ANALYSIS OF 12-YEAR WAVE MEASUREMENTS BY THE ITALIAN WAVE NETWORK

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Abstract: A modern directional wave measurement network is operating since 1989 around the Italian coasts. The remote-controlled buoy system is managed by the National Hydrological and Marine Survey with excellent results in terms of data acquisition rates, temporal coverage and reliability.

Recently this permanent system has been upgraded and expanded (from 8 to 14 stations) after a careful revision of both the sensors and the software for data transmission, acquisition and analysis. The developments of the monitoring system are now calling for real-time data control and distribution.

The present paper aims to inform about the results of the complete data analysis effort promoted by National Hydrological and Marine Survey and carried out by the University of RomaTre in order to better know the characteristics of waves and related storms in the Mediterranean sea.

INTRODUCTION

In 1989 the Italian Ministry of Public Works started up the national Sea WAve measurement Network (SWAN). Since the beginning of 1996 SWAN is managed by the National Hydrological and Marine Survey (NHMS) which provides systematically measurements and analysis of wave data, water levels and other meteoceanographical parameters recorded in the Italian seas.

In addition to the collection and the real-time supply of the recorded data, the NHMS is also concerned with a careful validation process of the measurements to provide more consistent statistical analysis as well as a better understanding of the physical characteristics of the Italian Seas. In this framework the full set of first 12 years data from the original 8 stations have been analyzed by the University of RomaTre as follows:

- data retrieval, gap filling and data validation;
- wave climate definition and wave spectrum parameterization;
- extreme wave statistics;
- statistical correlations between wave parameters observed at different locations;
- global meteorological analysis of the most dangerous seastorms.

The obtained results give a new insight of the wave climate and extreme events around the Italian coasts, which are useful to coastal designers and marine operators.

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THE BUOY NETWORK

SWAN was formed by 8 Datawell Wavec buoys till 1999 (see map in fig.1). Their location was also influenced by the availability of over 100 temporary wave measurement stations (Franco and Contini, 1997). In early 1999 two additional Datawell Waverider buoys and their relative onshore stations were installed in order to achieve a better coverage of the Italian Seas. All the buoys are moored in a depth of about 100m. The recorded data are transmitted on VHF band (assigned to NHMS on the entire national area) and are picked up onshore by receivers connected to two computers which supply the data storage. The complete description of the original buoy network can be found in Arena et al. (1997). The averaged efficiency, defined as the ratio between the retrieved valid data and the number of expected ones based on the three-hourly sampling, is over 90% while the network proficiency generally decreases in time at a mean rate of 1% per year, mainly due to obsolescence of PCs (Arena et al., 2001).

Figure 1. Location of the Italian directional wave buoy network.

The analysis of the seasonal occurrence of network failure has pointed out two factors that affect the data retrieval percentage, which is generally very good. Actually, in the fall and winter months the bad weather conditions affect the failure identification and reduce the rescue capability. Furthermore, in midsummer the rescue capability is affected by the holiday maintenance-staff reduction. The peak storm data loss in fall or winter could affect the extreme wave analysis. Therefore, a great effort was be made in order to reduce the loss of storm data. Based on the 12 years experience, SWAN has been upgraded. Namely, the 10 Datawell buoys have been substituted by new Triaxis ones, which allow a 4Hz sea surface sampling rate (previously it was 1.28 Hz), an onboard data storage and a simpler maintenance program. The number of stations has been increased to 14, resulting in a more complete coverage of the Italian seas. Also the onshore stations have been significantly changed: a new architecture has been designed whilst the control center has been provided by more powerful devices, which are able to easily handle and distribute the data in real-time. Namely, at NHMS headquarters in Rome a direct connection with the local stations is operational and the following activities are carried out: data storage; data validation and analysis; editing of bulletins; daily check of the local stations and synthetic data acquisition in real time by modem. In the last two years a sophisticated SQL data base has been developed in order to readily handle the amount of data now available and allow the development of further data processing tools.

WAVE CLIMATE

A basic topic in coastal engineering is the wave climate, which is generally illustrated by polar diagrams. Herein, these results are not reported for sake of brevity and just some general information is given. The analysis of wave directional characteristics have shown two different buoy clusters, which can be related to the buoys location in different geographical areas divided by the Italian peninsula. Namely, the western buoys (Alghero, La Spezia, Ponza and Mazara) measure waves coming mainly from II and III quadrants, whilst the wave

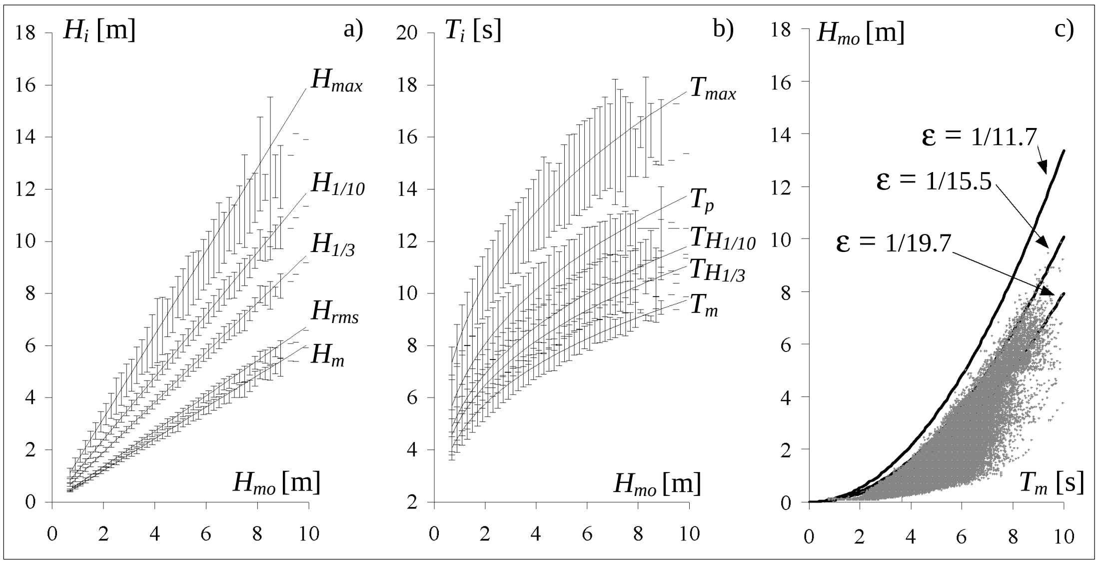

Figure 2. Correlations between spectral and zero-upcrossing wave parameters (averaged for all 8 stations).

recorded by the eastern buoys mostly come from the north. The wave intensity from south is everywhere milder and the frequency of the events is generally smaller, except in the Adriatic (Pescara and Monopoli) and Ionian (Crotone) Seas, where the wave climate is bimodal around the N and S-SE directions. Finally, the western stations are characterized by higher waves and the eastern ones have a marked seasonal variability.

