DIRECTIONAL WAVE SPECTRA AND WAVE KINEMATICS IN HURRICANES CARMEN AND ELOISE

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ABSTRACT

A realistic description of the kinematics of hurricane waves requires that the directional spectrum of the sea be known. Models for hindcasting the directional spectrum have existed for some time, but there has been a dearth of data available for checking the directional characteristics of the hindcasts. Hurricane Carmen in 1974 and hurricane Eloise in 1975 passed reasonably close to platforms in the Gulf of Mexico which were instrumented with wave staffs and electromagnetic current meters. The maximum recorded significant wave height was 29 feet. The simultaneous measurements of wave height and water particle velocity permitted estimates of the directional spectra to be made. The estimated directional spectra are complicated and often bimodal in frequency and direction. Swell from the center of the storm can propagate in directions over 90 degrees away from the direction of the shorter waves which are in local equilibrium with the wind. The hindcast model reproduces these directional features remarkably well. The measurements of wave kinematics also permitted tests of the accuracy of wave theories in high and confused storm waves. All of the unidirectional theories tested showed a bias toward overpredicting the velocity under the highest waves. However, the kinetic energy in the velocity components and the velocity probability distribution could be found to within a ten percent scatter using directional spectral concepts and linear wave theory.

INTRODUCTION

Hurricane waves are steep, confused, and short-crested. The directional spectrum provides a concise description of this chaos by giving the most important statistical measures of the motion of the sea surface. Knowledge of the directional spectrum is of obvious practical importance in predicting ship motions. Using wave height and velocity measurements made in tropical storm Delia, Forristall et al. (1978) showed that the details of the directional spectrum can also be important when the subsurface kinematics of the wave motion are needed, as for predicting wave forces on slender members of a structure. For the short-crested waves in that data set, unidirectional wave theories consistently overpredicted the subsurface velocities while linear directional theory came close to matching the observed velocity spectra.

Measurements of directional spectra in the most severe conditions are unlikely to be available, and hindcasts of historical storms are needed to establish design conditions. The hindcast models can be of either a discrete or parametric type, as discussed in the review by Vincent and Resio (1979). At the present state of development, the discrete models such as the one developed specially for hurricanes by Cardone et al. (1976) offer more flexibility in handling variable wind directions. However, parametric models based on the work of Hasselman et al. (1976) are well suited to fetch limited generation cases, and with the addition of discrete swell bands as discussed by Gunther et al. (1979), they may be extended to situations with rapidly changing winds.

Wave hindcast models have been reasonably well verified with wave height measurements, but there has been little data on the directional characteristics of storm waves available for verification of the hindcast directional spectra. The main purpose of this paper is a description of directional spectra estimated from wave staff and electromagnetic current meter measurements made in hurricanes Carmen in 1974 and Eloise in 1975. The measurements compare reasonably well with hindcasts made using the model of Cardone et al (1976).

The measurements of particle velocities under the waves were compared with the predictions of various wave theories and general confirmation of the results of Forristall et al. (1978) was obtained. That is, all unidirectional theories tested, including irregular and nonlinear theories, overpredicted the measured velocity. In contrast, the kinetic energy spectra and statistical distributions of the velocity were predicted to within a reasonable scatter using linear theory.

DATA AND METHODS OF ANALYSIS

The measurements were made in the northern Gulf of Mexico at the oil and gas production platforms designated EI331 and SP62 in Figure 1. The water depth at EI331 is 246 feet and the depth at SP62 is 315 feet. At both stations, continuous analog recordings were made from a Baylor wave staff and a string of cylindrical electromagnetic current meters manufactured by Marsh-McBirney, Inc. The current meters were hung from pairs of taut wires designed to hold them as rigidly as possible with minimum interference to the flow. Forristall and Hamilton (1978) give a more complete description of the instrumentation and suspension system.

Tank testing has shown that the cylindrical electromagnetic current meters respond linearly to the flow speed but that their response to flow 45° from an electrode axis is down by eight percent. It was easy to correct for this feature during the analysis. The meters included an internal calibration circuit which was switched on automatically once a day to provide a check on the gain of most of the amplifiers in the circuitry, and which was used to give the calibration to engineering units during the analysis. The 0.80 Hz low pass output filter used on the meters was squared off by applying the inverse filter during the spectral analysis.

