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The use of wave forecasts for maritime activities safety assessment

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ABSTRACT

Wave forecasting may represent a useful tool for safety assessment of maritime works and activities. To date, wave forecasting uncertainty is usually corrected by using either the mean calibration factor or the time series method. However, within the frame of maritime work management it is necessary to forecast – with an acceptable probability of error – whether or not the significant wave height at a given location will exceed a prefixed threshold within a specified temporal window, so as to assess the safety of the specified temporal window with respect to the activity to be carried out. The present paper aims to illustrate a general criterion useful to correct wave forecast, i.e. to provide an engineering tool able to assess the safety of the temporal window needed to complete a specified maritime work. The paper provides a detailed description of the method, together with the application to a real case.

1. Introduction

In maritime engineering it is often necessary to forecast – with a given probability of error – whether or not the significant wave height (H_s) at a given location will exceed a prefixed threshold (S) within a temporal window with specified duration (WD). In other words, it is necessary to achieve a probabilistic assessment of the safety of a specified temporal window, i.e. the future time interval of few days needed to complete a specific maritime work. It has to be stressed that the this safety forecasting is not as difficult, hence more reliable, as the forecasting of the whole synchronous time series. By way of example, this is essential to manage maritime works or activities that – needing a specified time interval to be completed – can be carried out only if H_s is smaller than a prescribed limit for a prescribed interval of time (e.g. the execution of open sea or closed basin maritime works, the management of up-and down-loading activities, etc.). Furthermore, reliable safety wave forecast may be of interest within the framework of emerging marine renewable industry, where aspects related to the survival (i.e. to activate emergency protocols) and maintenance of the installed devices are of crucial importance and often managed by means of real time wave forecasting.

It has to be stressed that this kind of forecasting is not aimed to define time series of significant wave height, rather its main aim is to assess the safety of the temporal windows with respect to the given threshold. This paper aims to propose a method able to correct the wave forecasts provided by whatever the meteorological prediction center in order to make them reliable enough to be safely used to manage maritime activities. Of course, the acceptable probability of error depends on the risk related to threshold exceedance (acceptable risk), i.e. on the technical and economical consequences of the safety forecasting failure.

To date, the improved accuracy of numerical models ran by meteorological prediction centers for wave forecasting makes it possible to face the stated problem limiting both the selected threshold and the acceptable probability of error, and extending the considered temporal window up to several days. As it is known, meteorological and wave forecasts, although often issued as deterministic forecasts, are affected by errors which have an intrinsic stochastic nature (e.g. [23]). Indeed, wave forecasts are affected by both systematic and random errors, while being often released as deterministic with no information about their accuracy (all but ensemble wave forecasting issued by the major weather prediction centers, e.g. [4,15]). The wave forecasts errors are intimately related to the accuracy of the forecasts of wind and pressure fields (e.g. [23,9]). It was found that the biases of the computed wind speeds are related to the resolution of the model and that for both wave and wind fields the biases increase for decreasing fetch length [6]. Moreover, negative biases (i.e. underestimation) are observed for

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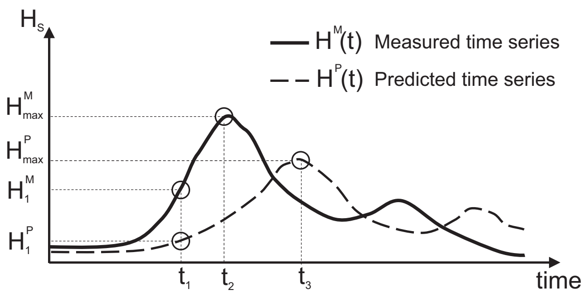

Fig. 1. Sketch of synchronous and maximum error.

small basins (or enclosed seas) with complicated orography, and the error in wind and wave forecasting decreases going offshore as the orography strongly influences the wind fields for distance of some hundreds of kilometers [7]. Furthermore, the effect of small deviations in the definition of the initial condition of the system may increase over the simulation time, reducing the reliability and accuracy of the prediction for increasing lead time.

The present paper illustrates the general criteria of a methodology for probabilistic safety forecasting, i.e. aimed to forecast the safety of a temporal window for maritime works.. Furthermore, a system that has been used in North Adriatic Sea is detailed. It was developed by the authors for Clodia S.c.a.r.l. to install the foundation caissons of the MOSE project in the Chioggia Inlet of the Venice Lagoon. The system is able to forecast the safety of temporal windows of five days needed to complete the work task of installing each foundation caisson within the MOSE project, recently completed.

The paper is structured as follows. Section 2 describes the main errors in wave forecasts by defining them in terms of significant wave height H_s. The methodologies used to evaluate the probability of error and the criterion of selection of the calibration factor are described in Section 3. Some examples of application of the proposed method are given in Section 4, while Section 5 describes the method application to a real case. Concluding remarks close the paper.

2. Definition of wave forecasting error

Errors are typically defined by computing the difference of observed (x^M) and modeled (x^P) quantities normalized by a likewise quantity (say it x^P):

$$\varepsilon = \frac{||x^M - x^P||}{||x^P||} \tag{1}$$

where Euclidean norm is typically used.

