The Effect of Fetch on the Directional Spectrum of Celtic Sea Storm Waves

LUCY R. WYATT

School of Mathematics and Statistics, University of Sheffield, Sheffield, United Kingdom

8 November 1993 and 19 October 1994

ABSTRACT

This paper describes measurements of the directional spectrum of storm waves obtained using the PISCES high-frequency radar. The storm occurred during the Netherlands UK Radar Wavebuoy Experimental Comparison 2 experiment in March 1987. Wind direction changes from southerly to northwesterly over a period of five hours led to a rapid change in short-wave direction but did not lead to changes in the mean direction of the long energetic wind waves. Wind waves generated in the changed wind direction are shown to be fetch limited, and the spectrum is shown to be dominated by long-fetch wind waves generated by the component of wind blowing from the southwest.

1. Introduction

In recent years there has been considerable interest in the measurement and modeling of the directional spectrum of ocean surface waves. The LEWEX (Labrador Extreme Waves Experiment) (Beal 1991) provided an opportunity for intercomparison of a number of new measurement techniques and models. Surface contour radar, radar spectrometer, and airborne and satellite synthetic aperture radar (SAR) were all deployed during this experiment demonstrating great potential although not yet good agreement. Comparisons with various wave models also revealed many differences, partly but probably not completely, attributable to uncertainties in wind input. New analysis techniques for the interpretation of wave buoy data to provide more detailed directional characteristics were also used but cannot yet be said to have been verified. The importance of information on the directional properties of sea waves was stressed in a contribution to the LEWEX report by Kjeldsen (1991).

Particular aspects of directional development have been the subject of a number of studies. The influence of fetch was studied by Holthuijsen (1983), Donelan et al. (1985), and Walsh et al. (1989). The response of the directional spectrum to changing wind direction was the subject of papers by Günther et al. (1981), Allender et al. (1983), Holthuijsen et al. (1987), Young et al. (1987), Masson (1990), and van Vledder et al. (1993). All of this work has demonstrated that there are many problems that remain unresolved. Timescales for change and in particular their variation with frequency are not yet adequately parameterized in wave models (SWAMP Group 1985).

In this paper, high frequency (HF) radar observations of the development of the wave directional spectrum in changing wind conditions will be described. The data described were collected during an experiment that was not designed to provide answers to the scientific issues of directional ocean wave parameterization. The aim was simply to verify the measurement technique by comparing the radar measurements with those obtained using a Datawell WAVEC directional wave buoy. Additional data required for a scientific study, for example collocated and upwind wind speed and direction, were not available so that the results to be described are suggestive but not conclusive.

2. The NURWEC2 experiment

The Netherlands UK Radar Wavebuoy Experimental Comparison 2 (NURWEC2) took place during the winter of 1986/87 (Wyatt 1991). The aim of the experiment was to establish the feasibility and test the accuracy of HF radar measurements of the ocean wave directional spectrum. In addition, the ability of the PISCES system (Shearman and Moorhead 1988) to measure ocean surface currents at long ranges (up to 250 km) was tested (Venn et al. 1988). The Netherlands Rijkswaterstaat, Wimpol Ltd., and the U.K. Department of Energy contributed to the provision of wave buoys, anemometers, and current meters for verification purposes. The PISCES system comprises two independent radar systems that were set up to monitor waves and currents in the Celtic Sea area (see Fig. 1). One was located on the South Wales coast and the other on the north coast of Devon, England. The first was operated by the University of Birmingham, and

Corresponding author address: Dr. Lucy R. Wyatt, School of Mathematics and Statistics, Applied Mathematics Section, The University of Sheffield, P.O. Box 597, Sheffield S10 2UN, England.
E-mail: L. Wyatt@sheffield.ac.uk

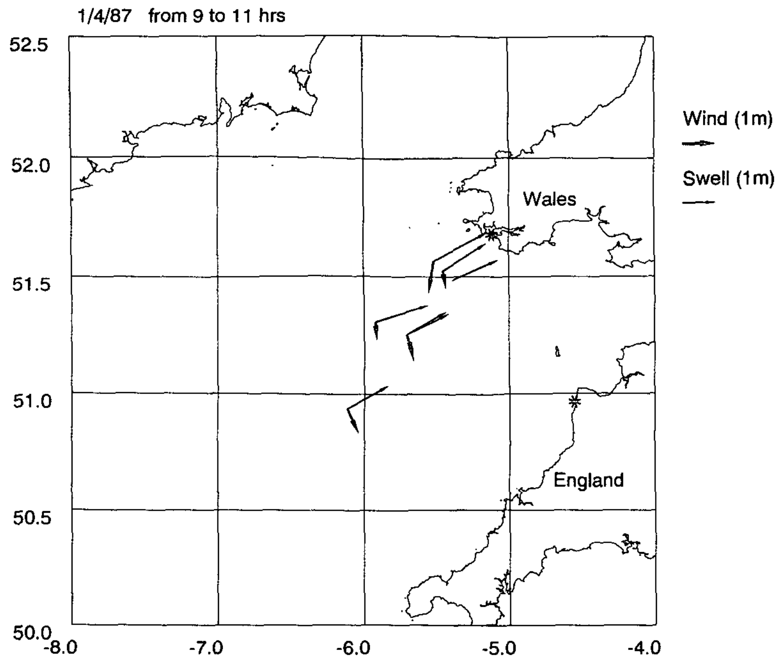

FIG. 1. Map of the NURWEC2 experiment site showing the two radar sites * and wave measurements on a particular day in April. The thicker arrows show a weak wind wave field (<1 m significant wave height) from the northwest, and the thinner arrows a more energetic swell (>1 m) from the southwest.

the second by Neptune Radar Ltd. Each system comprises an FMICW (frequency-modulated interrupted continuous wave) radar with flexibility in both transmit frequency (7–16 MHz were used in the measurements presented here) and bandwidth (10–20 kHz) to maximize data return in the congested European radio environment, to enable frequency reduction in high sea states, to ensure accurate wave measurement (see below), and to allow simultaneous operation. The bandwidths used provide a range resolution of 7.5–15 km. The receiver antenna arrays provide a beamwidth of

TABLE 1. Comparisons of parameters measured by the PISCES HF radar system with those measured by the WAVEC directional wave buoy. For the amplitude and period measurements, bias measures the difference from unity of the mean value of the ratio of the two measurements with a negative value indicating that on average the radar measurements were lower. The standard deviation of the ratio is given. For the direction measurements, a negative bias indicates that the radar measurements were on average anticlockwise relative to those of the WAVEC.