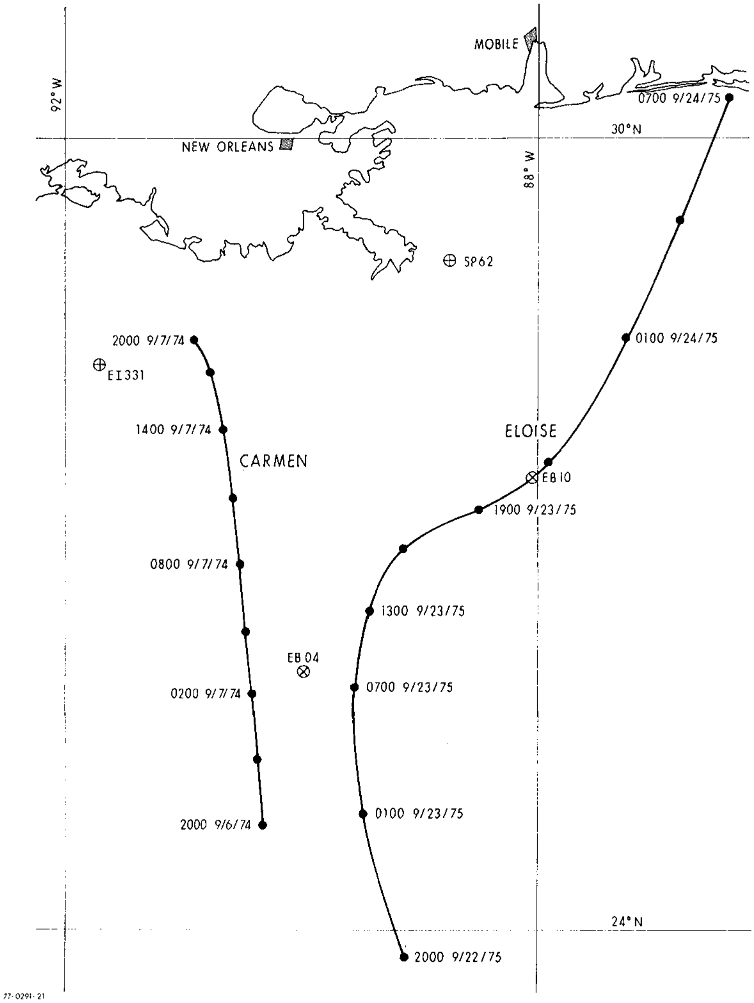

Fig. 1 - Storm tracks of hurricanes Carmen and Eloise, with OCMP stations and NOAA data buoy sites.

All the signals were transformed to the frequency domain using an FFT over 2048 samples. Power spectra and co-spectral estimates were formed by multiplying the Fourier transforms together and averaging over ten raw frequency lines. The estimates thus have 20 degrees of freedom and a resolution of 0.0098 Hz.

The information on wave direction available from a wave staff and current meter is equivalent to that from a pitch and roll buoy, and does not provide very sharp directional resolution. However, it is sufficient to determine the mean direction of travel and degree of directional spreading for waves in each frequency band. The co-spectra were thus used to find the best estimates for the parameters in the function

$$H(\theta) = N(s)\cos^{2s}(\theta - \theta_o) \tag{1}$$

where θ_o is the mean direction of travel, s is a spreading parameter which increases as the directional spread becomes narrower, and N(s) is included to normalize the area to unity. The details of the calculations, including a correction for the Dopler shift caused by steady currents, are given by Forristall et al (1978).

The hindcasts of directional spectra in the storms were made using the discrete model described by Cardone et al (1976). The processes of wave growth, dissipation, and propagation are simulated on a hexagonal grid system which covers the Gulf of Mexico with a grid spacing of 35 kilometers. At each grid point, the directional spectrum is resolved into 13 frequency and 24 directional bands. The growth of spectral components by linear and exponential mechanisms is limited by the Pierson-Moskowitz fully developed spectral form. Propagation of spectral components is accomplished by a simple Lagrangian scheme. For comparison with the measurements, the hindcast results were fit to equation (1) with a nonlinear least squares program.

The quality of a wave hindcast depends to a great extent on the accuracy of the wind field used as input. For hurricanes, it is possible to use a model storm approach since the similarity of hurricane pressure fields allows their description with relatively few parameters. Once the pressure field is specified, the wind speed and direction can be found by solving the equations of motion averaged over the atmospheric boundary layer.

HURRICANE CARMEN

Carmen was a rather severe storm with minimum central pressure of 937 mb and estimated peak gusts of 140 miles/hr. Figure 1 shows her track past EI331 and SP62 on her way to landfall near Vermillion Bay on the Louisiana coast. The NOAA data buoys shown in the figure were not operational during Carmen. Hope (1976) gives a description of the meteorological conditions in the storm.

The wave hindcast for Carmen was performed as part of an extensive study of waves generated by historical hurricanes in the Gulf of Mexico (Ward et al., 1978). For consistency, only the type of meteorological information available in the historical records was used in the windfield analysis. This limitation gives an indication of the accuracy of the historical hindcasts, but a better windfield could probably have been constructed using the additional data available for a storm in 1974. In particular, the modeled wind direction early in the storm at EI331 and SP62 was considerably clockwise from the measured directions. This discrepancy is probably due to a poor specification of the large scale pressure field.

Figure 2 shows the comparison between the measured and hindcast significant wave heights at EI331 as estimated from the total variance of the spectra. The solid line shows the half-hour maximum wave height, the dashed line shows the measured significant wave height, and the dotted line shows the hindcast significant wave height. The hindcast results are available for only a rather short stretch of the storm and the hindcast waves are slower in reaching their maxima than the measured waves. However, the eventual fit of the maxima is excellent. The conditions during this storm were the most severe during the measurement program, with the maximum spectral significant wave height equal to 29 feet and a maximum zero downcrossing 46 feet high.

There were several current meter failures at the measurement sites which affected the usefulness of the data for calculating directional spectra. In particular, the boat deck clamps holding the current meter taut wire assembly broke at both stations, making the particle velocity data completely unusable after 0930 at EI331 and after 1300 at SP62. Even before then, only the data from Current Meters 2 and 3 at EI331 and Current Meters 1 and 2 at SP62 could be used.

Despite the problems with the instrumentation, some interesting directional spectra are available for comparison with the hindcasts. Figure 3 shows a comparison for EI331 and Figure 4 shows data from SP62. The hindcast for EI331 at 0900 shows too little energy at all frequencies as would be expected from Figure 2. The hindcast energy is not spread as much as the measurements, which may be related to noise in the data. The mean direction of the hindcast energy at the higher frequencies is in error by about 30° in the same sense as the wind direction errors noted above. At later times in the storm, when only the power spectrum was measured, the total hindcast energy was nearly correct, but the peak frequency was considerably lower than that measured.