Despite the above mentioned differences, due to the lack of space, only general averaged statistical correlations between wave parameters recorded at all 8 stations are described in the following. All notations of wave parameters follow the IAHR-PIANC list (Darras, 1987).

In particular, aiming to provide a better statistical characterization of short-term sea states, the spectral wave parameters, which are routinely computed, have been correlated with the zero-upcrossing ones. The time analysis of all the raw records was carried out and its results also provided useful information to fill the accidental gaps, particularly those occurring during storms. Figure 2 shows all the obtained correlations as well as the mean and standard deviation of the zero-upcrossing wave heights (fig. 2a) and periods (fig. 2b) grouped by H_{mo} classes. Typically, H_{mo} is about 5% larger than $H_{1/3}$ (fig. 2a). The best fit regressions among H_{mo} and $H_{1/10}$, H_{rms}, H_m ($H_{1/10}$=1.20H_{mo}; H_{rms}=0.68H_{mo} and H_m=0.61H_{mo}) show a good agreement with the correlations theoretically based on the Rayleigh distribution ($H_{1/10}$=1.21H_{mo}; H_{rms}=0.68H_{mo} and H_m=0.58H_{mo}). The regression between H_{mo} and H_{max} results in a ratio (H_{max}/H_{mo}=1.60) slightly smaller than the theoretical one (H_{max}/H_{mo}=1.65).

The regressions among H_{mo} and T_{max}, $TH_{1/10}$, $TH_{1/3}$, T_m, T_p (fig. 2b) pointed out a cubic relationship, which is in agreement with the JONSWAP relation (Hasselmann et al., 1973). This kind of law involves a linear dependence between the mean period and the significant wave steepness, defined as $\varepsilon=2\pi H_{mo}/\left(gT_m^2\right)$. Figure 2c shows in fact that a constant value of ε gives poor fit to the total data even if the plot is bounded on the upper side by the curve ε=1/15.5. Also, the curve ε=1/19.7 (which corresponds to the Pierson-Moskovitz spectrum related to fully arisen sea) seems to fit only the lower part of the plot for H_{mo}>5m.

When characterizing a short-term sea state by only H_{mo} and T_p, the spectral shape is generally not completely defined. The shape variability is mainly reflected in an unsettled peakedness of the wind-generated part of the spectrum and in an undefined characteristics of the more or less frequent swell component. Accordingly, in order to describe completely the wave climate, the recorded wave spectra have been parameterized with an automatic fitting procedure, which was validated by Monte Carlo simulations. In the next section the parameterization procedure is briefly outlined and the obtained results are shown, whereas the Monte Carlo validation was not included for brevity.

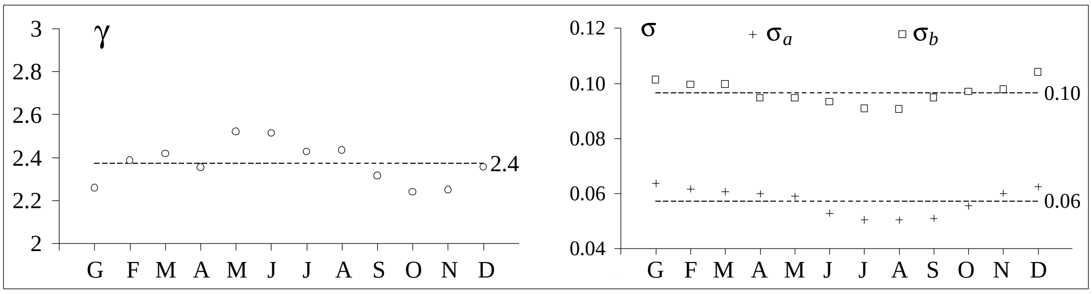

Figure 3. Seasonal variation of the averaged $\bar{\gamma}$, σ_a and σ_b for unimodal spectra.

SPECTRAL SHAPE CHARACTERISTICS

In the present work the parametric model used to represent the spectrum of random wave fields is the JONSWAP one. This formulation, obtained by Hasselmann et al. (1973) through the analysis of wave data recorded in the North Sea, is widely used around the world. For example, according to Evans and Kibblewhite (1990), this spectral shape can be fitted quite satisfactorily to the spectra measured in the south Pacific.

It must be noted that the JONSWAP spectrum accounts only for wind-driven seas and it is therefore a unimodal distribution. The fitting procedure is as follows: the shape parameter α is evaluated by Least Squares Method in the range $1.5f_p \leq f \leq 3.0f_p$. Afterwards, the peak enhancement factor (γ) can be easily found. Finally, the peak width factors σ_a ($f < f_p$) and σ_b ($f > f_p$) are evaluated by LSM in the range $0.9f_p \leq f \leq 1.1f_p$.

The parameters derived from a total of 40,743 unimodal spectra were analyzed for their statistical properties. Namely, the relations γ–T_p and γ–H_{mo} as well as the seasonal change of γ were investigated. The mean value of γ deviates significantly from the classic one: actually $\bar{\gamma}=2.4$, smaller than 3.3 (Ochi, 1998). A similar result ($\bar{\gamma}=1.9$) was previously obtained by Franco and Archetti (1993) using a different technique and analyzing spectra with H_{mo} > 2m.

Figure 3 shows the seasonal variation of $\bar{\gamma}$, σ_a and σ_b. It can be observed that in the summer the unimodal spectral shape is slightly narrower than in other months ($\bar{\gamma}$ increases and both σ_a and σ_b decrease). Conversely, winter is the season with broader spectral shape. Finally, figures 4a and 4b show the correlations between γ–H_{mo} and γ–T_p. Namely, the best fit lines are reported with mean and standard deviation of the enhancement factor, computed by classes of wave height (step 0.5m) and peak period (step 0.5s) using all the data. A parabolic dependence seems to exist between γ and H_{mo} ($\gamma = 0.025H_{mo}^2 - 0.282H_{mo} + 2.645$), with a minimum of γ=1.86 for H_{mo}=5.6m. On the contrary, an inverse power dependence exists between γ and T_p ($\gamma = 7.2T_p^{-0.631}$), quite similar to the one proposed by Mitsuyasu et al. (1980).