In order to estimate the error of wave forecast in terms of significant wave height (H_s), two different approaches may be used to select observed and modeled quantities in Eq. (1). Both methods rely on the availability at the same location of actually measured (H^M) and predicted (H^P) time series of H_s. The first and most direct method is that of comparing measured and predicted H_s occurring at the same time within the considered temporal window, i.e. comparing synchronous H^M and H^P (e.g. [13,14]). With reference to Fig. 1, such a method makes it possible to express the synchronous error as the ratio

$$\varepsilon^*_{s-\Delta t} = \frac{||H^M(\Delta t) - H^P(\Delta t)||}{||H^P(\Delta t)||}. \tag{2}$$

where Δt is the lead time. Of course, the error $\varepsilon^*_{s-\Delta t}$ is not a time series, while it depends on the given lead time. This error inherently depends on the phase shift occurring between $H^M(\Delta t)$ and $H^P(\Delta t)$. Indeed, the time shift may depend not only upon the wave forecast accuracy in predicting the time series of the significant wave height, but also upon the spatial shift between the computational point and the actual point of interest where measurements are collected, i.e. it depends also upon the model resolution. As the main aim of the present work is to forecast the safety of the temporal window, i.e. whether the significant wave height exceeds a selected threshold within the temporal window, a second approach may be used. Indeed, the forecasting error may be estimated by comparing the maximum measured ($H^M_{\max}$) and predicted ($H^P_{\max}$) significant wave height occurring within the considered window. Such a comparison makes it possible to define the maximum error as the ratio

$$\varepsilon^*_{\max} = \frac{||H^M_{\max} - H^P_{\max}||}{||H^P_{\max}||}. \tag{3}$$

being the error $\varepsilon^*_{\max}$ independent on the time shift occurring between $H^M(t)$ and $H^P(t)$. With reference to Fig. 1, this new definition of the forecasting error involves comparing the predicted and measured values of significant wave height for different times (t_2 and t_3 in the sketch). It can be observed that wave forecasts may be accurate in predicting the maximum value reached by wave height within a single storm, and therefore the maximum H_s within a temporal window *WD*. However, they may be far less accurate in predicting the time at which such a maximum occurs within *WD*. Accordingly, the adoption of the second method results in a smaller wave forecast error and in a more reliable probabilistic assessment of the safety of the temporal window. This is why the safety forecasting is not as difficult, hence more reliable, as the forecasting of the whole synchronous time series.

Errors clearly affect other wave parameters, i.e. period and direction. Whilst the forecasting uncertainty can be inferred from significant wave height errors (see the succeeding Section 3), when mean wave direction and period are concerned, specific analyses are needed. However, this paper does not focus on the wave direction and period forecasting errors. Nevertheless, the selection of wave height threshold may be related to wave period, especially when maritime activities involve the presence of floating bodies (see Section 5).

3. Methodology

As already observed, the aim of the proposed method is to forecast – with a given probability of error (i.e. failure probability) – whether or not the significant wave height H_s at a given location will exceed a prefixed threshold S within a specified temporal window *WD*. If the threshold S is not exceeded ($H_s < S$), the temporal window will be assessed as safe, while it will be assessed as unsafe otherwise ($H_s \geq S$).

The following parameters can be derived on the basis of the probabilistic assessment of safety forecasting:

(i) Agreement probability $P(AG)$: the probability that the analysis correctly assesses the considered temporal window as either safe or unsafe; it provides a measure of the system accuracy;
(ii) Missed Alarms probability $P(MA)$: the probability that the analysis assesses as safe temporal windows which are not; it provides a measure of probability of failure of the safety assessment;
(iii) False Alarms probability $P(FA)$: the probability that the analysis assesses as unsafe temporal windows which are actually safe.

Clearly, the following simple relationship holds between $P(AG)$, $P(MA)$ and $P(FA)$:

$$P(AG) + P(MA) + P(FA) = 1. \tag{4}$$

Say N_w the total number of temporal windows for a given period, then the empirical probabilities $P(AG)$, $P(MA)$ and $P(FA)$ read as follow:

$$P(MA) = \frac{N_{MA}}{N_w} \quad (5a)$$

$$P(FA) = \frac{N_{FA}}{N_w} \quad (5b)$$

$$P(AG) = \frac{N_{AG}}{N_w} \quad (5c)$$

where N_{MA} is the number of unsafe temporal windows assessed as safe, N_{FA} is the number of safe temporal windows assessed as unsafe and N_{AG} the number of temporal windows whose safety is correctly assessed, either safe or unsafe. Following the study of [2], it could be noted that the Agreement probability can be expressed as the summation of the Probability of Detection (PD) that a model correctly anticipates the exceedance of the threshold and the probability (PS) that a model correctly anticipates the non-exceedance of the threshold:

$$P(AG) = P(H_{\max}^{M} \geq S|AG) + P(H_{\max}^{M} < S|AG) = PD + PS. \quad (6)$$

Moreover, it could be observed that, within the frame of standard risk analysis, Missed Alarms are referred to as False Negative, False Alarms as False Positive and Agreement as Forecast Skill respectively. The former terminology is used in the following in order to underline the engineering philosophy of the proposed method. In particular, it has to be highlighted that we use the word “missed” for the alarms that are not spread although the actual significant wave height exceeds the prefixed threshold. On the other hand, we use the word “false” for the alarms that are spread although the actual significant wave height does not exceed the prefixed threshold.

