Observations of Directional Relaxation of Wind Sea Spectra

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ABSTRACT

Two-dimensional wave spectra were acquired through a NOAA Experimental Research Buoy in 34 m of water off the North Carolina coast (Atlantic Ocean). These are analyzed in ideal wave-growth situations and under rapidly turning winds. The relationship between variance and peak frequency for growing seas, determined from the buoy data, agrees well with relationships based on data from other methods. The response of mean wave direction as a function of frequency is documented graphically and by simple regression analyses for several cases of rapidly turning wind fields. The relaxation rates for wave direction are similar to limited previous estimates. The present results can be used in evaluating wave prediction models.

1. Introduction

A growing body of observations has quite well established the general features of the two-dimensional surface gravity-wave spectrum. The main features of interest here are that 1) for a sufficiently constant wind vector, the peak energy at all frequencies of the wind sea spectrum tends to travel in the wind direction, and 2) the angular spreading of energy is approximately symmetric with respect to the wind direction and increases with frequency. However, in important practical situations such as hurricanes, the mean wave direction at a given frequency can lag behind a rapidly changing wind direction. This lag apparently varies inversely with frequency, and some relatively low (swell) frequencies may not respond at all.

Some data from the JONSWAP experiments have been used to study selected spectra under rapidly turning winds. Two more-or-less ideal situations of particular interest are 1) a step-like change in direction of a roughly constant-speed wind, and 2) a wind changing direction at nearly constant angular velocity.

Hasselmann *et al.* (1980), in a study that focuses primarily on determining the angular spreading of wind seas, present results from four cases that approximately satisfy the preceding two idealizations. They investigated the relaxation of the mean wave directions for discrete frequency bands. This was done by fitting their data to a simple relationship involving the frequency itself and the sine of the angle between the wind and wave directions. (The mean direction is defined as the phase of the first harmonic in the directional Fourier transform; see, e.g., Longuet-Higgins *et al.*, 1963.)

Gunther *et al.* (1981), again using some of the JONSWAP data, developed a relation to simulate the relaxation time for turning the mean wave direction (of the entire wind-sea spectrum) into the wind direction in terms of the wind speed and the estimated frequency border between wind-sea and swell. Their relationship is tailored to fit into their hybrid-parametrical wave prediction model.

The importance of the spectrum's response to rapidly turning winds (directional relaxation) is made especially clear by the results of the wave model intercomparison (Hasselmann *et al.*, 1982). Highly disparate results from different models applied to the same situation could be attributed to the different directional relaxation effects inherent in the models.

Motivated by this comparison, our primary objective is to use our observations to provide a semi-quantitative description of four additional cases of directional relaxation. In addition to doubling the avail-

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able data, this description can be compared with those in previous studies.

A secondary objective is to compare the power-law relationship between variance and peak frequency based on the present data with relationships found in previous studies. As described in the next section, we use data acquired through the Experimental Research Buoy (XERB), developed by NOAA Data Buoy Office and sited off the North Carolina coast (Atlantic Ocean). Our results (Section 3) are summarized primarily by graphs and simple regression analyses.

2. Approach and measurements

In 1975 the NOAA Data Buoy Office (NDBO) began routine measurement and reporting of one-dimensional wave-displacement spectra from buoys. Approximately thirty 12 and 10 m discus and 6-m boat-shaped NOMAD hulls are now deployed. These report wave spectra hourly through the GOES satellite system from the Atlantic and Pacific Oceans, Gulf of Mexico, and Great Lakes. The wave-data-analyzer system for NDBO buoys is described by Steele *et al.* (1976).

During 1976 and early 1977 NDBO, in a program to expand their capabilities, assembled a special buoy to measure directional wave spectra. This 12-m discus hull, commonly called the Experimental Environmental Research Buoy (XERB), was tested in 1977 in the Atlantic Ocean. Further developmental testing and evaluation of XERB took place near Panama City, Florida, in 1979 and 1980. Burdette *et al.* (1978) and Steele *et al.* (1978) give synopses of the measurement techniques and system configuration, respectively; NDBO (1982) describes the entire system in detail. The buoy was deployed on 23 October 1980 off the North Carolina coast (36°17.9'N, 75°22.1'W) as part of the NOAA Coastal Waves Program. The water depth is approximately 34 m. The buoy began successful operation on the date of deployment and was recovered in May 1982. The site was selected to support the Corps of Engineers' Atlantic Remote Sensing Land Ocean Experiment (ARLSOE), which took place during October and November 1980.

