EUROPEAN WAVE ENERGY ATLAS:
An Interactive PC-Based System

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ABSTRACT

An Atlas of the offshore wave energy resource is being developed within the scope of the JOULE wave energy programme. The Atlas covers the Atlantic and Mediterranean coasts of the European Union member states as well as Norway, the area being delimited by 49°W-45°E and 26.5°-73°N. The wave data used for compiling the Atlas come from i) the numerical wind-wave model WAM for the North Atlantic and the Mediterranean Sea, and ii) in situ measurements, for the North Sea, Norwegian Sea and Barents Sea, where long-term directional wave data sets were available and the applicability of WAM is questionable. Except from the traditional statistical information for significant wave height H_S, energy (mean) period T_e, spectral peak period T_p, and wave power P_W, more advanced concepts are also presented as, e.g., the mean seasonal trend and the corresponding variation coefficient, as well as and the long-term directional resolution of wave power. Parameters and statistics for each site are presented in tabular and graphical form.

The Atlas has the form of a user-friendly, PC-based, interactive system, which enables the user to look easily through an extensive statistical description of wave climate and wave-energy resource at the 84 Atlas points distributed offshore the European coast. The system is designed to run under Windows on a personal computer (PC-486) which is a very common hardware configuration.

1. Introduction

Wave energy resource evaluation is clearly a basic prerequisite for the strategic planning of wave energy research and development. Resource studies have been carried out by different member states of European Union (EU) (see [1], [2] and references cited there), without, however, being based on a common methodology or a consistent set of data. The basic principles for such a common methodology were laid down in a previous EU project [3] and are currently being applied within the context of an on-going JOULE project (Atlas of Wave Energy Resource in Europe, subsequently referred to as WERATLAS project), the progress of which is partially described in this and a companion paper [4], presented in this Conference.

In the open ocean, wave climate varies slowly, being approximately homogeneous over distances of the order of a few hundreds of kilometers in the North Atlantic Ocean and of some tens of kilometers in smaller basins such as the Mediterranean Sea and the North Sea. However, close to the shore or at the shoreline, the wave conditions can vary considerably within distances of the order of a few hundreds or even tens of meters due to the modification of wave conditions by the sea bottom and/or the indented coastline [5]. Accordingly, a generic consistent methodology for the evaluation of the European wave energy resource should consist of a two-step approach. In the first step the offshore resource (wave climate) should be established, e.g. by analyzing the wave climate at a set of offshore reference sites, while, in the second step, a generic tool should be devised permitting the calculation of the nearshore/shoreline resource at promising areas or sites using the offshore wave climate as input, and shallow water-wave models for transferring wave conditions nearshore.

The present paper and the European Wave Energy Atlas described herewith deal with the implementation of the first step of the above described methodology, i.e. the characterization of the offshore wave-energy resource for the Atlantic and Mediterranean coasts of Europe. In addition they provide a complete set of wave-climate statistics which is of interest to the wider ocean-engineering community. The wave data used in compiling the Atlas, come from the numerical wind-wave model WAM, implemented at the European Center for Medium-Range Weather Forecast, and in situ measurements for the North Sea, Norwegian Sea and Barents Sea, where long-term directional wave data sets were available. The data selection and assessment procedure are described in a companion paper [4].

Using these data, the empirical probability density functions of H_S, T_e and T_p, as well as the empirical exceedance distribution of wave power P_W are calculated and presented, along with the corresponding analytic densities/distributions obtained by fitting analytic models to the data. Two-dimensional histograms for (H_S, T_e) and (H_S, T_p) are also calculated and presented along with iso-probability contour plots obtained by fitting appropriate bivariate analytic models to the data. Furthermore, the geographical distribution of wave power (mean value and mean direction) will be eventually presented on appropriate maps.

The Atlas is a user-friendly, PC-based computer environment, for the control, retrieval and presentation (on the screen, on paper or in files) of the wave-climate and wave-power information described above. The development, the population of the data base, and the compilation of maps required for the atlas were carried out in a GIS environment. The maps were then transformed to graphics files and stored along with the other data in the data base. Utilizing the capabilities of Microsoft Visual Basic for Windows for manipulating database contents (maps and related data) and developing a friendly and full-proof user interface, the application (software package) is available in object code running under windows without requiring any other specific software.