As shown in Figure 4, the hindcast compares much more favorably with the measurements at SP62. The fit of the power spectrum and the mean direction of travel is very good for all frequencies. The energy is more directionally spread in the measured spectrum, but the difference is slight.

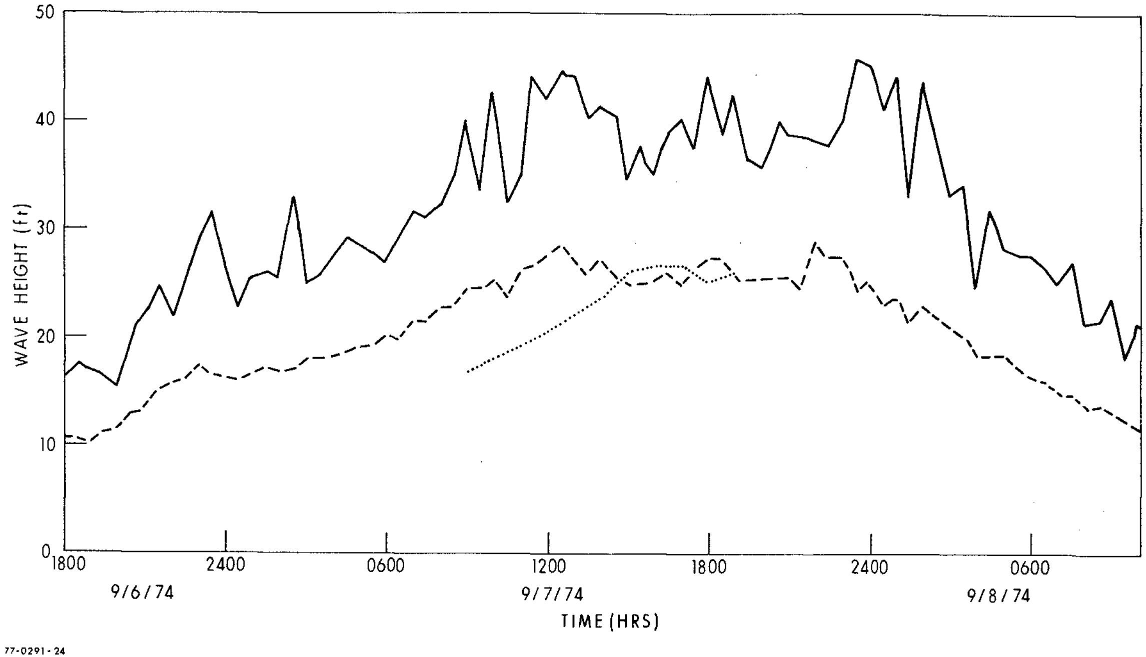

Fig. 2 - Wave height at EI331 during Carmen. Solid line--maximum. Dashed line--measured significant. Dotted line--hindcast significant.

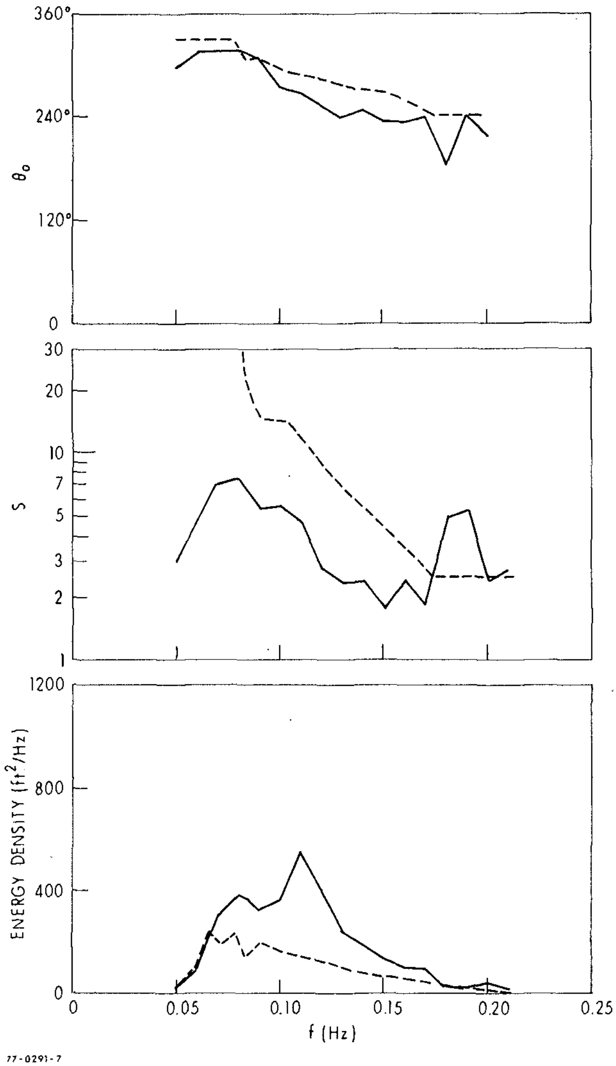

Fig. 3 - Directional spectrum at EI331, 0900 CDT, September 7, 1974. Solid line--measurements. Dashed line--hindcast.

