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Joint occurrence of high tide, surge and storm-waves on the northwest Spanish coast

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ABSTRACT

The probability of joint occurrences of astronomical tides, meteorological residues and wind-generated waves is examined by analysing simultaneous sea-level and wave-height data recorded at A Coruña from 1992 to 1996. Attention is focused on the existence of a possible statistical dependence among these parameters. Furthermore, marginal distributions for each of these parameters are examined.

Key words: High sea-level events, storm surges, astronomical tides, wind-generated waves, swell, northwest Spanish coast.

RESUMEN

Ocurrencia conjunta de mareas astronómicas, residuos meteorológicos y oleajes extremos en la costa noroeste de España

Se examina la probabilidad de ocurrencia conjunta de mareas astronómicas, residuos meteorológicos y oleaje, poniendo énfasis en la posible existencia de algún tipo de dependencia estadística entre estas variables. Para ello se analizan registros simultáneos de niveles del mar y altura de ola medidos en A Coruña desde 1992 hasta 1996. Además, se examinan las distribuciones de probabilidad marginal correspondientes a cada uno de dichos parámetros.

Palabras clave: *Mareas astronómicas, residuos meteorológicos, oleajes extremos, marejada, costa noroeste de España.*

INTRODUCTION

The coastal environment is multivariate, with astronomical tides, wind, waves and currents all contributing to the forces experienced by coastal structures. An important problem in applied coastal oceanography is the joint occurrence of high astronomical tides, storm surges and wind-waves. The combination of these phenomena leads to extremely high water levels, increasing the risk of coastal flooding, shoreline erosion and the misfire of urban drainage systems. Furthermore, an increase in the mean water level together with large wind-waves may produce severe damages to coastal structures, which are usually designed without considering the possibility of an abnormal rise in sea level.

An example of this is the event that occurred in A Coruña on 21 January 1996. Figures 1, 2 and 3 show the measured and predicted astronomical tides, the meteorological residues and the significant and maximum wave-height histories, respectively, for this month. It can be observed that, while wave heights were not excessive for the zone, high astronomical tides and storm surges were superposed during this period. Thus, though wave heights were not extreme, the sea surface rise made possible the elevation of the level of wave action. Consequently, the wave load smashed through the Riazor beach promenade. Furthermore, waves overtopped the wall, producing widespread flooding in the zone. This example clearly illustrates why the joint occurrences of abnormal water levels and wave heights must be considered in the design of coastal structures and the determination of the level of protection.

Many studies concerning the joint occurrence of extreme astronomical tides and storm surges can be found in the literature (e.g. Suthons, 1963; Pugh and Vassie, 1980; Twan and Vassie, 1991). However, the joint occurrence of high astronomical tides, storm surges and wind-generated waves has not been fully investigated.

The present paper addresses this important problem in applied coastal oceanography: the joint occurrence of high astronomical tides, storm