2. Geographical background and data sources

The WERATLAS data base will contain wave-climate and wave-power information for a set of locations (data points) distributed off the coastline of the Eastern North Atlantic Ocean, the North Sea, the Norwegian Sea and the Barents Sea, and the Mediterranean Sea. Thus, the major area studied in the context of WERATLAS is the one delimited by 50^0 W - 45^0 E and 20^0 N - 73^0 N, as shown in Figure 1. For clarity reasons, the major area has been divided in five (partially overlapping) subareas, named and defined as shown in Table 1.

Wave data primarily comes from hindcasting analysis, using the WAM model [6]. Extended verification of these data have been made by comparing model and measured data at various sites [1], [7]. For areas where the applicability of WAM is questionable, as e.g. in the Norwegian Sea and the Barents Sea, measured data have been used. The standard grid resolution of WAM is $3^0 \times 3^0$ in the Atlantic Ocean and the Norwegian Sea, and $0.5^0 \times 0.5^0$ in the Mediterranean Sea. Obviously, the selection of the data points included in WERATLAS is influenced by the set of WAM grid points and the set of points for which long-term measurements existed (and was made available to WERATLAS group). The set of Atlas points is also shown in Figure 1.

3. Offshore wave climate and wave-energy resource

Sea waves are a complex phenomenon that is satisfactorily modeled as a stationary stochastic field. The local (in space and time) behaviour of sea waves, i.e. a sea state, can be described by means of the directional spectrum $S(f,\theta)$ that provides the distribution of energy density in the frequency f and direction θ domains. The spectrum can, in turn, be summarized by means of a number of spectral parameters, the most important of which are: the significant wave height H_S approximated by means of the spectral parameter H_{m_0}, i.e. $H_S \cong H_{m_0} = 4\sqrt{m_0}$, the energy period (or mean period) $T_e = m_{-1}/m_0$, the peak period $T_p = 1/f_p$, where f_p is the frequency at which the frequency spectrum has its global maximum (m_n are the nth moment of the frequency spectrum). The knowledge of directional spectrum permits the calculation of the wave power or, more precisely, the flux of power per unit crest length, by means of the equation

$$P_W = \rho g \int_0^{2\pi} \int_0^{\infty} S(f,\theta) c_g(f,h)\, df\, d\theta\,, \qquad (1)$$

where ρ is the water density, g is the acceleration due to the gravity, and c_g is the group velocity (velocity at which the energy propagates), which depends on f and on the water depth h. In deep water the above equation is simplified to

$$P_W = \frac{\rho g^2}{2} m_{-1} = \frac{\rho g^2}{64\pi} H_S^2 T_e\,. \qquad (2)$$

According to equation (2) all information needed for determination the total wave power (without directional resolution) is contained in the minus-one spectral moment. Another important sea-state parameter is the mean direction parameter, for which various (non-equivalent) definitions are in use. (See [1] for detailed definitions of various mean-direction parameters). In this wok, the mean wave-power direction is used (see [1], equ. (10)).

All quantities discussed above characterize an individual sea state, which is a phenomenon lasting for some hours (e.g., 2-6 hours). When the time period of interest is longer, many successive occurrences of individual sea states come into play and the spectrum $S(f,\theta)$ should be modeled as a time-dependent quantity. Thus, in longer (slower) space χ and time τ scales, the directional spectrum should be considered as a quantity of the form $S(f,\theta;\chi,\tau)$. Accordingly, in these scales, spectral parameters and wave power also become functions of χ and τ, e.g. $H_S = H_S(\chi,\tau)$, $P_W = P_W(\chi,\tau)$, and the problem of their characterization arises. For long-term periods (tens of years), the time series of spectral parameters and wave power are considered as stochastic processes [8], [9], reflecting the randomness of wave-climate evolution at a given site. The variability of wave climate from site to site can be clarified by the study of the long-term probabilistic characteristics for an appropriate set of sites χ_i, $i = 1,2,\ldots,I$.