Parameter	Bias	Standard deviation
Significant waveheight	−1%	13.8%
Mean period	−1%	11.2%
Long waves (>10 s)		
amplitude (1.5–8 m)	5%	24.5%
direction	−7.2°	
period	−2%	4.8%
Waves 10–5 s		
amplitude (1–5 m)	−3%	13.8%
direction	−4.7°	
period	−1%	4.3%
Short waves (<5 s)		
amplitude (0.5–2 m)	10%	32.2%
direction	−3.2°	
period	−3%	3.7%

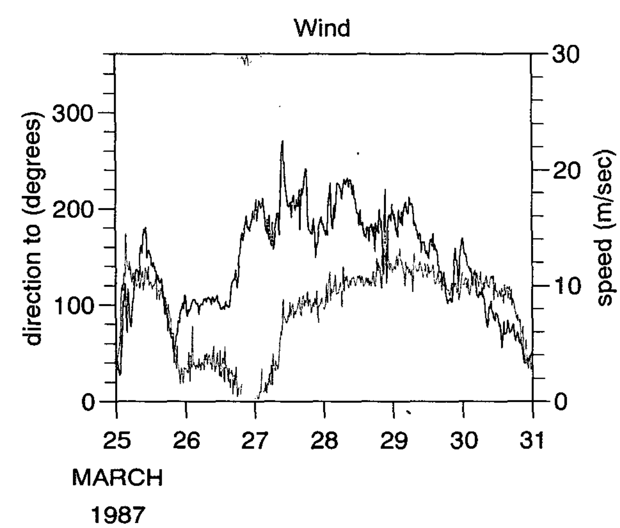

FIG. 2. Wind speed (solid line) and direction (dotted line) measurements during the NURWEC2 storm, March 1987.

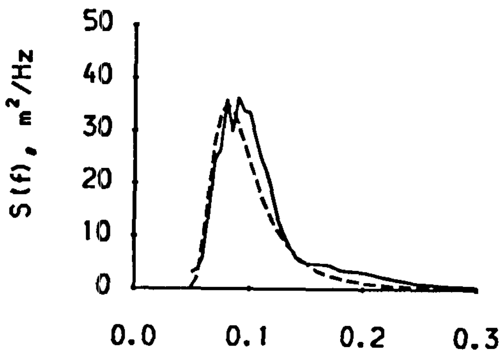

FIG. 3. Frequency spectrum measured by the radar (solid line) compared with a Pierson–Moskowitz spectrum (dashed line) obtained using the measured wind speed.

roughly 12° depending on the frequency used. The data presented here were collected at the intersection of one beam from each system at the location of the WAVEC buoy, with a dwell time of 30 min repeated hourly.

Data from both radars are combined to provide directionally unambiguous measurements of waves and currents. The wave analysis was carried out at Sheffield University using algorithms developed by Wyatt (1988, 1990). Directional spectra are obtained using an iterative numerical inversion of the nonlinear integral equation describing, to second order, HF backscatter from ocean waves (Lipa and Barrick 1986). The algorithm is initialized with a Pierson–Moskowitz (hereafter PM) wind-wave model combined with a simple directional model, using significant wave height and