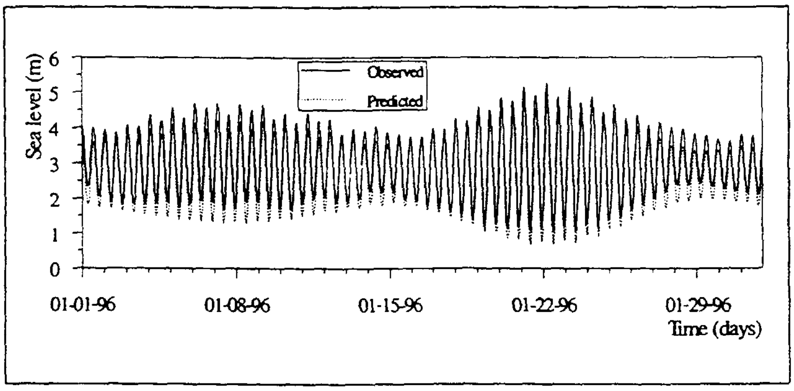

Figure 1. Observed and predicted sea levels during January 1996 at A Coruña

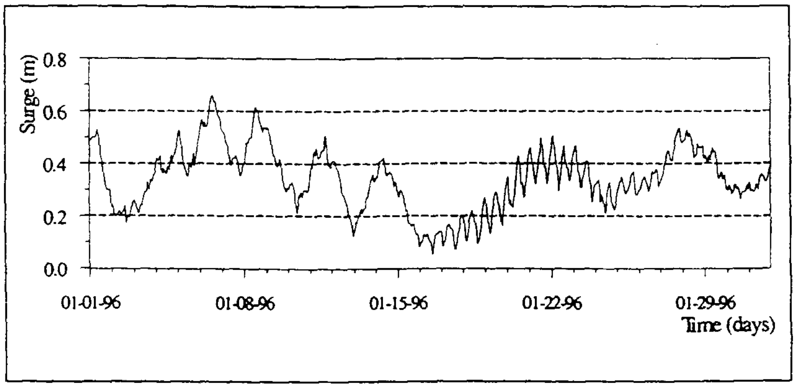

Figure 2. Observed residual surges during January 1996 at A Coruña

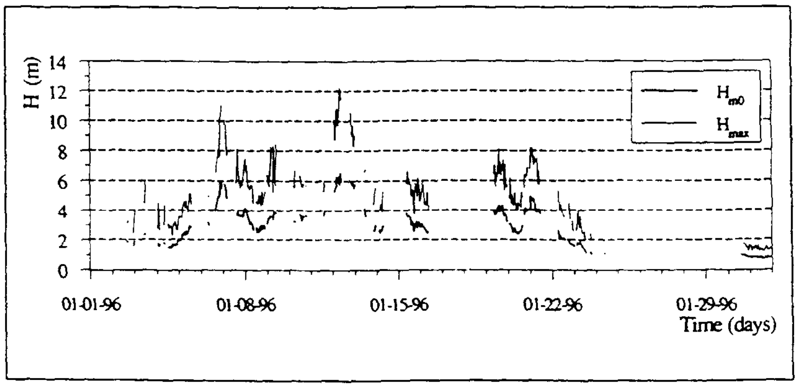

Figure 3. Observed significant and maximum wave heights during January 1996 at A Coruña

surges and high wind waves, which lead to extremely high water levels. However, it is not the objective of this study to design an adequate model to characterise the joint occurrence of extreme values of these three phenomena, but rather, to gain additional insight into the dependence among these marginal variables. This is because, although the probabilistic structure of each one of these phenomena is important, their joint probabilistic structure provides important information that is not often considered. Furthermore, it should be possible to obtain a probabilistic model of the multivariate extremes by combining the marginal models and the information on the mutual dependence among these variables.

We used experimental data to examine the possible dependence between the stochastic (storm surge) and deterministic (astronomical tide) components of the sea surface level. In addition, the correlation structures between the wave-height time histories and the storm-surge component, as well as with the astronomical tide, are examined.

DATA AND ANALYSIS

Hourly time series of seawater level and significant and maximum wave heights recorded at A Coruña by means of a tide gauge and a Waverider buoy, respectively, from 1 July 1992 to 31 December 1996, were analysed. Significant wave height, H_{m_0}, was estimated from individual wave records as

$$H_{m_0} = 4\sqrt{m_0} \qquad [1]$$

where m_0 is the zero order spectral moment, given by

$$m_0 = \int_{-\infty}^{\infty} S(f)\,df \qquad [2]$$

with S(f) being the estimated spectral density function. On the other hand, the maximum wave-height values are the largest wave heights observed in each hourly wave record.

It is well-known that astronomical tide can be considered a deterministic process. However, extremely high sea levels have a stochastic nature, resulting from the random occurrence of storm surges relative to the phase of the astronomical tide. Furthermore, wind-waves are also random in nature. Therefore, the prediction of the joint occurrence of these three phenomena results in a very complex problem.

Generally, a time series of observed hourly sea-surface fluctuations, Z_t, can be expressed as the sum of three components: the mean sea level, C_t, the astronomical tidal level, T_t, and the surge level, S_t, where the surface gravity waves effect has been eliminated by hydraulic filtering in the measurement device, so that

$$Z_t = C_t + T_t + S_t \qquad [3]$$

Here, the mean sea level is considered a static component. However, it is well known that it varies over long periods, due to changes in land and global water levels. Thus, it can be considered a trend component, which can often be characterised by means of a polynomial equation of order n

$$C_t = pt^n + qt^{n-1} + \Lambda + bt + a \qquad [4]$$

The astronomical tide, or periodic, component can be expressed by

$$T_t = \sum_{n=1}^{K} A_n \cos(\omega_n t + \phi_n) \qquad [5]$$

where the frequencies, n, are global constants and the amplitudes, An and phases, n, of the astronomical tidal components are properties of the location. Note that the mean seawater level, A_0, has been included in the trend term. Then, by detrending the observed time series, the stochastic surge component can be estimated as the following residual series

$$S_t = Z_t - \left[\sum_{n=1}^{K} A_n \cos(\omega_n t + \phi_n)\right] \qquad [6]$$

This definition of the surge component assumes that tide and surge are independent of one another. However, in many cases a simple subtraction of the predicted astronomical tide from the recorded sea-level heights does not work. Actually, the procedure of separating the surge from the astronomical tide in a sea-level record is a difficult task, because these phenomena are dynamically non-linear (Rossiter, 1961). Various practical methods for extracting the atmospheric effect from a sea level record have been described (e.g. Corkan, 1950, Miller, 1958). The present study used the most common procedure applied in practice, which is the simple subtraction of the predicted astronomical tide from the sea-level records.