The basic features of long-term time series of spectral wave parameters at a given site can be summarized as follows: they are non-Gaussian and nonstationary time series that also exhibit a year-to-year statistical variability and longer-term climatic variability. These characteristics are more or less common to many other environmental time series and have been extensively discussed, for example, in relation to hydrologic data [10], [11]. However, there are only few works studying these

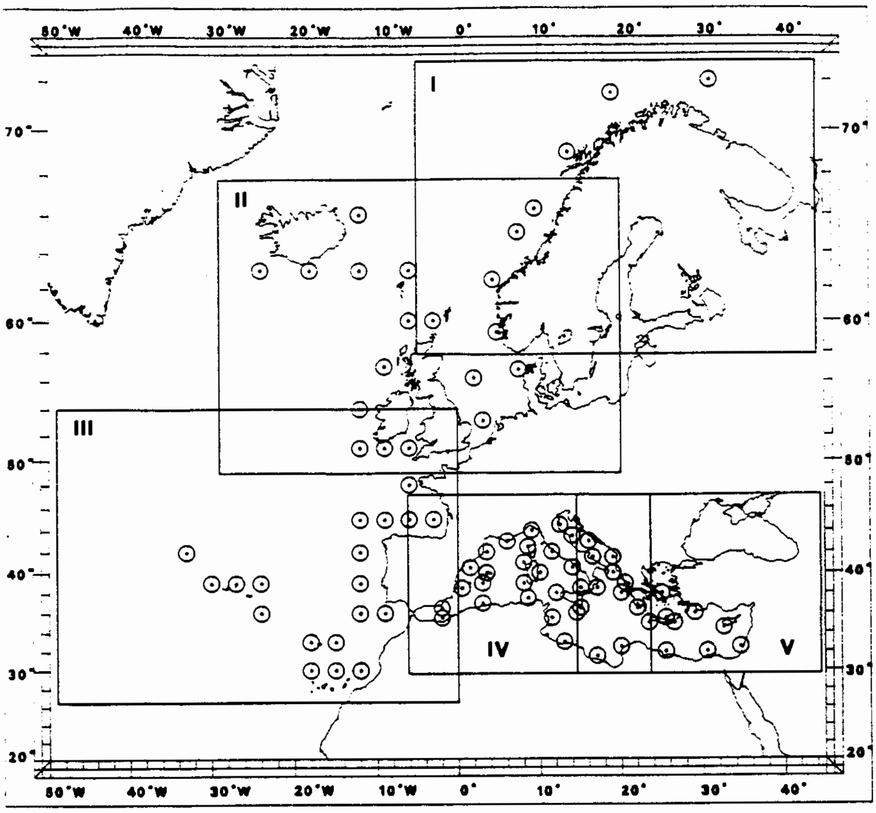

Figure 1: The examined area and WERATLAS data points.

TABLE 1: Definition of the five subareas			
Area	Name	Longitude	Latitude
I	Northern Europe / Norwegian Sea & Barents Sea	(5^0 W - 44^0 E)	(57^0 N - 73^0 N)
II	Mid Europe / Northeastern Atlantic Ocean & North Sea	(29^0 W - 20^0 E)	(49^0 N - 68^0 N)
III	Southern Europe / Atlantic Ocean - Azores	(49^0 W - 0^0)	(26.5^0 N - 54^0 N)
IV	Southern Europe / Western Mediterranean Sea	(6.5^0 W - 24^0 E)	(30^0 N - 48^0 N)
V	Southern Europe / Eastern Mediterranean Sea	(14.5^0 E - 45^0 E)	(30^0 N - 48^0 N)

characteristics for time series of sea state parameters [12], [9].