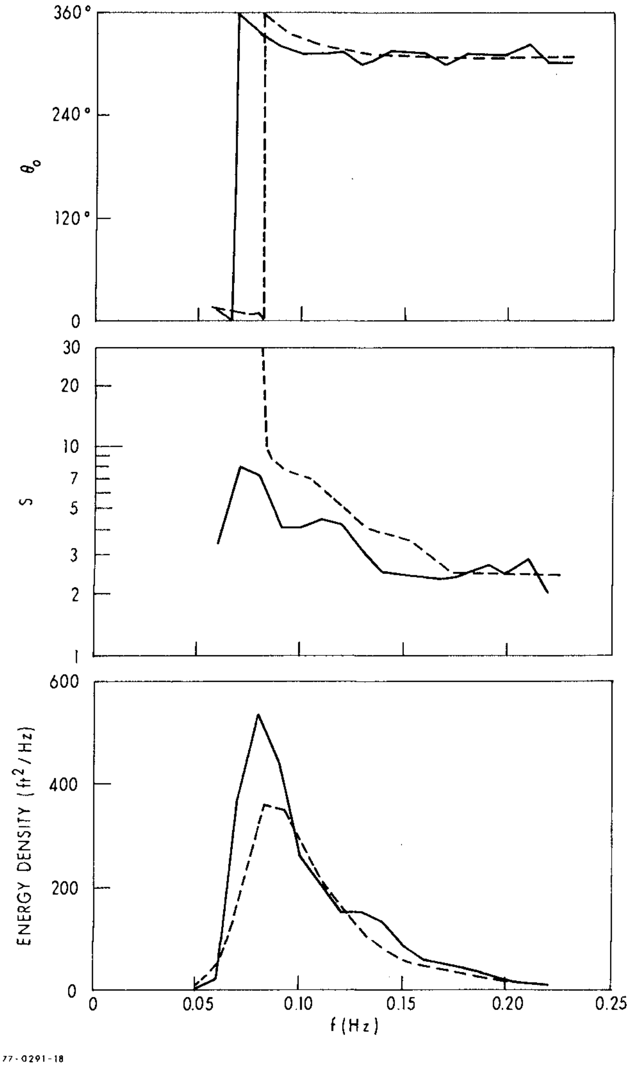

Fig. 4 - Directional spectrum at SP62, 1200 CDT, September 7, 1974. Solid line--measurements. Dashed line--hindcast.

HURRICANE ELOISE

The track taken by hurricane Eloise in September 1975 is shown in Figure 1. After heading northward in the direction of SP62, she was forced eastward by a cold front which had been moving southeast over Texas and Louisiana and made landfall near Fort Walton Beach, Florida. The minimum pressure recorded near landfall was 955 mb and wind gusts to 155 miles/hr were recorded. A review of the storm meteorology is given by Hebert (1976). Withee and Johnson (1975) summarize the measurements made from the data buoys located in Figure 1, and Friese (1977) used that data to discuss the oscillations of the thermocline caused by the storm. The Corps of Engineers (1976) has prepared a report describing the coastal damage caused by the storm.

The large amount of meteorological information available for Eloise permitted a detailed investigation of the windfield. Aircraft and satellite reconnaissance, shore radar, buoy data, and data recorded at EI331 and SP62 were all used in a determination of the storm track and pressure history. The storm winds were unusually asymmetric due to the intruding high pressure ridge, and thus the tangential pressure distribution was fit to a five-term Fourier series. The resulting wind field solution had several unusual features which were corroborated by the available data. There was very sharp inflow in the right rear and left front quadrants, pronounced outflow in the left rear quadrant, and a sharp almost front-like wind shift line extending to the south of the center.

Although the model wind field is very good, it does not perfectly match all the details of the observed winds. The model misses small scale variations due to individual rain bands, and the wind speed is underpredicted early in the storm at EI331 when the wind was dominated by the high pressure ridge intruding before the hurricane.

The underpredicted wind speeds at EI331 led to underpredicted significant wave heights until about midnight on September 22. The hindcast wave heights at SP62, shown in Figure 5, also began a bit low, but they followed the observed buildup quite well and were within a few feet of the observed peak. Some of the most interesting measurements during Eloise were made by National Data Buoy Office at EB-10 which was directly under the storm track. Figure 6 shows a comparison between the peak wave spectrum measured by an accelerometer on the buoy and the spectrum hindcast for the same time. The fit is quite good, and the hindcast would be well within the 90 percent confidence limits for the measured spectrum.

Figures 7 and 8 show measured and hindcast directional spectra at EI331 and SP62, respectively. At 1800 CDT on September 22 at EI331, the measured spectrum is strongly bimodal, with the swell component clearly separated from the locally generated sea. The directions of travel of the two components are over 90° different. The hindcast spectrum shows good qualitative agreement with the measurements, but the amount of energy is too low in every frequency band, in large part

