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Analysis of tide measurements in a Sicilian harbour

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Abstract

Designing of ports and coastal protection works and planning of coastal human activities require knowledge of tidal oscillations. The latter vary noticeably from site to site and present an “astronomic” component, which is roughly periodic, and a “meteorological” component, which is usually considered as random. In this paper, the tidal oscillations observed in a Sicilian harbour in the period 1999-2009 are analysed statistically, in order to recognize a probability distribution which allows one to predict the highest tidal levels. First, the measurements are used to obtain, for each year, the *astronomic tide* through harmonic analysis using the software package *T_TIDE*. The difference between the observed tide and the astronomic tide, indicated as “noise”, is imputed to meteorological factors and treated with a statistical approach. The noise imputable to sea storms moving onshore is divided from that imputable to storms moving offshore. Several probability distributions are then considered for each noise and it is established that each noise closely follows the Weibull extreme value distribution better than other distributions.

Keywords: Tide analysis, coastal protection, probability distribution, extreme value distribution, storm surges.

1 Introduction

Sea level oscillations, usually indicated as tides, are produced by superposition of many contributions, the main ones being *astronomic* and *meteorological* (Coastal Engineering Manual, 2002). The former (which produce the “astronomic tide”), are *persistent*, although not exactly periodic (Kamphuis, 2010), and can be predicted with adequate precision. Several models based on harmonic analysis are available for simulation of the astronomic tide (e.g., Pashova and Popova, 2011). Each model takes into account a different number of tidal harmonic constituents, each related to an astronomic, geographic or geophysical factor (Pawlowicz *et al.*, 2002). The meteorological contributions (“meteorological tide”) are *contingent,* depending on many factors, like changes in the atmospheric pressure, wind, storms, etc., related to the passing of atmospheric disturbances, whose duration varies between a few hours and several days. Such phenomena are roughly foreseeable within a few hours but not at all in the medium and the long term, so that a statistical approach proves to be necessary to forecast the meteorological tide.

In this paper, early results of analysis of tidal measurements taken in a harbour in the Mediterranean Sea are reported. The measurements are first processed to recognize in the total oscillations the meteorological part. The latter is then analysed statistically aiming at recognizing a probability distribution allowing one to predict tidal oscillations in the medium as well as in the long term.

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2 Data set and meteorological contribution

The harbour selected for the analysis is that of *Porto Empedocle* (lat 37° 17' 08.72'' N; long 13° 31' 36.64' E) which is located on the South coast of Sicily (Italy). The harbour is about 100 km from the wave buoy of *Mazara del Vallo* (lat 37° 38' 43.19'' N; long 12° 34' 57.0'' E); both are located along the same almost rectilinear coast (Fig. 1). The presence of the wave buoy close to the harbour makes it possible to investigate the connection between the tide measurements outside the usual astronomic oscillation range and the wave data recorded by the buoy. The study on this connection will be carried out in further papers. Both the tide gauge and the wave buoy record data every hour. The tide gauge of *Porto Empedocle* has operated since several decades ago, with different instrumentation, but continuous data recorded with the late gauge are available only for the period 1999-2009, which was adopted for the present study.

In order to recognize the *meteorological* tide, for each year the tide measurements were used to draw the *astronomic* tide by means of a harmonic analysis made by T_TIDE, which is a package of MATLAB routines (Pawlowicz *et al.*, 2002). By varying some input options, T_TIDE makes it possible to select up to 145 tide components. We chose to use four different configurations of the model, which were the following: *10comp* with the 10 basic components (SA, O_1, P_1, K_1, N_2, M_2, S_2, K_2, M_4, MS_4); *Default* with the components chosen automatically by T_TIDE between 68 components with a period smaller than or equal to one year, including 44 astronomic and 24 shallow-water ones; *allcomp-sw* with all the 68 components with a period smaller than or equal to one year; *allcomp* with the 44 astronomic components. Therefore, for each year we obtained four different tide simulations. Fig. 2 shows, as an example, the four one-year tide simulations relating to the year 2005.

