WIND AND WAVE MEASUREMENTS TAKEN FROM A TOWER IN LAKE MICHIGAN [1]

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ABSTRACT. In July 1977 the Great Lakes Environmental Research Laboratory installed a lightweight, solar powered research tower in Lake Michigan. The tower, located 2 km offshore from Muskegon, Michigan, in 16 m of water, provided a stable platform for two levels of anemometers and air temperature sensors, a surface water temperature sensor, and an array of four wave staffs to measure meteorological and directional wave variables. Solar power was successfully used to provide power for tower instrumentation. The measurements, while short-lived due to a guy wire failure in October 1977, comprise over 1300 well-documented hourly wind and wave data for further detailed studies. This report presents a detailed description of the instrumentation, data collection, and data reduction systems. The results show that the triangular array of wave staffs provides reasonable wave direction information, although nearshore waves appear to have a larger onshore component of momentum than would be indicated by prevailing winds. Further detailed studies of wind and wave processes are in progress.

INTRODUCTION

During the last two decades, the number of wave studies has increased rapidly and ample single-gage wave data covering a large number of gage stations are now available. However, for a proper understanding of the generation, growth, dissipation, and propagation of a wave field and for verification and improvement of wave prediction models, the essential detailed knowledge of directional wave characteristics and a simultaneously recorded wind field is still very scarce. Measurements that provide this critical information are needed immediately.

To this end, the Great Lakes Environmental Research Laboratory (GLERL) installed a lightweight, solar powered, portable research tower (Figure 1) in Lake Michigan to provide a stable platform for supporting anemometers, temperature sensors, and an array of wave staffs to measure meteorological and directional wave variables. The tower site (Figure 2), the same one used by the U.S. Army Corps of Engineers, Lake Survey District, during the late sixties, was first selected by Elder and Portman (1963). It provides a fetch of
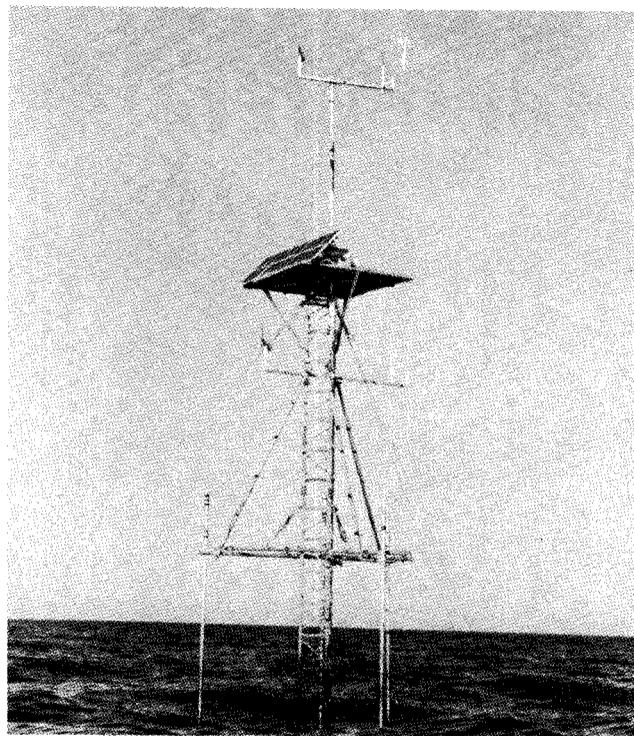