Let us denote by $X(\tau)$ the time series of a spectral wave parameter or the wave power at a given site χ_i, e.g., $X(\tau)=H_S(\chi_i,\tau)$ or $X(\tau)=P_W(\chi_i,\tau)$. Then $X(\tau)$ is decomposed into year-long segments $X(j,\tau^\alpha)$, where j counters the years and τ^α is the annual time, i.e. the time within each year ($0\le\tau^\alpha\le 1$ year). Using this approach, we can estimate the seasonal mean value $m(\tau^\alpha)$ and standard deviation $s(\tau^\alpha)$ by means of the formulae:

$$\hat{m}(\tau_k^\alpha)\equiv\hat{m}(k)=\frac{1}{J}\sum_{j=1}^{J}X(j,\tau_k^\alpha), \qquad (3)$$

$$\hat{s}(\tau_k^\alpha)\equiv\hat{s}(k)=\sqrt{\frac{1}{J}\sum_{j=1}^{J}\left[X(j,\tau_k^\alpha)-\hat{m}(\tau_k^\alpha)\right]^2}, \qquad (4)$$

where k is the discretised annual time ranging in $\{k=1,2,\dots,K\}$, where $K=1460$ since the time between successive sea-state observations has been set $\Delta\tau^\alpha$ = 6 hours. In order to smooth the estimated seasonal characteristics and reduce the number of parameters involved (something essential for modeling and presentation purposes), it is postulated that $m(\tau^{\alpha})$ and $s(\tau^{\alpha})$ admit a low-order Fourier series representation denoted by $\mu(\tau^{\alpha})$ and $\sigma(\tau^{\alpha})$, respectively, and the corresponding Fourier coefficients are calculated by integrating the estimates (3) and (4) (see also [9]). Only first-order harmonics are used for representing the mean value, while for the standard deviation all harmonics up to order 3 are used.

Traditionally, the time-series structure of spectral parameters and wave power is ignored and the quantities H_S, P_W etc. are treated, in the long-term case, as random variables. The non-stationarity is then taken into account by considering seasonal statistics. In the present Atlas both traditional and time-series type statistical information is presented for the wave climate at 40 data points in the Atlantic Ocean and 44 data points in the Mediterranean Sea. The statistics contained in the Atlas is summarized in Table 2. A more detailed description of the information content of the Atlas can be found in [13]. In each plot indicated in Table 2 both empirical and analytical probability density functions are shown. Analytical models used for univariate data fitting are the lognormal and Weibull densities. For bivariate data the Plackett model has been used, which accepts as marginals lognormal or Weibull (or any other) density models [14].

4. Atlas design principles

We now turn to the description of the fundamental design principles on which the Atlas has been based. Traditionally, an atlas is a special collection of maps in book form, conveying different aspects of one or more spatial phenomena in a specified geographical area. Contemporary technology provides various sophisticated means of expressing spatial and geographical themes. In CAD and GIS environments, spatial information can be dynamically portrayed by means of maps, images, graphs, texts and tables, collectively termed *electronic atlases*. An electronic atlas must provide visual information to users who are not necessary specialists in CAD, GIS or other information technology. This objective (Human Computer Interaction, HCI) is accomplished with appropriate development of the Graphical User Interface (GUI).

- Design criteria

In designing an electronic atlas a number of criteria is taken into account. In the case of WERATLAS two different categories of criteria are utilized [15]:

- *Information content criteria*, related to the thematic variation and the required level of detail (generalization level) of the atlas information. The properties expressing this category are: theme variation, map-scale variation, seasonal variation and update.
- *User-interaction criteria*, related to the technological capabilities provided to users for accessing the atlas. The properties expressing this category are: browse, query, data transferability, on-line spatial analysis and modeling.

Electronic atlases may have dynamic and static characteristics with respect to the way the atlas is updated and users interact with the available information. Due to current technological limitations, information updating of atlases is rather static, while user interaction with the electronic atlas can be dynamic.

5. Atlas implementation

WERATLAS is a user-friendly, PC-based computer environment, for the control, retrieval and presentation of wave-power and wave-climate information along the European coasts. Information to be retrieved and displayed utilizing WERATLAS, refer either to single sites (pointwise presentation) or to a number of geographical sites (global presentation). In pointwise presentation, information refer to a single data point and will be either in tabular or in graphical form (see also Table 2). In global presentation, information refer to the portion of the data delimited by the selected geographical area, and will be in graphical form.

For the global presentation, the geographical distribution of mean value and main direction of wave power will be displayed. For both cases annual as well as seasonal (for winter and summer) statistics is presented, in order to take into account the seasonal variability of the relevant phenomena. The above mentioned characteristics classify WERATLAS to the category of special-purpose electronic atlases [15].