Comparative examination of all the simulated one-year tides with the corresponding ones observed in the period 1999-2009 led us to choose, for the subsequent processing, the one-year simulations obtained using the 44 components that Pawlowicz *et al.* (2002) refer to as astronomic. Each of these simulations was assumed as the *astronomic tide* of the related year. Fig. 3 shows, as an example, the astronomic tide and the observed tide relating to the year 2005. The window in the figure allows one to observe that, generally, the astronomic oscillations follow the observed ones but they prove to range in a noticeably narrower band. The difference between the observed and the simulated tide, considerably varying from one cycle to another, is likely due to meteorological factors and its prediction then presents uncertainties at least analogous to those of the meteorological factors themselves. Indeed, such uncertainties are even higher, because of those proper to the models for transformation of meteorological factors into sea level oscillations. Therefore, a statistical approach based on the observed oscillations seems to be the best way for prediction of the sea level oscillations in the site of interest.

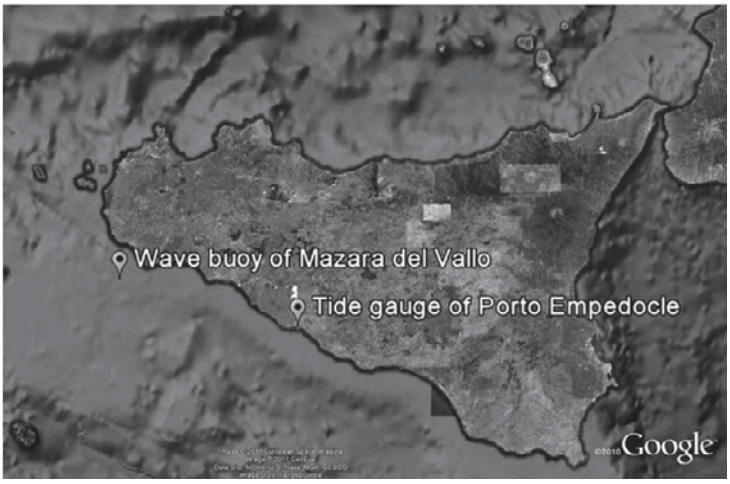

Figure 1: The wave buoy of Mazara del Vallo and the tide gauge of *Porto Empedocle* are located along the same almost rectilinear coast (source http://maps.google.com).