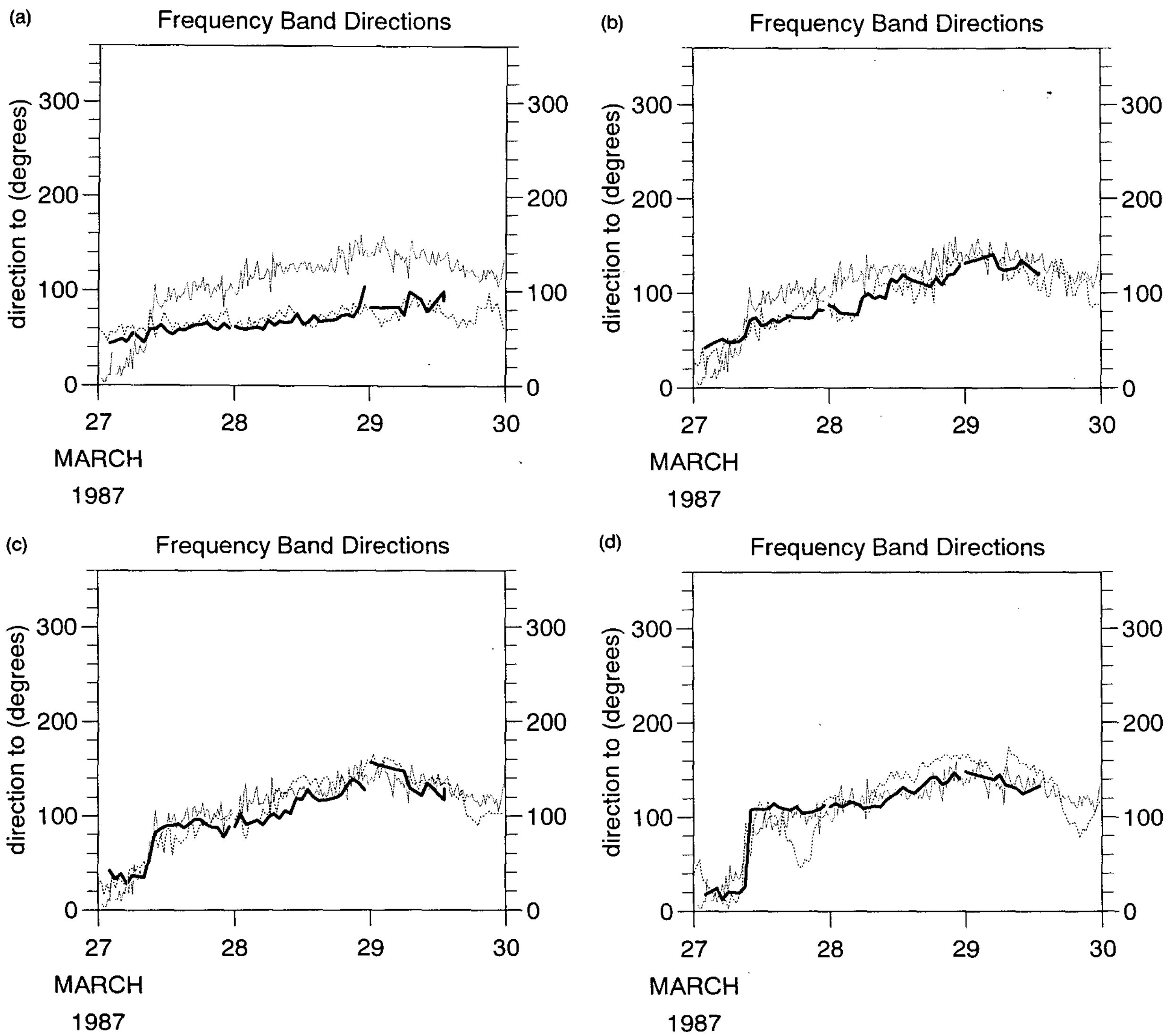

FIG. 4. Mean (in finite frequency bands) wave direction measurements obtained using the radar (solid line) and the WAVEC (dashed line) during the storm. The wind direction is the dotted line. Direction is always that toward which the waves and wind are going, measured clockwise from due north. The frequency bands shown are (a) 0.085–0.1 Hz, (b) 0.125–0.155 Hz, (c) 0.16–0.2 Hz, and (d) 0.33–0.5 Hz.

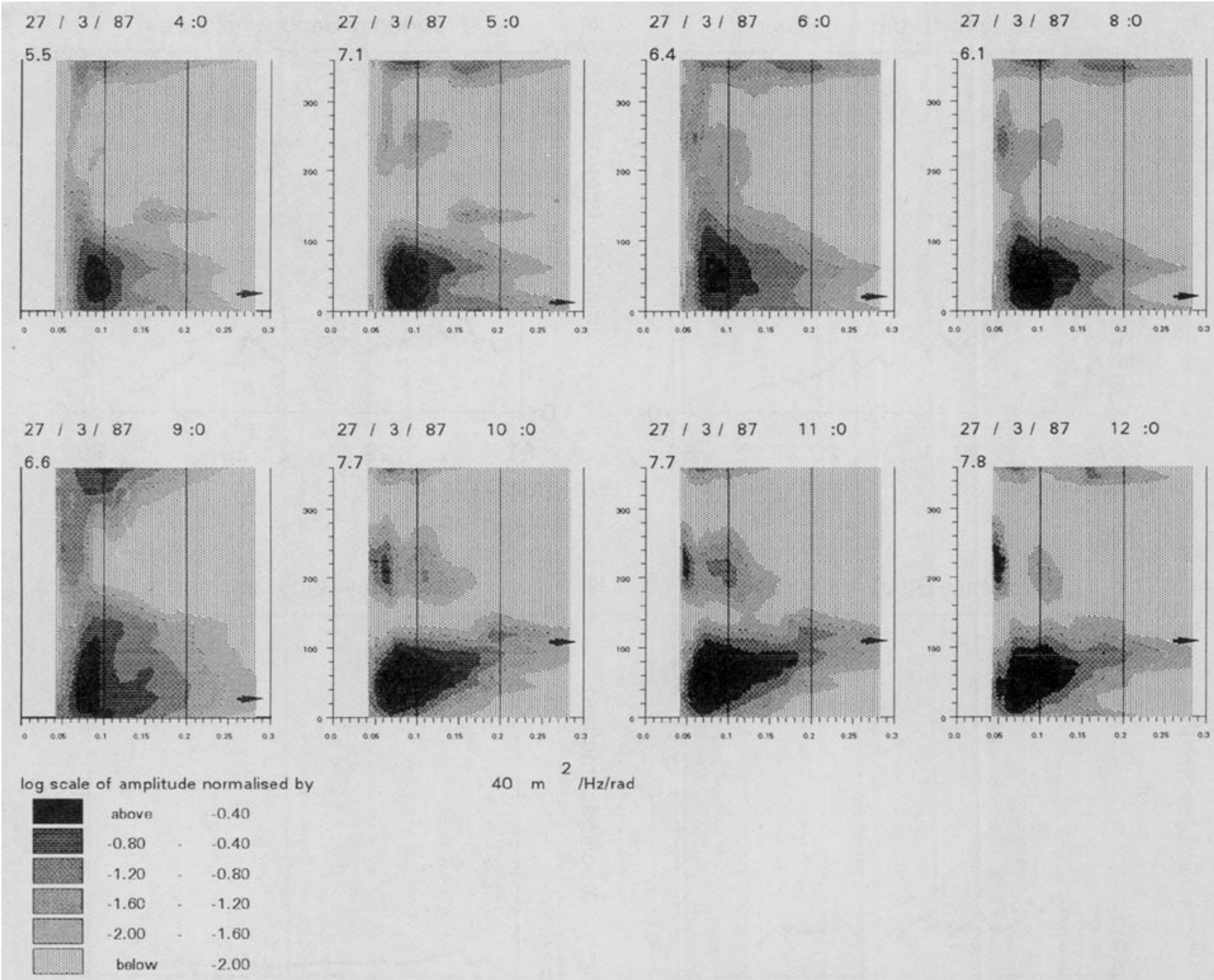

FIG. 5. Directional spectra measured by the radar during the morning of the 27 March 1987. The horizontal axis is frequency in hertz, and the vertical axis is direction. The spectra are normalized by 40 m^2 Hz^{-1} rad^{-1} and plotted in logarithmic levels as shown. The arrows indicate wind direction. The significant wave height at each time is shown in the upper left-hand corner.

wind direction derived directly from the backscatter power spectrum. The inversion proceeds using, alternately, integrations of the estimate of the directional spectrum to provide the associated backscatter power spectrum and modifications of the estimate using weighted differences between measured and calculated power spectra, until these differences are sufficiently small. Although the initializing spectrum is unimodal, the method has been shown to be capable of identifying multimodal spectra (Wyatt and Holden 1994).

The directional spectrum measurements were compared with those obtained using a WAVEC directional wave buoy. The buoy data were analyzed using traditional methods (Long 1980) to provide parameters of the directional spectrum. Good agreement between radar and wave buoy estimates of these parameters has been reported in Wyatt (1992). These parameters measure energy density, mean direction, and directional spreading as functions of frequency with both fine- and coarse-frequency resolution. Some statistics of the comparison between radar and WAVEC measurements for the entire experimental period are presented in Table 1. The verification was carried out with data measured in a water depth of 50 m. Verification in shallower water is the subject of current research.