The probability of detection and probability of False Alarms may be used to define the ROC curve (ROC stands for Relative Operating Characteristics, see [12]). The ROC curve can be drawn by changing the threshold S and by plotting the Probability of Detection versus the Probability of False Alarms. However, ROC curves do not serve to represent the quality of detection of forecast system in terms of Missed Alarms. Then the ROL curve (ROL stands for Relative Operating Levels, see [12]) may be defined by plotting the Probability of Detection versus the probability of Missed Alarms for varying threshold. In the succeeding sections a method similar (not equal, as the threshold is kept constant) to ROC and ROL curves is used to highlight the reliability of safety forecasts achieved by using the proposed method.

The probability of occurrence of safe temporal windows $P(W)$ within either a month, or a season, or a year is referred to as monthly, seasonal or yearly workability respectively, expressed as a fraction of the total temporal windows of the considered period (i.e. either a month, a season or a year):

$$P(W) = \frac{N_s}{N_w} \quad (7)$$

where N_s is the number of safe temporal windows within the considered period.

Comparing the workability estimated on the basis of actual measurements of the significant wave height (actual workability, $P^M(W)$) and on the basis of safety forecasts (predicted workability, $P^P(W)$) gives three possible outcomes:

(a) $P^P(W) = P^M(W)$: the safety forecasts are not affected by errors, at least in term of workability;
(b) $P^P(W) < P^M(W)$: the safety forecasts tend to overestimate – on the average – the actually measured significant wave height and therefore they result in a conservative assessment of safety, i.e. some safe temporal windows are assessed as unsafe;
(c) $P^P(W) > P^M(W)$: the safety forecasts tend to underestimate – on the average – the actually measured significant wave height and result in a not conservative assessment of safety, i.e. some unsafe temporal windows are assessed as safe.

Generally, condition (a) is not verified as it is not possible to eliminate the errors in the safety forecasts. Another aspect to stress is that the safety forecast tends to become more difficult as the threshold decreases. Indeed, it is difficult to forecast small values of the significant wave height which may be affected by local wind conditions, i.e. sea or land breezes. Asymptotically, the condition (a) may be reached if the selected threshold is higher than the highest measured significant wave height (i.e. $P^M(W) = P^P(W) = 1$). Obviously, this case has no practical interest.

It is trivial to observe that the probability of failure, represented by $P(MA)$, may be minimized by using a safety factor which increases the forecast significant wave height. Nevertheless, in this way the False Alarm probability grows and the predicted workability ($P^P(W)$) may decrease to unacceptable values from a technical and economical point of view. Indeed, it can be easily shown that the predicted workability depends on both Missed and False Alarms probabilities:

$$P^P(W) = P^M(W) + P(MA) - P(FA), \quad (8)$$

i.e. the predicted workability differs from the actual workability $P^M(W)$ as some unsafe temporal windows are assessed as safe and some safe temporal windows are assessed as unsafe. Indeed, when corrected forecasts are used to manage maritime activities, the workability $P^P(W)$ (i.e. based on the safety forecasting) should be as similar as possible to the real workability $P^M(W)$ (i.e. based on the collected measurements) by keeping both False Alarms and Missed Alarms as low as possible. Then, it is of crucial importance to limit the values of both $P(FA)$ and $P(MA)$. However, the lower the acceptable Missed Alarms probability, the higher the False Alarms probability and the higher the difference between the actual workability ($P^M(W)$) and the predicted workability ($P^P(W) < P^M(W)$). In other words, a method able to provide wave forecast for safety assessment has to be optimized by limiting the Missed Alarms probability while keeping False Alarms probability below an acceptable level, from a technical and/or economical point of view. The difference between $P^P(W)$ and $P^M(W)$ can be viewed as the cost paid to achieve the acceptable Missed Alarms probability in maritime activities management. Therefore, the strategy of the proposed forecasting calibration is quite different from previous works. Indeed, the main aim of past researches was to correct the whole wave forecasting time series by using either physics-based models (e.g. [11,25,30]) or statistical techniques based on neural networks, regression-based models and genetic algorithms (e.g. [20,21,17]). It could be noted that the latter methods aim to provide probabilistic forecasts of significant wave height time series. Then, the forecasts are given as prediction intervals (instead of single valued prediction) related to “nominal coverage rates” [18] for each lead time. An alternative method is proposed herein, even if within the same statistical approach of [18]. Indeed, we propose to forecast the safety of a given temporal window by using threshold analysis (e.g. [2]). It is proposed to correct the deterministic forecasts with the aim of achieving a given probability of failure in assessing the safety of temporal windows. Nevertheless, the whole significant wave height time series may be useful in managing maritime activities, i.e. it can be useful to know in advance not only if the temporal window will be safe, but also the evolution of significant wave height within the temporal window. When the deterministic forecasts have to be corrected with the aim of defining the most probable time series, the synchronous error given by relationship

(2) may be used. On the other hand, in order to correct the deterministic forecasts with the aim of assessing the safety of the temporal window, the maximum value error given by relationship (3) may be used.

In order to apply the error definition directly to correct the forecasts, a slight different definition of errors are used:

$$\varepsilon_{s-\Delta t} = \frac{H^M(\Delta t)}{H^P(\Delta t)} \tag{9}$$

$$\varepsilon_{\max} = \frac{H^M_{\max}}{H^P_{\max}} \tag{10}$$

Indeed, relationships (9) and (10) can be also viewed as the definition of calibration coefficients to be directly applied to the forecasts.

