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THE EFFECT OF SWELL ON THE GROWTH OF WIND WAVES

Several researchers have noted a pronounced reduction in the growth of wind waves in tanks when mechanically generated waves are added to the system. In order to isolate the cause of this effect, which occurs for long wave slopes as low as 5 percent, a laboratory experiment was performed to estimate the direct wind-energy input to short waves in a pure wind sea and in a wind sea contaminated with "swell." The wind input to wind-generated waves seems to be insensitive to the presence of additional long-crested paddle-generated waves. Furthermore, the changes in the development of the wind sea occasioned by the presence of paddle waves argues against enhanced dissipation as the cause of the reduction in growth rate. It is hypothesized that paddle-wave-induced detuning of the resonance conditions for weak nonlinear interactions among wind waves may be the dominant cause. This idea is somewhat tentative; further detailed exploration of the effect of long wave slope, frequency, wind speed, and fetch is needed to identify the cause more positively.

In the context of remote sensing of the ocean surface, the sensitivity of wind-sea development to quite gentle long wave slopes—whatever the cause—certainly strengthens the case for a spectral ocean-wave measurement capability in future satellite systems.

INTRODUCTION

It is well known that the addition of a train of long, mechanically generated waves ("swell") to existing wind waves in a laboratory tank has a dramatic effect on the energy density of the wind waves.[1-5] This fact is clearly illustrated in the set of three spectra in Fig. 1. Figure 1a shows the spectrum of a mechanically generated wave train of 0.707 hertz frequency and 0.067 steepness. Figure 1b is a purely wind-generated spectrum produced by an 11-meter-per-second wind measured 26 centimeters above mean water level. In Fig. 1c, both wind and paddle are operated together. All three spectra are on the same (linear) scales and are derived from observations at 50 meters fetch in water 1.2 meters deep. The growth of the mechanical waves in response to the wind and the attenuation of the wind waves are apparent when both paddle and wind are excited together. It is noteworthy that the wind spectrum is not only dramatically reduced but its peak is at appreciably higher frequencies with swell than without. What are the possible causes of this pronounced effect on wind waves by quite gentle swell?

The development of the wind-wave energy spectrum $E(\omega; x, t)$ is governed by the energy balance equation[6]

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$$\frac{\partial E}{\partial t} + (V_g + U_d)\frac{\partial E}{\partial x} = I + W + D , \qquad (1)$$

where V_g is the group speed, U_d is an appropriate fetch-dependent wind-driven current, I is the rate of energy transfer from the wind, W is the rate of nonlinear transfer among wave components, D is the rate of energy dissipation, and ω is the radian frequency. In laboratory experiments such as those described in Fig. 1, measurements are made at steady state so that the average spectral density at any fetch and frequency is determined by the entire upwind evolution of the source functions I, W, and D:

$$E(\omega; x) = \int_0^x [(V_g + U_d)^{-1}(I + W + D)]\, dx . \qquad (2)$$

The source functions are related to E and so are strongly fetch dependent. V_g and U_d may also be fetch dependent but much more weakly. The fetch dependence of the group speed arises through changes in amplitude dispersion,[7] while fetch differences in U_d may be the result of developing boundary layers.

Thus, the observations of attenuated wind waves in the presence of laboratory swell may be caused by changes in the rate of wind input, dissipation, or nonlinear transfer occasioned by the swell. Changes in the group speeds or drift currents are less likely candidates. Banner and Phillips[8] and Phillips and Banner[2] argue that dissipation of the wind waves is greatly enhanced in the presence of swell. Their arguments concern the additive effects of wind drift and orbital velocities at the

