11

Assessing the Wave Energy Resource

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11.1 INTRODUCTION

Wave energy, meaning the energy of ocean surface waves, is created by the drag of winds blowing over the sea. While the input density is low, seldom as much as $1\ \mathrm{W\,m^{-2}}$, the energy travels with little loss across oceans, so that the produce of a whole ocean can be 'harvested' at its boundary, where the mean power flux can average more than $40\ \mathrm{kW\,m^{-1}}$ ($40\ \mathrm{MW\,km^{-1}}$).

Locally, on a scale of tens of kilometers and minutes, the state of the sea is accurately described by a stationary Gaussian process. However, there are theoretical and practical limitations on the accuracy with which the spectrum of the sea state can be measured or estimated, and the sea state itself varies over any longer time scale, from occasional flat calms to storms with power levels of over $1000\ \mathrm{kW\,m^{-1}}$.

This chapter reviews some of the statistical problems that arise, particularly those of interest to the designer of wave power plants, both for productivity and survival. A brief account of the origin and nature of ocean waves is given in Section 11.2 (for more see, e.g., Mollison, 1986). The simulation of ocean waves in wave tanks is described in Section 11.3. Variability, over the range of time scales from individual waves to climatic change is discussed in Section 11.4. The evaluation of meteorological model estimates ('hindcasts') against more direct measurements of waves is described in Section 11.5. The selection of representative sets of spectra, and their use in tank tests and productivity estimates, are described in Section 11.6. The transformation of waves in shallow water and the efficiencies of 'greater than 100%' possible for a small-scale device are described in Section 11.7.

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We conclude in Section 12.8 with a brief discussion of some of areas of interest outwith the scope of this chapter, and an invitation to environmental statisticians to attack some of the fascinating problems associated with wave energy.

11.2 ORIGIN AND NATURE

11.2.1 Waves and the Earth's energy balance

Ocean waves, impressive as they can be, form only a small and inessential component of the Earth's energy balance. They are a side-effect of the movement of the major air masses that redistribute heat energy from the equatorial regions towards the poles. In doing so, the air masses lose some energy through drag to the sea surface, thus setting up 'deep-water waves', that is, oscillations of the sea surface under gravity. As a proportion of the global flux the power in these waves is only about 1 part in 10^5, with the input power flux into the ocean usually just a few $\mathrm{mW\,m^{-2}}$, as against the original solar input which averages $350\,\mathrm{W\,m^{-2}}$.

However, wave energy can travel thousands of kilometres with very little loss, so that a considerable proportion of the input to an oceanic area reaches its boundary. The year-round average, for a coast with good oceanic exposure (notably if facing west in the temperate zones) can reach $40\text{–}50\,\mathrm{kW\,m^{-1}}$ (*net*—see below, and Figure 11.3).

Another advantage of wave energy, which it shares with the wind, is that it is mechanical energy; moreover, unlike wind, its energy is in the oscillations rather than movement of its medium, so that the theoretical limit on efficiency of extraction is 100% (for wind energy, the limit is $16/27 \approx 57\%$).

A disadvantage of ocean wave energy is that its typical frequency is around 0.1 Hz, which is not ideal from the engineering point of view. Worse—a disadvantage it shares with wind, though with different details—it is highly variable on all time-scales.

For an excellent review of the wide variety of solutions that engineers have proposed to make wave power exploitation practical, see Salter (1989).

11.2.2 Description of sea states

The creation of waves is a complex nonlinear process, in which energy is slowly exchanged between different components. However, on a scale of tens of kilometres and minutes, the local state of the sea surface in deep water is accurately described by a stationary Gaussian random process.

Thus the local behaviour of the waves is fully determined by the spectrum of the sea state $S(f, \theta)$, which specifies how the wave energy, which is proportional to the variance of the surface elevation, is distributed in terms of frequency and direction. From this can be deduced many properties of the local sea state, ranging from the simple fact that the distribution of the instantaneous sea level at any point has a normal distribution to elegant results on the joint distribution of parameters describing the sea surface (Longuet–Higgins, 1957).

The spectrum in turn can be summarised quite accurately by a small number of basic statistics. The most important of these are

(i) the root mean square wave height H_{rms} (i.e. the standard deviation of the sea level)—it is common, especially in the engineering literature, to use $H_S \equiv 4H_{\mathrm{rms}}$: H_S is approximately equal to the highest one-third of trough-to-crest wave heights, and thus matches reasonably well one's visual impression of wave height; and

(ii) the energy period T_e, the mean wave period with respect to the spectral distribution of energy, i.e. m_{-1}/m_0, where $m_n \equiv \int f^n dS(f)$.

The mean power flux in a sea state is $P = kH_{\mathrm{rms}}^2 T_e$ (in $\mathrm{kW\,m^{-1}}$), where $k \approx 7.87\,\mathrm{kW\,m^{-3}\,s^{-1}}$; thus P is approximately $\frac{1}{2}H_S^2 T_e$ (in $\mathrm{kW\,m^{-1}}$). Typical oceanic values of T_e are in the range 5–15 s; H_S varies from 0 (flat calm) to around 15 metres (severe Atlantic storm), with median values of about 2 m in summer and 4 m in winter (Mollison *et al.*, 1976).

The third crucial parameter is the principal direction of the power flux. Often an oceanic sea state will include both locally generated wind sea, whose principal direction should be that of the local wind, and swell generated up to several days earlier by distant weather patterns, which may have a quite different principal direction. In this case an adequate summary of the sea state will require separate heights, periods and principal directions of wind sea and (occasionally more than one) swell components. For a more precise description, one can add standard deviations of period and direction for each component, or a numerical summary of the complete directional spectrum.

