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Comparison Between Wind Waves at Sea and in the Laboratory[1]

G. D. Hess[2], G. M. Hidy[3], and E. J. Plate

University of Washington
Seattle, Washington
National Center for Atmospheric Research
Boulder, Colorado
Colorado State University
Fort Collins, Colorado

ABSTRACT

Correlations between laboratory and geophysical data are presented for certain statistical properties of wind waves. The parameters chosen include: (i) relationships between wave height and the height of the highest one-third or one-tenth waves, as given by a Rayleigh probability distribution, and (ii) amplitude spectra for waves, as given by Phillips' equilibrium theory. The correlation between laboratory results and geophysical data is satisfactory over a wide range of wave size.

Introduction. The processes of interaction between the atmosphere and the sea are important because they determine the fluxes of momentum, heat, and moisture in the atmospheric boundary layer over oceans and the momentum, heat, and salinity in the surface layers of the water. This interaction also controls the characteristics of the air-sea interface through the presence of wind-generated waves and wind-driven currents. At present the mechanisms of air-sea interaction are only partially understood. Part of the reason for this limitation lies in the inadequate observational data available for testing the applicability of modern dynamical theories. It is often exceedingly difficult to obtain good experimental data in the field; hence, some investigators have retreated to the laboratory, where some confidence in reproducible measurements can be achieved on systems analogous to the geophysical case. Because of the difficulties in scaling dynamical processes in the laboratory to the much larger atmosphere-sea interaction, most investigators have considered that the labora-

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[1] Accepted for publication and submitted to press 20 February 1968.

[2] Present Address: ESSA, Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey.

[3] Present Address: Science Center, North American Rockwell Corporation, Thousand Oaks, California 91360.

tory results have only meager applicability to apparently similar geophysical phenomena.

The purpose of this note is to present a comparison between some typical statistical properties of water waves that have been generated by only the wind, in a wind-water tunnel, and at sea. Included are data for relationships between certain scale heights for waves and for amplitude spectra. The findings demonstrate that such results from the laboratory and the field can be correlated uniformly well in terms of known methods. By such comparisons, it is possible to have more confidence than heretofore that laboratory experiments and sea-air interaction processes are mutually relevant. Furthermore, it seems possible to easily model wave statistics, at least for engineering purposes in the laboratory, without sophisticated wave generators.

Experimental. The experiments were performed in the wind-water tunnel at Colorado State University. This facility has been described by Plate (1965).

Near the inlet of the tunnel, the water surface was covered with an aluminium plate supported by legs placed on the floor of the tunnel. The plate was placed at the same height as the mean water depth to ensure as smooth a transition as possible for the adjoining air and water flow. Also, the presence of the plate allowed definition of the flow conditions in the air before the air began passing over the water.

The mean air flow and water motion have been measured in the CSU tunnel; the methods used and results obtained have been described (Hess et al. 1968, Plate et al. 1969).

The displacement of the water surface resulting from the air motion was measured with a capacitance gauge described by Plate et al. (1969). This device has a sensitivity to surface disturbance to a lower limit of $\sim 1\ \mu$m amplitude over a frequency range 0–30 Hz. Strip-chart recordings of the time variation in the elevation of the water surface were recorded on a Brush recorder. These traces were later digitized, using a Gerber reduction system. The digitized data were analyzed on the NCAR-CDC 6600 computer, using programs for statistical processing that followed methods described by Plate et al. (1969) and Colonell (1966). Calculations presented here include ones for (i) correlation curves between the mean wave height and the r.m.s. wave height, the highest one-third waves, and the highest one-tenth waves, and (ii) the frequency spectra for wave amplitudes, $\Phi(n)$. The statistics were calculated for a sample exceeding 100 waves having a frequency equal to that of the spectral peak. The records were digitized at a sampling interval of 0.025 sec.

Results and Discussion. The conditions of mean air flow as measured in the CSU tunnel were correlated well by the logarithmic law of the wall. The air motion reflected a transition from flow over a smooth surface to flow over a fully rough surface throughout the length of the tunnel test section. The structure of air motion has been described elsewhere by Hess et al. (1968). For purposes of this note, the important point is that the wind developed in the CSU tunnel is essentially similar to that observed in air motion near ocean waves having corresponding conditions of surface roughness.

