Long term directional wave recording in the Northern Adriatic Sea (*)

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(ricevuto l'1 Aprile 1996; revisionato il 26 Agosto 1996; approvato il 23 Settembre 1996)

Summary. — We report on the instrumental system used on an oceanographic tower for the directional measurement of wind waves. The associated time series is one of the longest ones in the world. After a compact description of the instrumental part, we present some long term statistics of the wave conditions in the Northern Adriatic Sea. Then we discuss the applications of the results and the possible evolution of the system.

PACS 92.10 – Physics of the oceans.
PACS 92.10.Hm – Surface waves, tides, and sea level.

1. – Introduction

In July 1978 we installed on an oceanographic tower in the Northern Adriatic Sea a directional wave recording system. One year later we reported the first results in Cavaleri *et al.* (1981). Today, after 18 years, the system is still at work. It is probably the longest wave record in Italy, certainly the longest directional one and, as such, one of the longest ones in the world.

With this paper we want to provide a compact description of the system. First (sect. **2**) we describe the general outline and the recording system. The analysis technique is given in sect. **3**, while sect. **4** is devoted to show some summarizing results. Finally, in sect. **5**, we outline the main applications of the results and the future evolution of the system.

2. – The wave recording system

The wave recording system is installed on the oceanographic tower of the Istituto Studio Dinamica Grandi Masse, located in the Northern Adriatic Sea, on 16 metres of depth, 15 km off the coast of the Venice lagoon. The tower is equipped with a wide range of instruments. These include a complete meteorological station, a full spectrum of oceanographic instruments, chemical and optical measurements and, last but not least, several wave gauges. For the latter ones, the kind of instrument depends on the aim of the measurement. For long term, automatic recording we use three pressure transducers. For our purposes these have several advantages. They are small, sturdy, cheap, reliable, accurate, with low power requirements. Besides, they are placed under the

(*) The authors of this paper have agreed to not receive the proofs for correction.

surface, out of the occasional reach of eventual curious visitors or floating objects. The transducers are firmly located on three legs of the tower, at the corners of a rectangular triangle with the cross sides of 9 metre length. The three legs look, respectively, at the North, East and South direction. Three small horizontal frames keep the transducers at 1.2 m distance from the legs ($\phi = 0.60$ m). Manufactured by Bell&Howell, they are immersed in silicon oil, the water pressure being transmitted via a soft plastic membrane.

The three instruments are located at about 5 metres of depth, below the lowest wave troughs. A double pulley system allows their easy recovery without the need of a diver and independently of the wave conditions.

Power supply is by DC from the onboard batteries system. The electronics is located on the third floor of the tower, in the instruments room. The transducers are powered every three hours, at synoptic times, for 20 minutes. First, the system records for one minute. Evaluation of the overall excursion of the signal and comparison with a preestablished threshold leads to the decision of either skipping the record or to proceed with a 1024 s one. The sampling frequency is 1 Hz. A higher sampling rate has not been considered because the corresponding wave frequency components would be completely attenuated at 5 m depth.

The transducers provide a 5 VDC output for 16 or 25 m range with respect to the atmosphere. However, most of the time the output range actually used is only a fraction of the full scale. Hence, for an optimal use of the resolution (1/256), the signal, after subtraction of the approximate average deduced from the initial one-minute record, is amplified to make full use of the resolution.

The data are stored on solid state memory, and retrieved by PC control. Assuming continuous stormy conditions, *i.e.* one full record every three hours, the self-sufficiency of the system is 32 days. When the memory is full, the system loops on itself, overwriting the first records. This is done on the principle that, if we cannot go on board to retrieve the data because of stormy conditions, it is worthwhile to record them.

3. – Data analysis

For each record we have three time series available from the three transducers, each composed of 1024 pressure values.

The analysis is based on the method of Longuet-Higgins *et al.* (1963), modified and improved by Kuik *et al.* (1988). In principle the directional analysis could be carried out on the pressure values. However, the analysis is based on slopes, hence differences between the signals. As the transducers are not at the same depth, their signals are not similarly attenuated, which would spoil the analysis. Therefore, prior to the analysis each signal is transformed into a surface profile by means of the linear theory. During this operation care is required for the noise introduced in the high-frequency range. We have mentioned above that the recording resolution is 1/256. In practice this introduces a one unit white noise, showing up in the analysis as a white spectrum. Negligible with respect to the original pressure signal, the noise is strongly amplified in the high-frequency range, leading to unrealistic shapes of the surface spectrum. To avoid this, some numerical tests have suggested a convenient cut-off frequency, after which, only for energy evaluation purposes, the spectra are closed with a f^{-5} frequency tail.