Note that for resource estimation the relevant quantity is usually the power flux in a given direction, for instance the power flux crossing a line of prospective wave power devices. Even for the optimal direction, this net power flux in deep water will on average be at best about 75% of the gross power flux; though in shallow water, where wave components line up perpendicular to the depth contours, the two may be virtually equal (see e.g. Mollison, 1983). (The complexities of waves in shallow water will be discussed briefly in Section 11.7.)

The complete directional spectrum, or a good approximation to it, is usually more than is needed for studies of any one site, but is essential if we are to use data from one site to estimate the wave climate elsewhere (see Section 11.5).

11.3 SIMULATION

As a test facility for wave energy devices, the Edinburgh Wave Power Project led by Stephen Salter designed and built a computer-controlled wave tank capable of making simultaneously of the order of 100 wave components, each a simple wave of specified amplitude, frequency, direction and phase (Jeffrey *et al.*, 1978). The additivity of components implied here is possible because of the linearity of the Navier–Stokes equations. The wave tank can also absorb any incident waves: this feature, which is essential for the energy accounting required in tests of model device efficiencies, relies on the linearity and time reversibility of the Navier–Stokes equations.

Time reversibility also means that there is a close theoretical connection between the characteristics of wave makers and of wave energy absorbing devices. For both, good performance over a wide frequency range is important; however, an important practical difference is that for economic optimisation a wave energy device should be small relative to the waves. For instance, for the Salter Duck it was easy to obtain very high efficiencies at wavelength-to-diameter ratios of about 6 : 1; it took several years of research to obtain similar performance at ratios of around 20:1 (implying a roughly tenfold improvement in the cross-sectional area required for a given output). The implications of improved efficiencies $\eta(f)$ for overall output in a given wave climate is clearly shown when η is plotted against a 'stretchy' frequency axis, that is, where the scale of the frequency axis represents its distribution function, in this case with respect to power; the area under the efficiency curve then represents the overall mean output of the device in this wave climate (Figure 11.1).

Interesting statistical questions arise when a relatively small number of simple waves needs to be chosen to simulate a given directional spectrum. The target spectrum may be based on data or on one of a number of theoretical forms, and typically consists of a mixture of one to three smooth unimodal distributions.

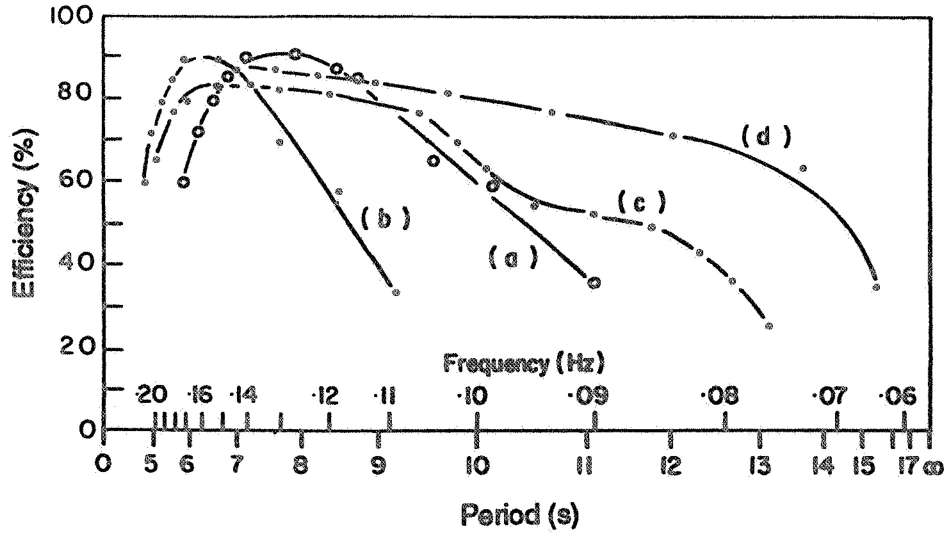

Figure 11.1 Efficiency curves for successive designs of the Salter Duck, plotted against a frequency/period axis 'stretched' to represent the empirical distribution of wave power at South Uist: (a) design of April 1975, scaled to 15 metres diameter full size; (b) the same, scaled to 10 m diameter; (c) design of September 1976, scaled to 10 m diameter; (d) design of December 1979, scaled to 10 m diameter. (From Mollison (1980).)

The simulation of the frequency spectrum on its own is relatively straightforward: dividing the spectrum, or one of its unimodal components, into successive intervals of equal energy generally gives satisfactory results. It is convenient to choose frequencies that are multiples of some (very small) base frequency Δf; a fast Foruier transform can then be used to calculate the wave record, giving a sea state with repeat period $1/\Delta f$. One potential problem, which needs to be checked for though it does not often arise, is that too many of the frequencies chosen might be multiples of some multiple of the base frequency, thus reducing the repeat period of the sea state by the latter multiple.

Another problem, whose solution depends on the purpose of our simulations, is whether to constrain the energy of each frequency interval to its long-term mean or whether to allow natural variation (which is approximately chi-squared with parameter twice the frequency interval divided by Δf); the latter is correct (Tucker *et al.*, 1984) if we want a random sample (of length $1/\Delta f$) from our sea state, but the former is arguably more appropriate for performance testing of devices.

A deterministic choice of directions for each chosen frequency works well for realistic spectra in representing the observed fairly slow change in the conditional directional distribution with frequency (Mitsuyasu, 1975)—Figure 11.2 shows scatter plots of the chosen components for a representative selection of Atlantic Sea States (this is the subset of 46 spectra from Crabb's (1980) stratified sample of synthesised directional spectra referred to in Section 11.6).

For ordinary behavioural and productivity tests, it is appropriate to choose the phases of components randomly (i.e. uniformly). However, control of the phase of components allows us also to simulate waves that occur in real seas only rarely or not at all. An example of the former is where many (or all) of the components are brought into phase with each other at one particular space–time point within the simulation; it is easy to create an extreme wave such as would occur only once in a hundred years within the sea state. Examples of the latter include a circular wave, which is of interest for the study of breaking waves, as well as party pieces such as the ideal surfing wave or the Scottish flag.