Under the steady urging of the wind, waves generated in the laboratory channel have wave lengths ranging from about 1 cm to 25 cm and standard deviations in the water-surface displacement of ~ 0.01 cm to 2 cm. Probability distributions calculated from the capacitance-gauge data for the sequences of 100 waves or more showed that the amplitudes of the wind waves are nearly Gaussian, with the principal deviation from such a distribution far downstream from the tunnel inlet.

Longuet-Higgins (1952) and Cartwright and Longuet-Higgins (1956) have derived a theoretical expression for the probability distribution of maxima in the water-surface displacement record (see also a review by Colonell 1966). By assuming that the wave spectrum is confined to a single narrow band, their probability distribution reduces to the Rayleigh probability distribution. That is, the probability density of maxima is given by

$$\Pr\left[\frac{\eta_{\max}}{\sigma_\eta}\right] = \frac{\eta_{\max}}{\sigma_\eta} \exp \frac{-\eta^2{}_{\max}}{2\,\sigma_\eta{}^2}, \qquad (1)$$

where $\eta_{\max}$ is the maximum water-surface displacement and σ_η is the standard deviation of the water-surface displacement.

The wave height, H, is defined as the vertical distance between the crest and the trough, or the dominant component observed on the wave record, or as $2\eta_{\max}$. By using (1), it is possible to calculate the relationship of the standard deviation in wave heights, the mean wave height of the highest one-third of the waves, the mean wave height of the highest one-tenth of the waves, and so forth, to the mean wave height of all the waves.

In Fig. 1, the geophysical studies by Goodknight and Russell (1963) and Putz (1952) and the wind-water tunnel studies by Sibul (1955) and Colonell (1966) are compared with the present study. It is seen that the results of the geophysical cases and those in the laboratory are consistent and are well represented by the theoretical Rayleigh distribution relationships. There is, however, a small but systematic deviation from the Rayleigh curve for the laboratory results for the highest one-tenth waves; here the laboratory results are lower than the Rayleigh curve. This deviation may be due to laboratory conditions, where waves are generated over a very limited fetch. There does not seem to be any reason based on physical grounds why this should be the case; this deviation may stem from our method for computing $H_{1/10}$, which was the same as that used by Colonell.