On the another hand, as noted above, the prediction of extreme sea levels should consider the total sea level as a time-varying function, Z(t), comprising these three components and the wind-generated waves. Hence, the global sea level should be represented by

$$Z_t = T_t + S_t + W_t \qquad [7]$$

where the first of these parts is a deterministic term, T_t, which can be predicted with acceptable accuracy, whereas the other two parts are non-deterministic, but can be predicted in a statistical sense. These two stochastic terms correspond to the meteorological storm surge, S_t, and the wind-generated waves, W_t, respectively. Naturally, while the trend component has been subtracted for simplicity, it must be considered when predicting the sea-surface elevation at a given location. With this in mind, we may use a predictor, S_t^*, for the storm surge and another, W_t^*, for the wind-generated waves. Consequently, the Z_t^* predictor will be

$$Z_t^* = \left[\sum_{n=1}^{K} A_n \cos(\omega_n t + \phi_n) \right] + S_t^* + W_t^* \qquad [8]$$

This model assumes that astronomical tide, storm-surge and wind-generated waves are mutually independent. However, the principal mode of generation of surges is by tangential wind stress and by changing atmospheric pressure disturbances. That is, surge properties are mainly governed by the local atmospheric conditions, which also control the characteristics of the locally wind-generated wave fields. Therefore, it is natural to expect a certain relationship between the surge and wind-waves observed at a given location. Two simultaneous surge and wave-height time series recorded at A Coruña during 1993 and 1995, respectively, are shown in figure 4. It can be observed that during these periods, a large correlation exists between the significant wave height (solid line) and the sea-surface elevation due to atmospheric effects, or surge, with the large surges occurring almost simultaneously with the larger wind-generated waves. Nevertheless, there is a small delay between both time series, which can be justified by considering the body of water's inertia in responding to wind stress and to atmospheric pressure fluctuations. Note that surge values have been multiplied by a constant factor [4] for easier comparison.

On the other hand, although tides and surges have a different physical genesis, both can be coupled. Thus, for example, when the tide propagates in shallow coastal waters, the water depth can be increased by surge action. In this case, the predicted tide will arrive at the coast earlier than expected and will be lower in amplitude, whereas the resultant sea level will be higher. Inversely, a lowering of the mean sea level retards the propagation of the tide (Rossetier and Lennon, 1968). Two time series of sea-surface level (solid line) recorded at A Coruña during 1995 and 1996, respectively, are shown in figure 5 together with the meteorological surge (dashed line) obtained by subtracting the predicted astronomical tide. Note that surge values have been multiplied by a constant factor for comparison.

It can be observed that surge values approximately follow the same pattern that the lower envelope of the sea-level observations. It is also im-

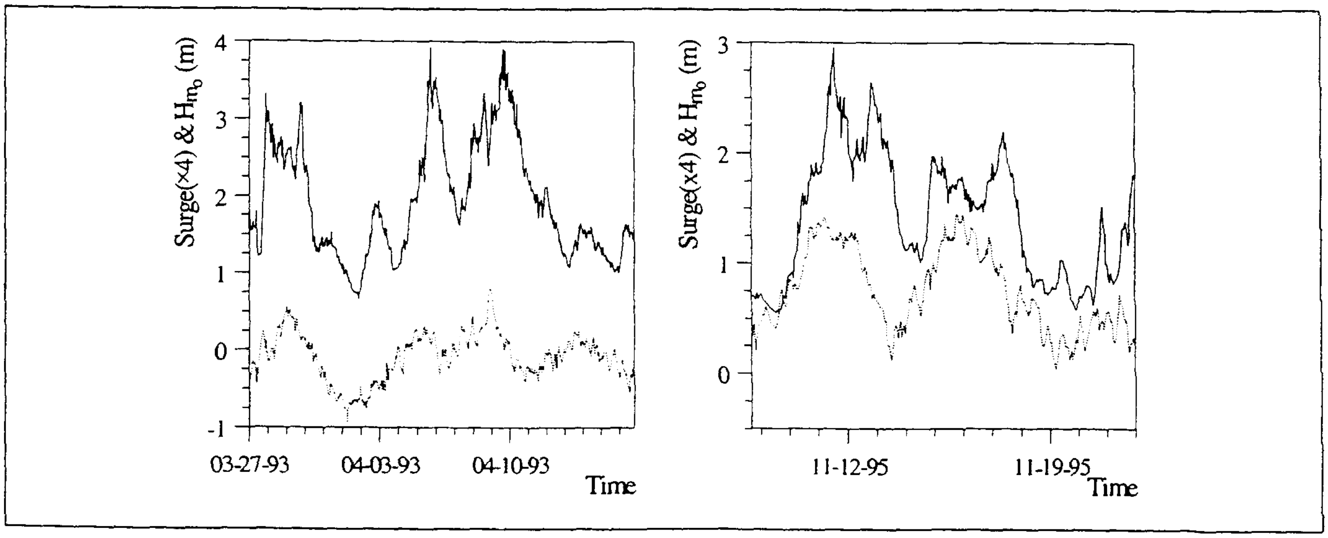

Figure 4. Significant wave height (solid line) and surge elevation (×4) (dashed line) observed at A Coruña