11.4 VARIABILITY

In order to describe fully the wave climate at a site, that is, the long-term distribution of waves, we need to consider their variability over the whole range of time scales, from an appropriate sampling interval short compared with the wave period up to year-to-year variability and the even slower scales of climatic change.

As already mentioned, the short-term variability of waves, over a few hours and a few tens of kilometres (in the open deep sea), is well described as a Gaussian random process.

Thus the wave-to-wave and group-to-group variation, which are crucial for modelling the power take-off of devices, can be calculated with sufficient accuracy

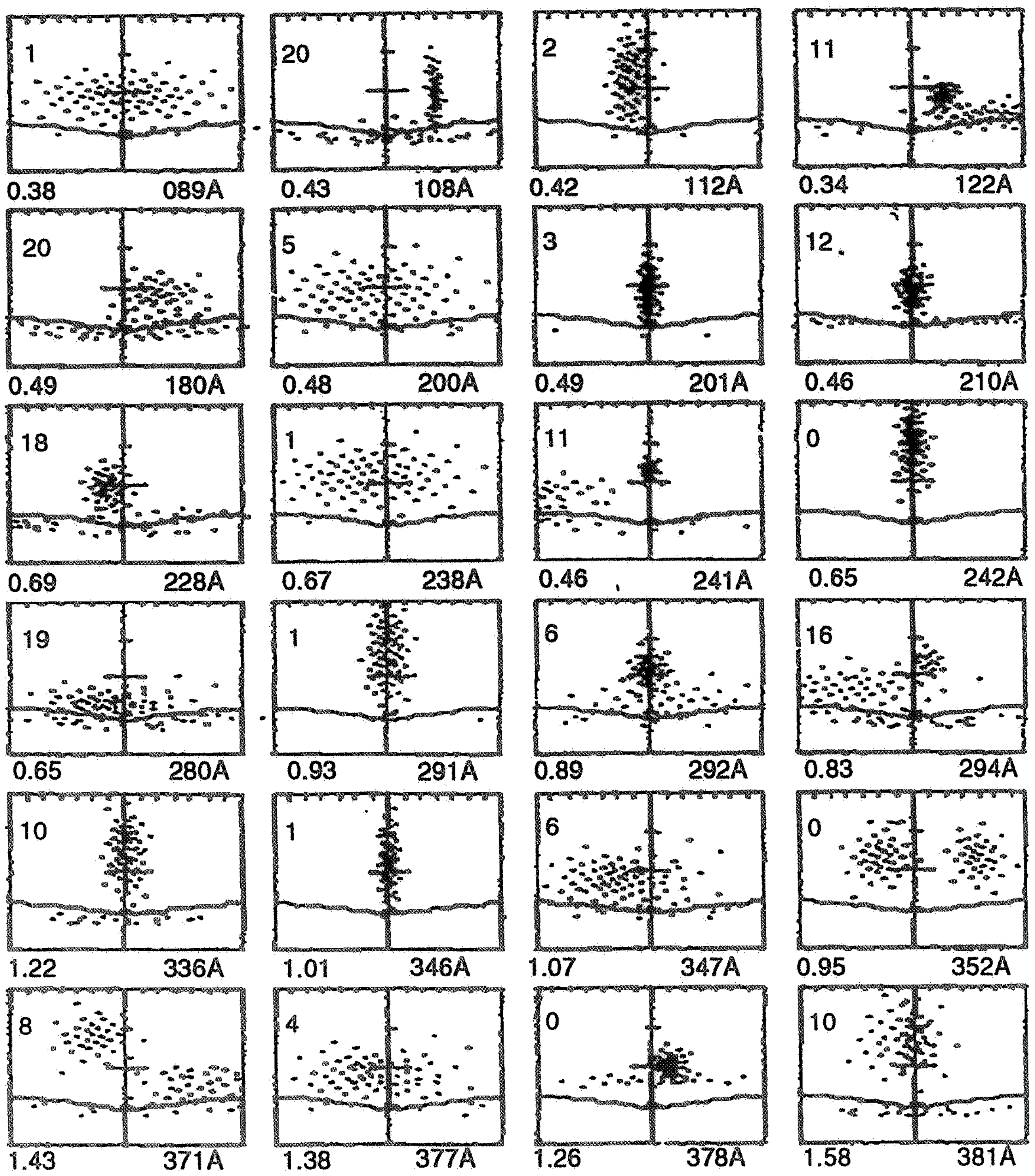

Figure 11.2 Scatter plots showing combinations of period and direction used in tank simulations of the wave climate off South Uist ('direction 0' here represents 260°, i.e. 10° S of W). Each spectrum is represented by about 75 'wave fronts' (simple sine waves), of equal amplitude within each component; over 50% of these sea states have two components, a concentrated long-period swell and a more scattered, shorter period wind sea. (Note that the curved line, and the number at the top of each scatter plot, refer to the number of short-period fronts that cannot be represented unambiguously in the tank because their wavelength is less than twice the wave-maker spacing; but these are all of very low power.) (From Taylor (1984).)

from knowledge of basic sea state parameters and the shape of the spectrum. For instance, 'groupiness' is associated with a spectrum that has only a narrow range of periods, such as arises in swell from distant storms. (See Longuet–Higgins