The operational schema of WERATLAS is the one presented in Figure 2. It consists of three distinct elements: The *atlas database*, the *user interface* and the *atlas output*. The inherent characteristics of WERATLAS call for a GIS environment. This is due to the fact that any GIS environment can implement all three elements of the operational schema. This approach, although straightforward, has a basic weakness: the requirement for the end user to purchase the GIS package along with the atlas package. This would reduce drastically the number of users due to the expense of purchasing the GIS package and the reluctance in working in a GIS environment. On the contrary, if the atlas does not require any specific software platform, its total cost would be kept to a minimum and the number of users would increase. The approach followed by the authors was a combination of the above, resulting to a package which runs on off-the-shelf equipment without any specific software requirement.

The development, the population of the data base, and the compilation of maps required for the atlas were carried out in a GIS environment. The maps were then transformed to graphics files (bitmaps) and stored along with the other data in the data base. Utilizing the capabilities of Microsoft Visual Basic for Windows, which is a programming language for manipulating database contents (maps and related data) and developing a friendly and full-proof user interface, the application is available in object code requiring minimum storage space (approximately 2Mbs).

5.1. The database

DBase IV was used as the database management system for the implementation of the database containing the wave-climate and wave-energy information. Considering the future addition of new data points and/or quantities, special care was taken during the design process for the normalization of the relations and the minimization of the

Table 2: Information content of WERATLAS

Part A. Time series statistical characteristics

Plots of seasonal mean value $\mu(\tau^{\alpha})$ and standard deviation $\sigma(\tau^{\alpha})$ for $H_S(\tau)$

Plots of seasonal mean value $\mu(\tau^{\alpha})$ and standard deviation $\sigma(\tau^{\alpha})$ for $P_W(\tau)$

Part B. Traditional statistical characteristics

Tables	**Plots**
Long-term statistical characteristics of P_W	
Frequency table of H_S	Probability density of H_S
Frequency table of T_e	Probability density of T_e
Frequency table of T_p	Probability density of T_p
Exceedance distribution of P_W	Exceedance distribution of P_W
Frequency table of P_W mean direction, and Directional distribution of P_W	Directional distribution of P_W
Bivariate frequency table of (H_S,T_e)	Bivariate probability density of (H_S,T_e)
Bivariate frequency table of (H_S,T_p)	Bivariate probability density of (H_S,T_p)

required storage space.

5.2. The user interface

The user interface directs the user of the atlas and performs the retrieval of the wave-climate and wave-energy information from the database and its display in tabular or graphical form. The design of the user interface is influenced by the content of the atlas and the user community it is addressed to. It consists of a number of menus (Main, Area, Season, Quantity, Mode, Help and Exit) and a special tool for on-line distance calculation. Pointing to a menu name, the menu is activated and the corresponding submenus are displayed. The menus are fool-proof allowing the user to proceed only if the required selections have been done (i.e. users cannot select a quantity if area and season have not been selected). Experiments carried out by the development group shown that there is no need for special user training as long as she/he is aware of basic PC-computer operation.

5.3. Output

Special consideration was given to the cartographic part of the atlas, i.e. cartographic background and symbolization. The delimitation of the five subareas (as defined in Section 2, above) was not based only on the distribution of the data points but also on the inherent characteristics of the projection used and the output medium, the computer's monitor. As far as the projection is concerned, the Mercator projection was adopted with latitude of zero distortion at 66° N, in order to distribute the scale distortion evenly throughout the area covered by the atlas. The geographical background of the atlas will be in the form of graphic files. Map scale is defined by the ratio between the bitmap dimension and the length it represents on the earth's surface. In order to achieve a standard scale for all maps and symbols portray on the monitor without noticeable deformations, the limits of each map were defined to comply with the ratio 3:4.

A sample of screen outputs is presented in Figures 3-6.