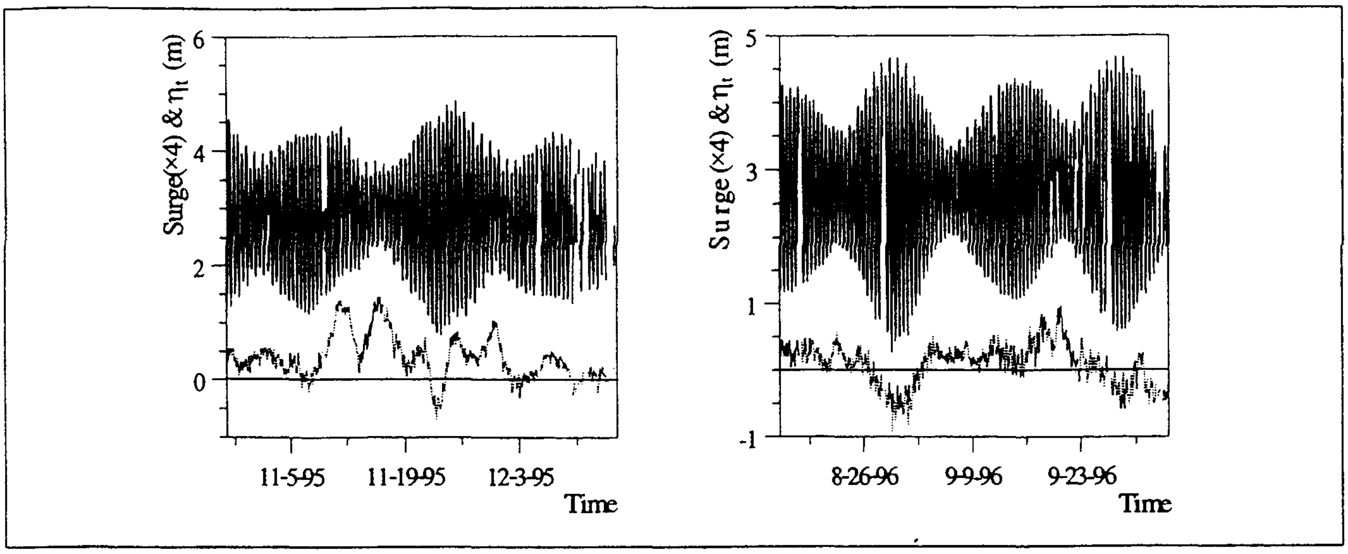

Figure 5. Sea surface level (solid line) observed at A Coruña and estimated surge (dashed line) (×4)

portant to note that the larger positive surges often occur during the low tidal-range periods, whereas the larger negative surges are more frequent at the rising tide.

In light of this experimental evidence, some degree of dependence among these physical processes should be suspected, at least in coastal waters. Thus, it becomes clear that an adequate analysis of extreme sea levels must take into account the individual probabilistic distribution of each one of the aforesaid phenomena, as well as the possible existence of some kind of dependence among the different terms giving rise to the actual sea-surface elevation. Results of such an analysis are presented in the next section.

RESULTS AND DISCUSSION

Marginal distributions

The histograms of the hourly measured significant and maximum wave heights are shown in figure 6. It can be observed that these distributions are skewed towards smaller wave heights, and that large storm-waves have a small relative frequency of