Then, in order to define the probability of failure of the safety forecasting, a statistical measure of the uncertainty of the forecasting error has to be defined. Both the synchronous and maximum value errors defined by the relationships (9) and (10) can be viewed as random variables whose probability density function (PDF) can be used to relate the probability of failure of the forecasts in terms of safety of temporal windows. As far as the maximum value error is concerned, only one random variable can be defined, depending on the temporal window duration:

$$x_{\max}(WD) = \frac{H^M_{\max}}{H^P_{\max}} \tag{11}$$

whilst for the synchronous error a series of random variables has to be defined, one for each given lead time Δt:

$$x_s(\Delta t) = \frac{H^M(t_0 + \Delta t)}{H^P(t_0 + \Delta t)}, \tag{12}$$

where t_0 is the initial time of the forecast. Comparison of observed and forecast significant wave height allows to extract realizations from the population of random variables defined by (11) and (12) and Empirical Cumulative Distribution Function (ECDF) can be used to gain insight on the Cumulative Distribution Function (CDF) of the random variables. Then, the proposed method relies on standard statistical techniques able to infer quantiles estimation based on Empirical Cumulative Distribution Function.

As already observed, the relationship (11) can be also viewed as the definition of a calibration coefficient C_{max} to be used to correct the forecasting values to assess the safety of the temporal window. On the other hand, the relationship (12) provides the series of calibration coefficients C_s to be used to correct the forecast time series. It has to be stressed that the calibration of forecasting values may be simply defined as its (sample) mean value. However, the mean value of the calibration coefficient cannot be used to assess the safety of temporal windows. Indeed, a higher quantile of the empirical data distribution (hereinafter referred to as q_α) should be considered in order to minimize the probability of failure of safety forecasts. The quantile to be used for safety forecasting will be selected by a test-and-try procedure aimed to keep the Missed Alarms probability below an acceptable level.

The next section details the practical aspects on the selection of the appropriate correction factor by illustrating some application examples carried out for a point located in the North Adriatic Sea by using ECMWF forecasting. Nevertheless, it has to be stressed that whatever the numerical model providing wave forecasts may be used in order to apply the proposed methodology.

4. Practical aspects of methodology application

This section illustrates an example application, carried out for a point of interest located in the North Adriatic Sea (Fig. 2, coordinates 45.41° N, 12.44° E) where "Consiglio Nazionale delle Ricerche – Istituto di Scienze Marine" (CNR-ISMAR, National Research Council Institute of Marine Science) and "Consorzio Venezia Nuova" (CVN, Ministry of Infrastructure and Transport – Venice Water Authority concessionary for work to safeguard Venice and the lagoon) carry out wave and wind measurements at the oceanographic tower "Piattaforma Acqua Alta" (e.g. [5,19]). The measurements have been compared to the operational forecasts issued by the European Centre for Medium-Range Weather Forecast (ECMWF) within the period ranging from the beginning of February 2010 up to the end of January 2013.

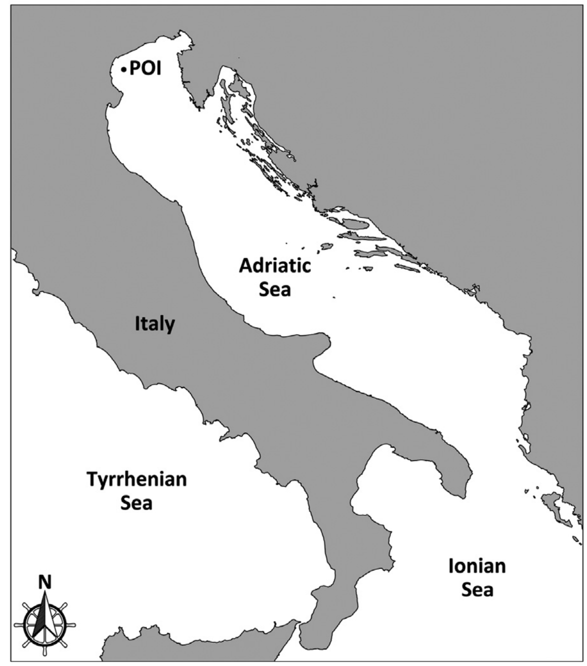

Fig. 2. Sketch of the Adriatic Sea. The black circle represents the point of interest (POI) used for the methodology application.

Fig. 3 shows the Empirical Probability Density Functions of the random variable expressed by the relationship (11) along with the bias, the mean and the standard deviation values for varying temporal window duration *WD*. It is clear that values larger than 1 (i.e. $x_{max} > 1$ or $H^P_{\max} < H^M_{\max}$) are frequent, i.e. the forecasts frequently underestimate the observed values of the maximum significant wave height occurring within the temporal windows. Furthermore, the absolute value of bias increases as the temporal window duration increases, while the mean and the standard deviation are almost constant for increasing temporal window duration.