To obtain more detailed directional information from the WAVEC data, for example to identify wave modes with roughly the same frequency but propagating in different directions, maximum likelihood and maximum entropy methods are beginning to be used [Lygre and Krogstad (1986), although note that an analysis of the mechanics of wave buoy motion suggest that such methods could yield erroneous results; Mollo-Christensen (1993)]. It was not possible to carry out such an analysis on the NURWEC2 WAVEC data. However, the directional spectra measured by the radar

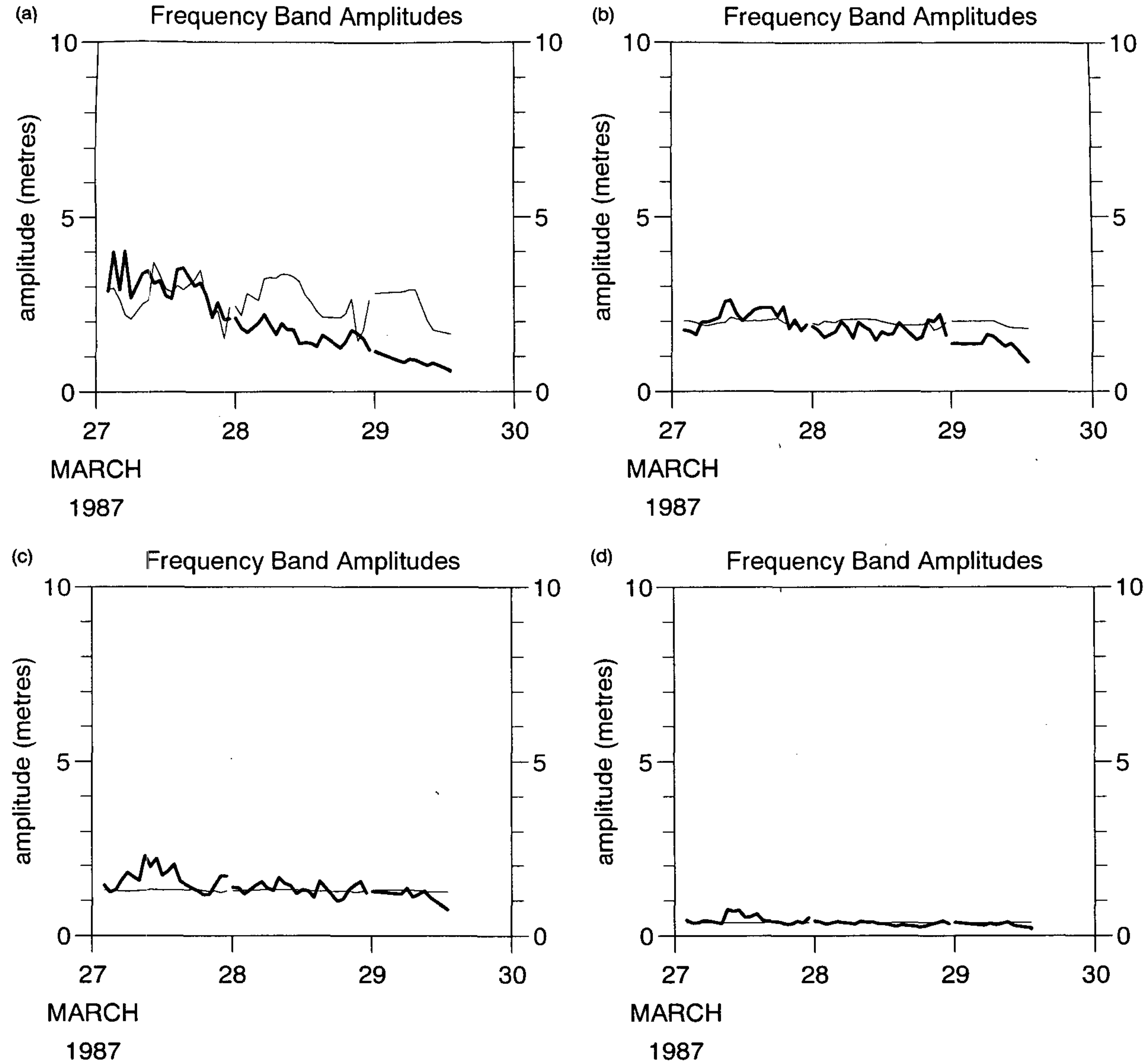

FIG. 6. Significant wave height (in finite frequency bands) measurements obtained using the radar (thick line) compared with those obtained using a Pierson–Moskowitz spectrum based on the measured wind speed (thin line). The frequency bands shown are (a) 0.085–0.1 Hz, (b) 0.125–0.155 Hz, (c) 0.16–0.2 Hz, and (d) 0.33–0.5 Hz.

do provide such information directly, since the measurement is of the two-dimensional wavenumber spectrum with no directional ambiguities (Wyatt and Holden 1994).

The work described in this paper was motivated in part by a need to verify the details of the radar-measured directional spectra and also, by looking at one particular well-monitored event, to highlight the important contribution that HF radar systems could make to further the understanding of ocean wave development. Wind speed and direction measured at the North Devon site (using an anemometer provided by Wimpol Ltd.) during March 1987 are shown in Fig. 2. The storm referred to here is at the end of March. These wind measurements were being made some 100 km from the buoy site at which most radar measurements were made and furthermore at a site located at the top of a 80-m cliff. They are not therefore necessarily representative of wind conditions at the wave measurement site.

Radar measurements were obtained on an hourly basis almost continuously from early on 27 March through to midday on 29 March. Unfortunately, the radar was not operating during the development of the storm that began in the evening of 26 March. By the time the radar was operational (at 0200 LT 27 March) the wind speed had already increased to over 15 m s^{-1} and the wave spectrum was fully developed. This is