The new buoys similar to XERB will be deployed in the Spring of 1983. These will measure directional wave spectra in the California Bight (Pacific Ocean off Los Angeles, California) and in the Gulf of Mexico.

The measurement site for the present study (Fig. 1) has essentially no fetch limitations for easterly winds. Shallow-water effects may come into play for frequencies of less than 0.15 Hz, for which the water depth is less than half the wavelength. These effects do not confound the conclusions we have drawn from the data, taken from October and November 1980 and from July–November 1981. Hourly spectral estimates are available for at least parts of these months.

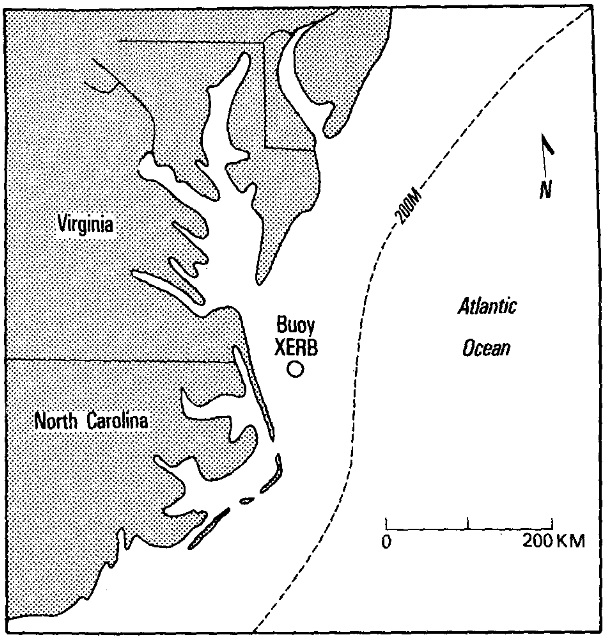

FIG. 1. Location map for buoy XERB.

Strong winds at the study site during the late summer and fall are usually associated with passing cold fronts or developing low-pressure systems. These weather patterns result in northeasterly winds, hence wind seas from the northeast much of the time. Tropical cyclones often occur over the open ocean southeast of the site, producing low-frequency swells approximately from the east.

3. Results

a. Relation between variance and peak frequency

We extracted eleven "ideal" growth episodes from the data, i.e., when the wind vector was fairly steady (by subjective judgement) and the variance of the spectrum increased while the peak frequency decreased. In addition these periods were dominated by easterly winds (little or no fetch limitation) and there was little or no energy in the low-frequency (swell) region of the spectrum.

Because of the cool easterly winds and the proximity of the Gulf Stream, all of the growth episodes apparently took place under unstable conditions; i.e., the sea surface temperature exceeded the air temperature (according to the buoy data) by 0.3–5.7°C, and was >1°C approximately 85% of the time. Wind speeds were 8 to 16 m s^{-1}, and peak frequencies of the energy density versus frequency (or one dimensional) spectrum ranged from 0.14–0.28 Hz approximately 75% of the time. At other times the peak fell between 0.12 and 0.14 Hz, where some shallow-water effects are possible.

We fitted our data to a power-law relationship between the nondimensional variance ($\epsilon = g^2E/U_{10}^4$) and nondimensional peak frequency ($\nu = U_{10}f_pg^{-1}$). In these relationships g is gravity, U_{10} the wind speed at 10 m, E the integral of the spectrum over frequency and direction (i.e., a measure of total energy), and f_p is the peak frequency of the one-dimensional spectrum. When the variables from the eleven episodes were combined as indicated at a given time, eighty-four pairs of ϵ, ν values were formed.

A simple regression analysis led to

$$\epsilon = 9.6(10^{-6})\nu^{-3.0}, \qquad (1)$$

which is compared in Fig. 2 with published results by Hasselmann *et al.* (1976) and Ross (1978). Equation (1) accounts for about 84% of the variance of ϵ. The figure also gives overly optimistic confidence limits for (1). These limits span one standard error (modified by the student's t-distribution for small sample size) above and below the regression line, and ν is assumed to have been measured perfectly (e.g., Snedecor and Cochran, 1967).