However, not all the sea states have single peaked spectrum whereas they are frequently due to the interference of various wave systems. As a consequence, the measured wave spectra often have additional peak (see fig. 5) and therefore a model given by the superposition of two JONSWAP spectra had to be used (see fig. 6). From a theoretical point of view a swell can not be described by a JONSWAP spectrum because of the lack of a real saturation

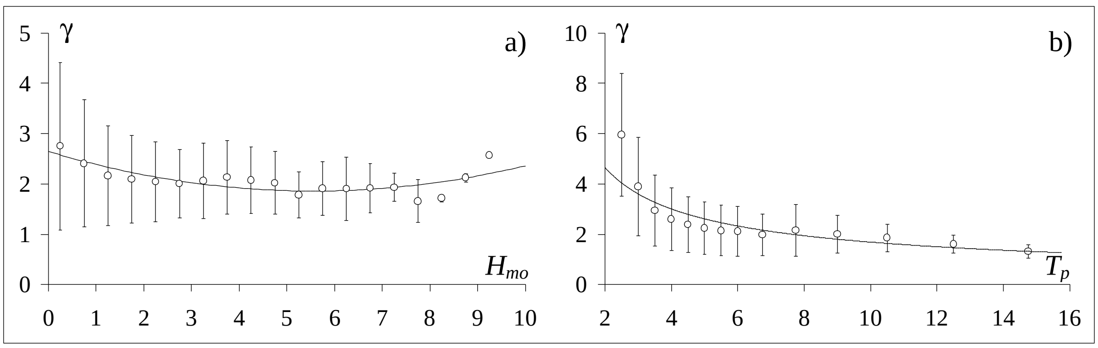

Figure 4. Correlations between γ–H_{mo} (a) and γ–T_p (b). Comparison of the obtained regressions with the mean and standard deviation of γ, computed by classes of H_{mo} and T_p.

band. It must be stressed however that the bimodal spectra measured around the Italian coasts are not resulting from the interference of ocean swells with local wind systems but they are usually related to sea states produced by wind rotation along the generating area. Moreover, the combination of limited fetch and wind field extensions can barely yield a swell system development. Therefore, the low frequency peaks are not related to oceanic swell but more properly to decaying seas with higher periods. This remark is confirmed by fig. 7, which shows the occurrence frequency of the periods related to the low and high spectral peaks. Finally, it is noted that almost all the observed bimodal spectra have low energy level (see fig. 5), denoting local generation condition.

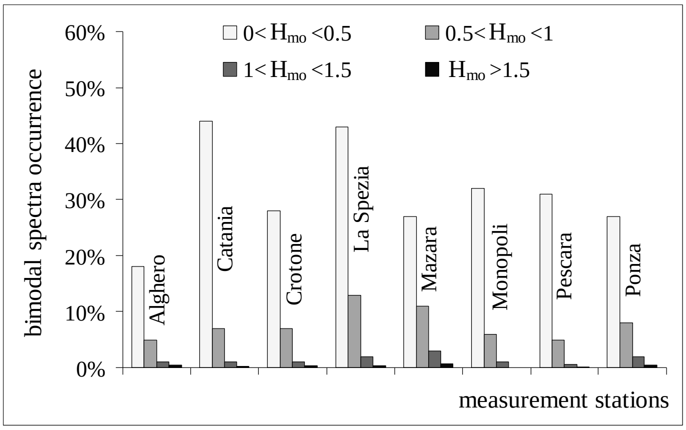

Figure 5. Occurrence of bimodal spectra for different significant wave height class at the original 8 SWAN buoys.

The fitting procedure is as follows: the first task is the peak number identification. The programmable identification criterion of the bimodal distribution was based on a minimum frequency difference combined with the lower 90% confidence limit requirement. Namely, the peak frequencies must be spaced at least by Δf = 0.03Hz and the smallest energy density in the range $f_{p1} < f < f_{p2}$ must be lower than the 90% confidence limit of the lower peak (Soares, 1984 and Aranuvachapun, 1987a-b). The peak number identification was significantly improved by using a logarithmic periodogram transformation (Rodríguez and Soares, 1999). The second task is the fitting of the 10 parameters model to the periodogram. An iterative procedure is used (see fig. 6): the high frequency peak (f_{p2}) is firstly parameterized as a unimodal spectrum; the fitted model is afterwards subtracted from the periodogram and the low frequency peak (f_{p1}) is parameterized fitting the residual energy density distribution. Therefore, the low frequency fitted model is subtracted form the original periodogram and the process restarts. The iterative procedure stops when the model parameters are stable.

The JONSWAP parameters derived from a total of 27,162 bimodal spectra were analyzed for their statistical properties. Namely, the mean value and the seasonal variation of the two peak enhancement factors γ_1 and γ_2 were investigated (see fig. 8). The mean value for the high frequency peak ($\bar{\gamma}_2 = 2.5$) is very similar to the unimodal one, whereas that for the low frequency peak ($\bar{\gamma}_1 = 4.0$) is much higher. The seasonal change of the bimodal averaged shape is different from the unimodal one. Actually, both the high and low frequency peaks are narrower in fall and winter whilst they are slightly broader in spring and summer, when bimodal spectra have longer persistence and are more frequent than in other months. Furthermore, in these seasons the frequency difference between the spectral peaks is reduced as well as the ratio between the modal energies (fig. 8).

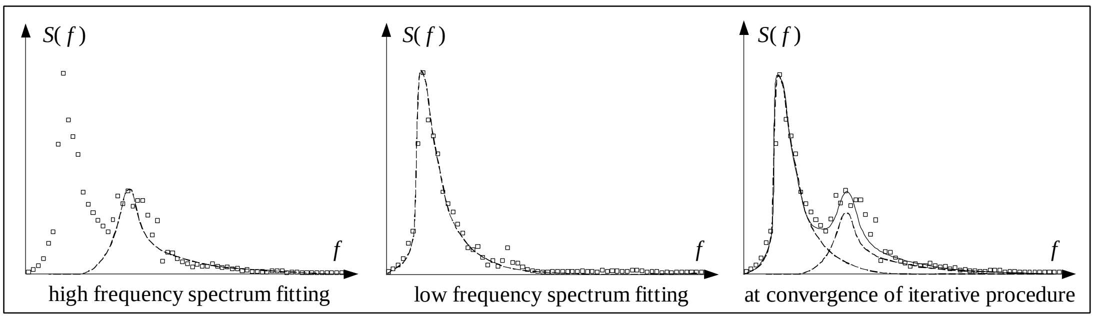

Figure 6. Fitting of ten parameters model to bimodal spectra.