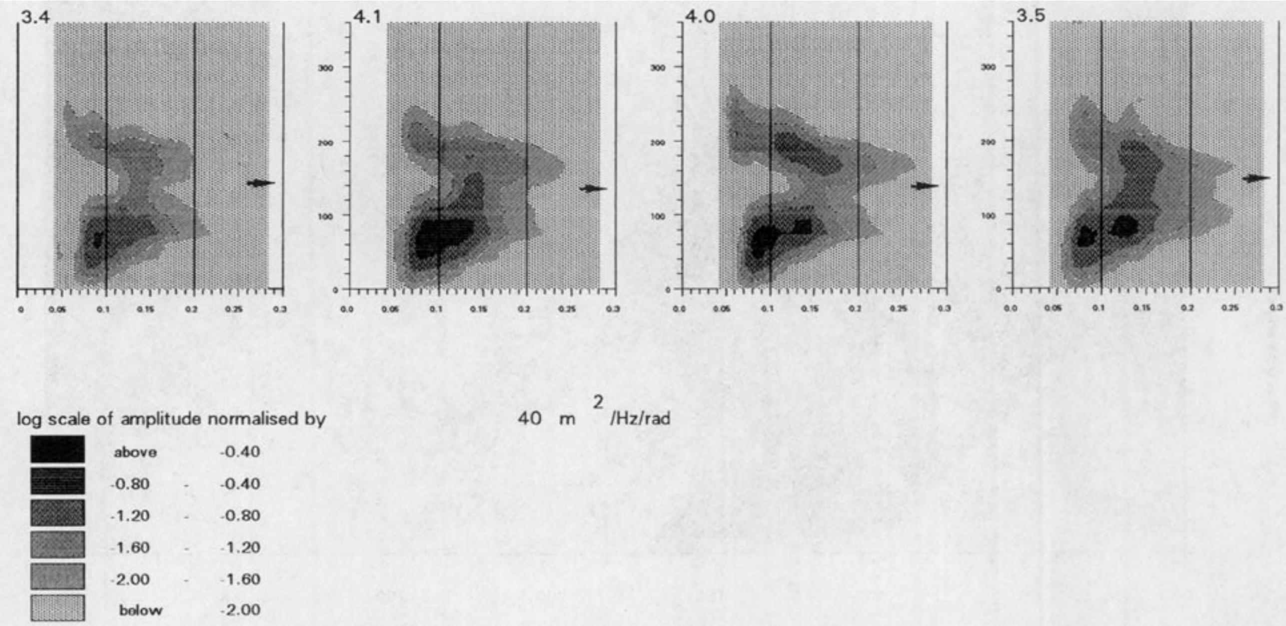

FIG. 7. Directional spectra measured by the radar during the evening of 28 March 1987 showing bimodality. The details are as described for Fig. 5.

seen in Fig. 3, which compares the frequency spectrum measured by the radar at 0200 LT with a PM spectrum using the measured wind speed. Wind direction at that time was southerly. Eight hours later the wind had veered to westerly and was thus blowing off the Irish coast. The wind remained roughly in this direction with a wind speed of 15–20 m s^{-1} for the next 48 hours. It seemed likely then that there would be a possibility to observe the timescale for the relaxation of wave direction to the new wind direction at different frequencies. The relaxation timescale is an important quantity in wave modeling work, and these measurements would have made a useful contribution to the debate over its parameterization. However, as will be shown, this dataset was not suitable for such a study. The need for careful experimental planning if directional relaxation is to be measured will be demonstrated.

3. Storm directional spectra measurements

Figure 4 shows mean direction measurements for four different frequency bands for the WAVEC and the radar for the period 27–29 March. Superimposed on these is wind direction. The short waves, that is, those with frequencies greater than 0.16 Hz do respond to the changing wind direction, showing surprising agreement given the difference in location of the wind measurement. If anything the radar measurements agree more closely with the anemometer wind direction and are more smoothly varying in time. There is a slow directional change in the 0.125–0.155-Hz band but both the wave buoy and the radar show very little response at the lower frequencies that were considerably more energetic. This is also seen clearly in the radar-measured directional spectra plotted in Fig. 5. The wind direction is shown on the plots by an arrow. Just preceding the wind direction change, the 0900 LT spectrum on 27 March is complex and suggests that the new wind direction is already having an influence as new swell propagates into the measurement location. By 1000 LT the spectrum has settled down again with very little change to the long-wave pattern. By 28 March the wind direction has veered to more north of west and the energy levels decrease even though the high wind speed is still maintained. This can be seen in Fig. 6, which shows the energy (converted to a significant wave height) in the same four frequency bands for which direction measurements were shown in Fig. 4. The radar measurements are compared with the corresponding figures for a PM spectrum using the measured wind speed at each time. The higher-frequency bins have energy levels comparable with the PM values whereas in the lower-frequency bins energy levels decay relative to those of the PM spectrum. Later on 28 March, the spectrum is becoming bimodal (see Fig. 7).

There appears to be evidence of a wave component reflected from the coast in many of these measurements. It is not yet clear whether this is real or an artifact of the radar inversion—this is the subject of current work. Such an effect is only seen in the radar data when there are high energy levels at very low frequencies.