On the basis of the JONSWAP experiments, Hasselmann *et al.* (1976) adopted the so-called equilibrium relationship $\epsilon = 5.1 \times 10^{-6}\nu^{-10/3}$. Ross' (1978) relationship for unstable conditions, from a combination of laser altimeter measurements over the North Sea and the western Atlantic, is $\epsilon = 1.64 \times 10^{-6}\nu^{-4.07}$. Near $\nu = 0.2$, where most of the present data lie, we cannot distinguish among the two previously published relationships and Eq. (1). Liu and Ross (1980), however, did find some support for Ross' relationship under unstable conditions.

So, the XERB data does lead to an ϵ–ν relationship for the range of wind speeds and frequencies given above. This is consistent with relationships found by other investigators using rather different methods. It is notable that the present relationship is based on duration-limited conditions, rather than fetch-limited conditions as in the studies by Hasselmann *et al.* and Ross.

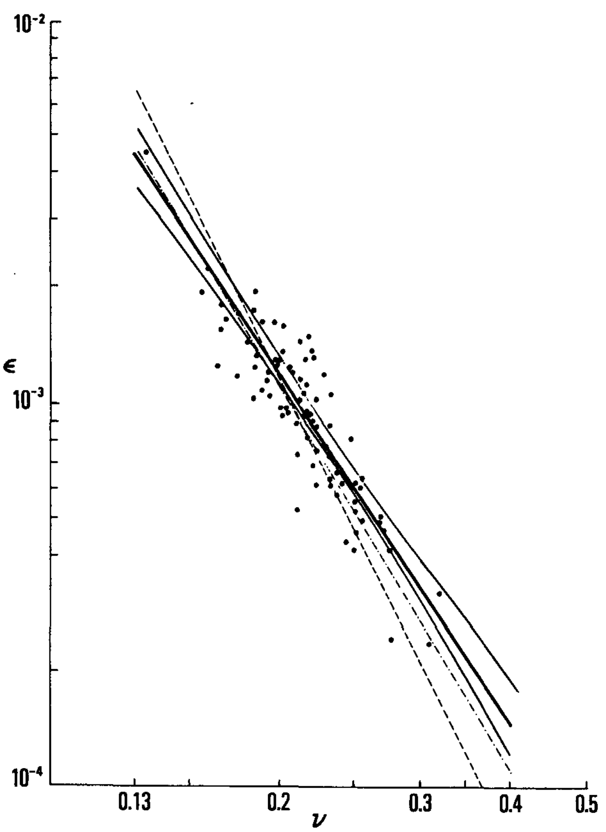

FIG. 2. Nondimensional variance ϵ versus peak frequency ν: Present study, solid line; Hasselmann *et al.* (1976), dashed-dotted line; Ross (1978), dashed line. Results are essentially the same for $0.15 \leq \nu \leq 0.25$.

b. Response to rapidly turning winds

The present data set contains four 1-day time periods suitable for analyzing the response of the two-dimensional wave spectrum to rapidly turning winds. "Rapidly turning" loosely means that the wind direction changes by an appreciable fraction over a time period that is short compared to what would be required to reach a fully developed spectrum at the existing wind speed. The actual spectral density is largely ignored here in favor of the mean wave direction as a function of frequency. In addition, direction values from three adjacent frequency bands (covering 0.03 Hz) are averaged to reduce the somewhat noisy behavior of individual bands.

Two limitations of the present results should be noted. First, the wave directions given below are simply the phase of the first harmonic of the Fourier-transformed buoy data. Turning winds can presumably lead to spectra with broad, asymmetric angular distributions. Hasselmann *et al.* (1980) found that the first harmonic could be predicted poorly in such cases, partly because of sampling errors for broad distributions.

Second, the wave directions for some frequency bands could include (unknown) integrated effects of changes in the upstream wind direction. Such changes are characteristic of low pressure systems such as those associated with the present data. Accordingly, we include estimates of the radius of curvature r_c of the surface pressure field near the measurement site in the following discussion. These estimates are based on surface pressure maps produced by the National Weather Service.