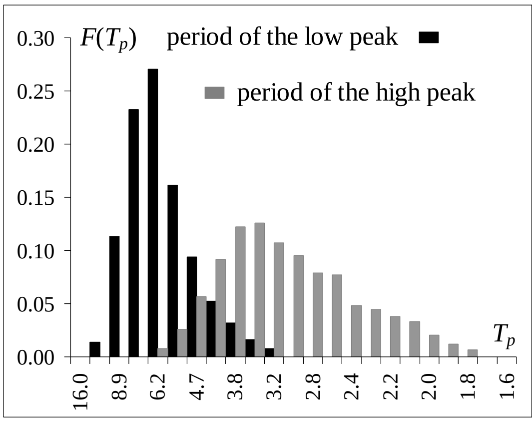

Figure 7. Occurrence frequency of peak periods for the low and high modes of bimodal spectra.

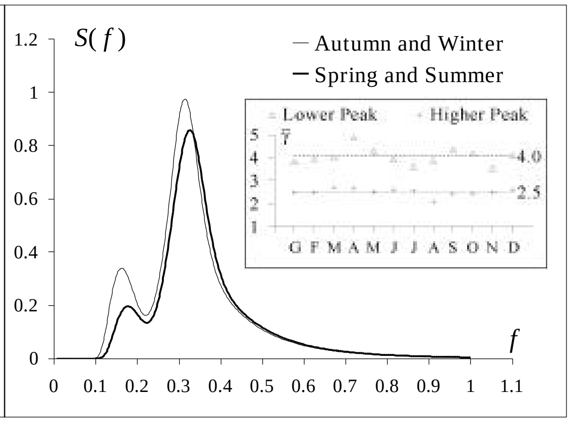

Figure 8. Seasonal change of both the averaged bimodal shape and the γ of lower and higher modes.

DIRECTIONAL ANALYSIS OF EXTREME WAVES

In the present paper the POT method was adopted. The annual maxima method was not considered due to the limited number of monitored years. The methodology used was recommended by IHAR working group on Extreme Wave Statistics (Mathiesen et al., 1994).

Many Authors have used the POT method. In Italy Archetti and Franco (1995) on the basis of SWAN and other buoy data recorded up to 30.6.1995 made the first comprehensive study about extreme waves. The difference between the various studies arises mainly in the selection of the extreme samples over which the procedure is applied. Therefore, great attention must be paid to extract only the peak significant wave heights of independent and homogeneous storms. Aiming to assure the sample independence, the data selection was based on the time series auto-correlation properties. Moreover, in order to preserve the homogeneity of the extreme sample, a directional analysis was carried out.

a - Definition of the wave directional sectors

With the aim of providing more reliable long-term statistics new criteria are used to define the directional sectors, which were delimited by comparing the directional frequency of the observed wave heights with both the directional distribution of storm highest wave heights and the geographical fetch (fig. 9). The sector limits for each station are outlined in table 1.

b - Selection of independent and homogeneous episodes

In the present work the following procedure was carried out:

1) identification of each storm in the time series;
2) choice of the independent peak from the storm series;
3) selection of the homogeneous sample from the peak series.

The identification of a storm peak is quite trivial as soon as the storm itself is defined. Aiming to automatically detect the development of a storm, some simple criteria were adopted: the storm

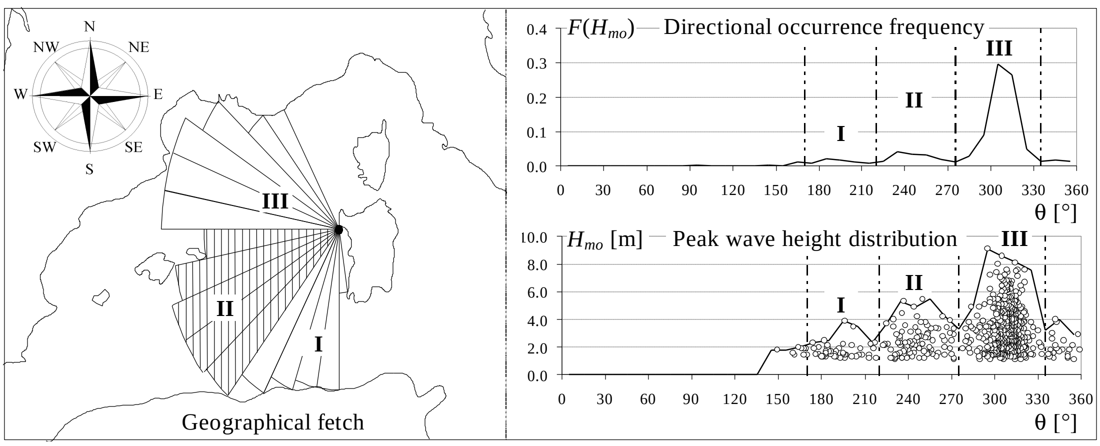

Figure 9. Definition of the directional sector for POT analysis at Alghero buoy.

starts when the wave height crosses upward the 1m threshold while it ends when the wave height persists below the same level at least for 6 hours. During the development of a sea state, if the wave direction varies more than 60° a storm ends and another one starts.

The independent peak heights were chosen from the storm series on the basis of the auto-correlation properties of the measured data. Namely, the auto-correlation function $c_{HH}(k)$ was evaluated over the complete 12-year three-hourly data set for all buoys with lags ranging from k=1 to k=32 (i.e. from 3 hours to 4 days). For all buoys c_{HH} (16) (corresponding to the lag of 48h) was found in the range 0.4-0.3, values small enough to consider the data weakly correlated. Therefore, only the storm peaks lagged by at least 48h were considered. Finally, aiming at selecting a homogeneous population, the independent height sample must be further sieved.

Generally speaking, storm waves can be generated by different meteorological disturbances; therefore they belong to different populations and should be analyzed separately. In particular, storms in Mediterranean seas are generated by cyclonic or anticyclonic systems. In this case, the data censoring is aimed to make a distinction between severe and mild storms. From a physical point of view, this distinction reflects different dimensions and intensities of the meteorological perturbations, which in fact can be related to large systems involving a European length scale or to local disturbance generated by mountain ridges and affecting regional areas.