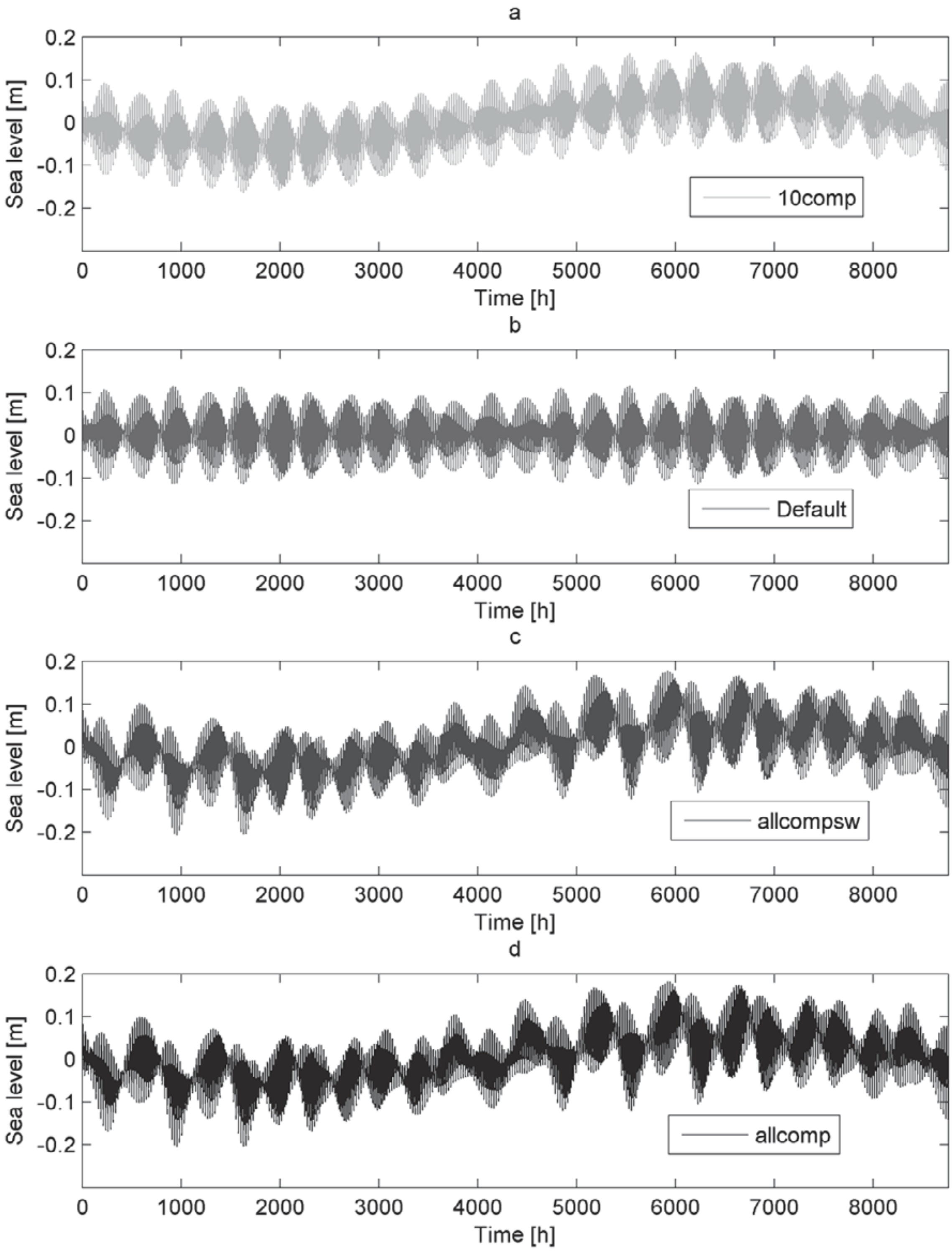

Figure 2: Comparison between the astronomic tides of the year 2005 simulated with the four different configurations of T_TIDE: a) the 10 basic components; b) components chosen automatically by T_TIDE between 68 components having a period smaller than or equal to one year; c) all the 68 components with a period smaller than or equal to one year; d) all the 44 astronomic components.

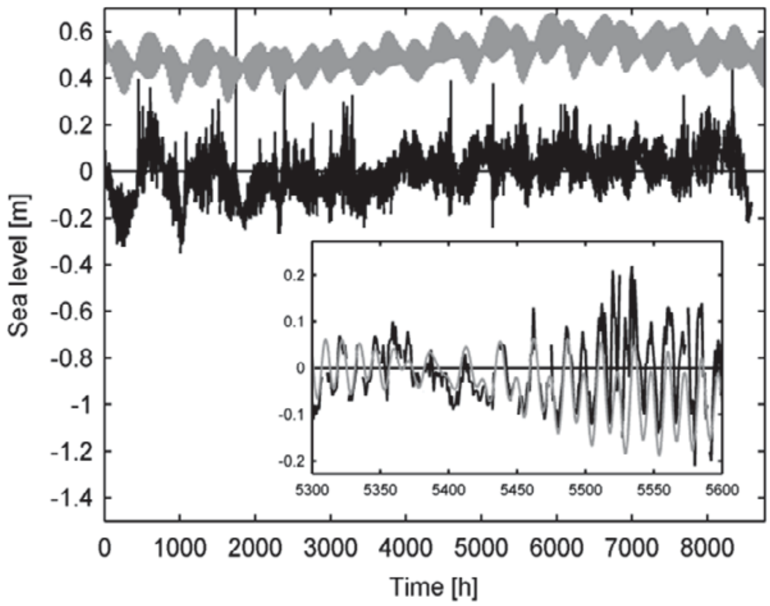

Figure 3: Comparison between the observed tide (black line) and the simulated tide (grey line) relating to the year 2005; the simulated tide is shifted to allow clear observation; the window shows a comparison between the two tides in a time-interval of 300 hours.