Our primary results are summarized in Figs. 3–5, which show wind speed and direction and mean wave direction for eight frequency intervals centered around 0.06, 0.09, . . . , 0.24, and 0.27 Hz versus time. Plots of the corresponding one-dimensional spectra at selected times are given in Fig. 6. The figures portray

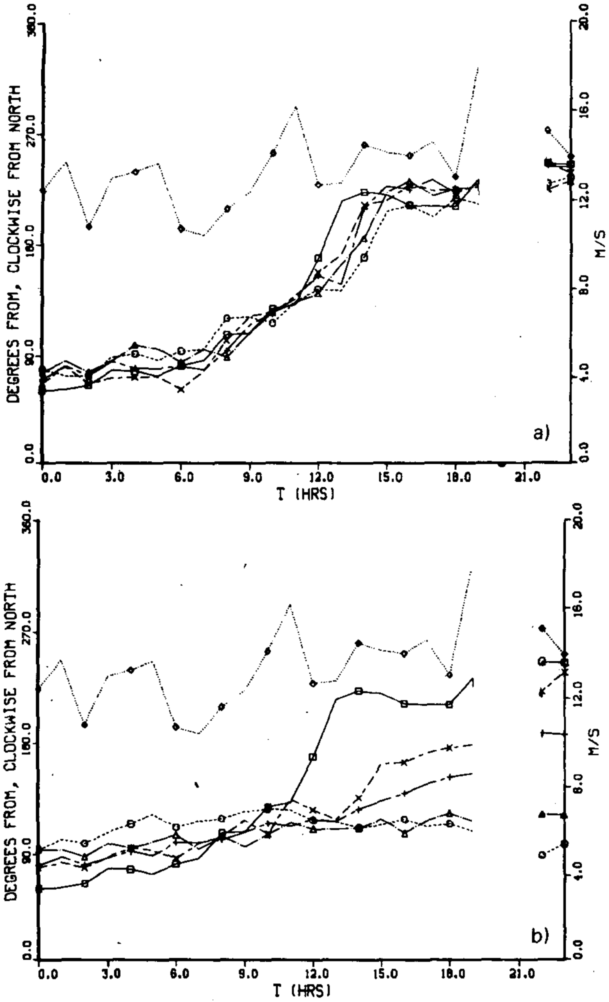

FIG. 3. Response of mean wave direction to turning winds; $t = 0$ corresponds to 25 October 1980 at 0000 LST: (a) wind speed, diamonds; wind direction, squares; and mean wave directions are circles, triangles, plus signs and crosses for frequency bands at 0.18, 0.21, 0.24, and 0.27 Hz, respectively. (b) Symbols as in (a) except the frequency bands are at 0.06, 0.09, 0.12, and 0.15 Hz, respectively; frequency-dependent lag in wave direction is evident during hours 11–18; see Fig. 6a for wave spectra.

the response of the spectra under qualitatively different circumstances: 1) an almost fully-developed sea subject to rapid change in wind direction (Figs. 3 and 6a), and 2) bimodal spectra with partly developed wind seas responding to moderately rapid changes in wind direction (Figs. 4, 5 and 6b–c). The figures give an immediate impression of directional relaxation, allowing estimates of rates. To illustrate better the physical situations, however, we describe the meteorology very briefly and attempt to tie the responses to familiar notions about the behavior of the spectrum.

On 25 October 1980 a very intense low pressure system formed off the north Florida coastline and moved rapidly northward. Wind speed at the measurement site ranged from 11–18 m s^{-1} during the storm while the wind direction was generally easterly, switching rapidly through southerly to westerly as the storm passed. At the outset the wind field had practically no curvature ($r_c > 1000$ km). As the low pressure system approached, r_c decreased to ~300 km at hour 6 (with winds more from the southeast farther offshore) and to ~100 km at hour 12. Figure 3 shows the response of the nearly fully developed sea ($f_U = 0.10$ Hz $\approx 0.13\ g/U_{10}$) to the passing storm. During and just after the primary shift in wind direction (hours 11–18), the mean wave direction at frequency bands below f_U showed no apparent response (Fig. 3b), while the directions for bands centered at 0.21 and 0.18 Hz (Fig. 3a) and 0.15 and 0.12 Hz (Fig. 3b) show an increasing lag behind the wind direction with decreasing frequency. Wave directions