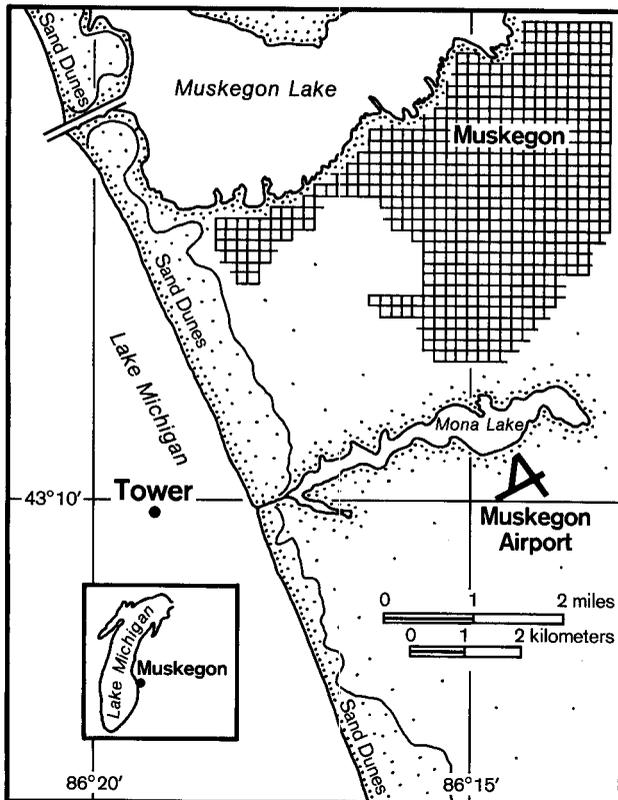*FIG. 1. Photograph of research tower from the southeast.*

FIG. 2. Map showing location of tower.

over 125 km from the directions of predominant winds. The tower began data transmission on July 19, 1977, and was active until October 11, 1977, when it collapsed because a guy wire snapped.

Special data collection and data processing systems were developed to facilitate the tower measurements. This report presents a detailed description and discussion of these systems and an overview of the results. Data analysis and interpretation will be presented in subsequent reports and articles.

INSTRUMENTATION AND DATA COLLECTION SYSTEM

The data collection system consists of an array of four water level gages and meteorological sensors designed to measure water and air temperature, wind speed at two levels, and wind direction. The wave gages are placed at the vertices and center of an equilateral triangle of 3.05 m sides as shown in Figure 3. Temperature sensors are at 5 and 10 m above water level. The data sample rate is two samples per second for water levels. The other variables are multiplexed at a rate of one sample per five seconds. Data are transmitted over a radio link from tower to shore, where they are recorded on magnetic tape.

The wave gages are Kelk, Model P116 Zwarts gages (Zwarts 1974), with individual synchronizers designed and built at GLERL. The significant variables for this installation are:

Active length: 6 m
Resolution: < 3 cm
Sampling frequency: two samples per second
Sample integration time: 0.07 to 0.13 sec, depending on water level during sample time, i.e. maximum level produces minimum sample time.
Data output: eight bit digital word
Time synchronization: Maximum time error of reading between any two gages is less than 0.035 sec and occurs when there are simultaneous maximum and minimum levels at two gages.

The meteorological system, purchased from Techecology, Inc., consists of the following:

a. one Model 020 wind direction sensor and signal translator with output of 0-5V for 0-540° (360°-540° is a wraparound of 0°-180°); linearity = ½% full scale.

b. two Model 010 wind speed sensors and translators with output of 0-5 V for 0.5 to 50 mph; threshold = 0.5 mph.

c. two Model 060 air temperature shields. Output is 0-5 V for ±50°C. The sensors are Yellow Springs Instruments Co. thermistors with combined linearity and accuracy of ±0.25°C. The shields keep down radiation error if wind speed is over 1.5 mph and sun angle greater than 10° and of an intensity of 1.2 lys or less. The maximum error would be 0.1°C.

d. one Model 060 w water temperature sensor and translator with output 0-5 V for 0-25°C. The translator cards and power supply regulators are housed in a weatherproof box mounted on the tower platform.