To this aim, the difference between the observed and the astronomic tide was then calculated for each year. From now on this difference will be indicated as "noise." The noise proved to be both positive and negative: it is likely that positive noise is imputable to sea storms moving onshore and negative noise to storms moving offshore. Fig. 4 shows, as an example, the noise relating to the year 2005; the same figure reports the time intervals during which the buoy recorded sea storms with a 1.5 m threshold. Note that intense noise may have occurred even for sea storms slightly less than 1.5 m which, however, are not reported in the figure; moreover, the occurrence of high sea levels also depends on storm duration. Anyway, as mentioned above, the noise-storm connection will be stressed in further papers. It is to be noted that the magnitude of noise often prevails over that of the astronomic oscillation (see also Fig. 3).

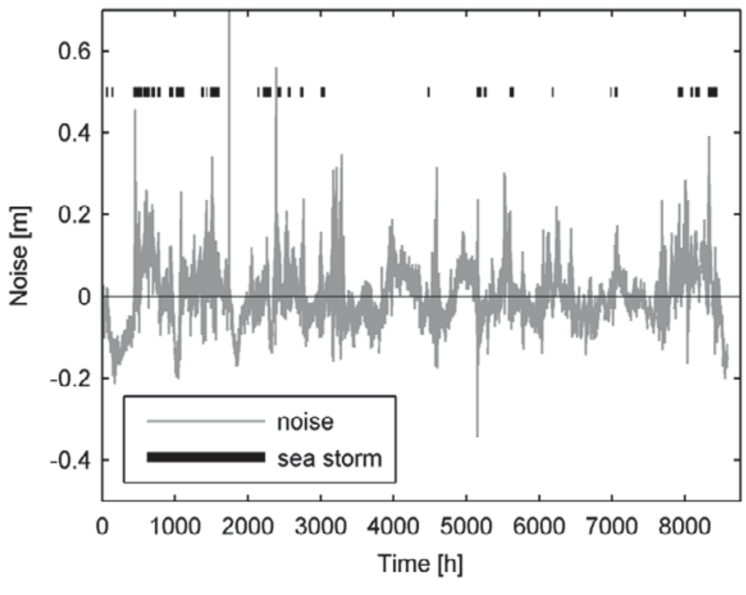

Figure 4: Comparison, relating to the year 2005, between the noise fluctuations (grey line) and the occurrence of sea storms equal to or higher than 1.5 m (bold black line).

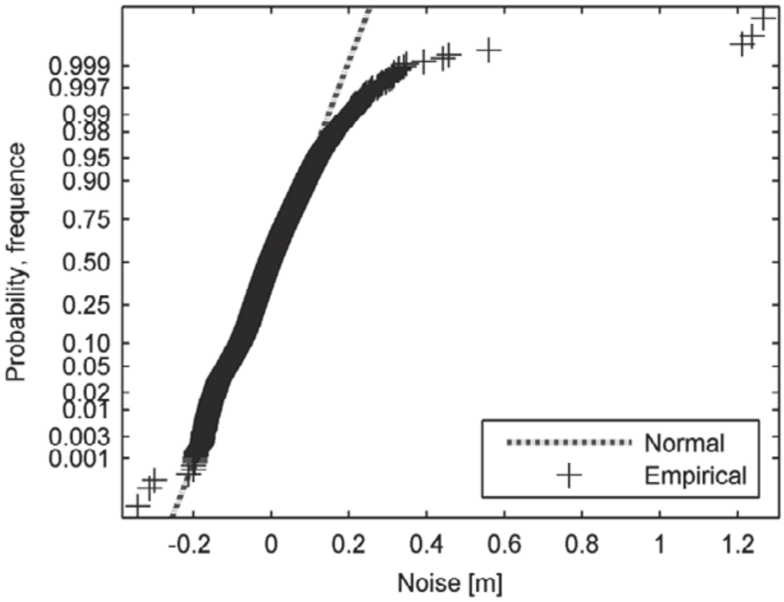

Figure 5: Normal probability plot of noise relating to the year 2005.