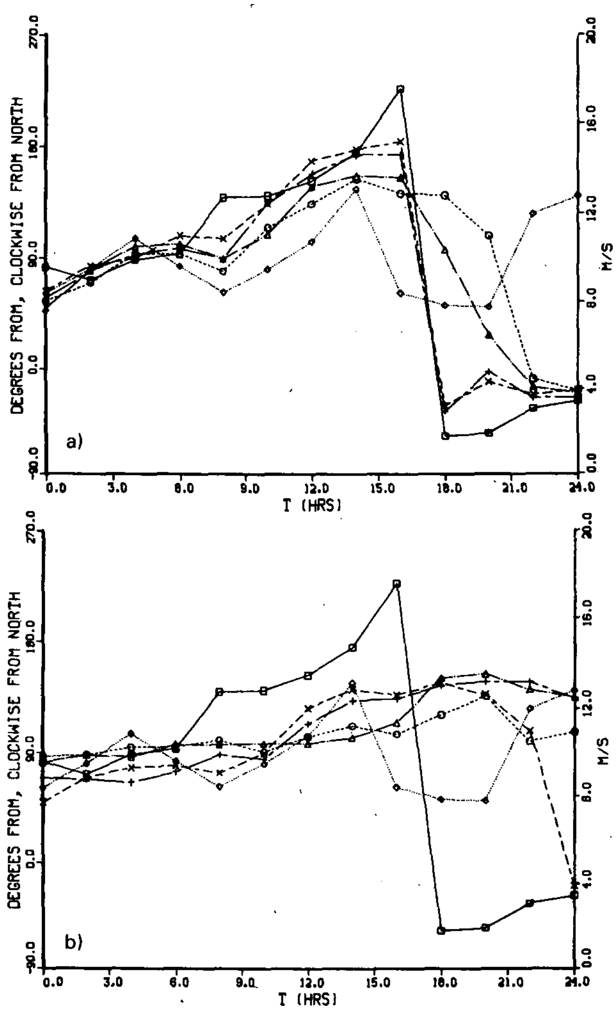

FIG. 4. Response of mean wave direction to turning winds; $t = 0$ corresponds to 17 November 1980 at 1800 LST; symbols as in Fig. 3; frequencies above $0.13\ g/U_{10} \approx 0.13$ Hz respond to wind direction change; at hour 24 sea and swell directions differ by >90°; see Fig. 6b for wave spectra.