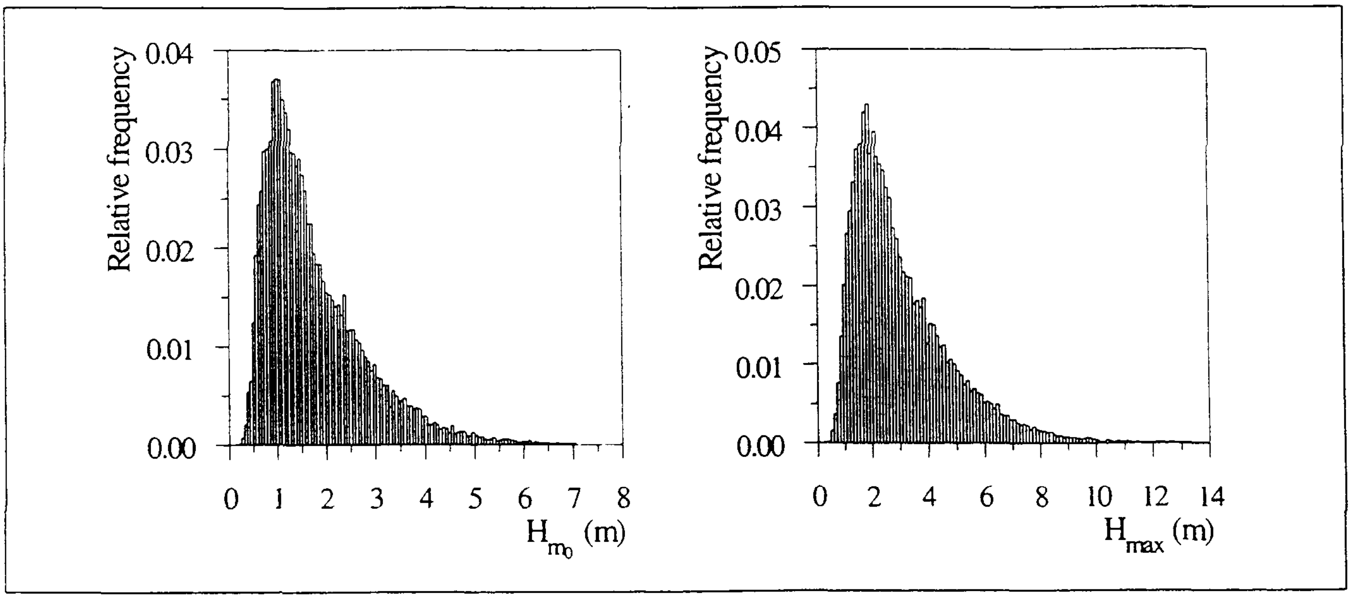

Figure 6. Experimental marginal probabilistic distributions for significant wave height (left) and maximum wave height (right)

occurrence. Both distributions are shifted to the right of zero, since the significant and maximum wave heights are not likely to attain values close to zero.

There is no accepted theoretical basis for choosing a specific distribution function to describe the hourly significant and maximum wave heights. Therefore, the experimental values have been fitted to the Rayleigh, log-normal, Gumbel and Weibull distributions, which are the most common distributions used to obtain a mathematical expression adequately describing the observations. The results suggest that the log-normal distribution provides the best description of the hourly significant and maximum wave heights. These results agree with those reported by Guedes Soares, Lopes and Costa (1988), who analysed wave data recorded at Figueira da Foz (Portugal) from 1984 to 1988.

The marginal statistical distribution of the astronomical tide was analysed by Tayfun (1979), who described the predicted component of the tide as a Gaussian process. This is a simple and natural way of representing the process, because on first consideration the model given by equation [5] represents the tidal heights as the sum of a large number of cosines. Then, by applying the central limit theorem, the process would follows a Gaussian distribution. However, the marginal distribution obtained for the predicted sea-surface level, shown in figure 7, shows a bimodal shape. This bimodal form has also been reported by Pugh and Vassie (1980) for the distribution of tidal heights at some Britisi. coastal sites, and by Walden, Prescott and Webbe. (1982) for some ports on the southern coast o. England. Walden and Prescott (1983) noted tha the sum of cosines denoted by equation. [5] will b distributed normally only if no constituent has a dominant effect on determining the tide.

The spectral density function estimated from the predicted tidal heights is shown in figure 7 (right) It is clear that the semidiurnal constituent is the dominant term of the tide at A Coruña. Walder and Prescott (1983) found similar conditions fo some locations in British coastal waters. These authors proposed a relatively simple stochastic mode to characterise the predicted tidal heights in this situation. The model suggested by these authors considers the superposition of a cosine wave plus a random noise to explicitly reflects the dominance of the semidiurnal constituent.

It noteworthy that the probabilistic distribution displayed by the measured sea-surface elevations. shown in figure 8 (left), is practically the same as that for the predicted tidal heights. The model proposed by Walden and Prescott (1983) is also useful to characterise the observed elevations. On the other hand, the marginal distribution obtained for the meteorological residues closely fits a normal distribution, as can be observed from figure 8 (right), although due to the existence of some anomalous bins the Gaussian distribution did not verify the chi-square goodness-of-fit test.