The procedure followed for the directional analysis is amply documented in the literature. We give here only a qualitative description of it. For the specific formulas the interested readers are addressed to the quoted references.

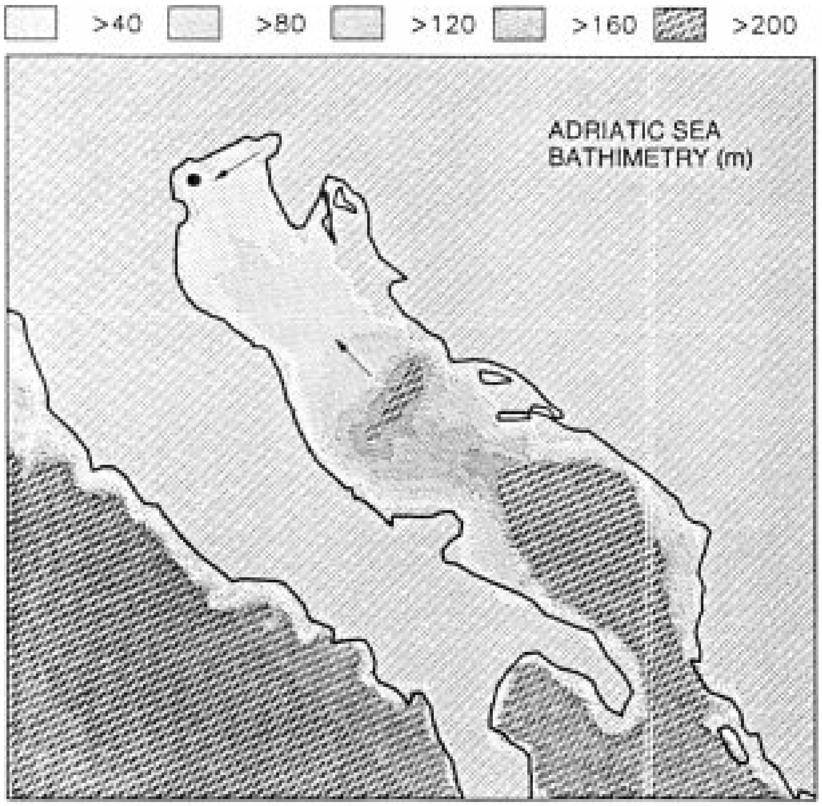

Fig. 1. – The Adriatic Sea. Its dimensions are about 750 × 200 km. The dot shows the position of the oceanographic tower. The two arrows indicate the main winds determining the wave climate in the northern area.

We start from the three surface signals or, which is equivalent, as originally done by Longuet-Higgins *et al.* (1963), from the surface elevation and the two cross slopes out of a pitch-roll buoy. By applying standard cross-spectral analysis to these signals, resulting in 9 auto-, co- and quad-spectral density functions, the first four Fourier coefficients of the directional distribution per frequency can be estimated, as a_1, b_1, a_2, b_2. We drop for simplicity the f dependence. Then, following Kuik *et al.* (1988), we assume four definitions for the mean direction θ_m, the spread σ, the skewness γ and the curtosis δ, evaluated on the basis of the above coefficients. The definitions are physically sound, free from model assumptions and computationally efficient.

In practice, from each record we obtain the one-dimensional spectrum, θ_m, σ, γ and δ for each frequency, and the usual summarizing parameters as significant wave height H_s, the mean frequency (period) f_m (T_m), and the mean flow direction θ_m.

It must be pointed out that this method cannot resolve bimodal spectra, *i.e.* when energy from two well separated directions is present in the same frequency bin. As a matter of fact suitable methods for this purpose do exist. Example are the variational method of Long and Hasselmann (1979), the data adaptive method of Oltman-Shay and Guza (1984) and the maximum entropy method of Lygre and Krogstad (1986). However, all these methods are computationally heavy and do not meet the efficiency requirements of a routine analysis. On the other side, the method of Kuik *et al.* (1988) provides some built-in checks to verify a possible bimodality in the input data.