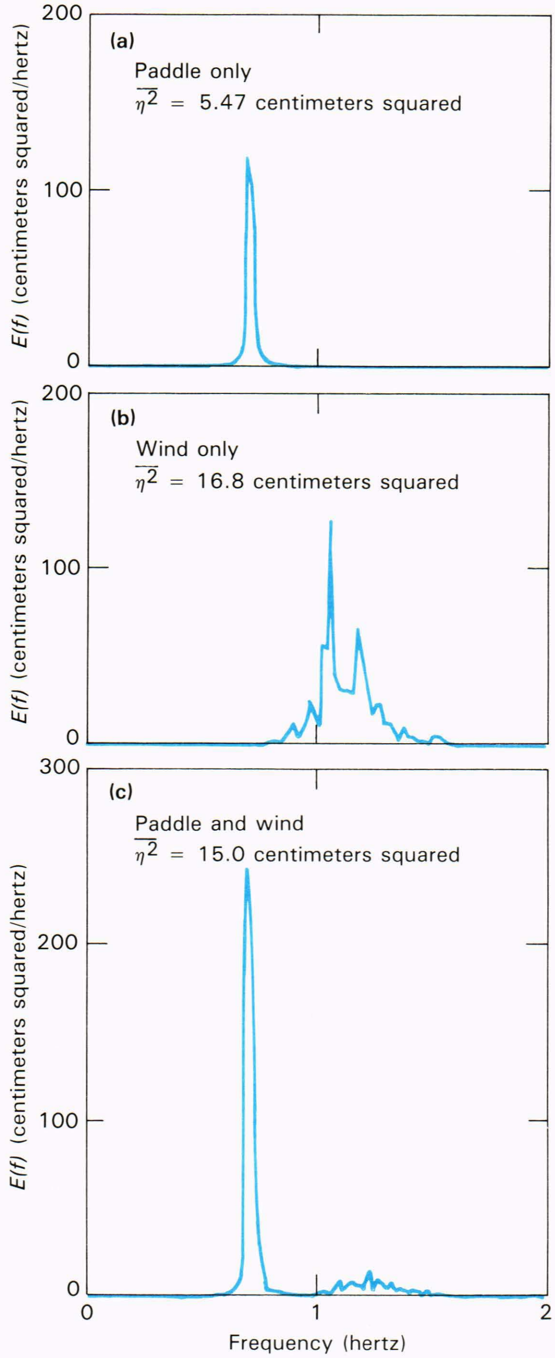

Figure 1—Wave spectra at 50 meters fetch in a laboratory wind-wave tank. (a) The spectrum of a continuous train of 0.707-hertz paddle-generated waves of steepness $ak = 0.067$. (b) The spectrum of a pure wind sea with measured wind of 11 meters per second at 26 centimeters height. (c) The spectrum of waves with wind and paddle excited together as in (a) and (b).

crest of the swell that act to reduce the amplitude at which the short waves break. Wright[9] and later Plant and Wright[10] explore the hypothesis of Phillips and Banner and found that it is unable to account for the magnitude of the attenuation of the short waves or its dependence on wind speed.

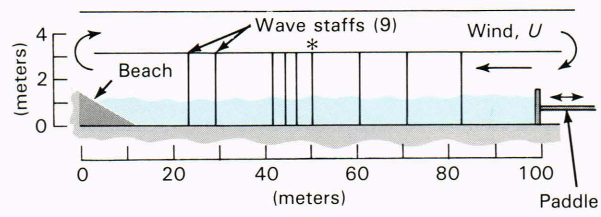

Figure 2—Sketch of the wind-wave tank showing the location of the wave staffs. The asterisk indicates the location of the wave follower and *x*-film anemometer. The vertical exaggeration is ×5.

In this article, we focus our attention on wind inputs, another of the source functions, which has the convenient property that it (or most of it) can be measured directly by measuring the pressure near the surface and the surface elevation. The experiments reported below are a preliminary attempt to explore the possible effect of swell on the wind-input rate to wind-sea components of the spectrum.

THE EXPERIMENTS

The wind-wave flume and relevant instruments are illustrated schematically in Fig. 2. The wind tunnel was closed, and the airflow could be driven at speeds up to 14 meters per second. The paddle waves were generated by a piston-type paddle and dissipated on a beach of fibrous matting with a slope of 1:8. Nine capacitance wave staffs of 1.1-millimeter external diameter were distributed along the 80-meter fetch. The flume was 4.57 meters wide and 3.06 meters high, and the water depth was 1.20 meters.

At the station shown in Fig. 2, an electrohydraulic wave follower kept a pressure probe close to the moving water surface. The pressure probe was of the disk type designed by Elliott[11] and was operated with the axis of symmetry horizontal and transverse to the flow. Pressure fluctuations were converted to electrical signals by an MKS Baratron (Model 223 AH) differential pressure transducer. The probe was connected directly to the positive port of the transducer and through a pneumatic low-pass filter to the reference port. Connections among probe, transducer, and filter were made with rigid metal tubing, and the complete system was mounted on the wave follower so that the motion of the follower produced no flexing of the interconnecting tubes and the concomitant wave-coherent (but spurious) pressure signal. A pair of capacitance staffs 10 centimeters on either side of the disk provided concurrent surface elevation and also crude estimates of the directionality and the long-crestedness of the waves under the disk.