Fig. 4 shows the Empirical Probability Density Function of the synchronous error as defined by Eq. (12) for varying lead time. The forecasts deteriorate for increasing lead time. If the lead time equal to 6 h is considered, the sample standard deviation of the synchronous error does not differ significantly from that of the error related to the maximum of significant wave height (hereinafter referred to as the "maxima error"). Nevertheless, as the lead time increases, the spreading of the synchronous error increases and the forecasting becomes potentially unreliable for safety assessment. Hence, the synchronous calibration coefficients may not be reliable enough if applied to the forecast time series with the aim of assessing the temporal window safety. However, they can be used for the calibration of the whole time series, keeping in mind that the reliability of forecast values deteriorates for increasing lead time and the time series does not serve as assessment of the safety of the temporal window, at least with acceptable probability of Missed Alarms. In other words, the maxima error should be used for the

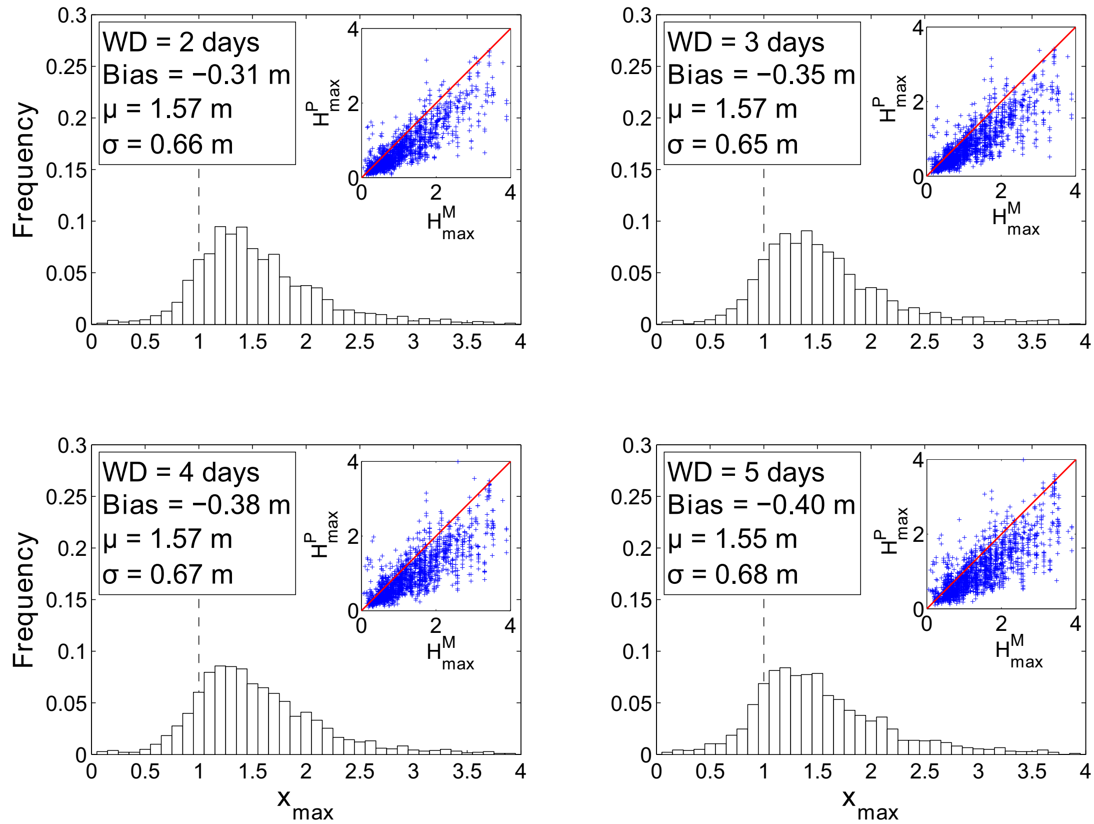

Fig. 3. Empirical probability density function of the random variable x_{max}. *WD* is the duration of the temporal window, μ is the sample mean, σ the standard deviation. Scatter diagrams of the maximum values predicted (H^P_{max} in meters) and measured (H^M_{max} in meters) within the temporal windows are also reported in each panel.