On a more physical basis, bimodality in the same frequency bin is not frequent in the Northern Adriatic Sea. This is associated to the climatology of the area. As seen in fig. 1, two main winds regulate the wave climate in the Northern Adriatic Sea, namely bora and sirocco. Bora, which is cold, gusty and violent, produces steep waves from North-East. Due to the short fetch, about 100 km, the wave period ranges between 5 and 7 s. Sirocco, from South-East, acts on a much longer fetch, up to 750 km. Less violent and more stable, it leads to longer, less steep waves, with typical periods between 7 and 10 s. Therefore, even when the two winds act together in the basin leading to crossed sea conditions in the Northern Adriatic Sea, energy from different directions is not present in the same frequency range.

We must call attention to the fact that before 1989 the number of transducers was limited to two, placed on two opposite legs of the tower. This implied a different, and simpler, analysis technique, described in Cavaleri *et al.* (1981). The main limitation was the lack of basic information on σ, γ and δ, while T_m and θ_m were regularly available.

Once the three-transducer system was at work after 1989, we have analysed the data with both the techniques to check if their results were similar and consistent. No significant difference was found, and we were therefore allowed to proceed with a single statistics.

4. – Statistical results

The large volume of data recorded since 1978 allows a variety of analyses, that depend on the specific purpose of the research. Here we concentrate on some basic statistics.

Table I presents the statistics, normalized to 10 000, of the integrated parameter H_s. The "coordinates" of each class represent the upper limit of that specific class.

The H_s distribution shows an expected concentration on the low values. The lowest class (up to 0.5 m) includes also the cases of flat calm sea (better, of wave height below the detectable threshold), which are 23% of the total. In a very approximate way, there is a progressive halving of the percentage with increasing wave height.

Tables II and III show, respectively, the combined H_s-T_m and H_s-θ_m distribution, including the marginal distribution for mean period and direction. Note that these statistics have been derived from the cases when waves were actually present, which is why the marginal distributions for H_s differ from the one in table I.

The characteristics of the recording system, with the filtering of the shortest waves at the depth of the transducers and the 1 Hz sampling rate, are reflected into the marginal distribution of the shortest periods in table II. The peak is between 3 and 4 seconds, with most of the cases below 7 seconds. In the conditioned distribution for constant H_s the peak period increases regularly with wave height. This reflects the more or less constant average slope of the sea with varying wave conditions. Note the relatively high frequency of swell, *i.e.* of sea conditions with low wave height with respect to the period. In the table these are given by the numbers below the peak for each H_s value.

The directional distribution in table III turns out to be more interesting. Remember we always consider flow directions. Considering first the marginal distribution of θ_m, the small percentages from 0 to 210 degrees represent the limited number of cases when detectable waves come from land. The limited fetch and the usually limited wind speed

TABLE I. – *Percentual distribution of the wave height. The percentages are normalized to* 10 000. *In each class the height shows the upper value of that class.*

(m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
(perc)	6925	1682	747	324	184	80	40	13	5	0	0	0

TABLE II. – *Combined percentual distribution of wave height* (*horizontal*) *and period* (*vertical*). *The percentages are normalized to* 10 000. *In each class the height and period show the upper value of that class.*

	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	51	47	4	1	0	0	0	0	0	0	0	0	103
4	3562	582	162	19	4	0	0	0	0	0	0	0	4329
5	1948	944	263	144	52	10	0	0	0	0	0	0	3361
6	358	521	427	180	90	45	14	2	1	0	0	0	1638
7	75	53	86	62	79	43	32	13	6	0	0	0	449
8	28	7	14	9	11	3	2	0	0	0	0	0	74
9	11	6	4	2	1	2	3	2	0	0	0	0	31
10	5	3	0	0	0	0	0	0	0	0	0	0	8
11	4	1	0	0	0	0	0	0	0	0	0	0	5
12	2	0	0	0	0	0	0	0	0	0	0	0	2
	6044	2164	960	417	237	103	51	17	7	0	0	0	10 000

TABLE III. – *Combined percentual distribution of wave height* (*horizontal*) *and direction* (*vertical*). *The percentages are normalized to* 10 000. *In each class the height and direction show the upper value of that class.*