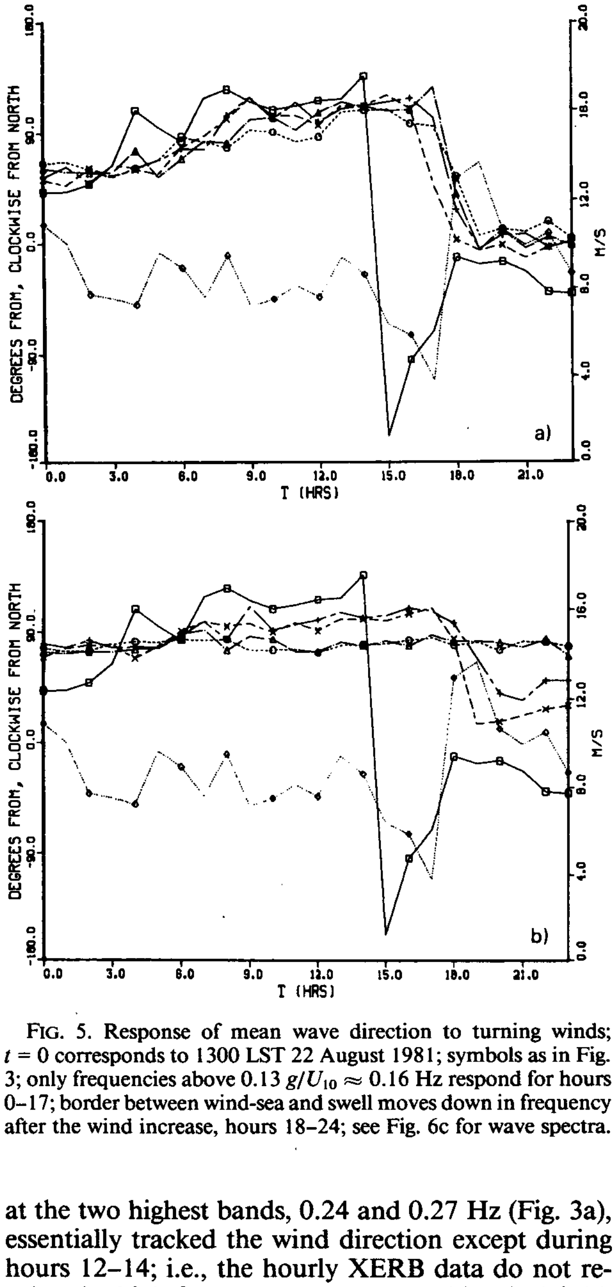

FIG. 5. Response of mean wave direction to turning winds; $t = 0$ corresponds to 1300 LST 22 August 1981; symbols as in Fig. 3; only frequencies above 0.13 $g/U_{10} \approx$ 0.16 Hz respond for hours 0–17; border between wind-sea and swell moves down in frequency after the wind increase, hours 18–24; see Fig. 6c for wave spectra.

at the two highest bands, 0.24 and 0.27 Hz (Fig. 3a), essentially tracked the wind direction except during hours 12–14; i.e., the hourly XERB data do not resolve the high-frequency response to this wind field. The one-dimensional spectrum at hours 0, 8, 12, 16, and 23 is shown in Fig. 6a. The spectrum reached a peak at 0.09 Hz by hour 12 and then decreased steadily until a new peak formed at 0.16 Hz by hour 23. Energy associated with the latter peak was aligned with the new wind direction (Fig. 3a).

On 17–18 November 1980 two low pressure systems passed near XERB. Winds along the coast were generally east to southeast at $\sim$10 m s^{-1}, veering to southwest as the storms passed through, then shifting to northwest after the storms moved off to the northeast. Surface isobars showed relatively little curvature ($r_c \approx$ 800 km) during hours 0–16. The proximity of a cold front after hour 18 precludes simple estimates of curvature thereafter. Figure 4 shows that wave directions at frequency bands 0.15, 0.18, 0.21, 0.24, and 0.27 Hz responded to the slowly changing wind direction during hours 0 to 15, while the lower three bands were mostly unaffected. When $U_{10} \approx$ 10 m s^{-1} (the average over hours 0–15), f_U = 0.13 Hz again provided an approximate division between the wind-sea and swell regimes, as expected. By the end of the period shown, wave directions at the highest and lowest bands differed by more than 90°. The one-dimensional spectrum at hours 0, 8, 12, 16, and 22 is

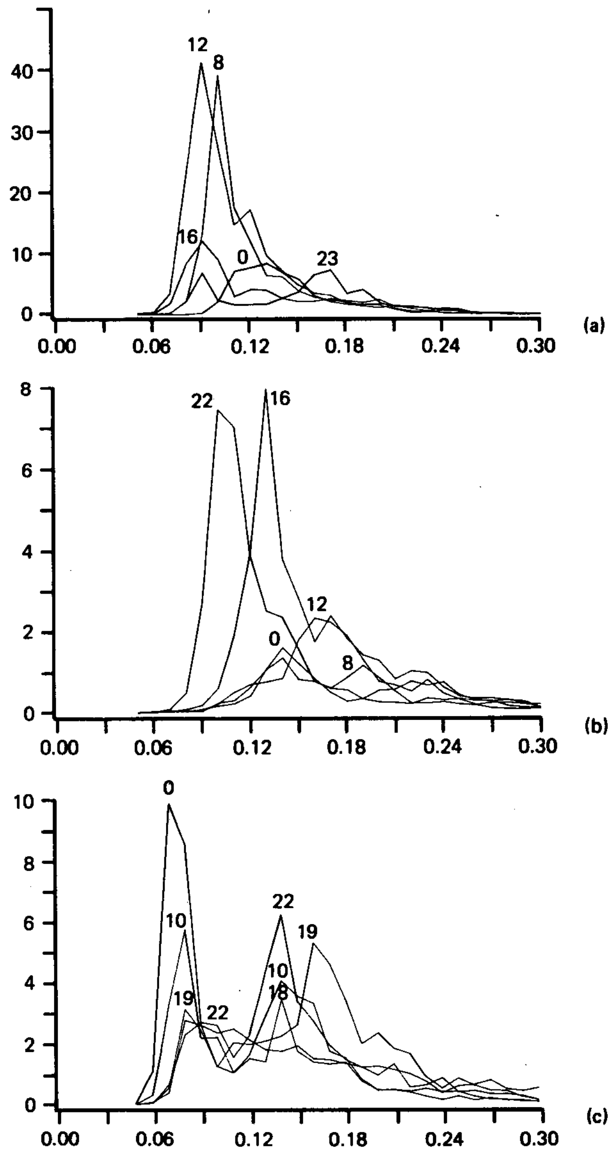

FIG. 6. Wave energy versus frequency spectrum at selected times (as indicated near peaks); units are m^2 Hz^{-1} versus Hz; parts (a), (b) and (c) correspond with the time periods in Figs. 3, 4 and 5, respectively.