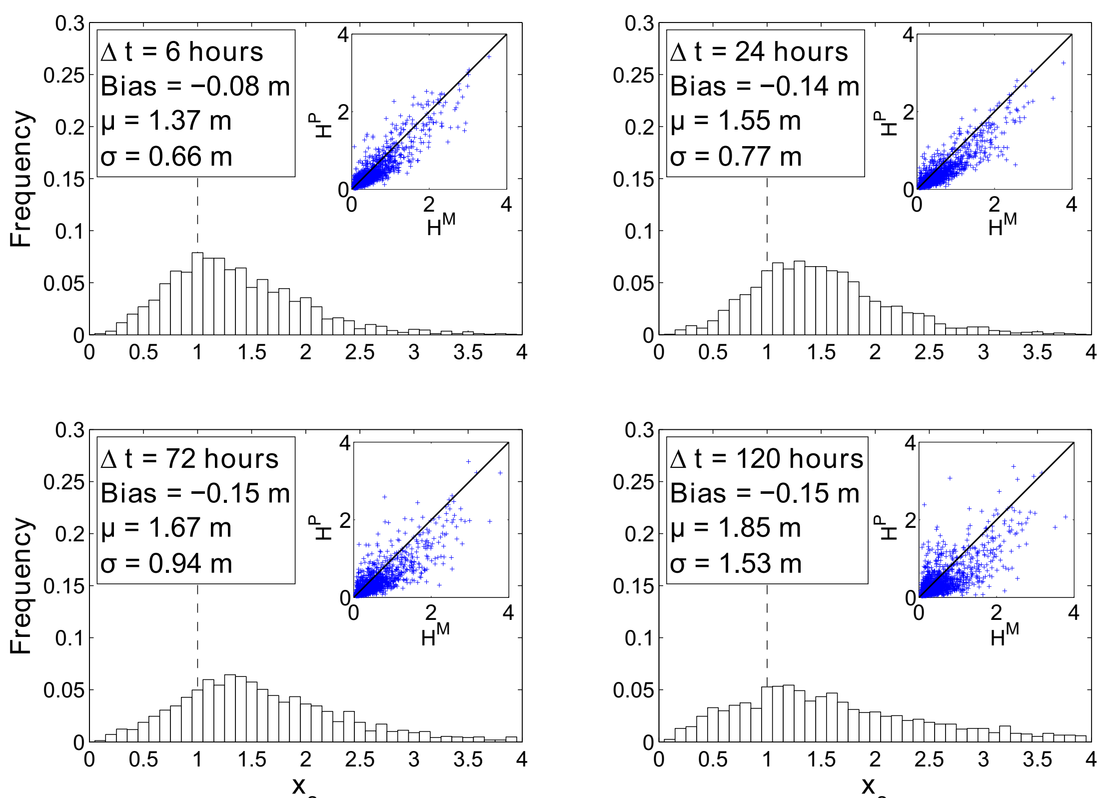

Fig. 4. Empirical probability density function of the random variable x_s. Δt is the lead time, μ is the sample mean, σ the standard deviation. Scatter diagrams of the values predicted (H^P in meters) and measured (H^M in meters) within the temporal windows are also reported in each panel.

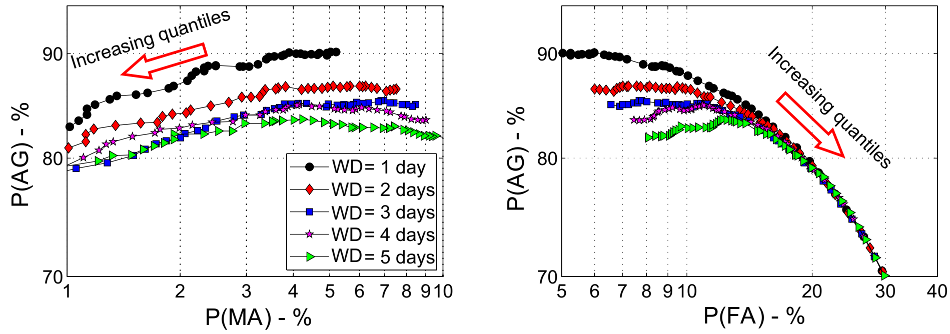

Fig. 5. Agreement probability as a function of Missed Alarms (left panel) and of False Alarms (right panel) probability for varying quantiles and temporal window duration (probabilities are expressed as percentages).

safety forecasting, whilst the synchronous error should be used to identify the instant when the significant wave height exceeds the threshold, then by allowing to identify the occurrence of secondary maxima within the temporal window.

The selection of the quantile of the Empirical Probability Density Function of the random variable (11) is based on a test-and-try procedure. Several quantiles are iteratively used to correct the forecasts. Then, the maximum corrected value of the significant wave height within the temporal windows is compared to the measured one, and Missed Alarms, False Alarms and Agreements are detected. The most suitable quantile is selected on the basis of acceptable Missed Alarm probability. In other words, the probability distribution of the calibration coefficient and the statistical performance of the correction are used to select the optimum value of the calibration coefficient.

More in details, once the significant wave height threshold S has been selected, different values of sample quantile q_α of the random variable x_{max} is used to correct the maximum forecast significant wave height resulting in either "unsafe temporal window" ($H^P_{\max-\alpha} \geq S$, being $H^P_{\max-\alpha}$ the maximum forecast significant wave height corrected by using the quantile q_α) or in "safe temporal window" ($H^P_{\max-\alpha} < S$). Then, the safety forecasts have been compared to the measured maximum significant wave height $H^M_{\max}$ that allows to define "temporal windows assessed as safe" as Missed Alarms (if $H^P_{\max-\alpha} < S$ and $H^M_{\max} \geq S$) and "temporal windows assessed as unsafe" as False Alarms (if $H^P_{\max-\alpha} \geq S$ and $H^M_{\max} < S$). Fig. 5 shows the results for $S = 1.00$ m in a way similar to ROC (left panel) and ROL (right panel) curves. It could be noted that as the quantile increases the Missed Alarms probability decreases and the False Alarms probability increases. In fact, as the quantile increases, the number of temporal windows assessed as unsafe increases too and the method gives a high number of False Alarms. Furthermore, as the temporal window duration decreases, the Agreement probability increases.

Fig. 6 shows how Missed Alarms and False Alarms vary if different quantiles of the empirical probability density function of the random variable (11) are used (threshold significant wave height set to $S = 1.00$ m). Diagram inspection reveals that the higher the quantile, the lower the Missed Alarms probability and the higher the False Alarms probability. It has to be stressed that the False Alarms growing induces decreasing of the achieved workability $P^P(W)$. Furthermore, it has to be underlined that the best fit line usually employed to correct the forecast values is similar to the quantile $\alpha = 0.5$ for which the Missed Alarms are rather high. Actually, as the acceptable Missed Alarm probability is selected, the most suitable quantile to be used for safety forecasting can be inferred, for given significant wave height threshold and given temporal window duration, from the results of the sensitivity analysis shown in Fig. 6. It could be interesting to test the method also if the (large) bias of the forecast data is corrected before the method application. To this end, Fig. 6 shows the performance of the method (bold lines) when the bias is corrected first and then the method applied. The False Alarms probability for given Missed Alarms probability remains almost unchanged, while the quantile distribution is distorted by the initial correction of the bias.