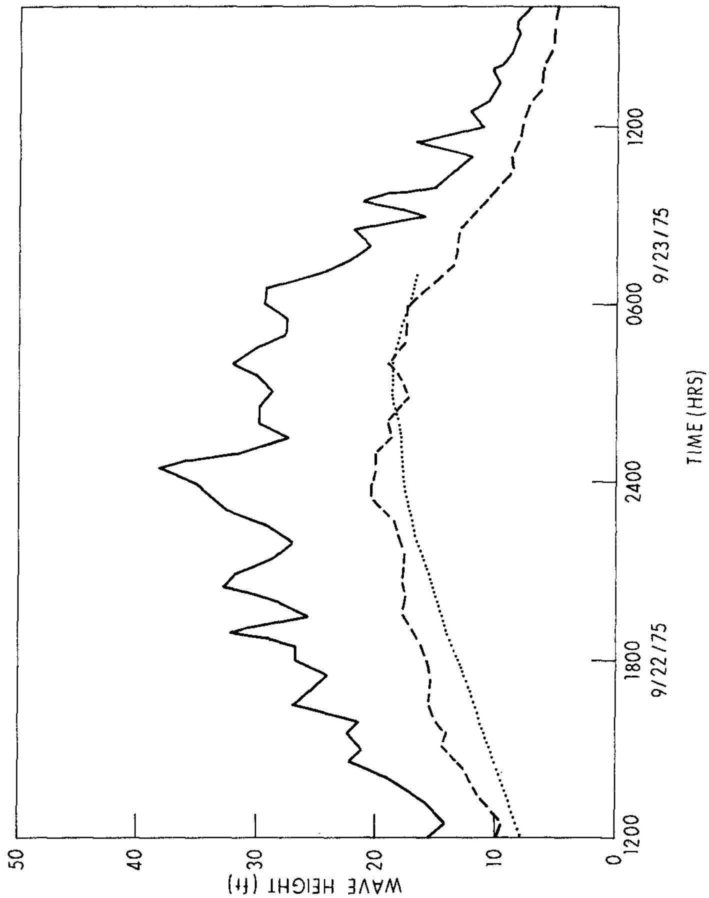

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Fig. 5 - Wave heights at SP62 during Eloise. Solid line--maximum. Dashed line--measured significant. Dotted line--hindcast significant.

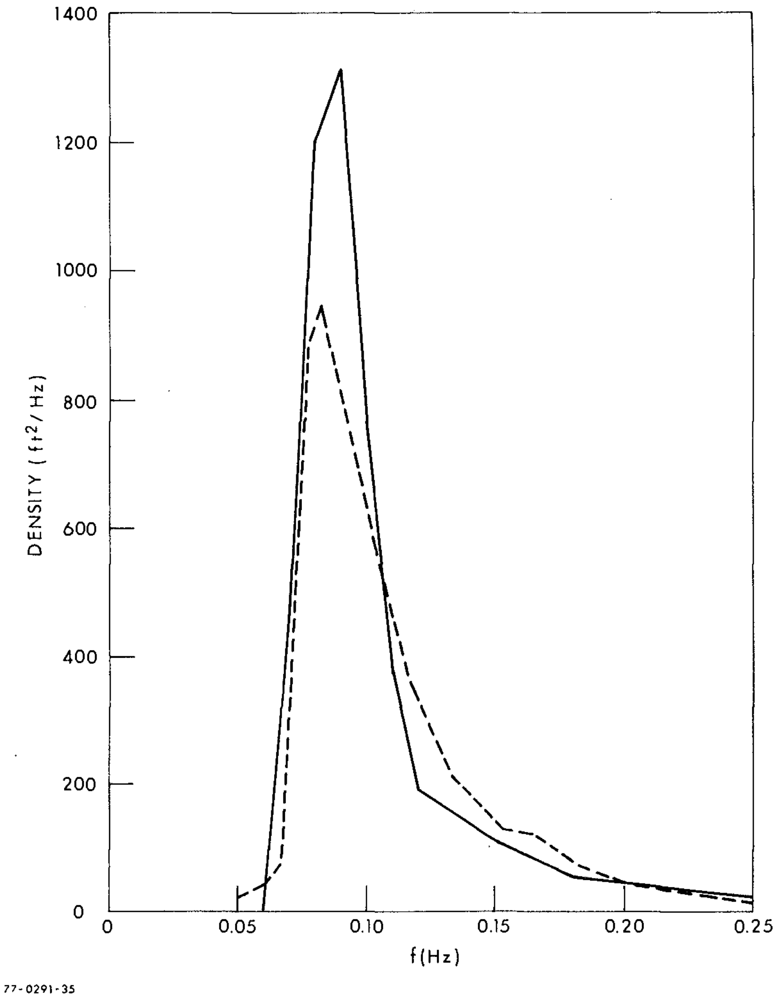

Fig. 6 - Wave frequency spectrum at EB-10, 2000 CDT, September 22, 1975. Solid line--measurements. Dashed line--hindcast.