According to the POT method, a wave height can be defined as extreme when it exceeds a given threshold. A thorny problem concerning this technique is just the threshold selection. Figure 10 shows the influence of the threshold level on the estimated 50 years return wave height at 4 SWAN stations. Actually, no dominant trend can be inferred except for Alghero station, where H_{50} constantly decreases as H_{thr} increases. Therefore, a general rule is needed to fix the threshold. Many criteria were proposed in the past, e.g. fixing the annual mean number of storms or assuming the threshold equal to the averaged maximum peak occurring during the calm season.

In accordance with the trend detected at Alghero, Van Vledder et al. (1993) found that "a lower threshold gives more peak wave data, which increase the estimated return wave height" and they suggested to fix the threshold at such a level to obtain a sample of 50-70 data. Nevertheless, a detailed analysis performed by means of the synoptic outputs of ECMWF meteorological model on the 80 major storms occurred in the Italian seas has shown different meteorological characteristics of storms which have developed in the western and eastern seas. Accordingly, a fixed storm mean rate per year does not seem to satisfactory fit to all the irregular Italian seas. Due to the different seasonal wave climates of eastern and western stations, in the present study it was preferred to set the threshold (H_{Thr}) equal to the maximum storm peak occurred in summer. An exception was made for the Crotone dataset because of the poor fit obtained. In this case, the threshold level was increased (Mathiesen et al., 1994).

Finally, it must be stressed that the censored sample analysis involves another sensitive aspect, which is related to the sample size used in the plotting position formula (see eq. 1). Actually, Goda et al. (1993) found that the LSM (as well as the MLM) "yield the prediction of the best-fitting distribution skewed toward the function with longer tail" when the actual sample size (n) was used instead of the total sample size (N_T). However, the Authors used a

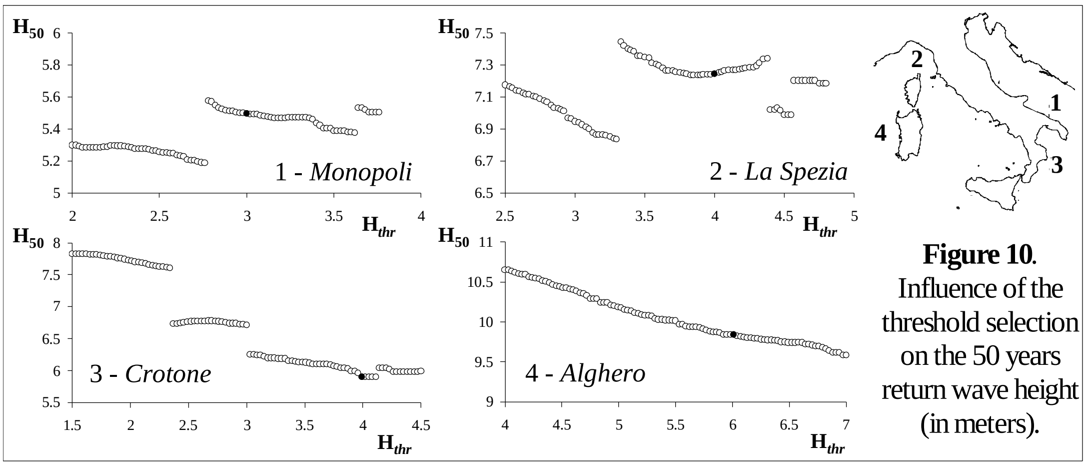

Figure 10. Influence of the threshold selection on the 50 years return wave height (in meters).

censored data that were obtained by discarding the below-threshold elements of randomly generated homogeneous populations. In the present work, the generation and analysis of mixed populations (which were assembled by joining data extracted from two different Weibull distributions) have shown that neither the actual sample size nor the total sample size ensure unbiased estimates. Actually, the results obtained from 30,000 Monte Carlo simulations performed using N_T show a normal distribution around an over-predicted mean value, whereas the results obtained from 30,000 Monte Carlo simulations carried out using n show an asymmetrical distribution around the true mean (larger than the modal value); these findings call for a more careful study. Anyway, in accordance with Goda et al. (2000), who stated the importance of splitting mixed populations into homogeneous parts, it was supposed that the data below and over the second threshold belong to different populations. Therefore, the actual sample size n refers to a homogeneous extreme sample (ideally uncensored) and so n was used in the plotting position eq. (1) instead of N_T.

c - Distribution function and return value estimates for extreme events

The selected peak series was ordered to find the best fit by means of a parametric probability distribution function. The employed method is fully described by Goda (1988). A rank index i was then associated to the ordered array (i ranging from 1 to n). The following plotting position formula was used to determine the no-exceeding probability of the array elements:

$$F(H_i)=1-\left[i-\left(0.2+0.27/\sqrt{k}\right)\right]/\left[n+\left(0.2+0.23/\sqrt{k}\right)\right] \qquad (1)$$

The candidate probability distributions were the 3-parameters Weibull, given by

$$P(H\geq x)=1-\exp\left[-[(x-B)/A]^k\right] \qquad (2)$$

with 4 different values of k (k_1=0.75, k_2=1.0, k_3=1.4, k_4=2.0). In eq. (2) A, B and k are respectively the well-known scale, location and shape parameters. The Least Squares Method was used to compute the set of A, B and k which gives the best data fitting. The goodness-of-fit was tested by the MIR criterion (Goda and Konube, 1990), i.e. the most likely distribution is assumed to minimize the following ratio

$$\Delta r/\overline{\Delta r}=(1-r)/\exp\left[c_1+c_2\ln n+c_3(\ln n)^2\right] \qquad (3)$$

where r is the correlation coefficient and c_1, c_2, c_3 are coefficients depending on k and ν (the censoring parameter which is defined as n / N_T and herein posed equal to 1).

According to the general definition, H_{mo} corresponding to the return period T is:

$$H_{mo}|_T=B+A[\ln(\lambda T)]^{1/k} \qquad (4)$$

where $\lambda=n/\Delta T$ is the storm mean rate per year and ΔT the measurement period. A confidence interval of $H_{mo}|_T$ was estimated with the standard deviation $\sigma=\sigma_r\sigma_H$, which is the product of the sample standard deviation (σ_H) and the following dimensionless deviation:

$$\sigma_r=\sqrt{1+c_4\left\{[\ln(\lambda T)]^{1/k}-c_5+c_6\ln\nu\right\}^2}\Big/\sqrt{n} \qquad (5)$$

where the coefficients c_4, c_5, c_6 are depending on k and are given by Goda (1998).

d – Obtained results

The influence on the estimated return value of the dataset size is shown in fig. 11, where the deviation ratio, which is defined by

$$d_{\%}=100\left(H_{50}^{i}-H_{50}^{2000}\right)/H_{50}^{2000} \qquad (6)$$

is plotted against the monitored years number. In eq. (6) H_{50}^{2000} is the 50 years return wave height computed from the complete dataset while H_{50}^{i} are the ones computed by using a i+1 years dataset (i=1…10). Figure 11 suggests that all directional extreme estimates are becoming stable except for the southern sector of La Spezia, which was affected by an extraordinary storm during November of 2000 (Piscopia et al., 2001). The large difference between the return wave heights estimated till 1999 and the one computed from the whole dataset is clear in the light of both the small number of peak heights over the 2 m threshold and the large ratio between the maximum (H_{max}) and the mean (H_m) values of the storm peaks (see table 1).

