m, or in other words, ERA5 significant heights of 4.0 m will correspond to 5.2 m in real.

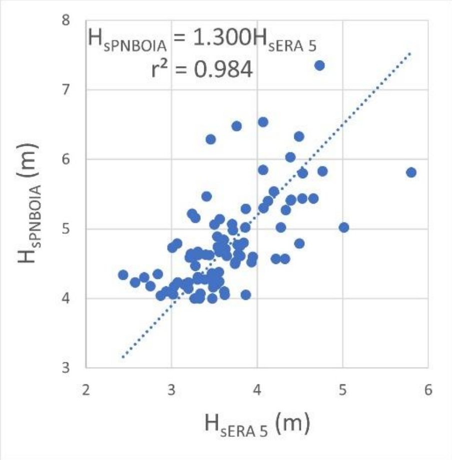


Figure 3. Scatter plot between significant wave height of PNBOIA and ERA5 model. From this graph, it was possible to conclude that, in general, ERA5 underestimates the real significant height of extreme wave events.

### 4.2 *Correlation between offshore and nearshore significant wave heights*

Fig. 4 shows the linear correlation based on a scatter plot between the significant wave heights recorded in the Santos Pilots ADCP and the wave heights of the ERA5 without any adjusting.

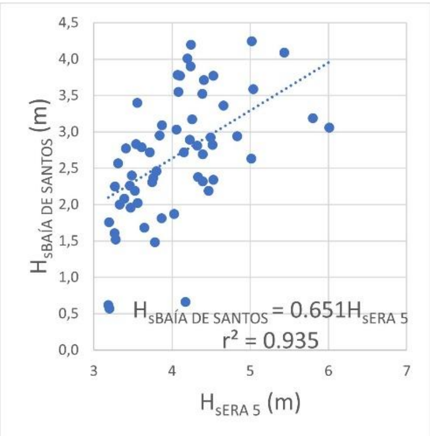


Figure 4. Scatter plot between wave heights recorded in Santos Pilots ADCP and the ERA5. This graph allowed estimating the effects of significant wave transformations of offshore extreme wave events in their progression to Santos Bay.

### 4.3 *Validation of the correlation offshore x nearshore significant wave heights*

Fig. 5 shows the linear correlation based on a scatter plot between the ERA5 (without any adjusting) x nearshore data, corresponding to 8 extreme wave events recorded from July 1982 to September 1984 and more 2 extreme wave events in May and July 1973, for validation of the correlation obtained in item 4.2.

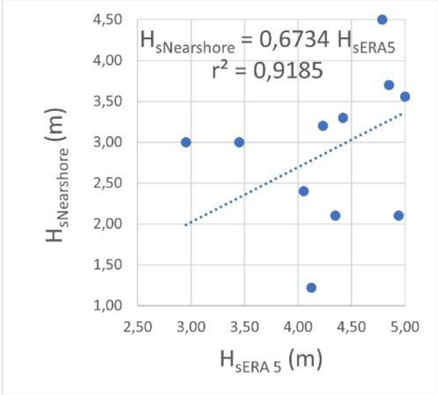


Figure 5. Scatter plot between wave heights recorded nearshore and the ERA5. This regression showed a very similar linear regression between the significant heights of offshore and nearshore extreme events with that obtained in Fig. 4, validating the reliability of the procedures for evaluating the transformations of wave heights in their progression towards the coast.

### 4.4 *Final correlation of the ERA5 series to the nearshore fairway*

A final weighted coefficient of 0,66 was used to correlate nearshore wave series to ERA5. It is to be noted that the coefficients obtained in items 4.2 and 4.3 are quite similar, denoting a good consistency of the analysis.