6. Discussion and Conclusions

WERATLAS exhibits a very important (and not commonly encountered) feature. It has been designed and implemented by the combined efforts of people from three different disciplines, namely: i) wave modeling and measurements, ii) probabilistic modeling and analysis, and iii) cartography and information technology. A lot of problems arose in the course of such a collaboration and most of them were solved successfully. In many cases the solutions chosen represent a balanced compromise between different philosophies, which, we believe, have been approached optimality. WERATLAS is neither a traditional Atlas nor a traditional scientific code. It combines Atlas' capabilities with scientific code modules to produce a result that makes easily available valuable wave-climate and wave-power information presented in the desired format on the screen, on paper or in ASCII files. Although the most time-consuming part of the processing has been performed outside the Atlas, a part of processing is carried out on-line, which minimizes the storage requirements and allows for dynamic redrawing of the plots.

As regards the specific application for which the Atlas is designed, WERATLAS represent a successful solution of the first step of the methodology for consistent wave-energy resource evaluation described in the Introduction of this paper. The second step of this methodology, i.e. the construction of an efficient tool permitting the calculation of nearshore resource by using the output of WERATLAS in combination to shallow-water models, can be conceived as an extension of WERATLAS, which will include an additional interface for dynamically controlling shallow-water models and geographical data for specific sites, provided by the user.

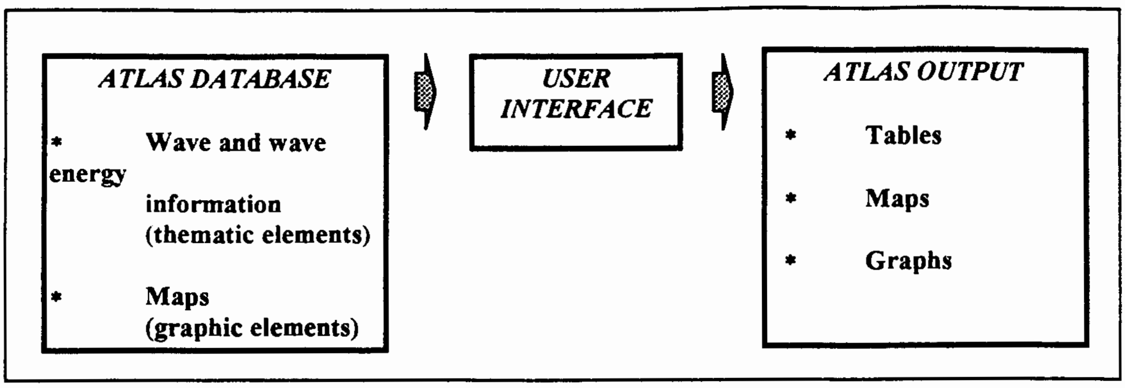

Figure 2: The operational schema of WERATLAS.

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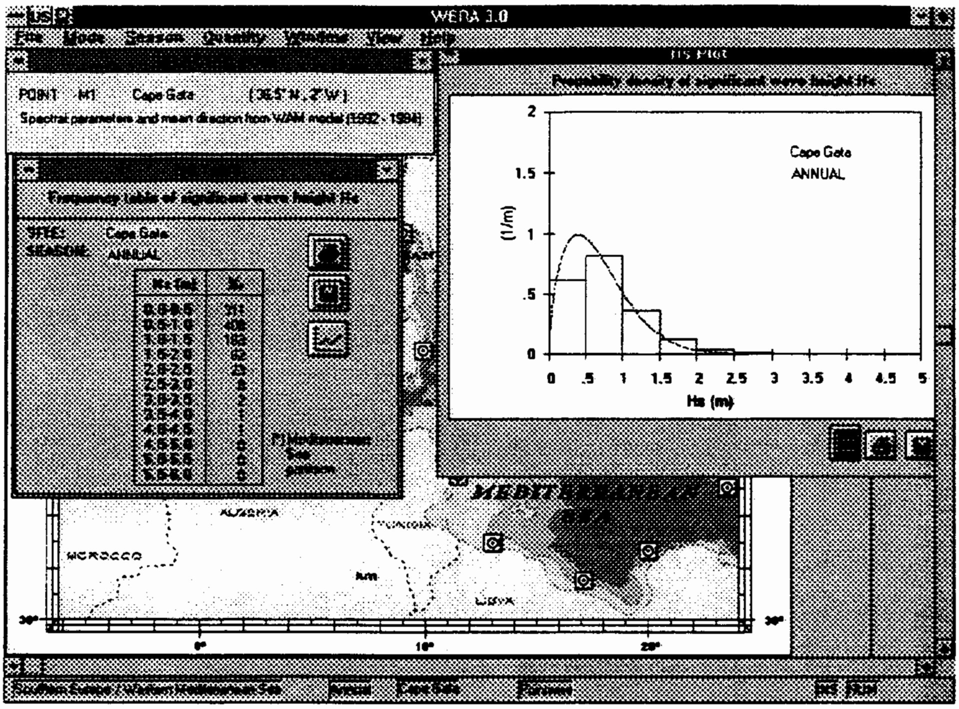


Figure 3: A univariate frequency table and the corresponding plot.