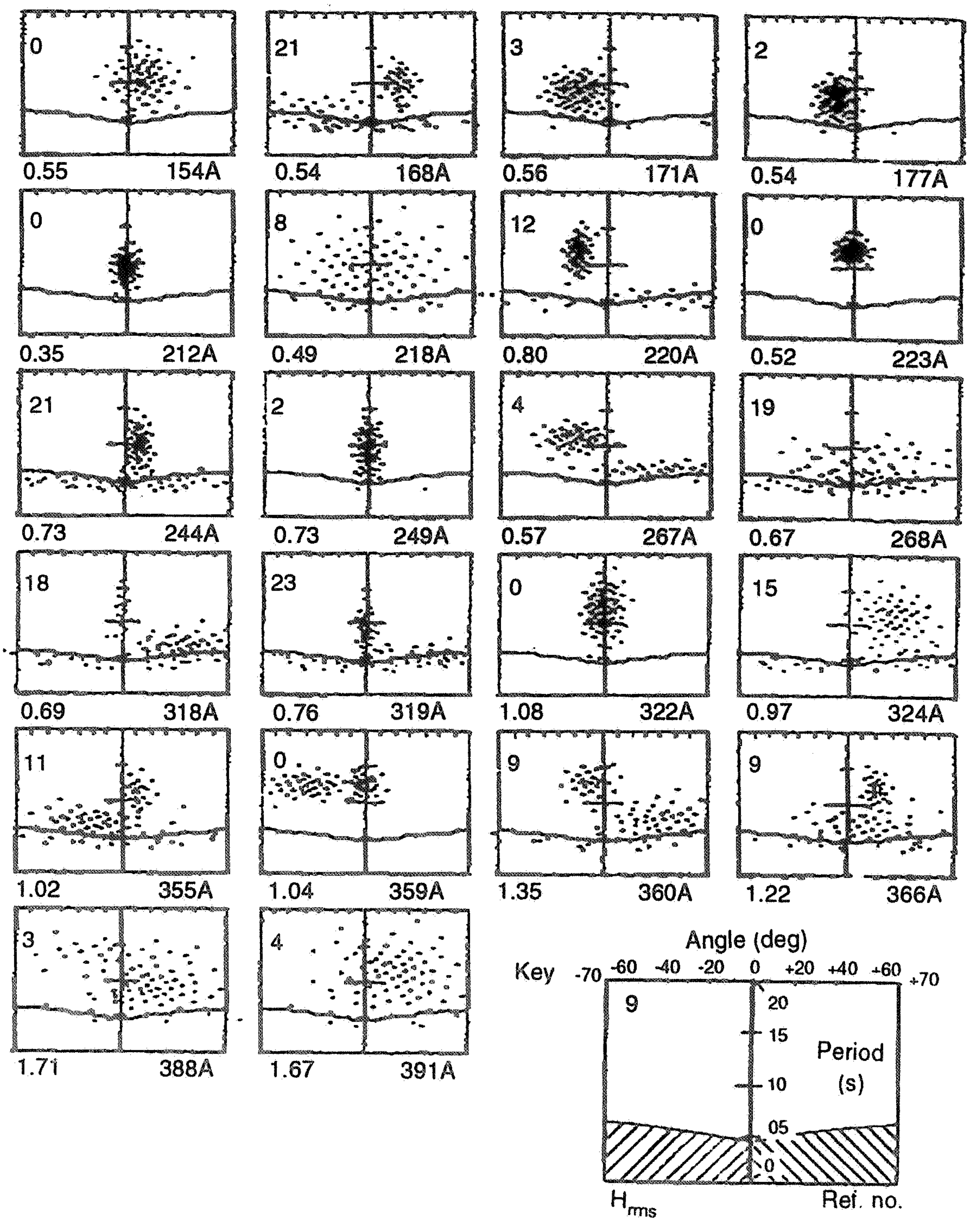

Figure 11.2 (*Continued*)

(1984) for a discussion of the modelling of groupiness, including Markov chain models; also Athanassoulis (1992).)

The duration of a sea state (typically a few hours) is important for estimating extreme waves within that state. The duration of weather systems (about 1–5 days) is important in determining the limits on forecasting, in particular forecasting calms when no power is available.

Although calms can occur at any time of year, power levels are generally much higher and more persistent in winter. In the Atlantic mean power levels are typically around five times as high between October and March as between May and August.

Year-to-year variability is also considerable—changes of 20–50% from one year to the next are common—making it difficult to estimate long-term means and trends when good measurement series of more than 2–3 years are rare (see Section 11.5.2). Year-to-year and longer-term climatic variability are especially important for estimating the lifetime extremes that a structure will experience.

The analysis of such long time series as do exist suggests considerable non-stationarity; in the North Atlantic wave power levels seem to have increased by 50–100% since the 1960s (Draper, 1988).

11.5 WAVE CLIMATE ESTIMATION

11.5.1 Requirements for device testing

The detail in which the designer of wave power devices requires knowledge of wave climate advances hand in hand with the development of device design. Basic information, such as the approximate overall mean power level, and the distribution of power over time and by frequency, is a prerequisite for matching any kind of device to its wave climate.

Details of spectral shape that will be more important for some devices than others include frequency bandwidth and the high-frequency tail of the spectrum. Narrow spectra will favour resonant features of device response, and will have relatively long runs of large waves. Wave breaking, which may pose a serious problem for some devices, depends on the high-frequency tail of the spectrum (Greenhow, 1989).

Fortunately, the need for a methodology of wave climate estimation that will allow evaluation of the resource at any site of interest necessitates full directional spectra (see Section 11.5.4) from which all the necessary details can be calculated (though some work may be needed to study whether certain details, such as the high-frequency tail, are adequately estimated).

11.5.2 Measurements

In the open sea the most widely used measuring devices are wave-recording buoys (scalar or directional), which integrate information from acceleration sensors to yield time series of buoy motions. To obtain spectral estimates, measurements are recorded (using a sampling interval of a second or less) over a time period, typically about 30 min, chosen as a compromise between the Scylla of non-stationarity and the Charybdis of sampling variability; spectra can then be calculated by Fourier transform. Such sample spectra are typically calculated at 3 or 6 h intervals; from them time series of spectral parameters, such a H_{rms} and T_e and the mean power level, can be derived.

Wave measurements close to the coast can be made by a number of devices besides buoys, including submerged pressure and ultrasonic probes, and wave-staffs and ultrasonic probes suspended above the sea.