### 4.5 *Nearshore waves hindcasting from ERA5 model*

The hindcasting analysis compares the remote period from 01/01/1940 to 31/12/1958 to the present period from 08/08/2005 to 08/08/2023. Considering the limit of significant height on the fairway established by the Maritime Authority's Pilotage Regulations for the total suspension of traffic regarding waves, i.e. 3.0 m, Fig. 6 shows that only 3 situations occurred in the remote period against 19 situations in present days. These numbers demonstrate how dramatically it has increased the frequency of extreme nearshore events and permit to compare the significant heights of the most extreme.

### 4.6 *Extreme value analysis from ordered nearshore significant wave heights*

Tab. 1 shows the results obtained from the extreme value analysis.

Table 1. Values of significant wave heights (m) for extreme value analysis in the fairway. Typical return periods of significant wave heights for projects in Port Engineering

| DISTRIBUTION | REMOTE PERIOD | | | PRESENT PERIOD | | |
|---|---|---|---|---|---|---|
| | (RETURN PERIOD - YEARS) | | | | | |
| | 50 | 75 | 100 | 50 | 75 | 100 |
| Log-normal | 3.33 | 3.38 | 3.41 | 3.66 | 3.70 | 3.73 |
| Gumbel | 3.70 | 3.81 | 3.89 | 3.83 | 4.10 | 4.16 |
| Weibull | 3.89 | 4.06 | 4.19 | 4.13 | 4.26 | 4.35 |

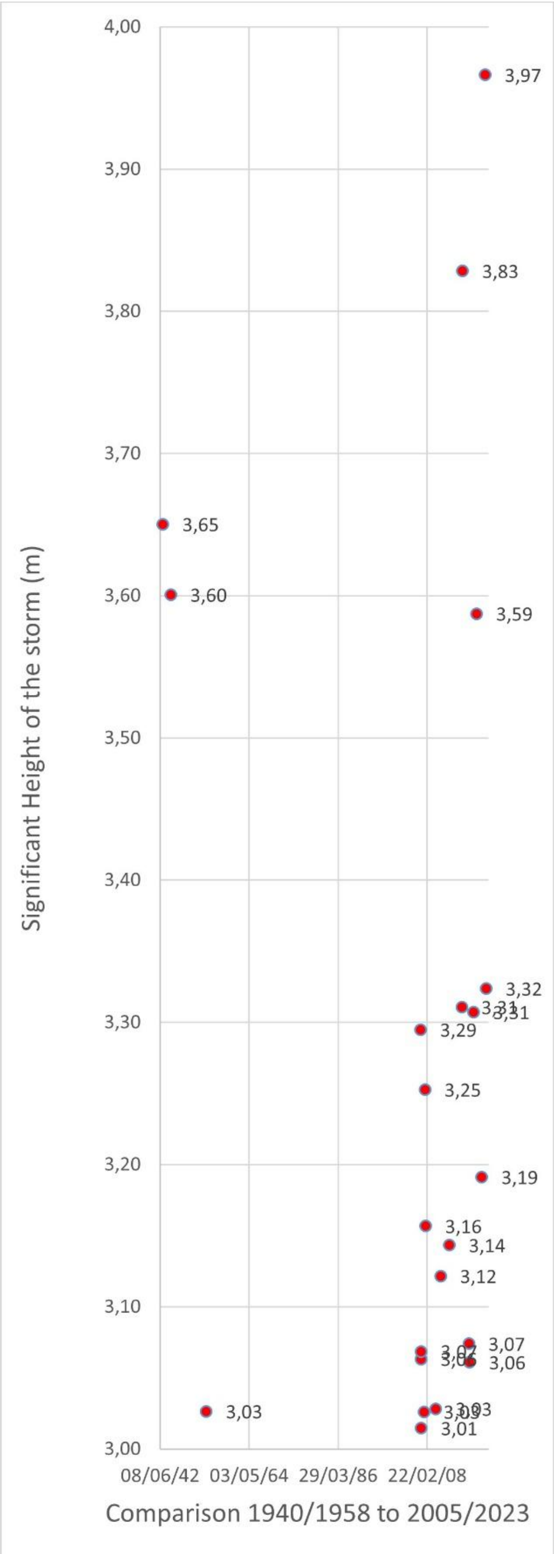


Figure 6. Chronology and intensity of extreme wave events of total interruption of traffic on the fairway.