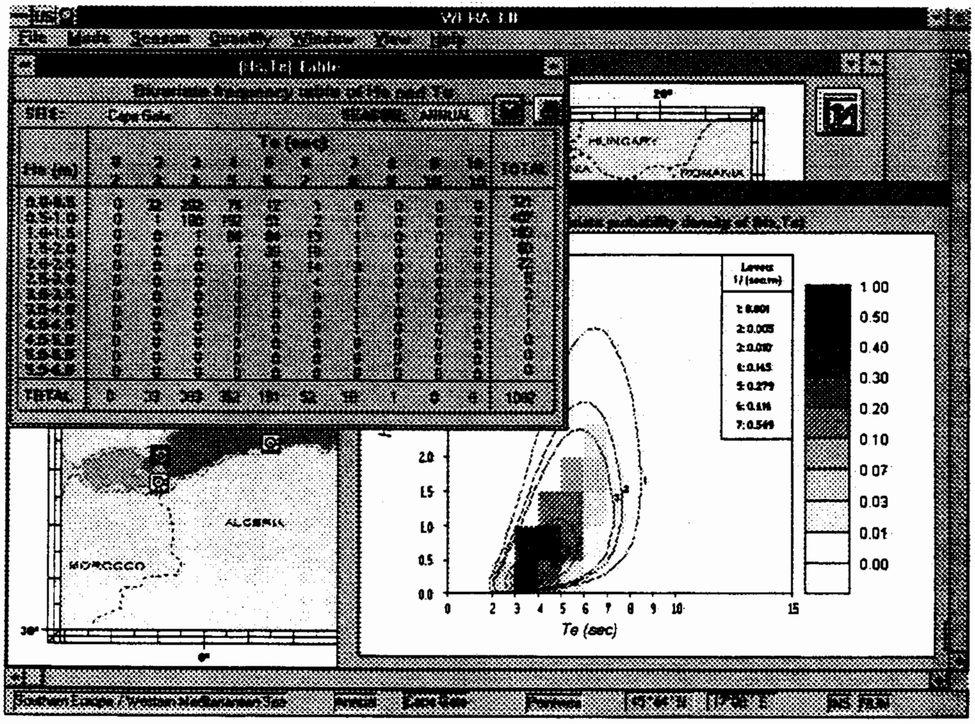
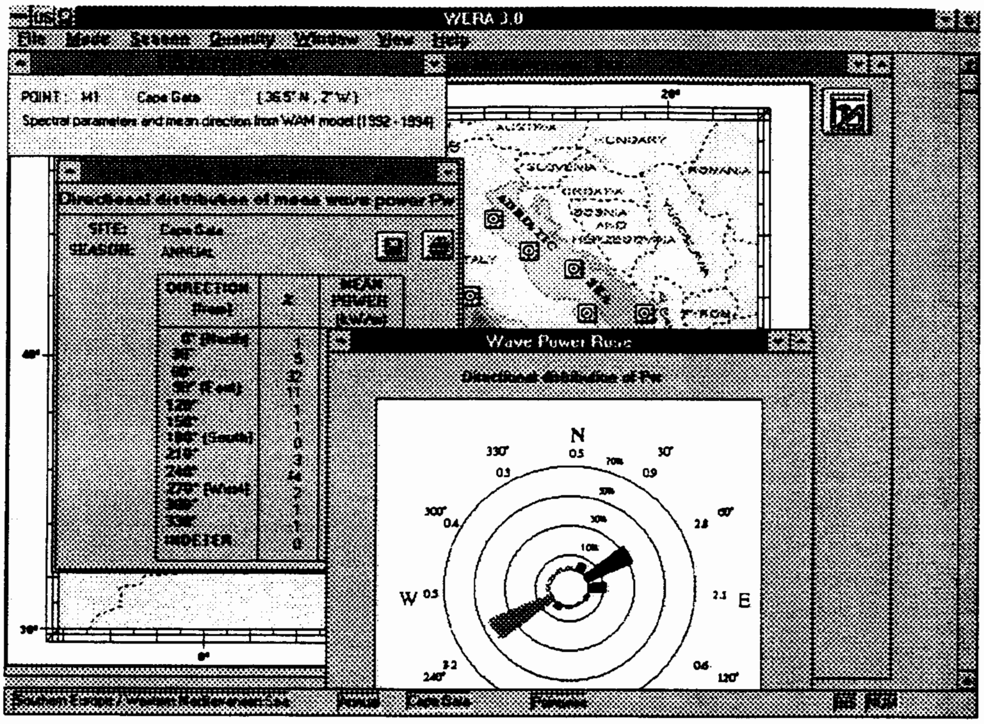