	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	
30	202	11	1	0	0	0	0	0	0	0	0	0	214
60	158	15	1	0	0	0	0	0	0	0	0	0	174
90	234	11	0	0	0	0	0	0	0	0	0	0	245
120	236	3	0	0	0	0	0	0	0	0	0	0	266
150	173	6	0	0	0	0	0	0	0	0	0	0	179
180	130	3	0	0	0	0	0	0	0	0	0	0	133
210	141	18	2	0	0	0	0	0	0	0	0	0	161
240	1378	669	234	60	29	17	6	1	0	0	0	0	2394
270	554	412	367	199	133	56	30	7	4	0	0	0	1762
300	942	271	112	66	35	19	13	5	2	0	0	0	1465
330	1571	553	170	65	36	14	4	4	0	0	0	0	2417
360	413	138	31	6	1	1	0	0	0	0	0	0	590
	6159	2110	918	396	234	107	53	17	6	0	0	0	10 000

from these directions impede the development of large waves. In the remaining sectors we clearly see the two main directions of action of the waves, namely bora (210–240 degrees) and sirocco (300–330 degrees). The intermediate directions represent all the various mix conditions possible in the Northern Adriatic Sea.

The two main wave regimes, bora and sirocco, are well shown also in the combined

H_s-θ_m distribution. All the three lower H_s classes have two-peaked distributions, corresponding to the two main wind directions. The two peaks merge with growing wave height, while the distribution narrows between 210 and 330 degrees. Note how the highest wave heights are along intermediate directions, an indication of the cross sea conditions often present during the worst storms in this part of the basin. See Bertotti *et al*. (1996) and Cavaleri *et al.* (1996) for a description of the various possible wave conditions in the area.

5. – Use of the results—evolution of the system

The general problem of the Venice lagoon, the protection of the littorals, the proposed construction of the barrages at the harbour inlets to protect the town from the periodic floods, are obvious areas of application of the wave data collected at the oceanographic tower.

Our results characterize the area in front of the Venetian coast. Two main lines of action can be immediately conceived. The first one concerns the use of the local wave climatology for long term calculation of the evolution of the littorals. The second one is the use of the extreme values for the design of the coastal structures, in particular of the proposed barrages. In either case the data need to be transferred to the coast. A wide range of possibilities exist for this problem, with different degrees of complexity. Sclavo *et al.* (1996), Osborne *et al.* (1996) and Viezzoli and Cavaleri (1996), among others, have shown the complexity of the problem. With different techniques, but all using the results available at the tower, these authors have evaluated the evolution of the wave conditions in the area between the tower and the coast and at specific locations of the coast itself.

On a wider perspective the measured wave data at the tower have been used to validate the long term hindcast of the wave conditions in the Adriatic Sea done by Bertotti *et al.* (1996). The hindcast covers the whole basin with a 20 km resolution grid and for the period 1980-1988. The calculations of the wave spectra have been done using WAM, a highly sophisticated wave model widely used and amply documented in the literature (see the two classical references WAM-DI, 1988, and Komen *et al.*, 1994).

Figure 2 shows a 40 day comparison between measured and modelled wave characteristics at the oceanographic tower. A more complete result is given in fig. 3, showing the overall scatter diagram between the measured and modelled quantities. The overall statistics indicates a bias of 0.1 m for the significant wave height, with a r.m.s. error of 0.5 m.

The validation of the wave results is twofold. On one side it validates the wave results, but implicitly it validates also the wind fields used as input to the wave model. The reason is that the waves represent an integrated effect, in space and time, of the driving wind fields. Besides, they are extremely sensitive to even small variations of the input fields. Any substantial error in the driving wind would have been dramatically reflected into the wave results. Therefore, the positive results at the tower implicitly validate the wind results (see Cavaleri *et al.*, 1996, for a full description of the wind hindcast in the basin). In turn, given the reliability of the WAM wave model, this ensures the quality of the wave hindcast throughout the basin.

Since the first installation in 1978, the system received a drastic improvement in 1989 with the increase of the number of transducers (from two to three, see Cavaleri *et al.*, 1981) and the substitution of the tape unit originally used for storing the data with a solid state recorder.