The return values of H_{mo} corresponding to periods of T=1,10,50 years and referring to the complete dataset are shown in table 1 for all measuring stations along with the values of A, B, k, c_4, c_5, c_6, λ, σ_H, n, H_{Thr}. In figure 12 the geographical distribution of the Weibull shape parameter is reported: the southern sectors of western stations can be clustered in a group characterized by k=0.75, whilst the north and western sectors of the same stations can be characterized by k=1.0, except the NW sector of Alghero buoy which shows a larger shape parameter (k=1.4). Also, the southern sea areas are uniformly marked by k=1.4 together with the northern Adriatic Sea whereas the southern Adriatic and the northern Ionian show a shape parameter equal to 1.0.

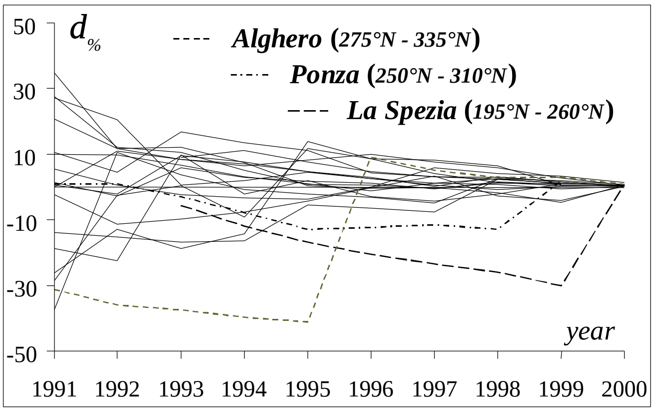

Figure 11. The influence on the estimated return value of the dataset size for all buoy directional sectors.

Although the shape of the extreme distribution are suitably clustered in geographical areas, a complete comparison between the Weibull parameter set is very difficult, particularly with the aim of describing the behavior of the right-hand tail of the distribution, which influences in fact the long-term performance of maritime structures. With the goal of efficiently describe the tail characteristics, Goda (2001, 2002) has proposed the new spread parameter which is defined by

$$\gamma_{50} = H_{50} / H_{10} \tag{7}$$

Table 1 shows the obtained results for the Mediterranean case: the mean γ_{50} values, which were computed by clustering the data with the same k, are in good agreement with those published by Goda (2001). Furthermore, clustering γ_{50} by similar directional sector, makes it possible to draw the following conclusion: the southern fetches are characterized by the greater γ_{50} (1.22±0.12), i.e. by distribution function with longer tail, the Western and Eastern sectors have quite similar spread parameter (respectively γ_{50}=1.16±0.04 and γ_{50}=1.18±0.04), whilst the northern sectors show the distribution functions with shortest tail (γ_{50}=1.14±0.04). At last, considering only the main sectors of all buoys makes $\overline{\gamma_{50}}$ equal to 1.15, which is quite similar to that obtained by Goda (2002) for the Japan Sea.

Finally, aiming at validating both the hypotheses herein made about the plotting position formula and the achieved results, a different technique to compute the spread parameter was adopted. Actually, a sample of external data is mainly characterized by its mean and standard deviation. These values can be related to the distribution parameters as well as to the return wave height. By using these correlations makes it possible to write the following expression of the spread parameter (Goda, 2002):

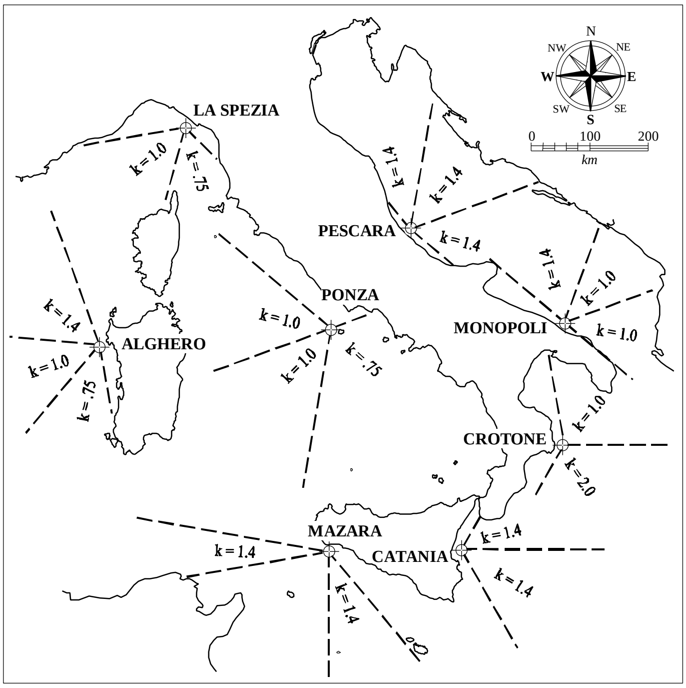

Figure 12. Geographical distribution of the shape parameter.