An insolometer was supplied by the Energy Research and Development Administration Photovoltaic Energy Conversion Program, National Aeronautics and Space Administration Lewis Research Center, to monitor available solar energy to the solar panels. The output of the device was 0-3 V representing integrated values of solar radiation. System battery voltage was monitored by a circuit to display battery voltage from 9.5 to 14.4 V with a resolution of 0.02 V.
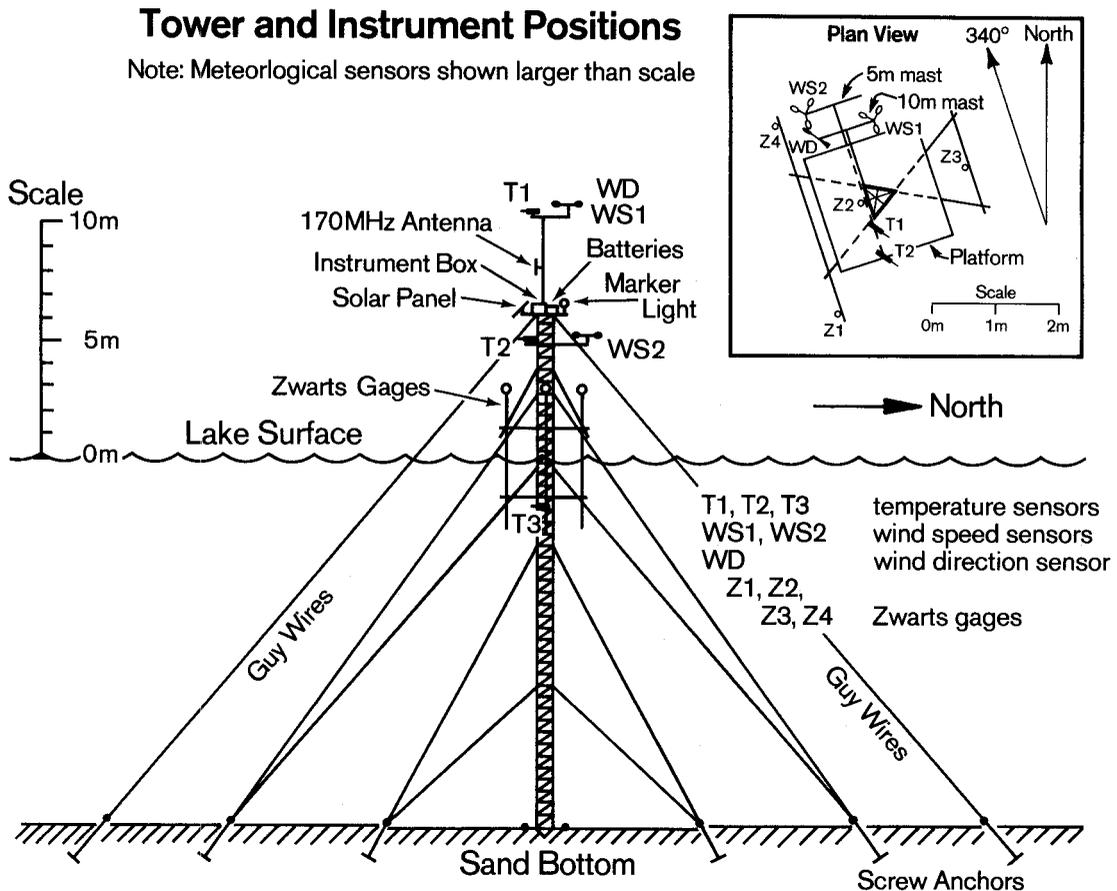
Tower and Instrument Positions

Note: Meteorlogical sensors shown larger than scale

FIG. 3. *Vertical section and plan view of research tower showing location of instruments.*

Data from the Zwarts gages are available in digital form from the synchronizers associated with each wave gage. Other data sources are scaled 0-5 V and are applied to a multiplexer analogue to digital (A/D) converter to provide digital data to the radio transmitter. The tower system is controlled by a quartz crystal clock, which provides required frequencies for data acquisition and transmission and time-of-year signals for temporal correlation of data.

The Zwarts wave gage system operates on a 1-h cycle, during which the system can be on in 5 min increments from 0 to 60 min and off for the balance of the hour. Initial operation was set for 30 min *on* times. At the beginning of an *on* cycle, a warm-up or time word is repeatedly transmitted to the shore stations for a period of 40 sec.