3 Statistical analysis of the meteorological contribution

By reporting the points of each year on the probability plot, it was first established that the noise values do not follow the normal distribution (Fig. 5). This is an expected result, since the noise, if really due to meteorological factors, should rather follow an extreme value distribution, as the crosses on the NE corner of the figure confirm.

Therefore, the Gumbel, GEV (Generalized Extreme Value) and Weibull distributions were considered (Kotz and Nadarajah, 2001). To this aim, the positive noise (onshore storms) was separated from the negative noise (offshore storms) and the latter considered in its *absolute value*, because, actually, what is connected with the contingent meteorological situation is the noise *intensity*. The two data sets were then treated separately, as belonging to different populations.

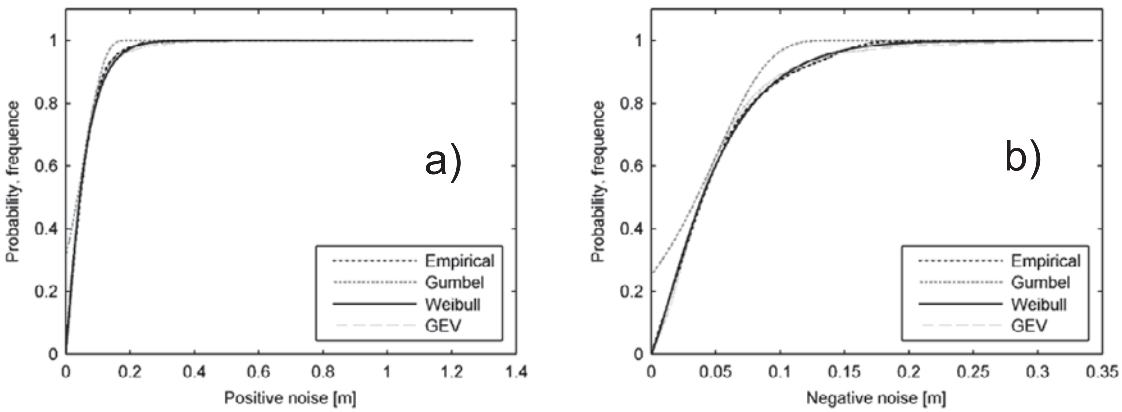

Figure 6: Comparison, for the noise relating to the year 2005, of the empirical cumulative distribution with GEV, Gumbel and Weibull distributions: *a*) positive noise; *b*) negative noise.