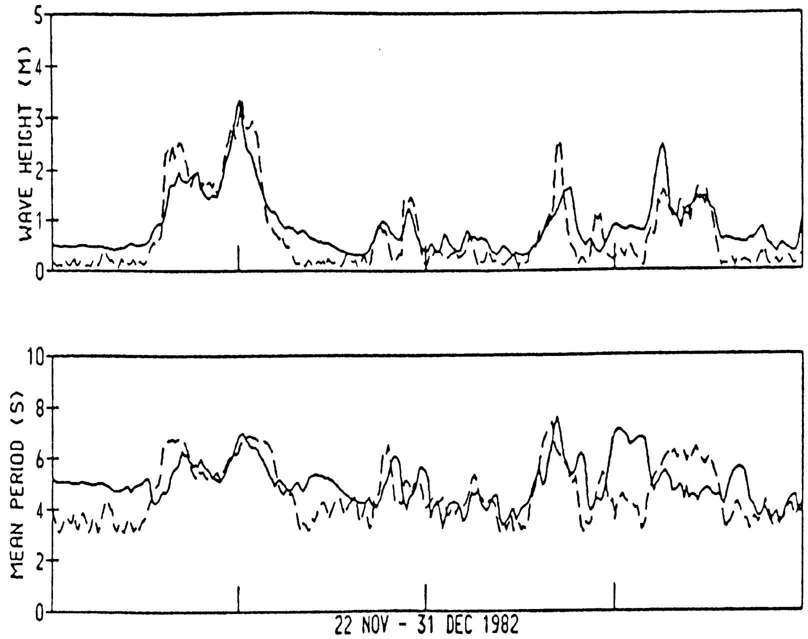

Fig. 2. – 40 day comparison between modelled (continuous line) and measured (broken line) wave height and mean period in the Northern Adriatic Sea (after Bertotti *et al.*, 1996).

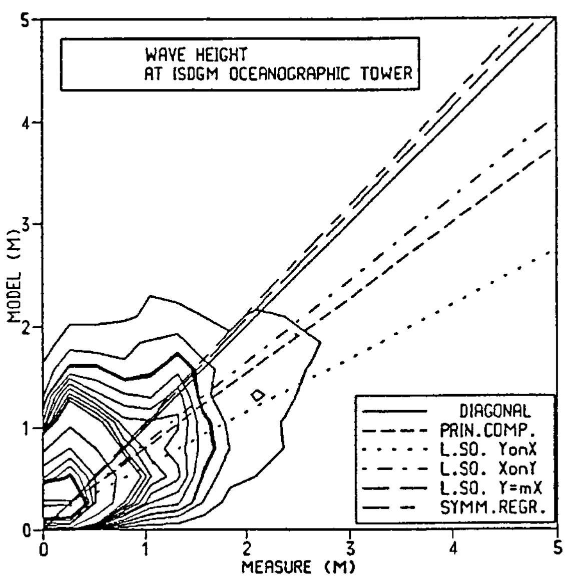

Fig. 3. – Scatter diagram between measured (*x*, horizontal) and modelled (*y*, vertical) wave height in the Northern Adriatic Sea. The straight lines represent different best fits to the data. The step between adjacent isolines increases towards the peak of the distribution. The two thick isolines include 50% and 90% of the cases, respectively (after Bertotti *et al.*, 1996).

On discussing possible improvements of the system, we have considered instruments and electronics. For the former, the pressure transducers have proven sturdy, reliable and accurate enough for our purposes. We do not envisage here any change. Also their number satisfies our requirements. A larger number would increase the directional resolution, but this would imply a much greater attention on the eventual malfunctioning of each single unit, which is out of our present interest. Also, even if accurate enough for our purposes, the transfer of the signal to the surface would probably not meet the accuracy requirements of a more sophisticated directional analysis.

Also the electronics satisfies our needs. Here we think to extend the self-sufficiency of the system up to three months. An improved user-friendship, with the possibility to explore the data in real time, is a desirable possibility.

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We have passed through many human and technical experiences during the 18 years in which the system has been in operation. We wish to warmly thank N. ZENNARO and A. PENZO, in charge of the logistics of the tower for all these years, for their invaluable help in keeping the system going. L. BERTOTTI has helped on the analysis of the data.

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