The purpose of the warm-up transmission is to allow the radio transmitter and the shore tape recorder to achieve stable operation. The warm-up data word contains a time-of-year code identifying the time of transmission. Following the warm-up transmission, the system transmits data words for the balance of the *on* time. Each word transmission consists of 56 bits, at a bit rate of 128 per sec, and an interval of 1/16 sec of no bit transmission, or interword gap. Each data word contains a 12 bit synchronized preamble, four bits identifying which A/D channel is being sampled, the eight bits of A/D data, and all four wave gage outputs (32 bits). Table 1 identifies the A/D signals and gives equations for converting from 8 bit data (n) to variable values.

System power is provided by two 93 Ah 12 V lead-acid batteries connected in parallel. These batteries are charged by an array of 16 Solarex P/N A0199 solar voltaic panels with rated output of 14 V, 3.5 W each. The panels are mounted facing south at a 45° angle. Continuous power is supplied to the clock controlling the power relays that supply the remaining system during *on* times. The battery voltage is monitored and included in the A/D data. Since system power consumption averages 10 W, a set of fully charged batteries alone could support power requirements for about 9 days.

TABLE 1. Conversion factors for recorded variables.

Time	Signal Source (see Figure 3)	Conversion	Range
0	WS1	0.1n	0-25 m/sec
1	WD	2.109n	0-540° w/wraparound
2	WS1	0.1n	0-25 m/sec
3	WS2	0.1n	0-25 m/sec
4	T1	0.39 (n - 128)	-50-50°C
5	T2	0.39 (n - 128)	-50-50°C
6	T3	0.1n	0-25°C
7	Battery	0.02n + 9.37	9.37-14.4v
8	Solarimeter	–	0-255
9	WD	2.109n	0-540° w/wraparound
all	Z1-Z4	0.0273n	-3.5-3.5 m

The FM radio transmitter used in this system is adapted from a Motorola 170 MHz "Dispatcher" walkie talkie and operates at a crystal controlled frequency of 171.025 MHz with an output power of less than 100 mW. Digital data inputs are converted to bi-phase, return-to-zero form; they frequency modulate the carrier at a deviation of about 4 KHz. In addition to data modulation, the carrier is also modulated with a 180 Hz sine wave from a tuning fork oscillator. A directional antenna is used to direct the signal to the shore station.

The shore receiving site consists of a directional antenna aimed at the transmitting site, a 171.025 MHz receiver, signal conditioner, power relay with interval timer, and instrumentation tape recorder. The 180 Hz modulator triggers the interval timer and power control relay, which start the instrumentation tape recorder. The timer is set to the system *on* time at the remote tower plus approximately 5 min. Thus, when a valid radio signal is received, the tape recorder is started. The timer keeps the recorder on for the entire *on* period even if the radio link is lost after initial start of a period; however, the data channel is blanked when the radio frequency power is lost.

The instrumentation tape recorder is a seven channel Sangamo, Model Sabre VI, FM recorder. The extra channels allow recording of other analog signals as needed.

DATA REDUCTION

The recorded data were played back with a time compression of 64:1. To translate the serial data into a nine-track, IBM-compatible tape for analysis, a microprocessor system we developed was used. The system consists of a Zilog Z80 central processing unit running at 2 MHz with a complement of 32 K bytes of user random access memory and a system monitor in programmable read-only memory. System support peripherals include a high-speed paper tape reader, teletype ASR33, Kennedy nine-track 800 BPI tape drive with a buffered formatter and an Intel programmable read-only memory programmer. The translation software was designed to check the control line and synchronize itself on recognition of the predetermined serial data pattern with smoothing to avoid false triggering due to incidental noise pulses in the recorded serial data stream.

The nine-track tape produced by the microprocessor system was further consolidated and edited on the in-house Hewlett-Packard 9603A Scientific Measurement and Control System. Each record was checked for correct time sequence; wave data and auxiliary variables were converted from an eight bit binary number, n, to dimensional units as shown in Table 1; and data were consolidated into 30 min data blocks, which were then processed on the Boulder, Colorado, Environmental Research Laboratories CDC 6600 large-scale computer system.