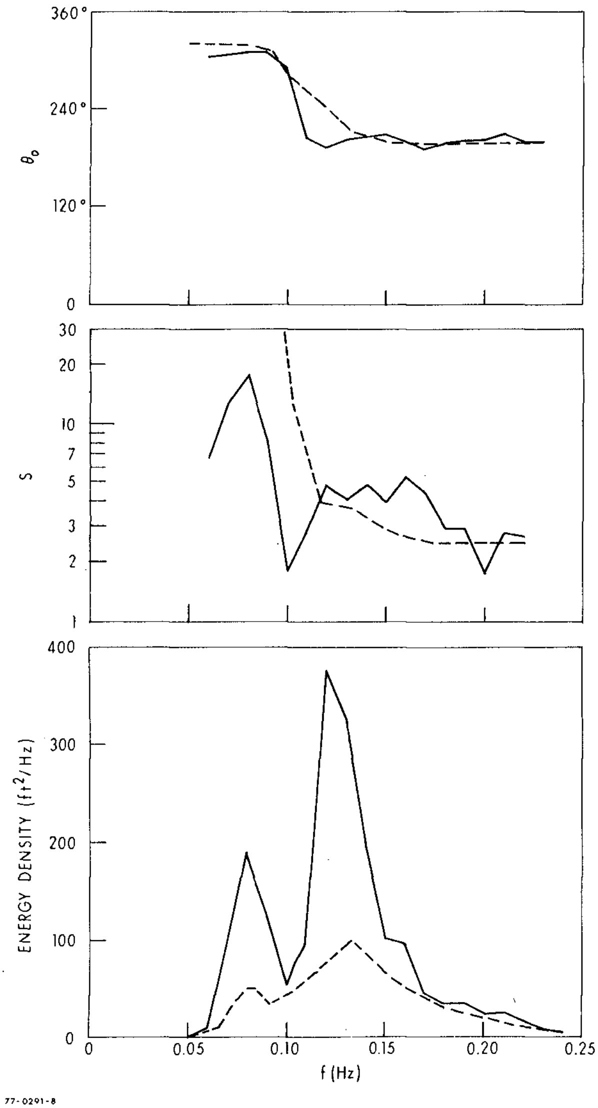

Fig. 7 - Directional spectrum at EI331, 1800 CDT, September 22, 1975. Solid line--measurements. Dashed line--hindcast.

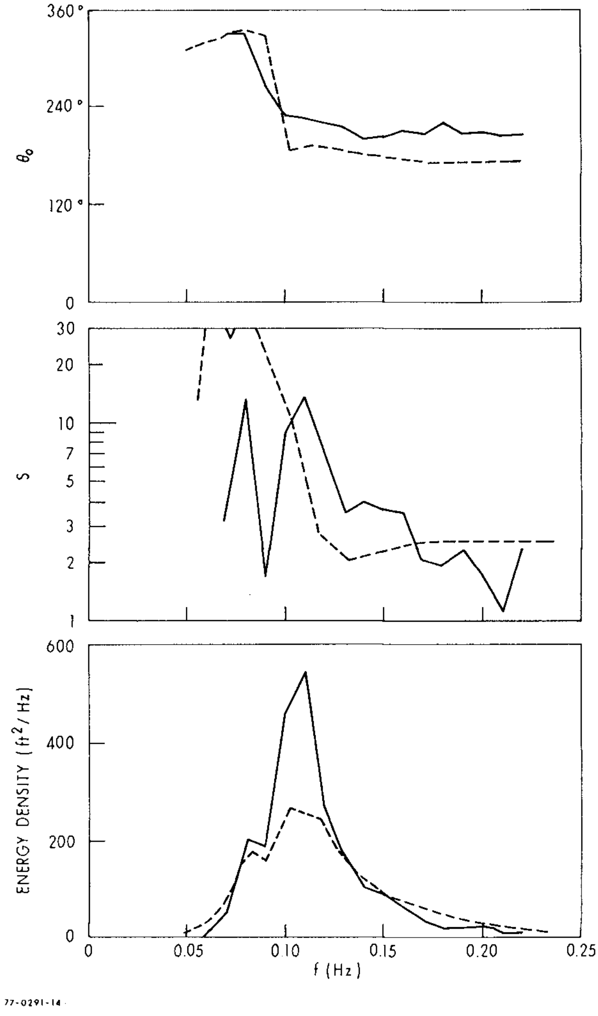

Fig. 8 - Directional spectrum at SP62, 0100 CDT, September 23, 1975. Solid line--measurements. Dashed line--hindcast.

due to the underspecification of the local wind speed. The transition in wave direction between sea and swell is much sharper in the measurements.

Throughout most of the storm at SP62, the spectra were also bimodal. This bimodality cannot always be recognized from consideration of the frequency spectrum alone, but in both the measurements and hindcasts there is a sharp break in the direction of travel at about 0.10 Hz, as shown in Figure 8. The error in the direction of travel of the high frequency waves is due to a small scale shift in wind direction at SP62 which persisted for a few hours and was not modeled.

Black (1979) used the EI331 and SP62 data sets to determine the wave power spectrum and mean direction of travel of waves in each frequency band. In general, his results are consistent with those presented here. However, at 2400 CDT, September 23 at SP62, he finds high frequency energy propagating upwind while we do not. The discrepancy could be due to the considerable difference in the methods of analysis or to the possibility that a calibration mark on the data tape was inadvertently included in Black's analysis.

The measured directional spectra show that the sea state in a hurricane is typically very complicated. Different frequencies can have greatly different mean directions of travel and directional spreads. The discrete model used for the wave hindcasts is well suited to accounting for the development and propagation of the energy in the various frequency bands, and the hindcasts generally agree well with the measurements. In fact, the directional parameters often seem to be more accurately hindcast than the power spectrum, although this is in part associated with the natural statistical variability in measured power spectra. Many details of the errors in the hindcasts can be ascribed to errors in the details of the local wind specifications, which again emphasizes the importance of the wind field specification to wave hindcasting.

WAVE KINEMATICS

The calculation of wave kinematics in confused seas is of considerable importance in the specification of wave forces on ocean structures. Forristall et al. (1978) showed that unidirectional wave theories consistently overpredicted measured velocities during tropical storm Delia, and this result was confirmed in the data sets considered here. Figure 9 shows a comparison between measured horizontal velocities and those predicted by Stokes' fifth-order theory for SP62 during Eloise. Data from the top current meter 16 feet below mean sea level are given, and each data point represents the highest wave in a half-hour segment of data. The measured velocity is the maximum resultant of the two horizontal measured components during the wave. The wave height and period for the Stokes' calculation were determined by the zero down-crossing method. The scatter in the comparisons and the bias toward overprediction are both quite large and both can be explained by the directional spreading of the confused waves.