Wave buoy measurements are expensive, and have therefore been made mainly for specific engineering purposes, often for durations of a year or less; some of the most useful open ocean measurements and climate studies have been made for the oil industry, and are subject to commercial confidentiality.

Satellites provide another source of wave information, but have a number of disadvantages. They do not, at present, give such detailed or accurate spectral estimates as wave buoys, and their data are only intermittent: in order to cover the widest possible area, a satellite is usually set in a shifted periodic orbit, which implies that any one location is covered only at fairly long intervals, varying from a week up to a month. However, this does give them the advantage of wide coverage, allowing a rough general assessment of the wave resource over very large areas.

11.5.3 Hindcasts from numerical wave models

Numerical wave models, developed over the last 30 years, provide the largest amount of wave information. Several centres around the world make routine runs of a wave model, driven by the output of a meteorological model. Their accuracy depends on the sophistication of the model itself and on the accuracy of the input wind field.

Such models have gone through three 'generations' in recent years, corresponding to increasing sophistication in the way that their equations represent numerically the physics of events. In practice, for extensive studies of very large areas only second- and third-generation models are sufficiently reliable.

The longest operating of these with wide coverage is that of the UK Meteorological Office (Golding, 1980, 1983). Data from this model for 1983–86 were compared with measurements from directional buoys for two offshore sites near the British Isles (in the SW Approaches and West of Shetland) by Mollison (1991), who found generally good agreement, though the numerical model gave slightly higher mean power levels. Since 1986 the model has undergone further refinement, and Pontes *et al.* (1993) found no evidence of bias in a comparison using post-1986 measurements from Portugal.

11.5.4 Methodology for resource evaluation

As described above, data of the quality required for a reliable estimate of wave climate are time-consuming and expensive to collect, and exist only for a few oceanic sites, whereas good quality indirect estimates for wave conditions in the open sea are now

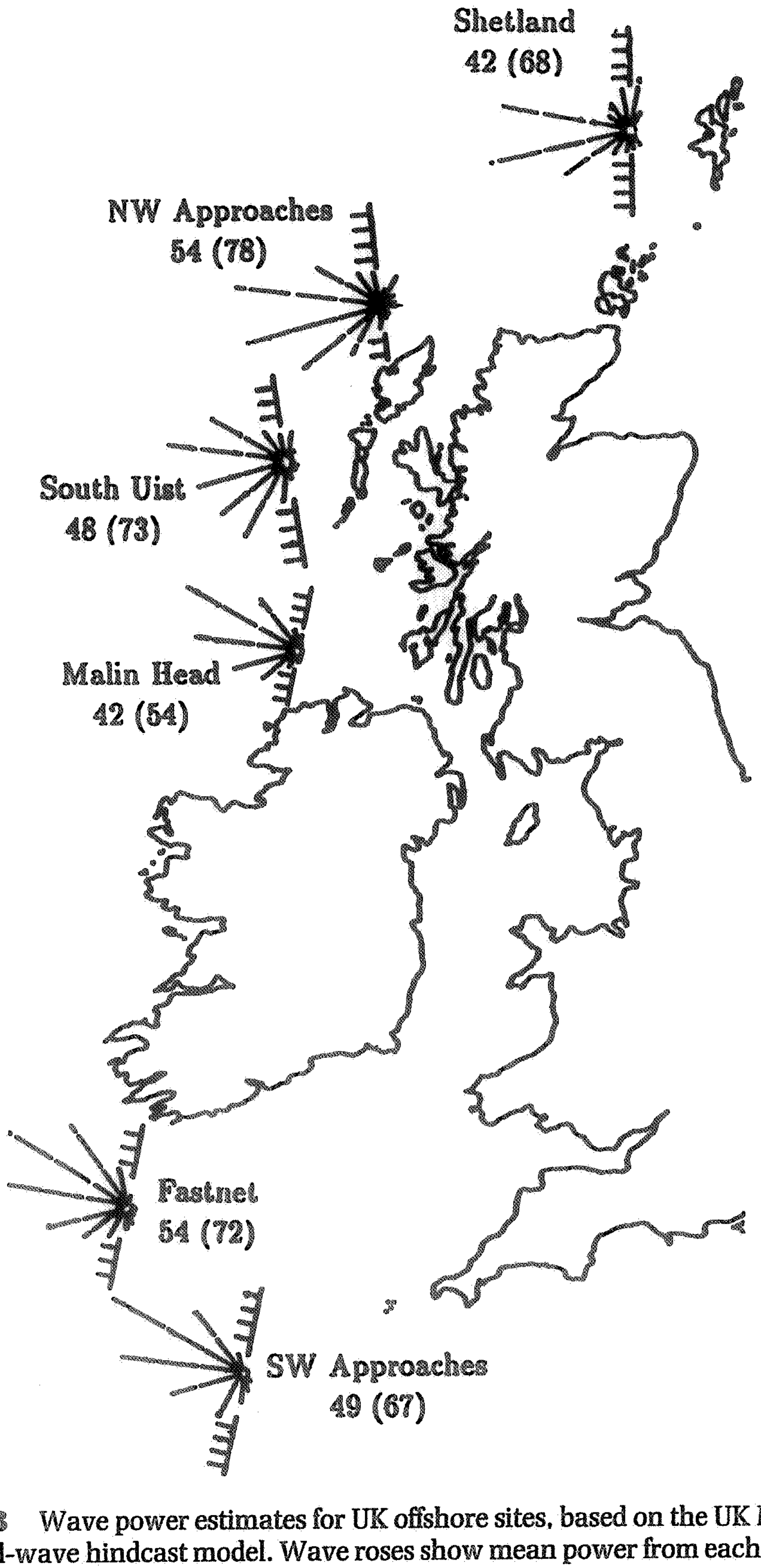

Figure 11.3 Wave power estimates for UK offshore sites, based on the UK Meterological Office's wind-wave hindcast model. Wave roses show mean power from each 22.5° sector, with marks at 5 kW m^{-1} intervals. Mean net (gross) power levels are shown in kW m^{-1}; the net figure is for power P_θ crossing the line (————) whose direction θ maximises P_θ for the particular site. (From Mollison (1991).)

routinely available from numerical wind wave models. Wave conditions at nearshore and coastal sites can be highly dependent on local topography.