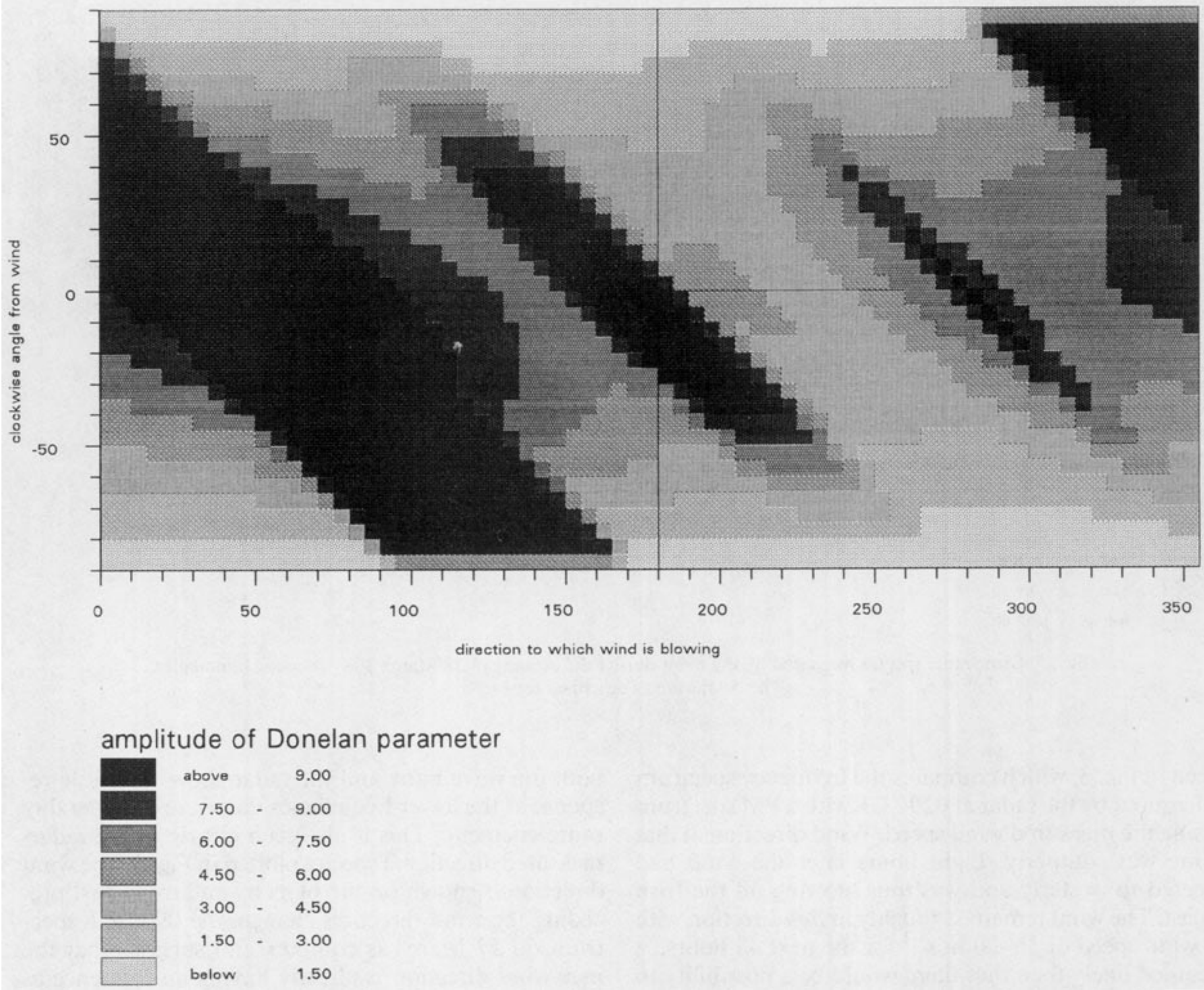

FIG. 8. Gray-scaled contours of $\cos\theta x^{0.426}$, where θ is on the vertical axis and x is the fetch associated with a wind blowing toward the angle on the horizontal axis. Light shading indicates low values; dark shading high values.

There are three aspects of the directional spectra to explain.

1) Why do the long waves not respond to the changing wind direction?

2) Why do the power density levels (and significant wave height) decay during 28 March when the wind speed stays roughly constant?

3) What is the cause of bimodality during the later part of the storm?

All of these can be explained by considering the geography of the region and the consequent variation in fetch with wind direction. This effect was discussed by Donelan et al. (1985), who used a similarity argument to deduce that the peak in the spectrum would have mean direction at an angle θ to the wind direction such that $(\cos\theta)x^{0.426}$ is maximized, where x is the fetch in the direction θ. This quantity is contoured in Fig. 8 using detailed fetch estimates from land and approximate fetches from the Irish Sea, the Bristol Channel, and the Atlantic. A uniform wind field across the entire region at the time of each measurement is assumed, and hence the fetch in a particular direction is the distance from the coast. The direction toward which the wind is blowing is shown along the horizontal axis, and the value of $(\cos\theta)x^{0.426}$ for θ up to $\pm 90°$ is shown. The figure implies that a spectrum driven by a wind blowing from the south (toward 0°) will tend to show a peak with propagation direction from the southwest, whereas a wind from the north (180°) will tend to show a peak with a propagation direction from the northwest, which in this case means from the Irish Sea. Waves generated in the wind direction off the Irish coast are much more fetch limited.

Clearly, for the storm wind directions waves with mean direction associated with propagation up the southwest approaches will dominate the spectrum throughout. This means that, once the winds have

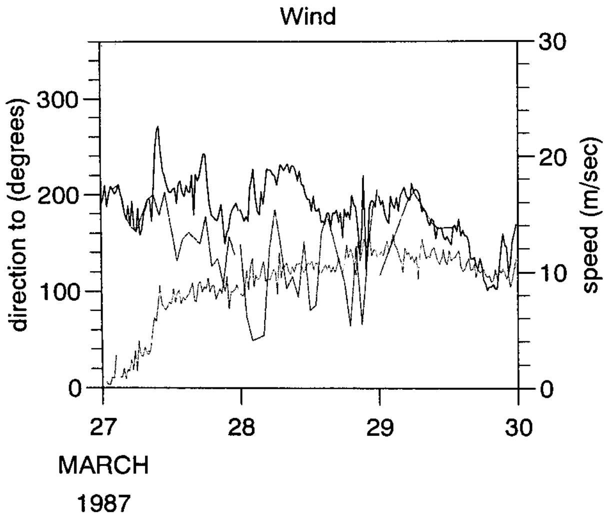

FIG. 9. Wind speed (solid line), wind speed component in the direction of the peak of the spectrum as measured by the radar (light line), and direction (dotted line) measurements during the storm.

veered to a direction off the Irish coast, an important parameter in determining energy levels is $U \cos\theta$, that is, the component of wind speed U in the direction of the peak and not U itself. This quantity is plotted in Fig. 9 and shows a decrease during 28 March consistent with the reducing energy levels.

The bimodal spectra measured during the later part of the storm are seen when the wind direction is from 100° to 150°. Figure 8 shows that waves propagating from the Irish Sea could have an influence on the spectrum in these circumstances in addition to those from the southwest.

The three aspects of the directional spectrum are thus interrelated and appear to suggest that a directionally uncoupled fetch-limited model might be useful in describing the spectra. That is, a slice through the directional spectrum in one direction might be described by a Joint North Sea Wave Project (JONSWAP) (Hasselmann et al. 1973) spectrum driven by the wind component in that direction. Figure 10 shows the radar directional spectra for 27 and 28 March sliced