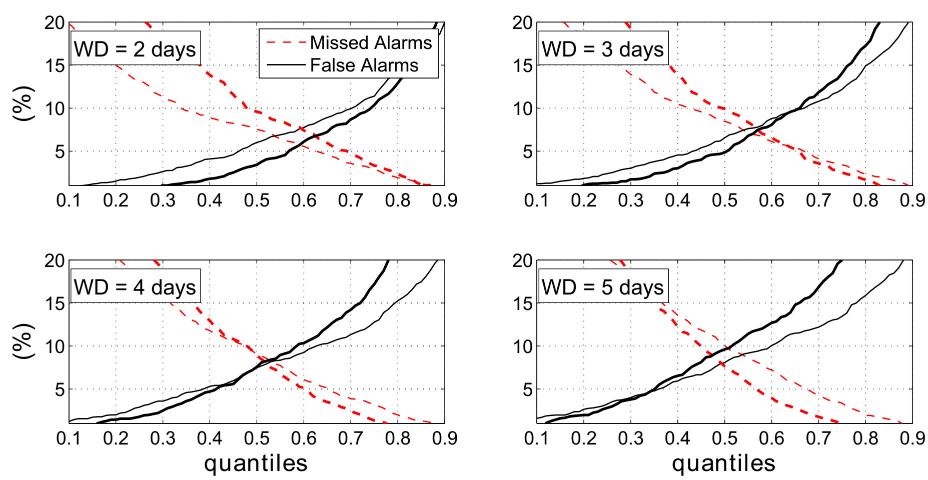

Fig. 6. Variation of the Missed Alarms probability (dashed lines) and False Alarms probability (solid lines) as a function of the sample quantiles order α for varying temporal window duration (WD). A significant wave height threshold equal to 1.0 m has been considered. Bold lines refer to the results obtained when the bias is corrected first and then the method applied (probabilities are expressed as percentages).

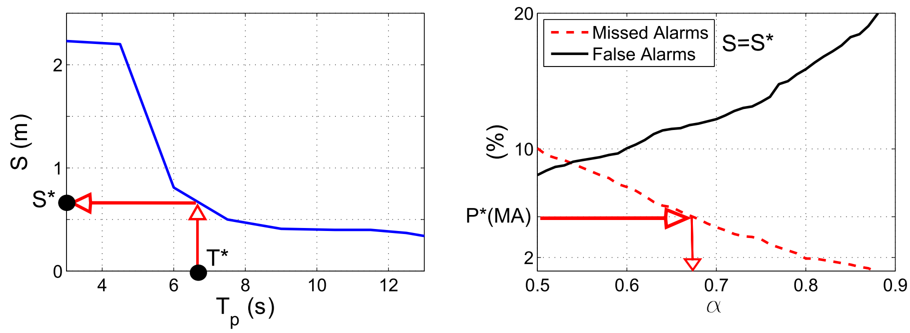

Fig. 7. Sketch of the quantile q_α selection for given acceptable Missed Alarm probability ($P^*(MA)$) when hydrodynamic stability has to be accounted for. The solid line in the left panel indicates the limit value of significant wave height over which hydrodynamic instability occurs (probabilities are expressed as percentages).

When maritime activities to be managed involve the use of floating bodies (see Section 5) also the wave period forecast should be corrected. In the present work, the wave period time series (either mean- or peak-period) is corrected by using the synchronous error approach applied to the forecast and observed wave period. Once the wave period has been corrected, the use of the hydrodynamic stability curves allows to select the significant wave height threshold S^*. In fact, the hydrodynamic stability curves provide acceptable significant wave height as a function of wave period (either peak or mean wave period), based on either numerical or physical modeling (e.g. [1]). Then the calibration of the system for significant wave height threshold S^* can be used to select the most suitable quantile to be used for safety forecasting. Fig. 7 depicts the proposed methodology. Once the mean (or peak) wave period T^* has been forecast, the significant wave height threshold (S^*, left panel) can be selected by identifying the significant wave height over which hydrodynamic instability may be suffered. As the significant wave height threshold has been selected, the results of the sensitivity analysis obtained for $S = S^*$ can be used to select the most suitable quantile to be used for safety forecast once the acceptable Missed Alarm probability $P^*(MA)$ has been selected (right panel).

5. Support to maritime works at the Venice Lagoon Inlets

The Project for the protection of the Venice Lagoon from flooding due to storm surge (worldwide known as the phenomenon "Acqua Alta", i.e. "High Water") is based on a system of bottom-hinged floating gates. The whole project has been extensively studied in the past by means of physical, numerical and analytical models (e.g. [10,26,27,16,8,24]). Four tidal barriers close the three inlets (Lido, Malamocco and Chioggia) of the Venice lagoon during high waters. The gates are hinged to foundation caissons, which provide the housing of the gates when they rest on the bottom. The foundation caissons span along the whole width of the inlets. Then, the Project involves construction, transport in floating conditions and installation of several precasted concrete cellular caissons.