This supports the following methodology, which was adopted for the evaluation of the nearshore wave energy resource in a recent study for the UK Department of Trade and Industry (Mollison, 1991), and which is the basis of a current EC project to compile an European 'Wave Energy Resource Atlas'.

A network of offshore reference sites is chosen, with a spacing of at most a few hundred kilometres, for which we obtain data from a numerical wave model; these data sets should ideally consist of full directional wave spectra for a time period of at least five years. This network of reference sites should include some for which direct measurements are available, as a check on the accuracy of the model. Figure 11.3 shows the main reference sites adopted for the UK study, which used hindcast data from the UK Met Office for 1983–86, calibrated against directional wave buoy measurements for 1984–86 for Shetland and the SW Approaches (Mollison, 1991).

An 'Atlas' of the offshore wave energy resource can then be compiled by filling in between reference sites, either with data from the numerical model if available, or by interpolation.

From such an Atlas the nearshore and shoreline resource can be calculated using one of the variety of hydrodynamic computer models available (see Section 11.7), taking the wave climate at one of the offshore reference sites, together with bathymetry from detailed charts, as input. (Again, quality checks should be carried out for the computer models, for a variety of situations where wave measurements exist, though this is at present problematic, because of the commercial confidentiality of many of the models.)

The level of detail required for these inshore calculations in such that it is not, at least at present, practical to carry them out for all of the European coastline of wave power interest. This suggests a two-level methodological approach, combining an 'Atlas' database for offshore reference sites with computer tools for calculating the resource at specific locations. This approach has major advantages of flexibility and long life, in that the components (both database and computer tools) can be updated individually as relative technological advances are made.

For Europe's Atlantic coasts and the North Sea, the quality of existing data and estimates from computer models is generally adequate to allow this methodology to be implemented now, but for parts of the Mediterranean better data and estimates are needed.

11.6 SAMPLES

Useful wave data sets are almost inevitably large, because of the complexity of spectral samples, the wide range of time scales of interest, and because to take small numbers of samples with long intervals between them does not make economic sense, whether for measurements or calculations. The question therefore arises as to how to choose a 'representative' subsample of our data. This might be for use as input to a numerical model to calculate nearshore wave conditions (see Section 11.5.3) or as input to a wave tank for testing models of wave energy devices or other structures (see Section 11.3).

Our criteria for selection will clearly vary, depending on whether we are interested in the full range of sea states or only in extremes (whether of wave height or some other aspect such as steepness). For the full range of sea states, we are faced with the problem of representing a high-dimensional parameter space; we can perhaps make do with three of these dimensions—height, period and principal direction—but, even then, for adequate coverage of the range of each we require a minimum of the order of 50 samples (e.g. taking 4 × 4 × 4 samples, with a few missing cells).

At a time when long-term directional data were not yet available, Crabb (1980) applied a method for reconstructing directional spectra to 399 samples from a year's measurements off South Uist, chosen by a simple stratification by height, period and season. From these, a subset of 46 was subsequently chosen by the UK Department of Energy's consultants as a standard set for productivity tests of wave power device designs. This selection gave good coverage of the core of the distribution of Crabb's original sample, but discounted about 30% on grounds that they were extreme in one parameter or another. Given that we are interested in estimating average values of functions of sea state (such as device efficiency), this seems a poor procedure: missing values in the core of the distribution could be estimated relatively accurately by interpolation; the extrapolation required to estimate values in the unrepresented 'outlying' sea states cannot be done accurately.

More recently, for the UK Department of Industry's resource evaluation (Thorpe, 1993), Mollison (1991) chose samples of about 50 spectra each from UK Meteorological Office hindcast data for 10 sites around the British Isles (including the six shown in Figure 11.3). These samples were chosen to cover the full ranges of height, period and principal direction, and within those with a view to allowing as accurate estimates of device productivity as possible. Thus, for instance, sea states were chosen, within each period range, with heights successively representing low seas in which devices may be expected to operate at their maximum efficiency, two medium seas ranging up to a value at which devices could be expected to have reached their limit, and finally a sea of extreme steepness (see Figure 11.4).

An 'objective-oriented' method was also used to assign weights W_J to the chosen sea states J: the weight of each member of the full data set was shared between its (at most four) nearest representatives in a way that would give exactly correct productivity estimates if a device had constant efficiency η up to the third of the four represented heights, and constant output above that height; thus the mean power in the sea is $\sum_J W_J$, and the mean output for such a device is $\sum_J W_J \eta_J$ (for details see Mollison, 1991).