Table 1: Extreme Wave Statistics, 1989-2000, SWAN, Mediterranean Sea

Measuring Station	A	B	k	c_4	c_5	c_6	λ	σ_H	n	H_{thr}	H_m	H_{max}	H_{10}	H_{50}	σ_{50}	γ_{50}
Alghero (170-220)	0.40	2.01	0.75	2.39	0.0	1.15	1.24	0.58	15	2.0	2.5	3.9	3.4	4.7	1.44	1.38
Alghero (220-275)	0.68	3.12	1.00	2.19	0.3	0.90	2.75	0.66	32	3.0	3.8	5.5	5.4	6.5	0.63	1.20
Alghero (275-335)	1.17	5.89	1.40	2.21	0.4	0.72	4.26	0.76	46	6.0	7.0	9.1	8.9	9.8	0.38	1.10
Catania (30-90)	1.07	2.40	1.40	2.40	0.4	0.72	2.51	0.69	27	2.5	3.4	5.1	4.9	5.7	0.47	1.17
Catania (90-150)	1.30	2.28	1.40	2.33	0.4	0.72	2.98	0.84	32	2.5	3.5	5.7	5.4	6.4	0.52	1.19
Crotone (350-90)	0.50	2.99	1.00	2.33	0.3	0.90	2.10	0.48	23	3.0	3.5	4.7	4.5	5.3	0.55	1.18
Crotone (90-210)	0.92	3.96	2.00	2.79	0.5	0.54	1.91	0.42	21	4.0	4.8	5.6	5.5	5.9	0.24	1.07
La Spezia (135-195)	0.54	2.00	0.75	2.05	0.0	1.15	1.89	0.81	21	2.0	2.6	5.6	4.3	6.1	1.52	1.42
La Spezia (195-260)	0.60	3.94	1.00	2.09	0.3	0.90	3.97	0.59	44	4.0	4.5	6.6	6.2	7.1	0.42	1.16
Mazara (100-180)	0.89	2.85	1.40	2.40	0.4	0.72	3.01	0.57	27	3.0	3.7	5.2	5.0	5.7	0.39	1.14
Mazara (260-320)	1.04	3.27	1.40	2.21	0.4	0.72	5.35	0.68	48	3.5	4.2	5.9	6.1	6.8	0.34	1.13
Monopoli (310-10)	0.71	2.47	1.40	2.20	0.4	0.72	4.49	0.46	50	2.5	3.1	4.4	4.3	4.9	0.23	1.12
Monopoli (10-70)	0.58	2.52	1.00	2.09	0.3	0.90	3.86	0.56	43	2.5	3.1	5.1	4.6	5.6	0.45	1.20
Monopoli (70-130)	0.40	2.01	1.00	2.36	0.3	0.90	1.98	0.39	22	2.0	2.4	3.3	3.2	3.9	0.45	1.20
Pescara (320-10)	1.06	2.75	1.40	2.46	0.4	0.72	2.18	0.69	24	3.0	3.7	5.2	5.1	6.0	0.51	1.16
Pescara (10-70)	0.78	3.45	1.40	2.42	0.4	0.72	2.37	0.50	26	3.5	4.2	5.7	5.2	5.8	0.35	1.12
Pescara (70-130)	0.56	1.91	1.40	2.46	0.4	0.72	2.18	0.37	24	2.0	2.4	3.1	3.2	3.6	0.27	1.14
Ponza (70-190)	0.25	2.58	0.75	1.87	0.0	1.15	3.13	0.38	32	2.5	2.9	4.1	3.9	4.7	0.56	1.22
Ponza (190-250)	0.75	2.55	1.00	2.08	0.3	0.90	4.51	0.74	46	2.5	3.3	5.5	5.4	6.6	0.57	1.22
Ponza (250-310)	0.75	3.51	1.00	2.05	0.3	0.90	5.09	0.73	52	3.5	4.3	7.1	6.4	7.6	0.53	1.19

$$\gamma_{50} = 1 + \frac{\left[(\ln 50\lambda)^{1/k} - (\ln 10\lambda)^{1/k}\right]\sigma_H/(H_m \alpha\kappa)}{1 + \left[(\ln 10\lambda)^{1/k} - \beta\right]\sigma_H/(H_m \alpha\kappa)} \tag{8}$$

where α, β are function of the shape parameter while κ is function of both the shape parameter and the sample size (see Goda 2000). Eq. 8 was then used to compute γ_{50} for all the buoy sectors by means of just the statistical features of the selected sample. The obtained results have been compared with those reported in tab. 1. The comparison, which is shown in figure 13a, gives good evidence of both the hypothesis efficiency and of the estimate goodness. That evidence can be even strengthen by considering figure 13b, which refers to the comparison performed between the results obtained by eq. (8) and those achieved applying eq. (7) to the censored POT method (GODA, 1988) estimates. It is clear that using the total sample size in the plotting position formula gives generally overestimated results for the settled sectors, whilst provides underestimated results for the unsettled ones (i.e. for the southern La Spezia sector). In short it could be stated that for the Italian seas the use of the actual sample size provides better results.

HEIGHT PERSISTENCE OVER THRESHOLD

The model proposed by Mathiesen (1994) was adopted to estimate the averaged duration of a sea state over a given wave height threshold. The method assumes that both the H_{mo} distribution and H_{mo} average rate of change determine the threshold exceedance duration. All the observed data in the 3-h time series were taken into account. The expression for the average duration of exceedance of a threshold H is

$$\tau(H) = 2P(H)/\left[f(H)S(H)\right] \tag{9}$$

where $P(H)$ is the Weibull distribution, $f(H)$ is the probability density function, $S(H)$ is the H_{mo} rate of change, empirically posed proportional to the r power of H_{mo}, i.e. $S(H) = qH_{mo}^r$. The parameters q and r are determined from the time series. Figure 14 shows that, when the H_{mo} threshold levels and the time duration are suitably made non dimensional by using respectively a length and a time scale, the relation $\ln(\tau^*) = -\beta \ln(H^*)$ holds for all the buoys. The non-dimensional τ^* and H^* are respectively given by $\tau^* = \tau/1$ and $H^* = H_{mo}/\exp(-\alpha/\beta)$ with α and β site depending parameters, which were determined by means of power-law regressions. The results are reported in table 2: β is close to a value of 2 on the average, being in the range 1.5÷2.3, whilst α is strongly site dependent, being function of the maximum observed H_{mo}.

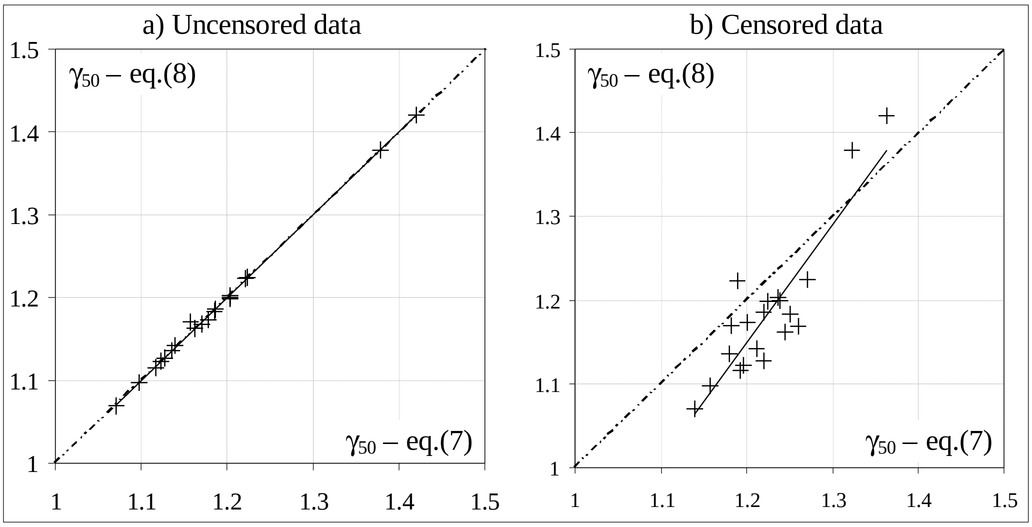

Figure 13. Comparison of the shape parameter computed by means of both the POT inferences and the selected sample statistical features: a) uncensored sample; b) censored sample.