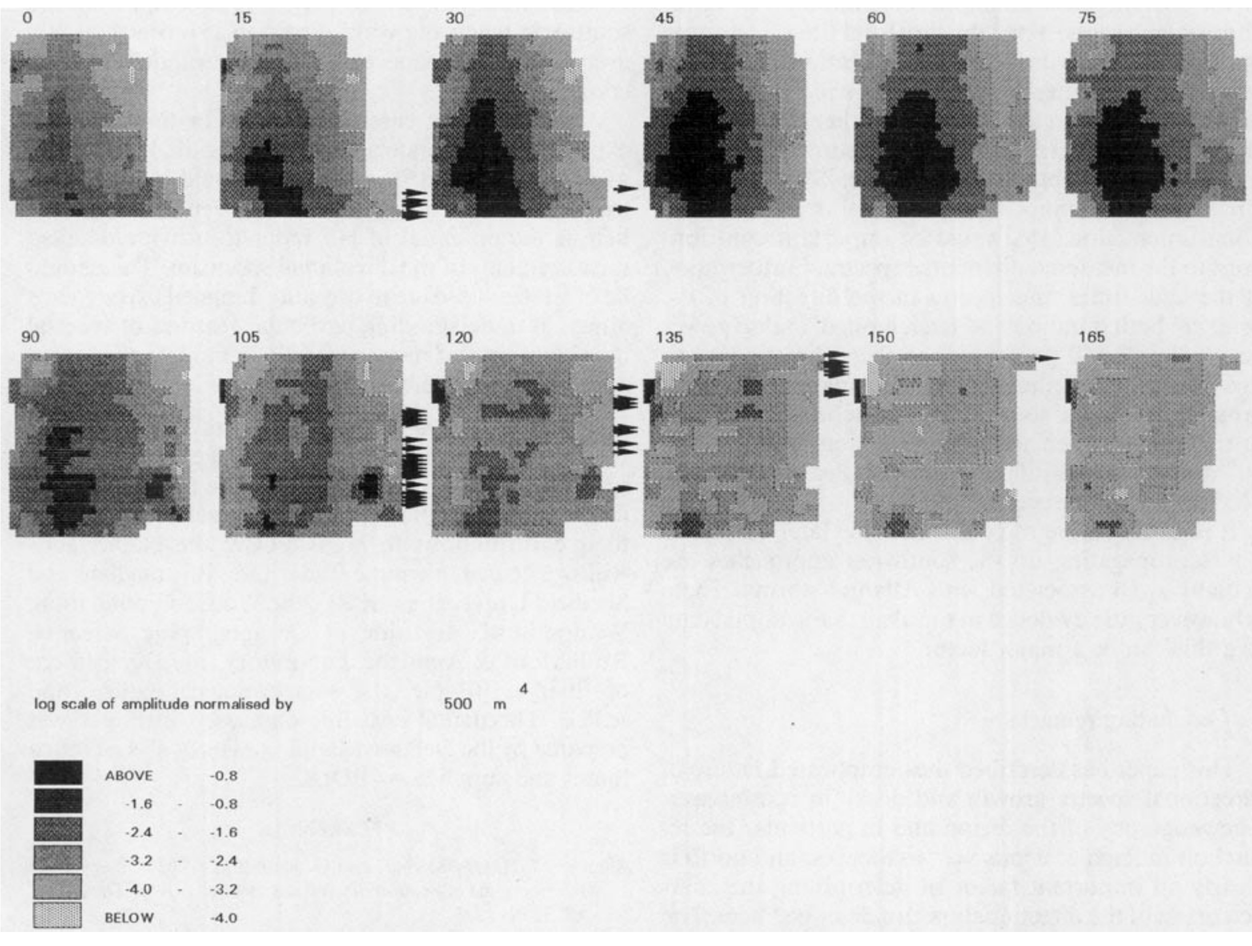

FIG. 10. Slices through the radar-measured directional wavenumber spectra in the directions indicated by the numbers at the top of each plot. Time increases vertically, and each plot shows the measurements over the two days, 27 and 28 March. The horizontal axis in each case is wavenumber. The presence of a black arrowhead to the right of a plot at a particular time indicates that the measured wind direction was in that direction. Gray shading is in six equally spaced logarithmic levels as shown normalized to a maximum of 500 m^4.

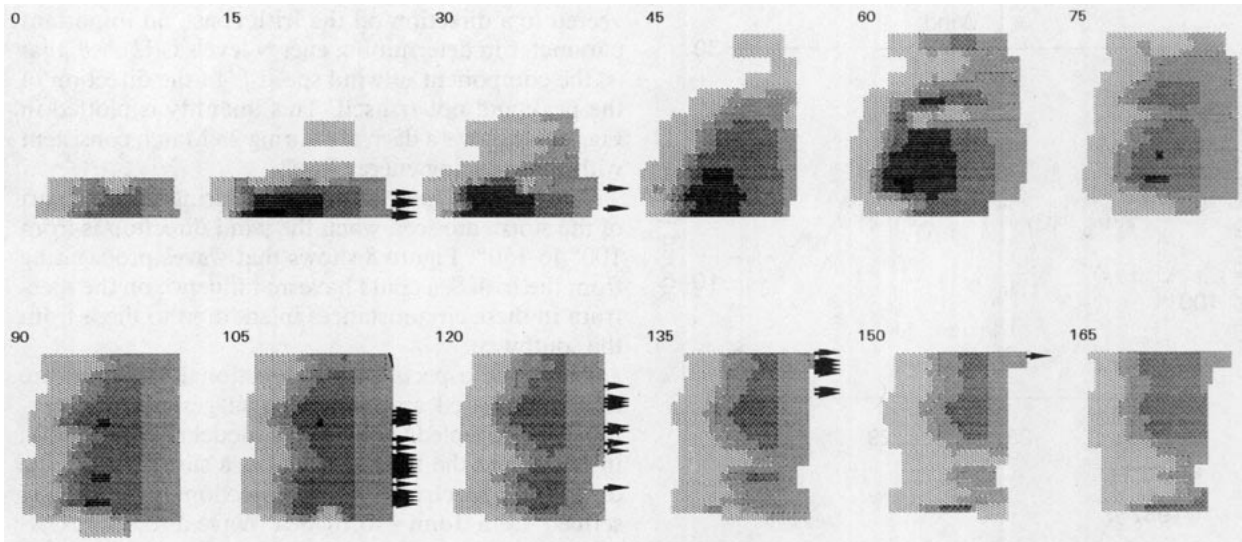

FIG. 11. As in Fig. 10 but for spectra modeled using the JONSWAP model.

in 15° increments and amplitude contoured in wavenumber (measured along the slice) and time. The arrow shows where the wind was in the direction of the slice at a particular time. The change in wind direction is picked up clearly in the 105° slice. Other features have already been described. Figure 11 shows the corresponding figure obtained with a JONSWAP model. Obviously this cannot model spectral decay or directional interactions that must be important contributions to the measured directional spectra. Furthermore, at the later times, the spectra in the direction of the wind are both duration and fetch limited, and so power density levels will be too high in these directions with this model. Nonetheless, the dominance of waves propagating up the southwest approaches, until cut off in this model when the wind direction is more than 90° away, and the influence of Irish Sea waves in the 165° sector can be seen.