For all tapes, averages and standard deviations for each 30 min sampling interval were calculated for 13 variables: wind speeds and eastward and northward wind components at 5 and 10 m, air temperatures at 5 and 10 m, water temperature, and four wavestaff water levels. In some cases the 30 min data blocks contained more or less than the expected 3520 points for water levels or 352 points for other variables (30 minutes of ½ sec data minus 40 sec warm-up). Long data blocks resulted from the unavoidable merging of portions of two or more 30 min blocks. Short blocks were due to gaps in the data or to intermittent transmission. Blocks with less than 2400 or more than 5000 points were discarded. In addition, occasionally data blocks with undecipherable dates and times were rejected.

Energy density functions for water levels at the central wavestaff were calculated for all data blocks of 2400-3520 points. Wave spectra were computed by fast Fourier transform (FFT) from the first 10 min (2400 points) in each block and smoothed by ensemble averaging. Fourier transforms were calculated for 30 segments of 80 points each to yield a spectrum with 60 degrees of freedom.

For all spectra the peak energy frequency, f_0,

was determined as the frequency of the energy density maximum. In some cases a secondary spectral maximum was observed. For fully developed wind wave spectra, Phillips (1958) has shown by similarity arguments that for all frequencies $f > f_0$ the energy spectrum $E(f)$ should be of the form

$$E(f) = \beta g^2 f^{-5}$$

where g is the gravitational acceleration and β is the equilibrium range constant. For all single peaked spectra,

$$\beta_i = \frac{E(f_i)}{g^2 f_i^{-5}}$$

was determined for all frequencies $1.5 f_0 < f_i < 1$ Hz and averaged to yield an estimated equilibrium range constant β. For double peaked spectra at frequencies f_a and f_b, two β's were calculated. Double peaked spectra were identified as those with a secondary peak at least 10% as great as the primary peak and at least six frequency bands away. Individual β's were averaged from frequencies f_a to f_{MIN}, the frequency where energy density is a local minimum, for the first peak and from f_b to 1 Hz for the second. True wave directions $\Theta(f_i)$ for given frequency f_i were calculated from phase differences between two pairs of gages for each three-gage array as described in Esteva (1977). Phase differences were obtained by calculating cross spectra between gage pairs. In order to characterize the directional characteristics of the wave field, the wave momentum vector for each set of spectra was calculated. It was felt that this variable was a better indication of the mean propagation direction of the wave field than the direction associated with the peak energy frequency. From the directions, $\Theta(f_i)$, and the relationship between wave momentum, M, wave energy, E, and phase velocity, C,

$$M = E/C$$

the east-west (x positive eastward) and north-south (y positive northward) components of wave momentum were calculated by

$$M_x = \sum_i \frac{\overline{E}(f_i) \cos(\Theta(f_i))}{c(f_i)} \Delta f$$

$$M_y = \sum \frac{\overline{E}(f_i) \sin(\Theta(f_i))}{c(f_i)} \Delta f$$

respectively, where $\overline{E}(f_i)$ is the average energy density at frequency f_i, $c(f_i)$ is the phase speed at f_i, and f is the frequency band (equal to 1/40 Hz). Energy density functions for all working wave-staffs were averaged to give $\overline{E}(f)$. Significant waveheight was calculated as four times the square root of the variance of $\overline{E}(f)$.

RESULTS

During the 2281 hours between the time the tower began transmission and the time it collapsed, 1324 measurements of wave directional information were obtained for a data return rate of about 60%. All available hourly data with calculated variables as described in the previous section were tabulated on punched cards as shown in Table 2. In addition to the tower data, pertinent routine measurements taken at the Muskegon airport by the National Weather Service and at Holland, Michigan, by the National Ocean Suvey are included. One wave staff failed on September 2, 1977, and the 5 m air temperature sensor proved to be unreliable, but all other sensors functioned well. The number of hourly averages obtained for each variable, the average value of that variable, and some of the extreme values are also shown in Table 2. Over the period of observation, average 10 m wind speed at the tower was 1.31 times the average wind speed at Muskegon Airport. This ratio has a significant diurnal variation as shown in Hunt (1959), but the ratio of the average windspeed for this period is consistent with the observations of Hunt and others. Average wind speeds over 20 m sec^{-1} are probably underestimated because the range of the wind speed sensor was limited to 25 m sec^{-1}. The maximum significant waveheight of 3.24 m and maximum 10 m wind speed of 21.8 m sec^{-1} were recorded just before the tower went down. The directions of mean and maximum winds at both the tower and the airport are all very close to southwest. The mean and maximum wave momentum vectors are also in this direction.