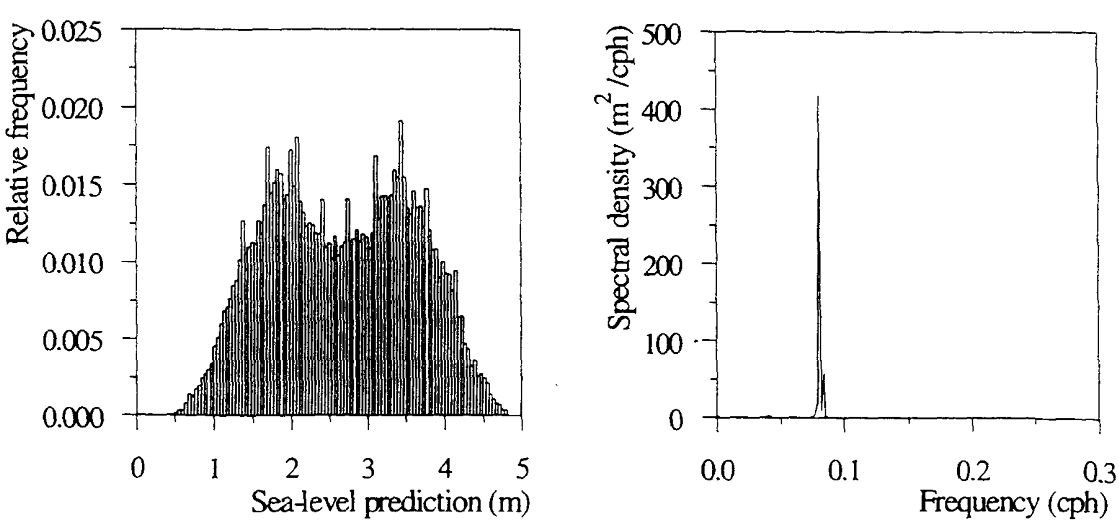

Figure 7. Experimental marginal probabilistic distributions for tidal prediction heights (left) and the corresponding spectral density function (right)

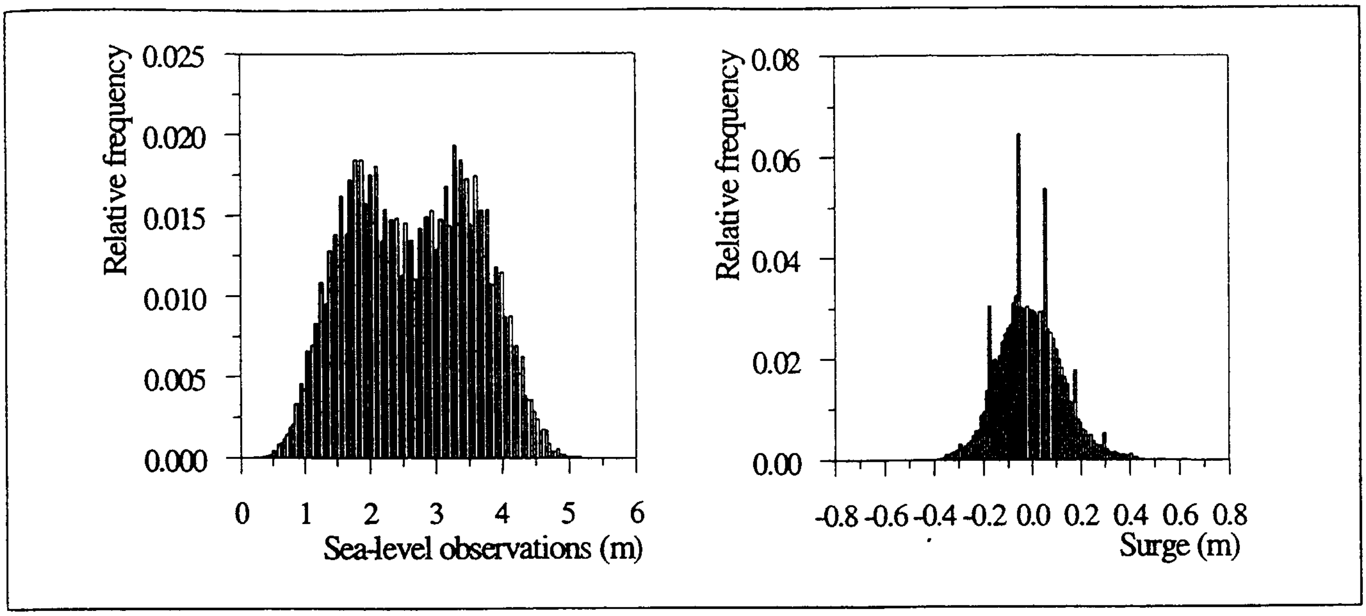

Figure 8. Experimental marginal probabilistic distributions for sea-surface level (left) and meteorological surges (right)

Joint distributions

The bivariate distributions observed for the simultaneous pairs of surge and sea-level measurements reflect a slight tendency of the surge to increase with the astronomical tidal height (figure 9, left). On the other hand, there is no evident relationship between the measured sea level and the significant wave height (figure 9, right). However, a hidden relationship between the surge level and the significant wave height can be guessed from this figure. It can be observed that the measured sea-level range decreases as the significant wave height increases, indicating that the probability of negative surges during low tides and negative surges during high tides increases with the significant wave height.