Estimates of the pressure slope correlation, and hence the wind input I, are particularly sensitive to the phase between waves and surface pressure. Therefore, the phase distortion introduced by the probe was measured in the manner of Snyder et al.,[12] and appropriate phase corrections were made. The pressure-sensing ports were necessarily a few centimeters above the surface. The elevation above the moving surface was varied between and 9 centimeters, depending on the strength of the wind and, therefore, the likelihood of a drop of spray hitting the probe and blocking its ports. Consequently, the pressure measurements were corrected using the observed exponential decay with height without a change of phase.[13] The fractional energy increase per radian $\zeta(\omega)$ was computed from the quadrature spectrum $Q_u(\omega)$ between pressure p and surface elevation η after correcting for the phase and amplitude response of the pressure measuring system:

$$\zeta(\omega) = \frac{1}{\omega E(\omega)} \frac{\partial E(\omega)}{\partial t} = \frac{[Q_u(\omega)]_{p\eta} e^{kz}}{\rho_w \, g E(\omega)} , \tag{3}$$

where k is the wavenumber of the wave of radian frequency ω, z is the height of the pressure measurement above the moving surface, ρ_w is the density of water, and g is the acceleration due to gravity.

Six runs, analyzed to investigate the effect of swell on the wind input to the wind waves, are summarized in Table 1. Two different fan speeds were used. The small differences in measured (pitot-tube) wind speeds arise because of changes in the surface stress occasioned by the different wave fields. At each fan speed there are three runs of 0.527-hertz paddle waves with various initial steepnesses: ak = 0.0 (no waves), 0.053, and 0.105.

Table 1 — Fetch dependence of wind-sea variance.

Run No.	*Wind Speed at 35 Centimeters (meters per second)*	*Paddle Slope, ak*	α	γ	*Fetch (meters) at Intersection with* 381	397
381	6.86	0.0	0.0087	1.32		
382	10.72	0.0	0.015	1.56	0.16	4.2
418	7.29	0.053				
419	11.08	0.053				
400	7.10	0.105	0.019	0.925	6.2	0.27
397	11.09	0.105	0.026	1.18		

An x-film anemometer was used to measure the momentum flux 35 centimeters above the mean water level, and the result was corrected, assuming a linear stress gradient, to yield surface friction velocity. The pressure-elevation cross spectra were computed from 2^{14} samples converted at 20 hertz using a 12-bit analog-to-digital converter. The x-film data were sampled at 200 hertz. In each case, all signals were filtered with matched 12-decibel-per-octave Bessel (linear phase shift) low-pass filters, with −3-decibel points set at the Nyquist frequency.

RESULTS AND DISCUSSION

The spatial growth of the wind sea only is illustrated in Fig. 3 for four of the runs of Table 1: the runs with wind only and the runs with wind and the steeper (ak = 0.105) paddle waves. In each case, a straight line (or power law) fit of wind-sea variance $\overline{\eta^2}$ to fetch x represents the data very well:

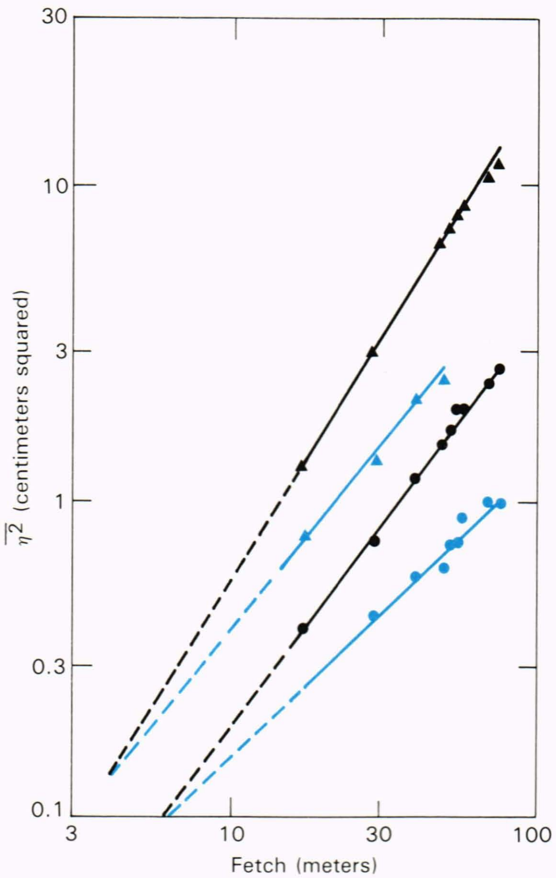

Figure 3—The spatial evolution of the variance of the wind sea only with (colored symbols) and without (black symbols) paddle waves. The initial steepness of the paddle waves, ak, was 0.105. The triangles refer to the 11-meter-per-second wind cases and the circles to the 7-meter-per-second cases.

$$\overline{\eta^2} = \alpha x^{\gamma} \tag{4}$$

In run 397 beyond the 50-meter fetch, the second harmonic of the paddle wave (1.054 hertz) and the wind-sea spectrum merge, making it difficult to assign a value to the purely wind-sea variance. Longer fetches are therefore omitted in that run.

The values of α (with η in centimeters and x in meters) and γ are tabulated in Table 1 as are the (extrapolated) fetches at intersections of pairs of lines.

Several interesting changes in the fetch dependence are apparent in Table 1 and Fig. 3. There is a clear increase in the exponent with wind speed for the wind-sea-only cases, but the lines intersect at small (essentially zero) fetch. On the other hand, the addition of paddle waves to the wind sea without appreciably changing the wind speed causes a marked decrease in the growth rate of the wind sea. These pairs of lines (with and without paddle waves) intersect at 6.2 and 4.2 meters for the lower and higher wind speeds, respectively. Perhaps the waves develop to this point before the influence of the paddle waves changes their spatial development. Certainly, in the first few meters at these wind speeds, the waves are not yet limited by breaking and may not be steep enough for nonlinear interactions to affect the spectral balance. In fact, Kahma and Donelan[14] have shown that at a fetch of 4.7 meters the spectral peak begins to move toward lower frequencies only when the wind exceeds about 4 meters per second. This change in spectral development occurs at lower fetches for higher winds and corresponds to the point where the fastest growing wavelets (approximately 8 hertz) begin to be limited by breaking. Does the paddle wave enhance the breaking of the wind waves, alter the nonlinear interactions among wind waves, or cause a substantial reduction in the rate of wind input to the wind waves? We now direct our attention to the last part of this question.

Figure 4a illustrates the observed dependence of the rate of wind input, ζ, in terms of the ratio of the friction velocity, u_*, to phase speed, c. Plant,[15] on the basis of the wave amplification theory of Miles,[16] collected various estimates of ζ and showed that there was general agreement with the line shown, although the scatter in ζ covered 5 decibels for the laboratory data. The data in Fig. 4 are from the wind-only runs at the peak frequency and higher frequencies (30 and 70 percent higher). Figure 4b shows the same data but plotted versus $(U(\pi/k)/c) - 1$, a form suggested by Jeffreys' ideas[17,18] of wave amplification by wind and explored in more detail by Donelan and Pierson.[19] $U(\pi/k)$ is the wind at one-half wavelength height estimated from the measured wind speed and friction velocity. The fitted line shown corresponds to

$$\zeta = 4.1 \times 10^{-5} \left(\frac{U(\pi/k)}{c} - 1 \right)^{2.42} \qquad (5)$$

When estimates for the wind input for the cases with paddle waves are added (Fig. 5), the scatter is considerably increased, but no appreciable bias is evident. Note that the wind-sea variance is reduced by a factor of about 2.5 (4 decibels) in the presence of paddle waves, so that if this is due to changes in the wind input, the values of ζ for the paddle plus wind cases should be significantly less than those for the wind-only cases. In the paddle cases, the frequencies selected are, as before, the peak of the wind sea and two higher frequencies, although the wind-sea peak frequency is always greater when paddle waves are present. In two cases (397 and 400), the coherence between pressure and elevation was too low to allow a reliable estimate of ζ at the third frequency.