It is also possible of course that the later measured waves propagating up the southwest approaches are actually swell associated with Atlantic storms. There is however little evidence in the available synoptic data that this can be a major factor.

4. Concluding remarks

This paper has described the complicated nature of directional spectra growth and decay in coastal seas. The geography of the region and in particular the reduction in fetch as winds veer to the west and north is clearly an important factor in determining the characteristics of the directional spectra described here. The use of a directionally decoupled JONSWAP model to explain the qualitative nature of the spectral development is of course by no means sufficient. Wave interactions and perhaps local slow decay must play a role in maintaining the wave energy propagation from the southwest when the wind direction is more than 90° away. There is scope here for wave model hindcast comparisons.

A great deal of care is necessary in the design of experiments to isolate and study individual features of wave development in a way that would be useful for model parameterization. What has been demonstrated here is the potential of HF radar to provide detailed measurements of the directional spectrum. This should be of enormous value in carefully designed experiments aimed at understanding particular features of spectral development and more generally in model verification and wave measurement applications.

Acknowledgments. The support of SERC (Grant GR/F25860) is gratefully acknowledged. The PISCES system is being developed by Neptune Radar Ltd. The following organizations are gratefully acknowledged for their contributions to NURWEC2: the Netherlands Rijkswaterstaat, Neptune Radar Ltd., Birmingham and Sheffield Universities, SERC, the Wolfson Foundation, Wimpol Ltd., Institute of Oceanographic Sciences, Rutherford & Appleton Laboratory, the Department of Energy, BP plc, the Meteorological Office, and A.R.E. The digital coastline data used in Fig. 1 was prepared by the Defense Mapping Agency of the United States and supplied by BODC.

REFERENCES

Allender, J. H., J. Albrecht, and G. Hamilton, 1983: Observations of directional relaxation of wind sea spectra. *J. Phys. Oceanogr.*, **13**, 1519–1525.

Beal, R. C., Ed, 1991: *Directional Wave Spectra*, The Johns Hopkins University Press, 218 pp.

Donelan, M. A., J. Hamilton, and W. H. Hui, 1985: Directional spectra of wind-generated waves, *Philos. Trans. Roy. Soc. London A*, **315**, 509–562.

Günther, H., W. Rosenthal, and M. Dunckel, 1981: The response of surface gravity waves to changing wind direction, *J. Phys. Oceanogr.*, **11,** 718–728.

Hasselman K., T. P. Barnett, E. Bouws, H. Carlson, D. E. Cartwright, K. Enke, J. A. Ewing, H. Gienapp, D. E. Hasselman, P. Kruseman, A. Meerburg, P. Müller, D. J. Olbers, K. Richter, W. Sell, and H. Walden, 1973: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). *Dtsch. Hydrogr. Z. (Suppl. A),* **8**(12), 95 pp.

Holthuijsen, L. H., 1983: Observations of the directional distribution of ocean wave energy in fetch-limited conditions. *J. Phys. Oceanogr.*, **13,** 191–207.

——, A. J. Kuik, and E. Mosselman, 1987: The response of wave directions to changing wind direction. *J. Phys. Oceanogr.*, **17,** 845–853.

Kjeldsen, S. P., 1991: The practical value of directional ocean wave spectra. *Directional Wave Spectra,* R. C. Beal, Ed., The Johns Hopkins University Press, 13–19.

Lipa, B. J., and D. E. Barrick, 1986: Extraction of sea state from HF radar sea echo: Mathematical theory and modelling. *Radio Sci.*, **21,** 81–100.

Long, R. B., 1980: The statistical evaluation of directional spectrum estimates derived from pitch/roll buoy data. *J. Phys. Oceanogr.*, **10,** 944–952.

Lygre, A., and H. E. Krogstad, 1986: Maximum entropy estimation of the directional distribution in ocean wave spectra. *J. Phys. Oceanogr.*, **16,** 2052–2060.

Masson, D., 1990: Observations of the response of sea waves to veering winds. *J. Phys. Oceanogr.*, **20,** 1876–1885.

Mollo-Christensen, E., 1993: Directional response of a discus buoy to waves. *Symp. on the Air-Sea Interface,* Marseille, France, Environment Canada, p. 124.

Shearman, E. D. R., and M. D. Moorhead, 1988: Pisces: A coastal ground-wave radar for current, wind and wave mapping to 200 km ranges. *Proc. Int. Geoscience and Remote Sensing Symp.*, ESTEC, Edinburgh, United Kingdom, European Space Research and Technology Centre, 773–776.

SWAMP Group, 1985: *Ocean Wave Modelling.* Plenum Press, 256 pp.

van Vledder, G. P., and L. H. Holthuijsen, 1993: The directional response of ocean waves to turning winds. *J. Phys. Oceanogr.*, **23,** 177–192.

Venn, J. F., G. T. Mardell, J. Howarth, and C. G. Holmes, 1988: Current measurement by long range HF ground-wave radar. *Proc. Int. Geoscience and Remote Sensing Symp.*, ESTEC, Edinburgh, United Kingdom, European Space Research and Technology Centre, 783–786.

Walsh, E. J., D. W. Hancock, D. E. Hines, R. N. Swift, and J. F. Scott, 1989: An observation of the directional wave spectrum evolution from shoreline to fully developed. *J. Phys. Oceanogr.*, **19,** 670–690.

Wyatt, L. R., 1988: Significant waveheight measurement with HF radar. *Int. J. Rem. Sens.*, **9,** 1087–1095.

——, 1990: A relaxation method for integral inversion applied to HF radar measurement of the ocean wave directional spectrum. *Int. J. Rem. Sens.*, **11,** 1481–1494.

——, 1991: HF radar measurements of the ocean wave directional spectrum. *IEEE J. Oceanic Eng.*, **16,** 163–169.

——, and G. Holden, 1992: Developments in ocean wave measurement by HF radar. *IEE Proc.* **F, 139,** 170–174.

——, and ——, 1994: HF radar measurement of multi-modal directional wave spectra. *The Global Atmosphere and Ocean System,* **2,** 265–290.

Young, I. R., S. Hasselmann, and K. Hasselmann, 1987: Computations of the response of a wave spectrum to a sudden change in wind direction. *J. Phys. Oceanogr.*, **17,** 1317–1338.