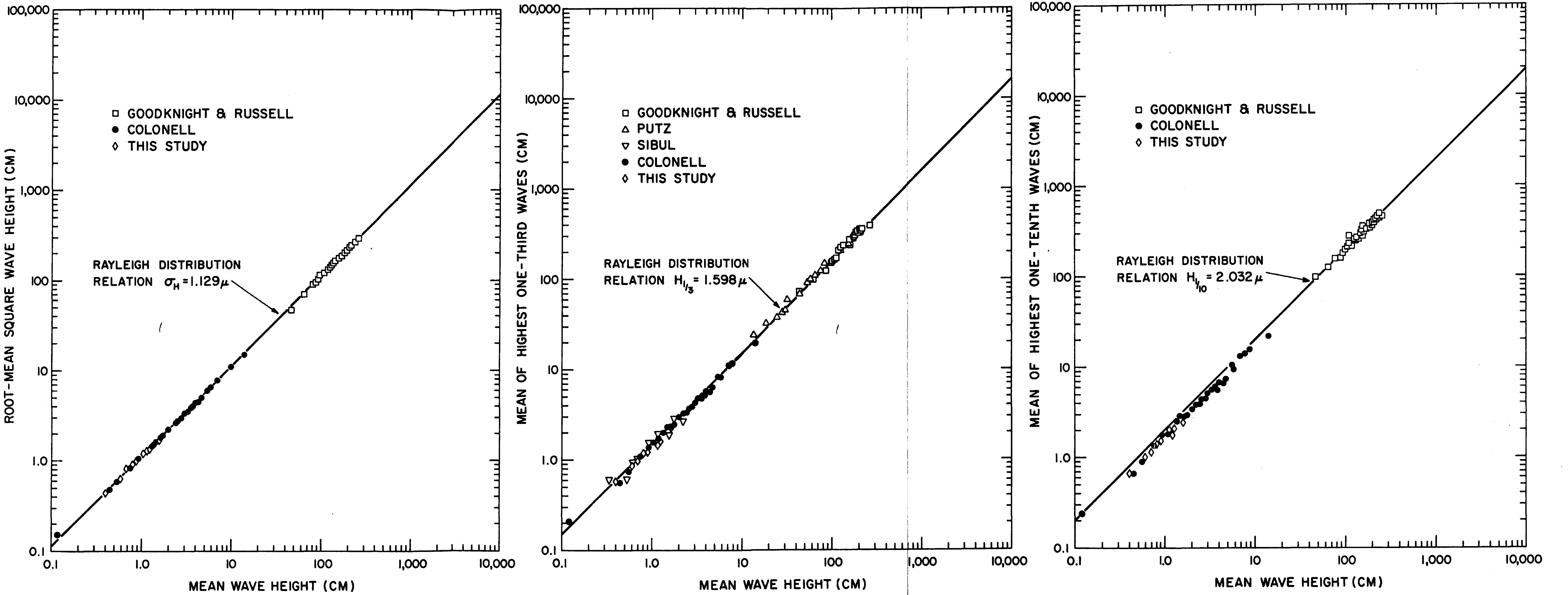

Figure 1. A comparison of theoretical relationships for the mean wave height with data from wind-water tunnels (this study and Colonell 1966) and geophysical data from Goodknight and Russell (1963). Here μ is equal to $(2\pi)^{1/2}\sigma_\eta$.

Perhaps the amplitude spectra of waves are more interesting to the oceanographer than the relationships for the mean wave heights. Spectra for wave data were taken at three successively longer fetches as measured by Plate and Hidy (1967) from the upstream edge of the water (Fig. 2). For comparison, several cases of geophysical data have been included in Fig. 2; these data range from wave spectra taken by Longuet-Higgins et al. (1963) for waves derived from a 500-km fetch and for waves observed at 17.9 km from Hurricane Dora (Collins 1966) to data taken over a limited fetch, such as those of Kinsman (1960). For the longest fetch achievable in the laboratory—about 7 m, waves raised by a wind of 10 m-sec^{-1} have grown to an amplitude that is roughly equal to the small ocean waves observed, for example by Kinsman (1960). A solid line with a -5 slope is drawn. This corresponds to Phillips' theoretical relationship for the equilibrium spectrum:

$$\Phi(n) = \beta g^2 n^{-5}. \tag{2}$$

Analysis of a number of oceanographic observations indicates that $\beta \cong 1.17 \times 10^{-2}$ (Phillips 1966). This value agrees satisfactorily with our laboratory data. However, our value of β is likely to be more like 2.0×10^{-2} for the wind-water tunnel results. Even with the difference in β, it is remarkable that Phillips' predicted results correlate satisfactorily with our results. Representative spectra in the gravity-wave regime, taken both in the laboratory and at sea, evidently follow the predicted equilibrium spectrum over a range of more than nine decades in spectral density.

The data taken at limited fetches of less than 100 km, including all the results except those obtained by Pierson (1960) and Longuet-Higgins et al. (1963), tend to be systematically higher in spectral density than is indicated by Phillips' curve, using $\beta \approx 1.17 \times 10^{-2}$. These accumulated data together with the laboratory results may indicate that β itself is a weak function of fetch. On the other hand, the range of scatter between results shown in Fig. 2 may reflect the range of error in wave-gauge measurements taken with various instruments and under experimental conditions. In the case of the wind-tunnel results, the drift current in the water might be responsible for the apparent systematic positive deviation from Phillips' curve. The data taken in the tunnel involve measurement of frequency by a fixed probe. Thus n in these cases reflects a drift velocity in addition to the celerity of the waves. Hidy and Plate (1966), for example, found that the celerity of waves in the tunnel, measured relative to a fixed point, exceeded those predicted by gravity-wave theory by 10%–20%, depending on the water depth. If the results shown in Fig. 2 were corrected in frequency for the effect of surface drift, agreement between Phillips' curve and our results could be improved.

In connection with the correlation shown in Fig. 2, Plate et al. (1969) have found that Phillips' equilibrium spectrum, as given by (2), may apply best to