As mentioned in Section 11.4, even annual wave power averages can vary considerably. Long-term time series of wind speed and direction exist, and can be used to throw some light on this aspect, and to weight wave climate samples taken from relatively short time series so as to make them more representative of the long term distribution. (Though we should note, as a caution, that Draper (1988) did not find

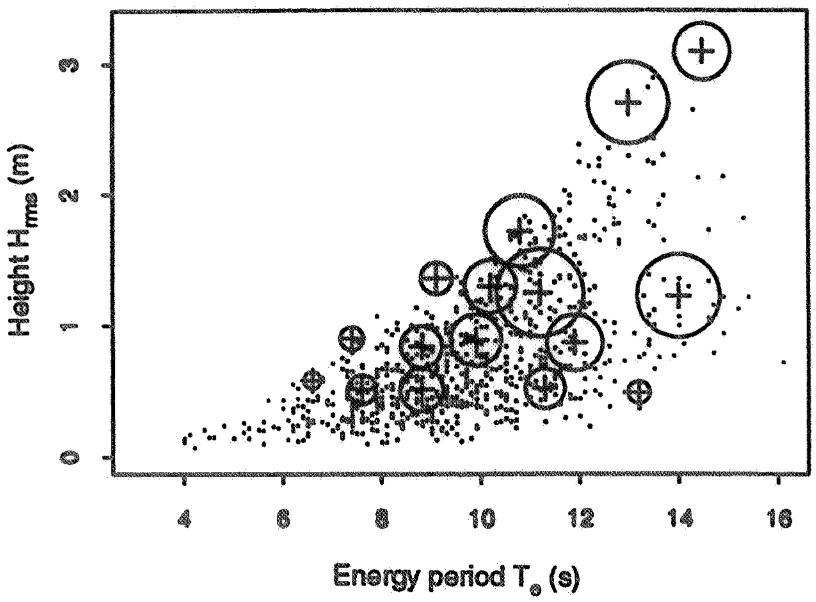

Figure 11.4 Scatter plot of H_{rms} and T_e for one directional sector (the 50–80th percentiles of the power distribution, 279–296°) for the SW Approaches, showing selected representatives J (+), with circles whose area is proportional to their weight W_J. (From Mollison (1991).)

an increase in wind speeds corresponding to the trend he described in wave data for the North Atlantic.)

Mollison (1980) fitted a log–linear model for the dependence of monthly averages of wave power P_i on monthly averages of wind input W_i, where the wind input is defined as the fifth power of the wind speed U (the physical justification for this is that $P \propto U^5$ for fully developed sea states; Pierson and Moskowitz, 1964). He found that a model using only the ordering of the W_i gave a lower standard error for the long-term wave power average, and had the advantage that it could be used directly to weight the existing data. The 95% confidence interval for the long-term average was $50.3 \pm 5\,\mathrm{kW\,m^{-1}}$, as compared with the crude average for two years' data of 41.0. This estimate agrees well with the average of $47.8\,\mathrm{kW\,m^{-1}}$ from Crabb's (1980) stratified sample (see above). This is particularly impressive in that that sample came only from the first year's data, for March 1976 to February 1977; and the wind input model suggests that this 12 month period had a lower power average ($35.7\,\mathrm{kW\,m^{-1}}$) than would have been obtained if measurements had started in any of the preceding 132 months—a confirmation of the Law of Bad Luck (putting it politely) significant at the 1% level!

11.7 THE SMALL-SCALE AND SHORELINE RESOURCE

In the early years of modern wave energy research, the mid to late 1970s, the emphasis was on the search for solutions to a large-scale energy crisis. A key result in persuading designers to think small was the discovery by Budal, Evans and Newman (see e.g. Evans, 1988) of the 'point-absorber' effect, which says that a device can absorb power from a 'capture width' wider than its own physical width by up to L/π (where L is the wavelength).

This has led to a wide variety of designs of small-scale devices, with widths of the order of 10 m but exploiting the resource over a capture width of the order of 50 m, and thus with potential mean output in the range 100–1000 kW: for instance the pioneering Norwegian prototypes of Kvaerner–Brug (Malmo and Reitan, 1986) and TAPCHAN (Mehlum, 1986). The devices built to date have been at the shoreline, because of advantages such as the availability of specific accessible sites, and the greater potential for using established technology, but the point-absorber effect applies equally to offshore designs, as is illustrated in