A practical problem concerning the construction process was that of installing the foundation caissons on the bottom of the lagoon inlets, where both tidal currents and waves occur. Several studies have been carried out to design systems able to guarantee safe mooring of the caisson during the installation phases and to define procedures for placing these structures with high accuracy (e.g. [10,28,29]). These studies provided a limitation on the maximum wave conditions (significant wave height and peak period) that are compatible with the installation of the foundation caissons. Then, the significant wave height had to be forecast in order to manage the installation operations that required about five days to be completed. Therefore, for each of the four tidal barriers, a Safety Forecasting System was needed. Actually, the system based on the proposed approach issued a forecast every 12 h since November 2009. In particular, both safety and synchronous forecasts were issued as follows:

(i) for the safety forecast related to temporal windows of five days (i.e. $WD = 5$ days) the considered significant wave height threshold (S) was selected on the basis of stability hydrodynamic curves of the foundation caissons floating during the installation phase. The quantile to be used for each safety forecast has been estimated by considering 2% as acceptable Missed Alarms probability (expressed as a percentage). However, higher acceptable Missed Alarms probabilities have been used (up to 5%) in order to get information about sensitivity of the method;
(ii) the synchronous probabilistic forecast of the significant wave height time series is issued by considering the most probable values (i.e. by applying the quantile 0.50 of the variable x_s used in Section 3).

The proposed method is based on the wave forecasting given by ECMWF at a computational point located close to the oceanographic tower "Piattaforma Acqua Alta" placed offshore the Venice Lagoon. Indeed, the system calibration has been performed by using wave measurements available at "Piattaforma Acqua Alta" (coordinates 45.41° N, 12.44° E). The offshore forecast waves were propagated by means of a series of high resolution (i.e. spatial resolution equal to 25 m) SWAN simulations (e.g. [3,22]) up to the offshore boundary of each inlet. Then, the estimated waves parameters have been used to force a numerical model able to compute wave penetration up to the barrier sections inside the inlets. The sensitivity analysis described in Section 3 has been carried out by using the wave measurements collected into the inlets. To date, the foundation caissons deployment is completed and the system was actually used to manage the works. Table 1 summarizes the performances of the method offshore the Venice Lagoon (significant wave height threshold $S = 1.00$ m) and inside the inlet of "Chioggia" (significant wave height threshold $S = 0.50$ m) for target Missed Alarm probability equal to 2% and 5%. From a practical point of view, the system shows a satisfactory performance offshore, whilst the performances deteriorate (i.e. False Alarms probability increases) when the safety forecast inside the inlet is considered. Nevertheless, it has to be stressed that the performances of the system are strongly affected by the complexity of the wave-current interaction occurring within the inlet where ebb/flood currents occur. Indeed, if standard method of synchronous calibration is applied, unreliable safety forecasting is achieved: Table 2 shows the results in terms of $P(FA)$, $P(MA)$ and $P(AG)$ if the sample mean of synchronous errors are applied (numbers between parentheses indicate the performance when bias is corrected before the calibration). It could be

Table 1
Performances of the system implemented for managing foundation caissons installation within the Project for the protection of the Venice Lagoon from flooding.

	Acceptable Missed Alarms (%)	Actual Missed Alarms (%)	False Alarms (%)	Agreement (%)	$P^P(W)$ (%)	$P^M(W)$ (%)
Offshore	2.0	1.99	16.2	81.8	21.7	35.9
(S = 1.00 m)	5.0	4.98	11.0	84.0	29.9	
Chioggia	2.0	1.83	21.9	76.2	11.2	31.3
(S = 0.50 m)	5.0	4.92	18.0	77.1	18.3	

Table 2
Performances of the forecasting correction if the sample mean of synchronous errors are applied. Values between parentheses indicate the performance when bias is corrected before the calibration.

	Missed Alarms (%)	False Alarms (%)	Agreement (%)	$P^P(W)$ (%)	$P^M(W)$ (%)
Offshore	15.0	4.93	80.1	45.9	35.9
(S = 1.00 m)	11.9	6.24	81.9	41.5	
Chioggia	36.5	2.4	61.1	65.4	31.3
(S = 0.50 m)	38.4	2.0	59.6	67.7	

noted that the performance of such a method is rather unreliable to manage the caissons deployment as the number of Missed Alarms, as expected, is quite high.

6. Concluding remarks

Ocean and coastal management often involves the needing of safety assessment of maritime operations, such as the execution of open sea or closed basin maritime works, the management of up- and down-loading activities, dredging activities involving the usage of floating objects, etc. as well as of the real time management of renewable energy devices.

Within the framework of maritime works management, it is often necessary to forecast the estimated safety of a specific operation within a given temporal window. This paper illustrates a possible approach in wave forecasting aiming at providing safety assessing instead of time series forecasting. Indeed, past studies were mainly addressed at forecasting the wave parameters by comparing forecast values with actually observed ones with the aim of correcting the whole wave forecasting time series. The proposed method is based on an alternative approach aiming to forecast the safety of future temporal windows, giving the reliability needed to manage maritime activities. Indeed, the safety forecasting is not as difficult, hence more reliable, as the forecasting of the whole synchronous time series. A specific analysis is carried out to achieve given probability of failure of the safety forecasting, i.e. that the forecasting assesses as safe temporal windows which are not. We propose to use the forecasting error defined as the error in predicting the maximum significant wave height within the temporal window instead of the synchronous error, often used to correct the wave forecasting. The calibration procedure of the method for safety forecasting is detailed through the paper and main results are shown by means of applications, also in a real case, that highlight the practical importance of safety forecasting.

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