The results suggest that the wind-input rate to the wind sea is rather insensitive to the presence of longer mechanically generated waves of small steepness.

Figure 6 traces the spatial development of the spectrum for run 400 (U = 7.1 meters per second, ak = 0.105). The corresponding smoothed spectra for run 381 are superimposed to illustrate the changes caused by the paddle waves. Since the spectra cover more than six decades, care must be taken in the analysis to avoid the

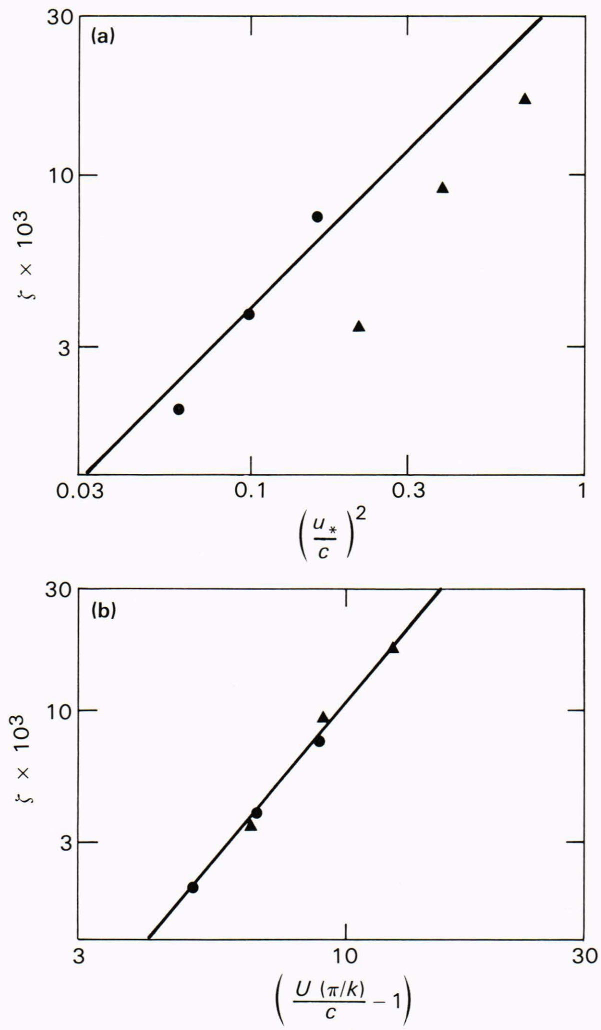

Figure 4—The measured fractional energy input per radian from the wind for the pure wind-sea cases at three frequencies at and above the peak. The triangles refer to the 11-meter-per-second case and the circles to the 7-meter-per-second case. The line in (a) is from Plant's[15] compilation of various sources of data.

spurious effects of window leakage. The paddle frequency (0.527 hertz) and sampling frequency were selected so that an integer number of cycles fit within a fast Fourier transform block of data (2048 points). No such control is possible with the wind waves, and therefore a data window with very low sidelobes was applied to the blocks of 2048 points before the Fourier transforms were performed.

Harris[20] has explored in detail a wide range of data windows. On the basis of his analysis, the Blackman-Harris four-term window was applied to these data. The window has sidelobes that are no larger than −70 decibels and therefore is suitable for our purpose. The window's 3-decibel bandwidth is 0.0186 hertz so the paddle-wave line spectra are slightly broadened. Spectra from eight consecutive blocks of 2048 samples were averaged so that the wind-wave spectral estimates of Fig. 6 have 16 degrees of freedom and a 90 percent confidence interval of −2.2 to +3.0 decibels as shown.