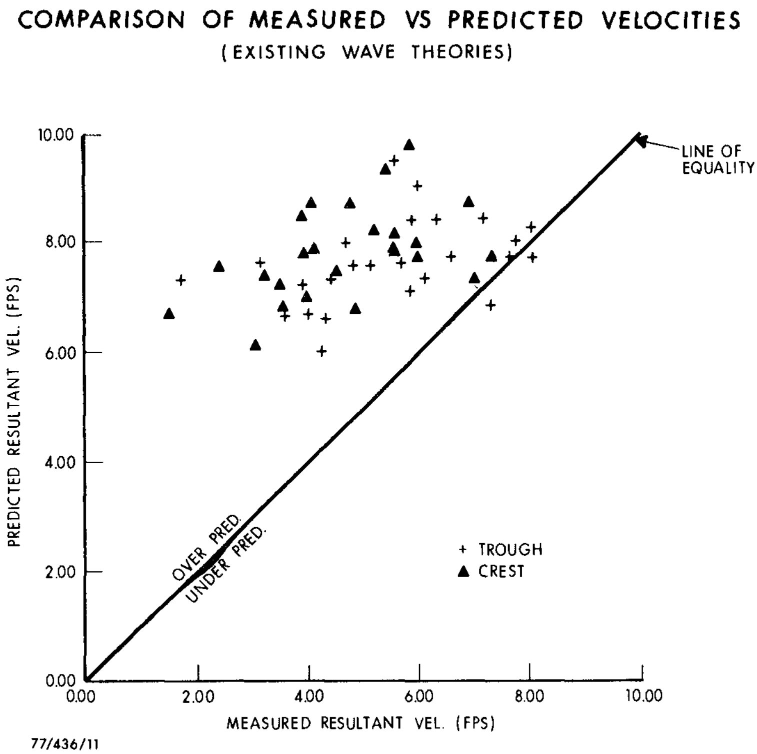

Fig. 9 - Measured compared to Stokes wave kinematics at SP62 during Eloise.

Linear wave theory can be extended to directionally spread seas since linear waves with different frequencies and directions can be combined by superposition. However, the applicability of linear theory is questionable for the high and steep waves of a hurricane. It is possible to check the theory by comparing the measured and theoretical horizontal kinetic energy. The measured kinetic energy is found by adding the spectra from the two horizontal axes of the current meter, and the theoretical energy is found by attenuating the measured wave height spectra by the factor given by linear wave theory. An amplitude ratio of measured-to-theoretical velocity may then be found by taking the square root of the ratios between the spectra. This process is complicated somewhat by the Doppler shift due to steady currents as described by Forristall et al. (1978), but for the moderate currents measured during the storms, the change in the ratios is slight.

The amplitude ratios of measured over theoretical velocity for SP62 during Carmen and EI331 during Eloise are shown in Figures 10 and 11, respectively. The ratio for the top meter at SP62 was about 0.9 at the peak of the wave spectrum, rising to 1.1 at the higher frequencies. In contrast, the ratio at the top meter at EI331 was about 1.1 throughout the energetic part of the spectrum. Note that the rise to a higher ratio at about 0.10 Hz corresponds to a notch in the wave spectrum. The meter at the 47-foot depth at EI331 had a ratio near 1.0 for all frequencies, while the deeper meters at both stations showed wide variations due in part to the very small predicted velocities at these levels. For high frequencies, electronic noise or turbulent fluctuations in the flow can overwhelm the signal from the wave induced oscillations.

Similar amplitude ratios were calculated for many hours of each storm at each station. The results were nearly constant for a given storm and current meter, but varied as noted between storms and meters. The meter at the 47-foot depth at EI331 during Carmen had a ratio of about 0.95 while the meter at the 16-foot depth at SP62 during Eloise had a ratio of only 0.85. There does not seem to be any consistent pattern of change in velocity amplitude ratio with different sea states, and it seems most likely that the observed changes are due to changes in the response of the instrumentation systems.

There have been several other field studies of wave kinematics in recent years and it is interesting to compare results. The results were not all presented as amplitude ratios, but they can easily be discussed in that form. Thornton and Krapohl (1974) used electromagnetic meters to measure the kinematics of a moderate swell off the coast of California. The amplitude ratio for the horizontal velocity was 0.94. Cavalieri et al. (1978) made measurements using electromagnetic meters mounted on a tower in the Adriatic Sea and found a ratio of 0.9. Battjes and Heteren (1980) used acoustic travel time meters in the North Sea and found a ratio of only 0.85. Our previously reported measurements during tropical storm Delia (Forristall et al., 1978) showed ratios of 1.1, decreasing to 0.9 at frequencies twice that of the spectral peak.