Summaries of wind, temperature, significant waveheight, and peak wave energy frequency are presented in Figures 4-7 in the form of directional histograms. The meteorological convention of plotting parameters in the sector *from* which they occur is used throughout. Figure 4 shows that the most common winds were 5-10 m sec^{-1} from the

TABLE 2. Description and summary of hourly averaged data.

Card Columns	Format	Description of Data	Total Measurements	Overall Average	Maximum or Range
01-02	I2	Month			
03-04	I2	Day			
05-06	I2	Time (EST, end of half hour recording period)			
		Tower measurements			
07-10	F4.1	10 m wind speed	1337	7.1 m sec^{-1}	21.8 m sec^{-1}
11-14	F4.1	5 m wind speed	1337	6.5 m sec^{-1}	21.4 m sec^{-1}
15-18	F4.0	Wind direction	1337	227°[†]	226°[§]
19-22	F4.1	10 m air temperature	1163	15.2°C	3.2-22.1°C
23-26	F4.1	Water temperature	1285	17.0°C	6.1-22.8°C
27-30	F4.3	Water level displacement	1340	0[*]	-0.20-0.24m
31-34	F4.2	Significant waveheight	1340	0.68 m	3.24 m
35-38	F4.3	Peak energy frequency	1315	0.278 Hz	0.125-0.875 Hz
39-42	F4.0	Phillips equilibrium range constant (x 10^{10})	1293	693	2-2461
43-46	F4.3	Eastward wave momentum, M_x/gA	1324	0.425 cm-sec	5.951 cm-sec[+]
47-50	F4.3	Northward wave momentum, M_y/gA	1324	0.318 cm-sec	5.390 cm-sec[+]
		Ancillary measurements			
51-54	F4.1	Muskegon airport wind speed	1333	5.4 m sec^{-1}	14.9 m sec^{-1}
55-58	F4.0	Muskegon airport wind direction	1333	222°[†]	240°[§]
59-62	F4.1	Muskegon airport air temperature	1340	17.5°C	-0.6-31.1°C
63-66	F4.1	Muskegon airport dew point	1340	13.8°C	-15.0-23.3°C
67-70	F4.3	Holland water level displacement	1340	0[*]	-0.18-0.20 m

[†] Direction of vector average wind
[§] Direction of maximum wind
[*] By definition
[+] Maximum momentum vector

FIG. 5. Frequency of occurrence of hourly average air-sea temperature difference as a function of wind direction at tower.
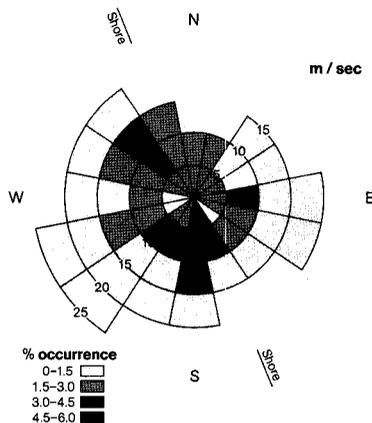

FIG. 4. Frequency of occurrence of hourly average winds at tower.

south. The strongest winds, however, were southwesterly. Frequency of occurrence of air-sea temperature differences as a func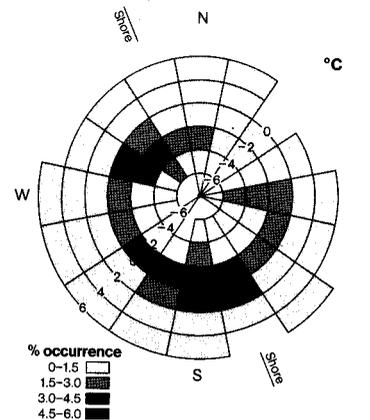tion of wind direction is shown in Figure 5. Temperature differences ranged from -8°C to 6°C. The 10 m air temperature was usually 0-4°C less than the water temperature, implying a slightly unstable boundary layer. Southerly winds generally resulted in a closer to neutral or slightly stable boundary layer.