shown in Fig. 6b. The broad peak at hour 8 shifted downward in frequency as the spectrum sharpened through hour 16. Energy due to swells (from east northeast) predominated by hour 22.

On 22 August 1981 a rapidly intensifying low pressure system moved northeastward past the buoy. Winds shifted slowly from northeasterly to southeasterly during hours 0–15 and then changed rapidly to north northwest between hours 15–18. Curvature increased steadily (winds more northerly offshore) from $r_c \approx 750$ km at the outset to 400 km at hour 6, and to less than 100 km at hour 12. As in the previous case, the cold front was too close by hour 18 to allow a simple curvature estimate. When $U_{10} \approx 9$ m s^{-1}, frequency bands above $f_U \approx 0.14$ Hz responded to the changing wind direction, although the rate of change was small enough that the simple picture (higher frequency, faster response) broke down. Following the step-like change in wind direction after hour 18, the increased wind speed caused all but the two lowest frequency bands to change direction. The one-dimensional spectrum at hours 0, 10, 18, 19, and 22 is shown in Fig. 6c. A bimodal spectrum existed throughout the period, with a swell peak at 0.08 Hz and wind-sea peaks between 0.14 and 0.17 Hz. The wind-sea peaks show a remarkable change between hours 18 and 19 that is consistent with the abrupt change in the wind vector (Fig. 5).

We have attempted to quantify the behavior seen in Figs. 3–5 by fitting our data to the relationship proposed by Hasselmann *et al.* (1980). Associating the time rate of change of wave direction with the component of the wind perpendicular to that direction, and using frequency and gravity as scaling parameters, we obtain

$$\frac{\partial \bar{\vartheta}(f)}{\partial t} = B'(U/C)2\pi f \sin(\vartheta_U - \bar{\vartheta}), \qquad (2)$$

where $\bar{\vartheta}$ is the mean wave direction at frequency f, and c is the phase speed $g/2\pi f$. Rather than group our data in ranges of U/c, we retained this dependence explicitly and did a simple regression to determine B'.

The present results are compared with those of Hasselmann *et al.* (1980) in Table 1, where $B = B'U/C$. The B values are generally within the ranges given by Hasselmann *et al.* The correlation coefficient is only ~0.25; however, if we assume 100 or so independent data points, then we are 95% confident that the correlation between variables is not zero. We expected the wind to play a role, of course, but not surprisingly we found that other variables are probably involved.

The relationship of Gunther *et al.* (1981) between wind direction and the average direction for the entire spectrum is not useful for the present data set. This is so because of the mixture of wind sea and swell involved in the episodes we call directional relaxation.

TABLE 1. Comparison of regression factors [Eq. (2)], present analysis uses 129 entries: correlation is ~0.25.

U/c	$B'U/c$ ($\times 10^5$)	B* ($\times 10^5$)
1.1	1.3	1.6 ± 0.4
1.4	1.7	2.4 ± 0.5
1.8	2.2	2.0 ± 0.5

* Hasselmann *et al.* (1980).

4. Summary

We have analyzed wind and wave data from the experimental research buoy XERB developed by the NOAA Data Buoy Office. Eleven episodes of wave growth were used to find a relationship between variance and peak frequency consistent with previously published relationships. The four cases of directional relaxation documented by figures or regression analyses appear at least qualitatively similar to the four cases discussed by Hasselmann *et al.* (1980). The present information can be used to assess wave model performance and to evaluate models of spectral evolution.

It appears that rapidly turning winds have important effects on wave fields at time and space scales of interest to coastal areas. Documentation covering the open ocean is lacking, but relaxation effects are likely to be important for large frontal systems and major cyclones. As more data become available, better scaling arguments are needed to investigate parameter dependencies. The recent calculations of spectral evolution by Hasselmann and Hasselmann (1982) may provide some clues for these arguments.

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