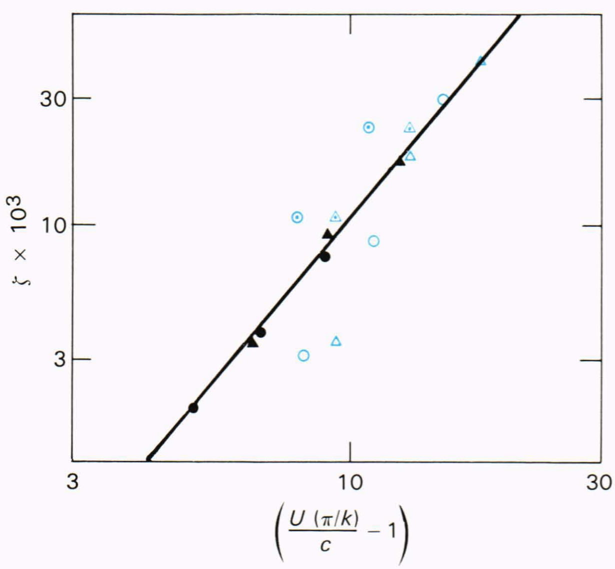

Figure 5—The fractional energy input per radian to the wind sea as in Fig. 4b but with the cases with paddle waves added (open triangles refer to the U = 11-meter-per-second cases, open circles refer to the U = 7-meter-per-second cases). The centered dot denotes the steeper paddle waves, ak = 0.105.

It is apparent that the spectral density near the peak of the wind-only spectrum (colored line) is greatly reduced (about 10 decibels) in the presence of paddle waves. At higher frequencies, however, the trend is reversed but the differences are not as pronounced. Here the wind waves with paddle are only about 1 decibel higher than the wind waves without. Doppler smearing of the spectra can introduce some differences, but in this case they are likely to be small since orbital velocities added by the paddle are roughly compensated for by the reduced orbital velocities at the spectral peak.

It is interesting to note that the spectral density just above the peak of the paddle-modified wind sea is generally close to the spectral density at the same frequency in the pure wind sea. But in the latter case, the peak frequency is appreciably lower so that the reduction in total wind-sea energy occasioned by the introduction of paddle waves arises because the rate of progression of the wind-sea peak (to lower frequencies with increasing fetch) is slowed. It is well known that the downwind growth of the forward (low-frequency) face of a fetch-limited spectrum is far greater than either theoretical or experimental estimates of direct wind input would support. Hasselmann[6,21,22] has demonstrated that the additional energy flux may come from weak nonlinear interactions involving a quartet of wavenumbers and frequencies that satisfy the resonance conditions for gravity waves:

$$\mathbf{k} + \mathbf{k}_1 = \mathbf{k}_2 + \mathbf{k}_3 \ , \qquad \omega + \omega_1 = \omega_2 + \omega_3 \ , \tag{6}$$

where ω and k are linked by the dispersion relation $\omega = (gk)^{1/2}$.