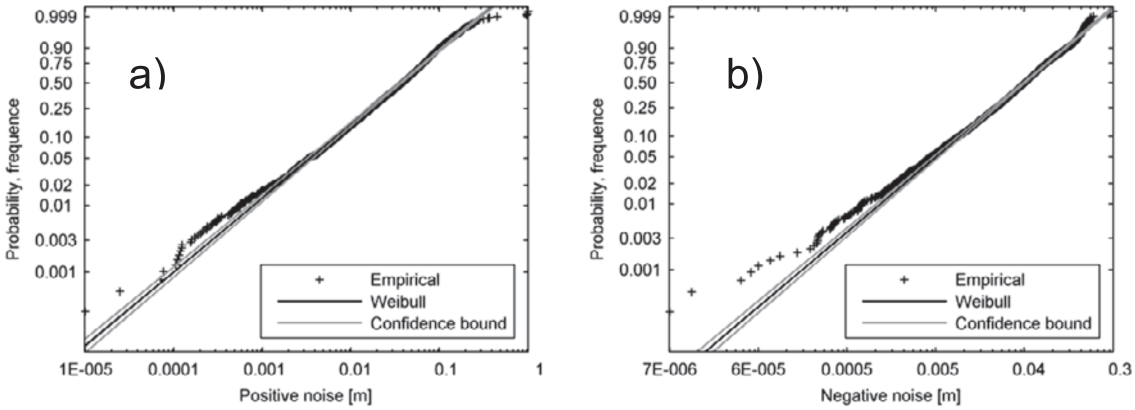

Figure 7: Weibull probability plot, with 95% confidence bounds, relating to the noise of the year 2005: *a*) positive noise; *b*) negative noise

For each data set of each year, the empiric frequency curve was compared with the curves of the three laws considered. Fig. 6 shows, as an example, the comparison relating to the year 2005. On the whole, both the positive (Fig. 6*a*) and negative noises (Fig. 6*b*) follow the Weibull distribution more closely than the other two. The same result was obtained for the other years.

Fig. 7, shows, as an example, the Weibull probability plot relating to the positive noise (Fig. 7*a*) and the negative noise (Fig. 7*b*) of the year 2005. This figure too shows an overall good fit, for the practical purposes, of the Weibull distribution with the experimental points, both for the positive and the negative noise, even though more than half of the points fall outside the confidence bounds. It has to be noted that the deviations of the lowest points seem appreciable because of the logarithmic scale. Similar results were obtained for the other years examined. However, in order for reliable predictions in the medium and long term to be carried out a multi-year distribution has to be recognized.

Therefore, the noise data of the whole observation period 1999-2009 (the positive values being separated from the negative values) were processed *altogether*, considering the same extreme value distributions as above. Once again the Weibull distribution proved to be the best and, therefore, it was assumed by us as the *noise distribution*. Figs. 8*a* and 8*b* show the probability plots with 95% confidence bounds of the Weibull distribution for the positive and negative noise respectively. Both panels show a good fit of the Weibull distribution with the points. Once again, the apparent noticeable detachment of the lower points of the negative noise from the line, due to the logarithmic scale, is actually less than 1 cm.

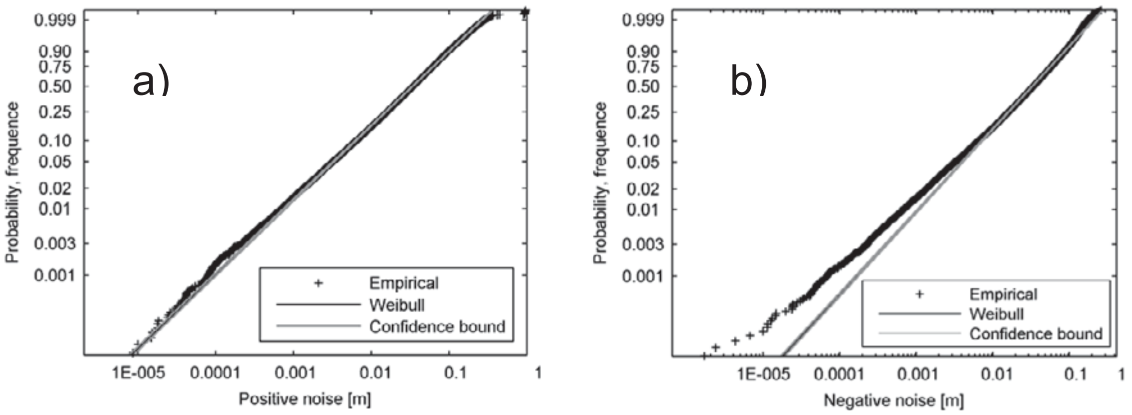

Figure 8: Weibull Probability plot, with 95% confidence bounds, relating to the whole period 1999-2009: *a*) positive noise; *b*) negative noise