ANALYSIS OF THE MAJOR STORMS AND LONG-TERM WAVE VARIABILITY

Aiming to obtain a deeper insight into the extreme wave climate of Mediterranean seas, both a meteorological analysis of the major storms occurred in the Italian seas and a long-term analysis of wave height variability were carried out.

It should be noted that the identification of the wave height interannual variability could be useful to explain part of the extreme event variance, therefore giving more accurate statistical forecasts. Moreover, interannual variability of the wind wave characteristics could be considered as an effective sign of climate changes in the atmospheric circulation, because sea waves are influenced by the surface wind characteristics in space and time. A detailed description of this matter is beyond the purpose of the present paper. However, preliminary results agree quite well with those obtained by Carter and Draper (1988) and Gulev and Hasse (1999). Namely, we observe that in the western Italian seas the mean wave height increases at a mean rate of 0.1m per decade, whilst in the southeastern Italian seas the mean wave height shows a negative trend at a mean rate of 0.1m per decade.

Moreover, a detailed meteorological analysis was performed on the 10 major storms recorded at each measuring station by complementing the buoy data with the synoptic outputs of meteorological and wave models running at ECMWF. Some results have been published by Arseni et al. (2000), Piscopia et al. (2001) and Palmieri et al. (2002). It is found that the meteorological perturbations which generate storms in southeastern Italian seas are generally local disturbances, whilst the perturbations which generate storms in western Italian seas are usually large system developing on a European length scale. This meteorological difference is confirmed by the maximum H_{mo} values measured in the two areas (see Table 1 - H_{max}):

Table 2: Duration Statistics

Station	β	α
Alghero	2.3	0.58
Catania	2.0	0.69
Crotone	2.3	0.48
La Spezia	1.8	0.81
Mazara	2.0	0.57
Monopoli	2.1	0.46
Pescara	1.9	0.69
Ponza	1.5	0.73

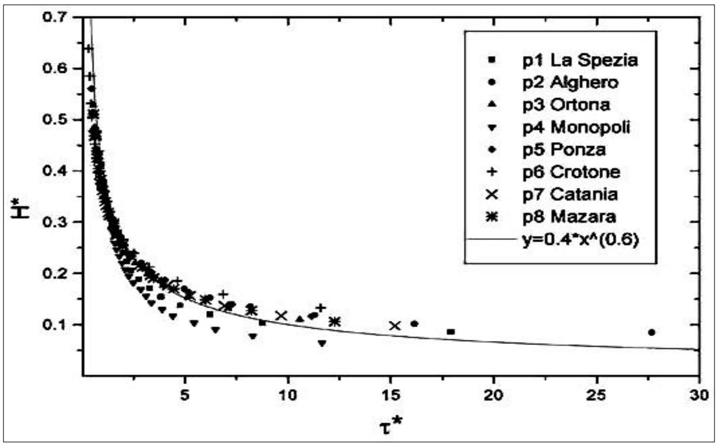

Figure 14. Wave height duration over threshold for all the 8 original SWAN buoys.

namely, despite the longest fetch extension, Crotone and Catania are affected by storms with the lowest peak heights. Moreover, this difference probably causes the different interannual trend shown by the series measured in western and southeastern seas.

CONCLUSION

The systematic analysis of 12 years of an excellent set of directional wave data from 8 stations in the Italian Seas allows a better definition of the characteristics of the wave climates especially during storm conditions. The wave statistics herein described will be also issued in the form of an Atlas to provide useful guidance for oceanographers, shipping operators and coastal engineers.

A few interesting finding can be summarized here: *1)* the ratio between H_{max} and H_{mo} in a 20 min. record is equal to 1.6 on average, value in a good accordance with the theoretical one (1.65); *2)* the routinely computed H_{mo} is generally 5% greater than $H_{1/3}$; *3)* H_{mo} and T_{max}, $TH_{1/10}$, $TH_{1/3}$, T_m, T_p are related by a cubic law, which is in agreement with the JONSWAP results and it is reflected into the linear dependence existing between T_m and ε; *4)* the mean value of the peak enhancement factor for an unimodal spectrum is 2.4, which is less than the standard one (3.3); *5)* bimodal spectra frequently occur, especially in the calm season and for low energetic sea states; *6)* a log-log relationship exists between the threshold exceedance duration and the wave height.

The main results about extreme wave analysis carried out with a modified POT method are: *1)* the use of the actual sample size (n) in the plotting position formula gives better results than the use of the total sample size (N_T); *2)* the southern wave sectors are characterized by milder storm and by distribution function with longer tail, (γ_{50} = 1.25); *3)* the northern sectors are characterized by distribution functions with the shortest tail; *4)* clustering and averaging γ_{50} of the main sector of all the buoys, makes the mean spread parameter equal to 1.15, a value which is in good agreement with the one obtained by Goda (2002) for the Japan Sea; *5)* the severest storms occur in the western Mediterranean seas and are incoming from NW.

ACKNOWLEDGEMENTS

This work was funded by the Italian National Hydrological and Marine Survey under contract Conv.7-97/pos.65/Rep.088.

The authors are grateful to Prof. Y. Goda for the valuable advice and the fruitful discussions. Moreover, the authors thank Eng. Lorenzo Belloni and Guido Bentivoglio for their useful contribution to the analysis of major storms.

Finally, the authors acknowledge the ECMWF, which provided the synoptic output of both meteorological and wave model.

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ANALYSIS OF 12-YEAR WAVE MEASUREMENTS BY THE ITALIAN WAVE NETWORK

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Stefano CORSINI[2] and Leopoldo FRANCO[4]

Wave Measurements
Wave Monitoring network
Spectral shape
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