A histogram of significant waveheight as a function of momentum vector direction is shown in
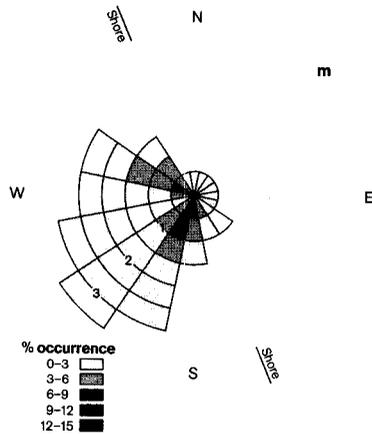
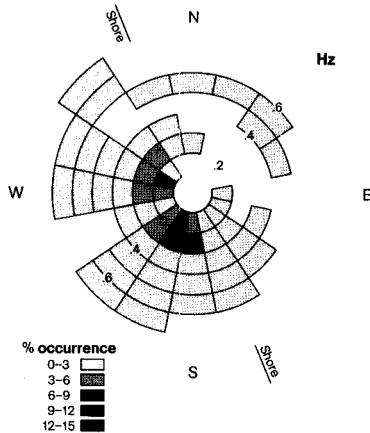FIG. 6. *Frequency of occurrence of significant wave height as a function of wave momentum direction.*

FIG. 7. *Frequency of occurrence of wave peak energy frequency as a function of wave momentum direction.*

Figure 6. It is clear that the wave momentum vector almost always has an onshore component even though the winds are quite well distributed with direction. The highest waves propagate toward the northeast. The most common significant waveheights are less than 1 m. Figure 7 shows the histogram for peak wave energy frequency as a function of momentum vector direction. Peak energy frequencies are generally between 0.1 and 0.3 Hz. Southerly winds generated waves of slightly higher frequency than northwesterly winds. Low frequency waves almost always are associated with a momentum vector that has an onshore component.

CONCLUSIONS AND RECOMMENDATIONS

The solar powered portable tower has proved to be a useful tool for examining wind and wave directional characteristics. The triangular array of wavestaffs is useful when waves from all directions are to be examined, but provides only a first approximation to directional spreading of wave energy. Determination of the directional characteristics of wave components higher than 0.5 Hz requires closer spacing of wavestaffs because the expected wavelengths at these frequencies are comparable to the dimensions of the wavestaff array. The direction of the momentum vector was used as the primary directional parameter here because it is not as sensntive to the high frequency components of the spectrum. Maximum winds exceeded the recording range of the anemometer, suggesting that an expanded range should be used in future deployments.

The recorded waves 2 km off Muskegon, Michigan, have a larger onshore component of momentum than would be indicated by wind frequencies. This is owing in part to refraction of the low frequency, high momentum components of the wave spectrum and in part to the preferential growth of wave components in the direction of largest effective fetch (not necessarily the wind direction). Further examination of the data set provided by the tower in Lake Michigan and data gathered from future deployments are necessary to determine the relative importance of these factors in determining wave directional characteristics.

REFERENCES

Elder, F. C., and Portman, D. J. 1963. *An investigation of atmospheric turbulent transfer processes over water.* Rep. No. 1, The University of Michigan, Office of Research and Administration, Rep. 05677-1-F.

Esteva, D. C. 1977. *Evaluation of the computation of wave direction with three-gage arrays.* U.S. Army Corps of Engineers, Coastal Eng. Res. Center, Tech. Paper No. 77-7.

Hunt, I. A. 1959. *Winds, wind set-ups, and seiches on Lake Erie.* U.S. Army Corps of Engineers, Lake Survey District.

Phillips, O. M. 1958. The equilibrium range in the spectrum of wind generated waves. *J. Fluid. Mech.* 4(4):426-434.

Zwarts, C. M. G. 1974. Transmission line wave height transducer, pp. 605-620. *In* Proc. Internat. Symposium on Ocean Wave Measurement and Analysis 1.