4 Discussion of results

The result that the Weibull distribution fits both the points of each year and the points of all the years together, on the one hand, gives robustness to the assumption that the noise is produced by “extreme” meteorological factors, and, on the other hand, makes likely the supposition that this law can be used to forecast extreme sea levels even in the long term, as is required in many practical applications. To the latter aim, obviously, the measurement data set in the site of interest should concern an observation period longer enough than the 11-year period considered in the case study on *Porto Empedocle*. Of course, in order for the Weibull distribution to be recognized as a “general” law for tide noise, further investigations have to be performed in many different sites, in the Mediterranean Sea as well as in other seas and oceans.

As for the practical applicability of these results, it has to be noted that in the practical applications a probability expressed in terms of a return period *in years* is required, which is not the same probability as expressed by the Weibull distribution we obtained processing *hourly* data. Actually, the connection between these two probabilities is not immediate, because in each year we find positive and negative noise values which differ in numerousness and magnitude: usually, in our data set the positive values are less numerous than the negative ones, but on average they are higher; numerousness and magnitude vary from year to year. Therefore, when calculating the empirical frequency of a noise value, belonging to the one-year observations either of positive or negative noise, the allocation of the noise values between positive and negative *in that year* has to be taken into account. The calculation becomes more complicated when we have to process altogether the data collected in a multi-year period. This basic topic will be developed in further papers.

Another major question to be developed, in the perspective of a more organic view, is the relationship between storm surges and tides, or the compound probability that a storm surge of fixed intensity (and consequent probability) will effect a tide of given amplitude (and consequent probability). In this respect, it is interesting to observe that the Weibull distribution is that usually adopted for the wave heights (Coastal Engineering Manual, 2002). The storm-tide connection, as already mentioned, will be developed in further papers, using the tide measurements of the present paper together with the wave measurements of the nearby buoy.

5 Conclusions

Analysis of tide measurements taken in a harbour located in the middle of the Mediterranean Sea was carried out in order for a robust law able to predict sea level oscillations to be recognized. The harbour chosen as a case study is located on the south coast of Sicily (Italy) and is relatively close to a wave buoy located along the same almost straight coast, which will allow us to study the connection between tides and storms in this site.

It was first recognized that sea level oscillations are a result of so-called astronomic factors, persistent and quasi-periodic, and meteorological factors, by contrast contingent and not predictable for certain in the medium and the long term. As a consequence, the extreme tides, mainly produced by extreme meteorological situations, are not predictable by a deterministic way, so that a statistical approach proves to be necessary.

For each year of the period 1999-2009, during which data were continuously recorded, the measurements were used to draw the astronomic tide through the harmonic analysis carried out by means of the software package T_TIDE. Then, the tide part imputable to meteorological factors, that we called the “noise”, was estimated as the difference between the observed tide and the astronomic tide. The positive noise was imputed to sea storms onshore and the negative noise to sea storms offshore: consequently, statistical analysis was carried out separately for the positive noise and negative noise, considered as distinct populations.

Having discarded the Gaussian distribution, which of course proved to be unfit for a variable like noise, the Gumbel, GEV and Weibull distributions were tested, which in contrast with the former are expressly conceived for extreme values, as the higher and the lower sea levels have to be considered. The tests showed that the Weibull distribution fits the points better than the other two, both for the data of each year and for the data of the whole observation period altogether.

This result shows that the Weibull distribution can be adopted for predicting exceptional sea levels in the study site. Of course, in order for a robust prediction in the long term to be carried out a measurement data set related to an observation period rather longer than the 11-year period considered in the present study is necessary.

Further tests in different sites, both in the Mediterranean Sea and in other seas and oceans, are necessary to confirm whether the Weibull distribution can be assumed as a "general" probability law for sea level oscillations.

The next steps of this research will concern attainment of a probability expressed as a return period in years on the basis of hourly recordings and the connection between the storm surges observed by the buoys and the tides gauged onshore.

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