Figure 4: A bivariate frequency table and the corresponding plot.



POINT : M1 Cape Gata (36.5°N, 2°W)

Spectral parameters and mean direction from WAM model (1992 - 1994)

Directional distribution of mean wave power Pw

SITE: Cape Gata
SEASON: ANNUAL

DIRECTION (from)	%	MEAN POWER (kW/m)
0° (North)	1	
30°	5	
60°	22	
90° (East)	11	
120°	1	
150°	1	
180° (South)	0	
210°	3	
240°	44	
270° (West)	2	
300°	1	
330°	1	
INDETER.	0	

Directional distribution of Pw

Figure 5: Directional distribution of wave power and the corresponding power rose.

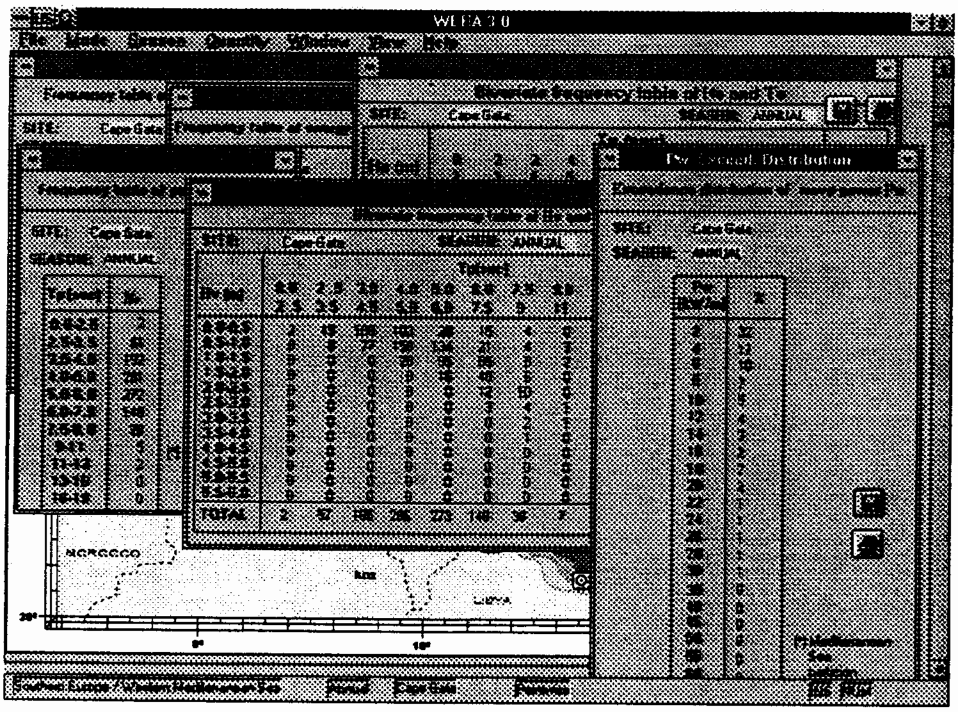


Figure 6: Most of frequency tables available for a single data point (presented through multiple windows).