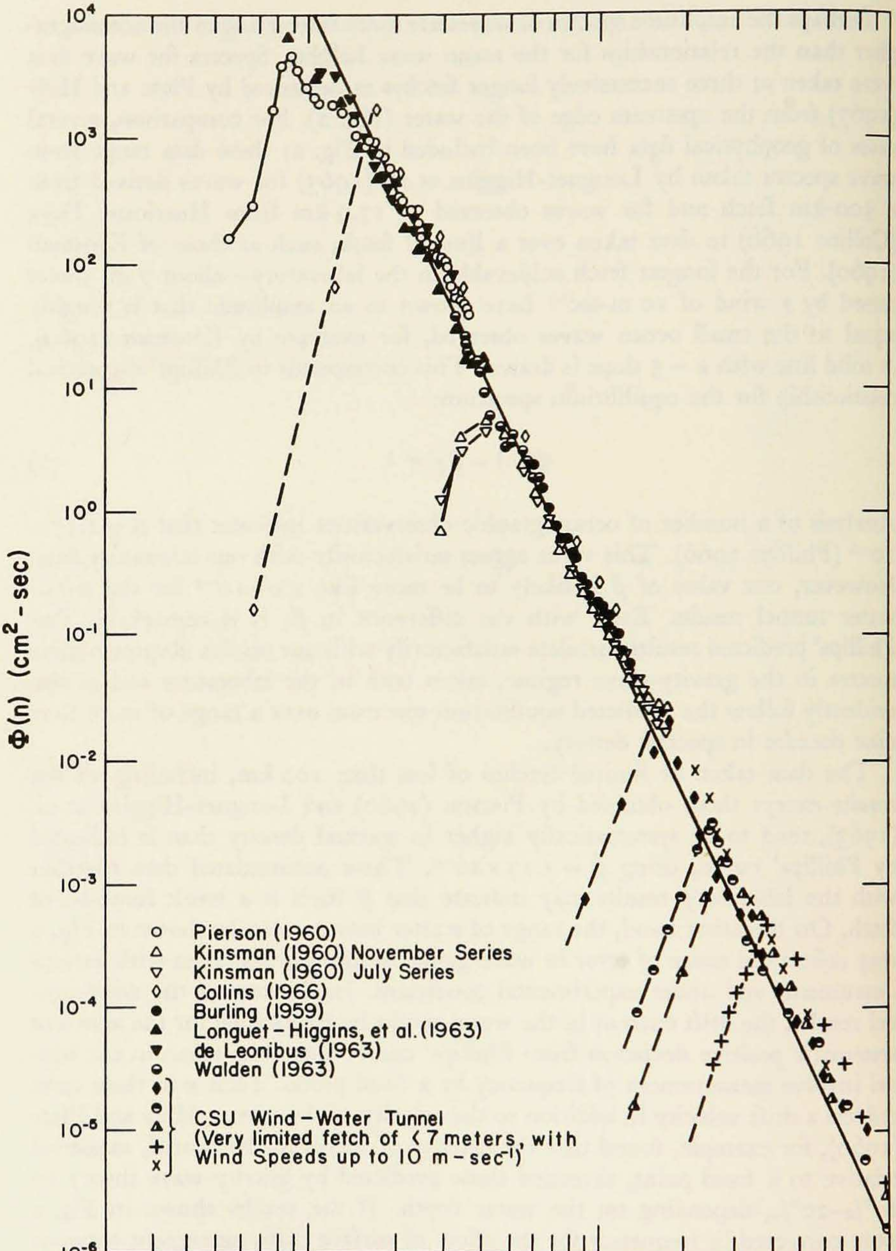

Figure 2. Comparison between wave spectra taken in a wind-water tunnel with ocean wave spectra.

the envelope curve for the spectral peaks of growing wave trains in the limited fetch data, but this does not obtain throughout a complete range of frequencies in individual spectra beyond the spectral peak. Careful examination of such spectra indicates that their shape is steeper than n^{-5} over much of the range of high frequencies just beyond the spectral peak. Plate et al. (1969) have shown that, if all spectra are similar in shape, the n^{-5} rule should correspond to the shape of the envelope curve of peak spectral densities. Provided that (i) the limiting acceleration of water particles at the wave crests is proportional to the acceleration of gravity, and (ii) the wave heights are related to the variance in the water surface displacement by the Rayleigh distribution, it is possible to derive a value of β equivalent to Phillips' (1966) empirical value of about 10^{-2}. For assumption (ii) above, virtually all of the data obtained in the CSU tunnel and the empirical similarity spectrum of Hidy and Plate (1965) lend justification. To derive $\beta = 1.17 \times 10^{-2}$, the proportionality factor between g and the maximum in water-particle acceleration was taken as 0.3, as indicated by Plate et al. (1969).

The data shown in this note indicate that wind waves tend to behave in a uniform way regardless of the size or origin. Statistical relationships such as those for mean wave heights and amplitude spectra show a pattern that is self consistent between the laboratory and the field. The ability to correlate such results by known theory points toward the fact that it should be possible to construct useful direct analogies between laboratory studies and the geophysical counterpart. In particular, the similarity in shape of the wave spectra generated by wind in the laboratory suggests that relatively simple experimental procedures could be developed, for example, by constructing dynamic models for wave forces on structures in wind-water tunnels.

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