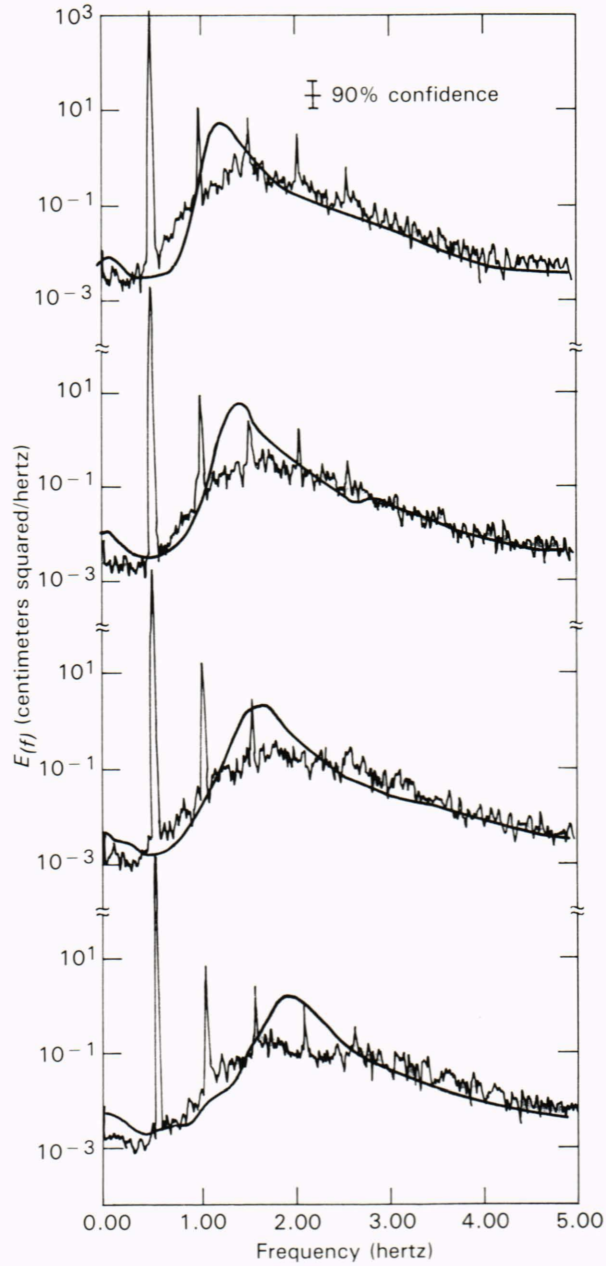

Figure 6—The spatial evolution of power spectra on log-linear scales. The solid lines are the spectra with paddle waves of steepness ak = 0.105 and wind U = 7.1 meters per second. The colored line is the corresponding smoothed wind-only case. The fetch increases upward, x = 29.1, 39.2, 55.0, and 69.8 meters.

Since the nonlinear transfer to the forward face is sensitively dependent on the steepness of waves at and above the peak, it may be argued that the paddle waves reduce the steepness of the wind waves at breaking and consequently also suppress the nonlinear flux of energy to the forward face. However, as previously noted, at each fetch the paddle-modified wind waves equal or exceed the energy density of the pure wind sea at frequencies above the peak of the paddle-modified wind waves. Thus, the slower reduction of the peak frequency of the paddle-modified wind sea does not appear to be due to weaker nonlinearities in the waves themselves.

Mechanisms that lead to the modulation of short-wave energy (e.g., Longuet-Higgins and Stewart[23]) and, hence, enhanced breaking in steep wind seas and direct dissipation enhancement mechanisms (e.g., Phillips and Banner[2]) become less efficacious as the ratio of short-wave phase speed to long-wave orbital velocity increases. This would be reflected in Fig. 3 by increasing the slope with fetch in the paddle-modified cases as the increasing phase speeds in the wind seas far exceed the modest orbital velocities of the paddle waves.

As we have seen from the experiments described above, the rate of energy input from the wind seems to be insensitive to the presence of the paddle waves.

What remaining consequence of the introduction of quite gentle paddle waves can have such a pronounced effect on the development of the wind sea? As a working hypothesis, we suggest that the paddle waves may act to detune the sharp resonance at the heart of the weak nonlinear interactions among quartets of gravity waves. One way in which this may occur is through the changes in apparent gravitational acceleration experienced by the wind waves riding on the long waves. As shown by Phillips and Banner,[2] if the long-wave slope is small, the dispersion relation for the short waves is altered to

$$\omega_S = \{gk_S[1 - a_L k_L \cos(k_L x - \omega_L t)]\}^{\frac{1}{2}} , \quad (7)$$

where the subscripts L and S refer to long and short waves. Thus, as paddle waves pass through groups of wind waves, the latter experience variations in their dispersion relation and consequent detuning of the resonance leading to nonlinear interactions and, in particular, the development of the forward face of the spectrum. It is noteworthy that the forward face of the wind-sea spectrum (Fig. 6) is considerably less sharp when paddle waves are present than otherwise. The slightly larger spectral densities at high frequencies in the presence of paddle waves may also reflect a detuning and consequent broadening of the nonlinear transfer region of influence.

CONCLUDING REMARKS

Evidence from various laboratory experiments leaves little doubt that quite gentle long waves, added to a pure wind sea, cause substantial reductions in the growth of the wind sea. The reason, however, is not so clear. Proposed mechanisms for enhanced dissipation of the wind waves by long waves and wind drift do not seem to explain the observed spectral evolution, and measurements of direct wind input to wind waves reported here appear to be insensitive to added paddle waves.

We suggest that a possible candidate for the reduction in the wind sea induced by paddle waves is the detuning of resonant nonlinear interactions. We will continue to examine the wind-sea evolution for the effects of long-wave slope, frequency, and wind speed, attempting thereby to clarify the mechanisms for arresting wind-sea development.

In the context of ocean-wave forecasting, this effect of swell on wind sea is clearly important yet is not, to our knowledge, included in forecast models. The correct prediction of the development of storm seas may depend on accurate swell predictions in global wave models. The storm seas themselves eventually become swell, and it is not difficult to see that errors may accumulate and propagate from one storm to a subsequent one elsewhere. This would seem to strengthen the case for a capability to sense directional spectra of ocean waves in future ocean satellite systems.

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