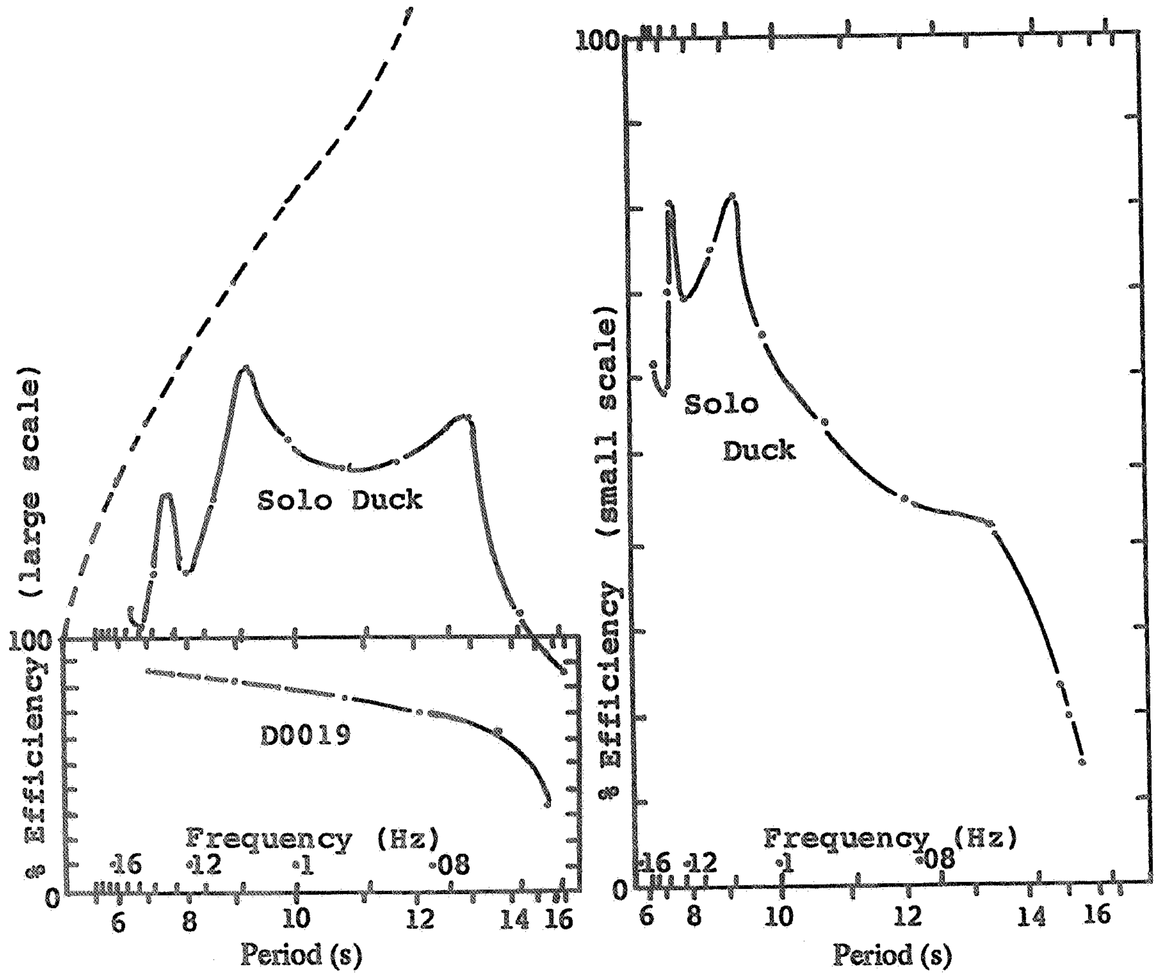

Figure 11.5 *Left*. Dependence of output on frequency for a solo Duck model at 1:100 scale, compared with efficiency curve for a spine-based unit, curve (d) of Figure 11.1; as in that figure, the frequency/period axis is 'stretched' to represent the empirical distribution of wave power at South Uist. The dashed curve shows the theoretical output limit for the solo device. *Right*. The same output curve for the solo Duck, replotted as a percentage of the theoretical output limit. The frequency/period axis has been modified correspondingly, so that the area under the efficiency curve still represents the overall mean efficiency in this wave climate. (From Mollison (1986).)

Figure 11.5, showing how efficiencies nominally of well over 100% can be achieved.

The estimation of the shoreline resource poses considerable problems. The offshore wave climate varies slowly over space, being approximately steady over distances of tens of kilometres (Mediterranean, European continental shelf) to a few hundred kilometres (North Atlantic). But in the nearshore region (water depth 15–25 m) or at the shoreline the wave climate can vary significantly over distances of tens of metres (see e.g. Pontes and Pires, 1992), the resource generally being lower compared with offshore conditions.

As the waves travel towards a coast through waters of decreasing depth, interaction with the seabed (and currents) may lead to major changes. These include energy-conserving effects such as shoaling and refraction, diffraction and certain types of reflection; these, especially refraction, can be a positive factor for wave energy utilisation, concentrating wave energy into specific areas ('hot spots'); however, such focusing will normally only apply to part of the directional spectrum, so that there may also be an undesirable increase in variability in the wave climate.

The principal energy-dissipating mechanism is wave breaking, though over wide continental platforms, such as off the Hebrides and in the North Sea, energy loss by bottom friction can have a major effect (Mollison, 1983).

Computational models have been developed (see e.g. Southgate, 1987) which describe the individual shallow-water phenomena satisfactorily (except perhaps wave breaking), but the interaction of all the phenomena is too complex to be fully modelled at present.

Thus a 'Wave Energy Atlas' as described in Section 11.5 can be extended to give estimates of the nearshore and shoreline resource, but this requires judgement in choosing an appropriate computational model, and the accuracy of the result will depend on the complexity of the local topography.

It should be noted that long stretches of coastline may be ruled out for wave power exploitation on practical grounds such as access and shoreline structure (Mollison and Pontes, 1992; Whittaker *et al.*, 1992).

11.8 DISCUSSION

This chapter has ranged over a variety of topics, principally simulation techniques, methodology for the estimation of wave climates, and the choice of representative samples of wave data.

Current problems in the estimation of wave climates are mainly practical: how to bring together, calibrating or verifying where necessary, a range of existing sources of data and numerical calculation programmes. Both data gathering and programming are expensive and specialist activities, and their results are consequently commercially sensitive, which hampers progress both in utilising and comparing them.

One particular problem requiring further study is that of extremes, where our knowledge is necessarily imperfect because of inadequately long time series of reliable measurements and estimates, and because of the possibility of significant climate change over periods of a decade or more. In estimating extremes, and the correlation between sites, we could learn from work on other environmental series, for instance of sea levels (Tawn, 1993) and of wind speed and direction (Haslett and Raftery, 1989). It must also be borne in mind that what constitute extreme conditions for a wave power plant will depend on the design: for one device it might be the highest wave or largest surge, for another the steepest wave, or a combination of large waves with extreme crest length. In calculating extreme individual waves from spectra we need to take account of nonlinear effects: steep waves have more pointed crests and flatter troughs than linear theory predicts.

It is important for engineering optimisation that wave power device designs should be tested in realistic and representative sea states, with careful attention to their effect on the successive stages of the power conversion chain (see e.g. Mollison, 1980). The methods described here are somewhat heuristic, and there must be scope for a more general approach to the problem of choosing 'representative samples'. Another problem that also could be generalised is the weighting of samples from a shorter time series of an environmental variable using a long term series of a related variable.

The fascination and reward of studying wave energy statistics lies in the wide range of problems that arises, not just within statistics—though these range from exploratory data analysis to theoretical stochastic processes—but across a range of other subjects, principally physics and engineering.

One could also mention economics. Earlier UK assessments of wave energy were marred by statistics abuse, or at least inexcusably poor statistical practice (see Mollison, 1984). While the recent assessment of Thorpe (1993) shows a very welcome improvement, there remain problems of great social importance in evaluating costs and benefits in a field such as renewable energy. Such problems are often ignored, being regarded as either too simple or too intractable, but statisticians should take an interest, if only to press the need for clear thinking and proper recognition of uncertainty.

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CHAPTER 11

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