The bivariate distribution of meteorological surges and significant wave heights is represented in figure 10 for data from A Coruña. The expected trend of the surge to increase with the significant wave height, since both processes have the same

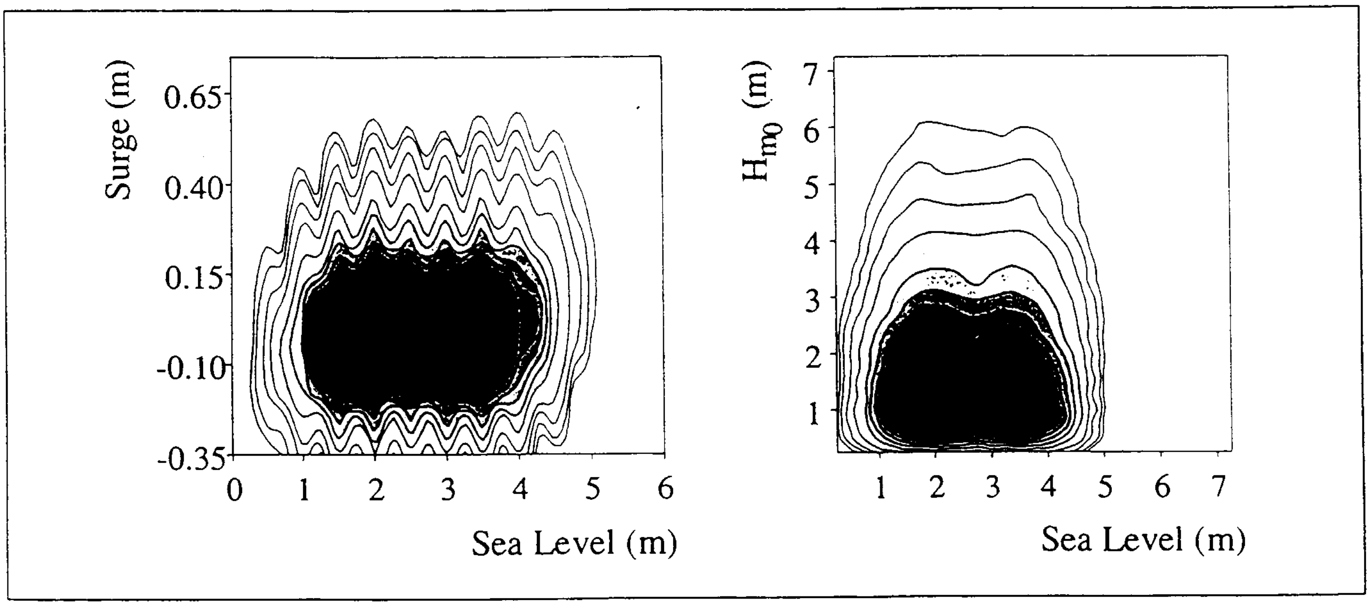

Figure 9. Observed joint probability distribution of measured sea level and meteorological surge (left) and of sea level and significant wave height (right)

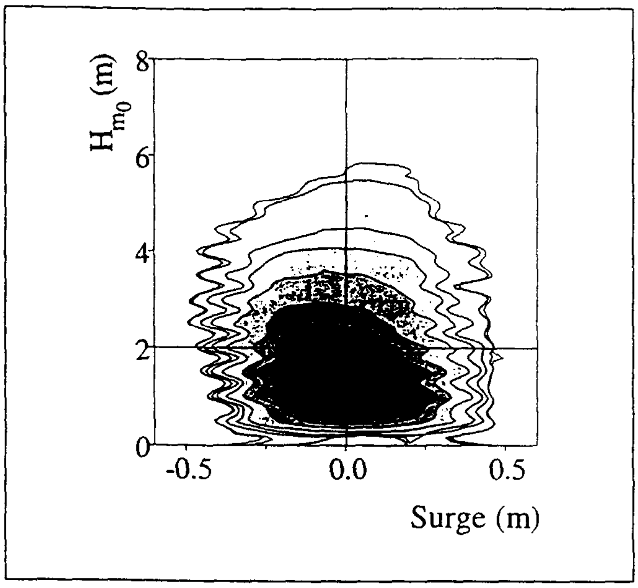

Figure 10. Observed joint probability distribution of surge and significant wave heights

physical origin, can be observed, although this becomes clear only for significant wave heights of more than 2 or 3 m.