## 5 ASSESSMENT OF LIMITATIONS AND RELIABILITY OF FINDINGS

Wave records on the Brazilian coast, which has approximately 8,500 km of development, are still relatively sparse and scarce in terms of sufficiently long historical series with few gaps. In the case of this study, the PNBOIA measurements in Santos, which lasted for 90 months, had an effective rate of 84.17%, i.e. the gaps represented 15.83%, which allowed a sampling period of approximately 76 months, or 6.3 years. This effectiveness rate can be considered suitable, one of the best of the PNBOIA, in terms of representations of the wave climate. For the ADCP measurements, during the period of 99 months, the effectiveness rate was 95.10%, due to the excellent maintenance provided by the Maritime Authority's Pilotage.

Wave measurements from the 1980s and, especially, those from the 1970s were subject to greater inaccuracies and failures, but since they were used more for validating the correlation coefficient between offshore and nearshore wave heights, they resulted in a correlation coefficient very close to that obtained with ADCP measurements. This finding, in itself, is an indication of the reliability of this adjustment, despite the different accuracies of the different recording equipment.

The ERA5 data has certainly become more accurate since the early 1980s, when satellite data became more accessible to the general public. The atmospheric synoptic information from the most remote data for estimating wind parameters (speed, fetch and duration) was still often produced manually. Despite these limitations, the ECMWF sought to improve this information in order to make it suitable for oceanography applications. Despite these limitations, the findings showed a comparatively significant increase in extreme wave events over the last 8 decades, and the wave estimates for extreme wave events with return periods of 50 to 100 years were consistent with this trend.

## 6 CONCLUSIONS

This hindcasting study quantitatively demonstrated the impact of climate change on the extreme wave event regime in the fairway of the Port of Santos, the most strategically important port in the South Atlantic. Using the historical series from 1940 to 2023 of the oceanographic model ERA5, at a grid point located in deep water, it was possible to identify offshore extreme wave events with significant wave heights greater than 4.0 m in correspondence with an oceanographic buoy that operated nearby between 2011 and 2018. By associating the offshore extreme wave events with the events recorded by an ADCP located nearshore in the vicinity of the fairway, it was possible to obtain, and successively validate independent nearshore wave data, a correlation coefficient between the significant heights of the offshore and nearshore extreme events. By comparing two 19-year periods, one without climate change (1940 to 1958) and one under its influence (2005 to 2023), these effects can be clearly demonstrated. In fact, the extreme wave events that lead to the total interruption of maritime traffic through the fairway have increased more than 6 times, and the severity of wave heights in these extreme wave events has also increased (by about 10%). Finally, a statistical analysis of extreme wave height values for return periods of 50, 75 and 100 years revealed increases of 3.8% to 9.9% depending on the statistical distribution used and the return period considered.

The awareness of stakeholders and operators in the port sector in Brazil has not yet been sufficiently mobilized in terms of the reality that we are already facing with climate change, and which will probably have a greater impact in the coming decades. Planning to face this new reality is still in its beginning, with little dissemination of systematized information about these impacts from managers to the workforce directly involved in operations. This is the practical significance of this study, that is, the applicability of the findings to areas such as port operational safety and environmental downtime management.

## ACKNOWLEDGMENTS

The authors would like to thank Zenith Litoral Hidrografia Ltda and Santos Pilots for providing the ADCP data maintained by the Santos Pilotage. We extend our gratitude to the National Oceanographic Data Bank of the Navy Hydrography Center, of the Hydrography and Navigation Directorate of the Brazilian Navy for providing the Santos Buoy data of the National Buoy Program. The first author expresses gratitude towards the support received from the SP Águas – São Paulo State Water Agency of the Secretariat of Environment, Infrastructure and Logistics of the São Paulo State.

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