Our interpretation of the variability of results, both in our work and that of other investigators, is that present instrument

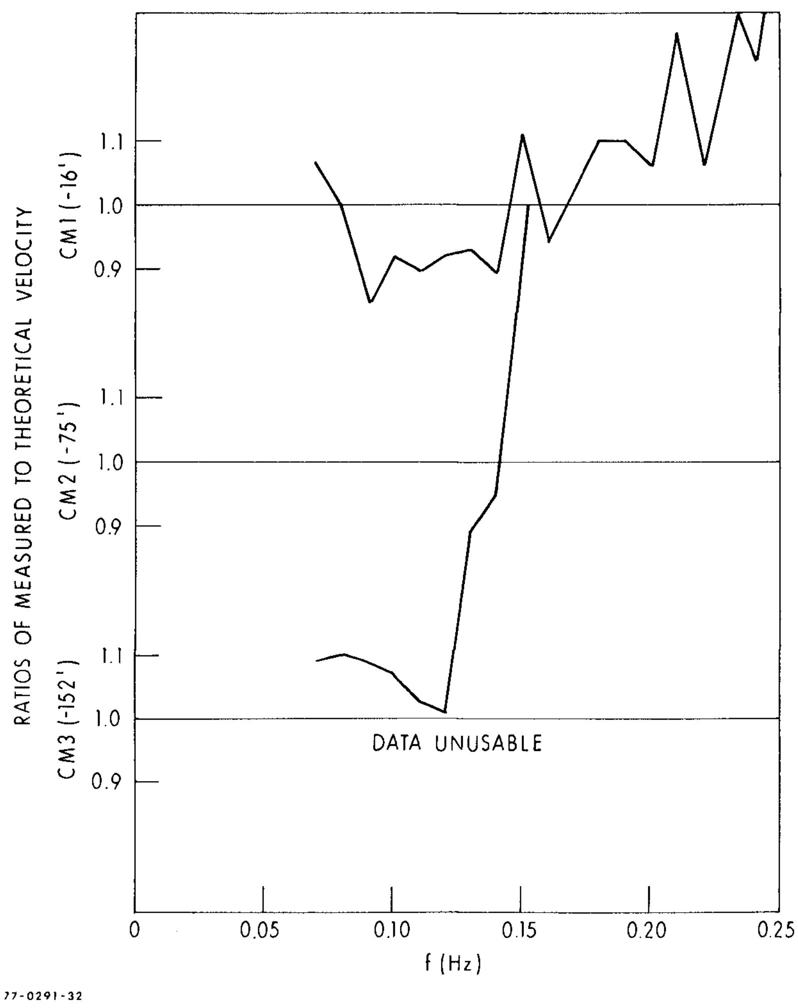

Fig. 10 - Ratio of measured to theoretical velocity, SP62, 1200 CDT, September 7, 1974.

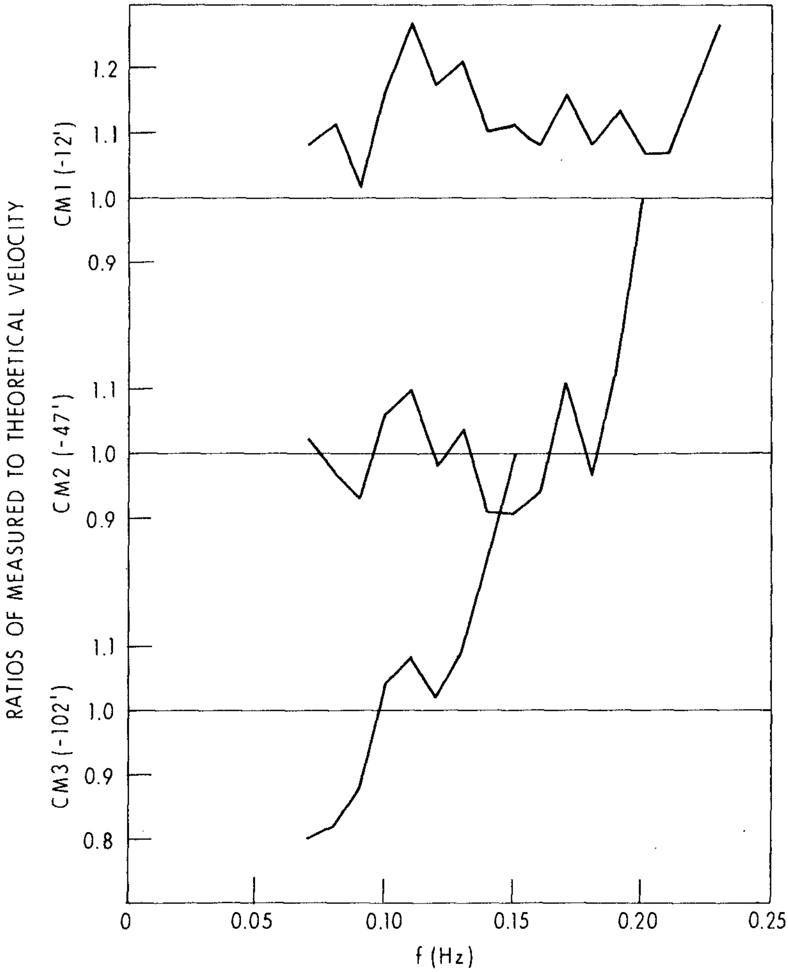

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Fig. 11 - Ratios between measured and theoretical velocity, EI331, 1800 CDT, September 22, 1975.

technology is capable of making field measurements of wave kinematics with an accuracy of about ten percent. This accuracy is sufficient to determine that unidirectional wave theories perform poorly in confused seas, but it is not sufficient to enable any conclusions to be made about the nonlinearity of storm waves.

The results also indicate that it is appropriate to make engineering calculations of forces on structures using wave kinematics derived from the superposition of directionally spread linear waves. A kinematic field for a given directional spectrum can be generated using a Monte Carlo simulation of wavelet phase angles and the fast Fourier transform, and we are presently developing and testing design programs using this approach.

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