Gaffney and Williams (1993) analysed hourly values of surge and significant wave height recorded in North Carolina coastal waters during one month. By applying a linear regression procedure, they reported the following empirical relationship between both parameters

$$S = -0.028 + 0.255H_{m_0}$$

Figure 11 shows the scatter diagrams obtained by representing all the hourly couples measured during the entire period of measurements (left) and those with surge values higher than 0.4 m (right). It can be observed that an inverse relationship is obtained by means of linear regression when using all of the data; i.e. it seems that the surge decreases as the wave height increases. This paradoxical result is due to the large percentage of mixed sea states found on the west coast of the North Atlantic, as reported by Guedes Soares and Nolasco (1992) for a site off Portugal. These authors observed a range of between 23-26 % of double- peaked sea states, corresponding to the combination of a wind sea and a swell coming from distant storms. Furthermore, during periods of low local wind velocities, the background swell becomes dominant along the North Atlantic west coasts, as reported by Rodríguez (1992). The swell-dominated sea states are characterised by long wave periods and small wave heights, and are unrelated to local wind action. Thus, the expected relationship between surges and significant wave heights would be different for the eastern North Atlantic, which is not significantly affected by the presence of swell waves, and the swell-dominated west coasts. Therefore, if only the surge values associated with meteorological residues higher than 0.4 m are considered (figure 11, right) the linear relationship between both parameters becomes positive. Note that although in this case the data

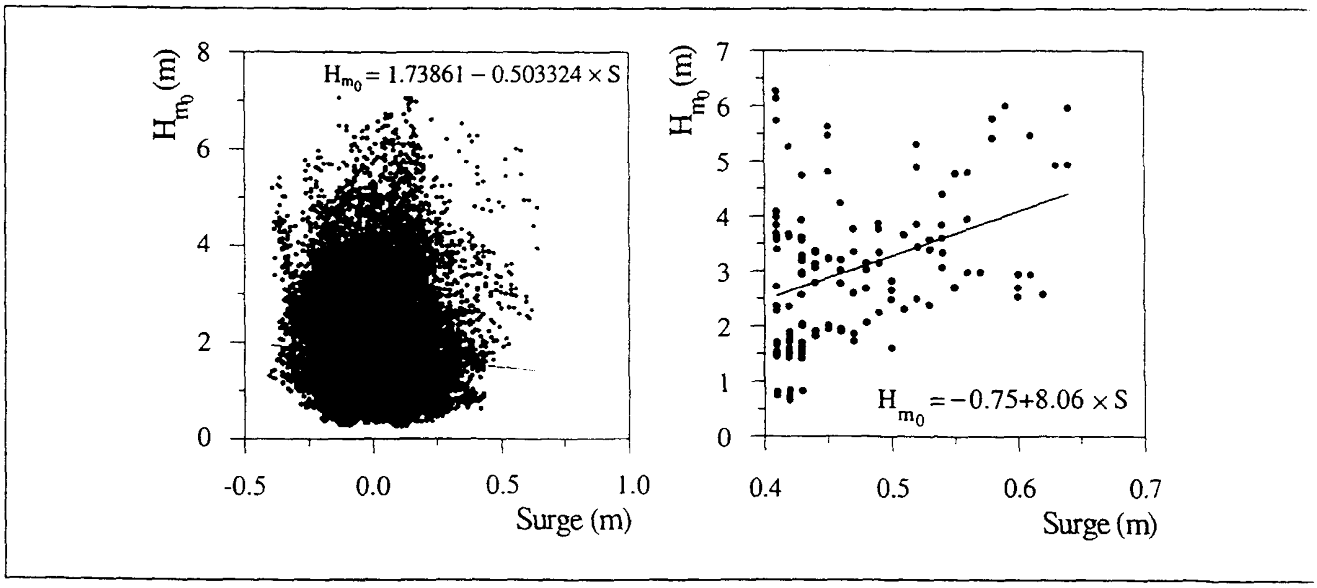

Figure 11. Scatter diagram of simultaneous observations of surge and significant wave heights, for all the observations (left) and for observations with surge higher than 0.4 m (right)

are better fitted by a linear function, the scatter remains large with a a very low correlation coefficient (close to 0.2).

CONCLUSIONS

It has been shown that the astronomical tides, meteorological residues or surges and wind-generated waves should be jointly considered, in practice. The marginal probabilistic distribution of significant and maximum wave heights are adequately described by means of the log-normal distribution, and the meteorological surges with the Gaussian probability law. However, the measured and predicted sea level required can be characterised by using a cosine plus random noise model to include the dominant effect of the semidiurnal constituent, giving rise to a bimodal probability distribution.

There is a certain degree of correlation among these processes. The relationship between surge and wind-wave heights is because both phenomena are governed by the meteorological conditions at the study locations. Surges and tides are generated by different physical processes; however, they can be related due to a coupling effect. Thus, larger positive surges often occur during low tides and the larger negative surges are more frequent at the rising tide. On the other hand, significant wave height seems to increase with surge level. However, the relationship between these two parameters is masked by the presence of a large quantity of low wave heights associated with swell-wave fields, which are not related to the local wind field.

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