Remote observations of the initial generation of surface waves

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Abstract — **We present laboratory experiments on the initial generation of surface waves and related Langmuir circulations. Using quantitative remote optical and infrared flow visualization techniques, we acquired collocated surface wave slope and temperature. We show that the classical wave generation problem is accompanied by other phenomena, including Langmuir circulations, that occur over comparable space and time scales. Of particular interest is the influence of the sub-surface velocities associated with the Langmuir circulations on the structure of the growing wave field. Direct measurements of wave variables show a clear cross-wind modulation which is qualitatively consistent with geometrical optics and wave action conservation. The temporal evolution of the directional slope spectra show that the wind waves are initially generated near the minimum phase speed. Energy is then transferred to both lower and higher wavenumbers as the wave field evolves to a fetch-limited state with the appearance of parasitic capillary waves. Once the wave field has grown sufficiently, microscale breaking is observed in both the slope and infrared images. We show that the generation of the surface waves by the wind triggers a transition to turbulence of the near-surface flow.**

I. INTRODUCTION

Various methods of oceanographic remote sensing depend on the structure of short wind waves. With the globally averaged wind speed in the range 6-7 ms^{-1}, and 40% of the time below 6 ms^{-1}, much of the air-sea interface is in a low wind speed regime, and therefore the initial generation of waves under these conditions is of special interest. At low wind speeds, both waves and currents are generated but there is no comprehensive understanding of the full evolution of the wind-generated wavy surface current field. Consequently, the variability of remotely sensed variables at low wind speeds is large and poorly understood.

The generation of wind waves at the surface of the ocean is a problem that has been of interest since antiquity. Modern studies of wave growth began with Jeffreys [1] and Lock [2], and later Phillips [3] and Miles [4] contributed greatly to theories of wind wave generation. Experiments were conducted by Larson and Wright [5], Kawai [6], and Kahma and Donelan [7]. However, the generation of waves is accompanied by the turbulent transition of the developing surface shear flow through the generation and instability of small scale Langmuir circulations (LC) [8]. Veron and Melville [8] showed that the Langmuir circulations interact with the surface waves implying that the initial generation of wind waves might rapidly become three-dimensional and that it therefore cannot be completely understood without including the complex sub-surface flow. In this paper, we present a series of experiments on the generation of waves and Langmuir circulations and the transition to three-dimensional surface wave and velocity fields.

II. SETUP

The experiments were conducted in the large wind-wave facility at Scripps Institution of Oceanography. The channel is 45 m long, 2.39 m wide and 2.44 m high with a water depth of 1.25 m and a wind tunnel section 1.19 cm deep. One end of the channel is fitted with a computer-controlled fan exhausting to the atmosphere. At the other end is the inlet section that provides a smooth entry for the airflow. The setup is similar to that described in Veron and Melville [8]. A calibrated IR video camera was used to image the surface temperature at a 60 Hz rate. This permitted the measurement of the evolution of the surface temperature field modulation resulting from the LCs and, when used with a CO_2 laser laying down thermal markers on the surface, the data can be processed to give the surface velocity. Over the same footprint, the wave field was measured using a color imaging slope gauge which is a refractive optical gradient instrument developed by Jähne and Reimer [9] and Zhang and Cox [10]. It provides a two-dimensional slope measurement of the water surface over a 36.8 cm by 27 cm area and at a 60 Hz rate.

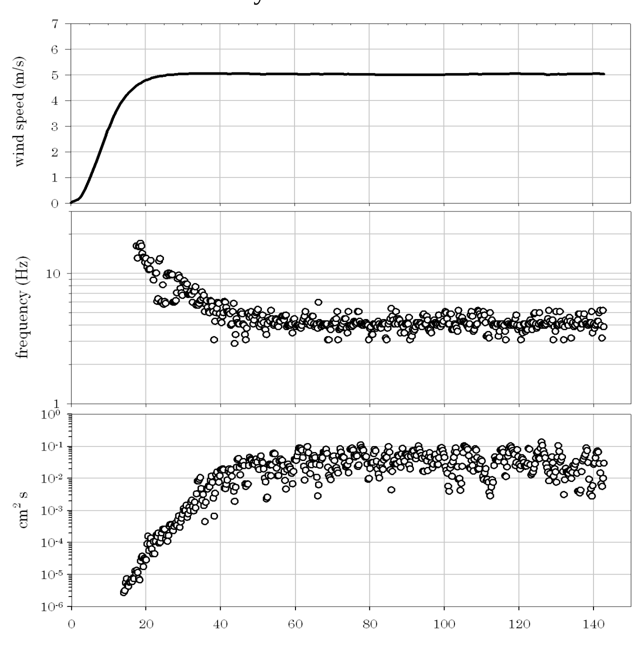

Fig. 1 Wind speed, peak frequency and peak power density of the wave field as a function of time.

III. Results

A. *Surface wave height measurements*

Fig. 1 shows the surface wave peak frequency and peak power spectral density as a function time as the wind (fig. 1a) accelerates to a final value of 5 ms^{-1}. The first detectable waves appear at approximately t=14s with a frequency of 14-16 Hz. With time, the peak frequency undergoes a downshift as the wave field evolves from duration to fetch limited. Similarly the power spectral density rises until the wave field is limited by fetch at t=45-50 s.

B. *Surface wave slope measurements*

Fig. 2 shows the evolution of the surface wave slope field for t=15, 25, and 35s for a final wind speed of 5 ms^{-1} (fig. 2). At t=15 s, the first detectable waves become visible with a wavelength of 1.5 – 2 cm. As shown on fig. 2, the directional saturation spectra $B(\mathbf{k})=\mathbf{k}^4F(\mathbf{k})$ where $F(\mathbf{k})$ is the wave height spectrum, indeed confirms that the waves are initially generated as two-dimensional (with the wave fronts perpendicular to the wind direction), and at a wavenumber near that of the minimum phase speed (λ=1.7 cm, k=360 rad.m^{-1}). At t=25 s, the wave field is clearly three-dimensional with the cross-wind slope spectrum showing a distinct signal from the cross-wind waves (Fig. 2). Also, the spectrum of the along-wind slope shows that the initial peak begins to separate into two distinct maxima. Finally, at t=35 s the waves show signs of non-linearity as parasitic capillary waves appear on the front face of the carrier gravity waves. The spectra for both the cross-wind and along-wind waves exhibit a bimodal shape where the lowest peak is due to the long gravity waves, and the second peak around 800 rad/m corresponding to a wavelength of 0.8 cm is believed to be caused by the parasitic capillary waves riding on the longer gravity waves. The two peaks are separated by a “dip” which lies approximately at the wavenumber corresponding to the waves with the minimum phase speed: the location of the single first peak observed on the spectra. As for the wave height data, the slope image measurements show the

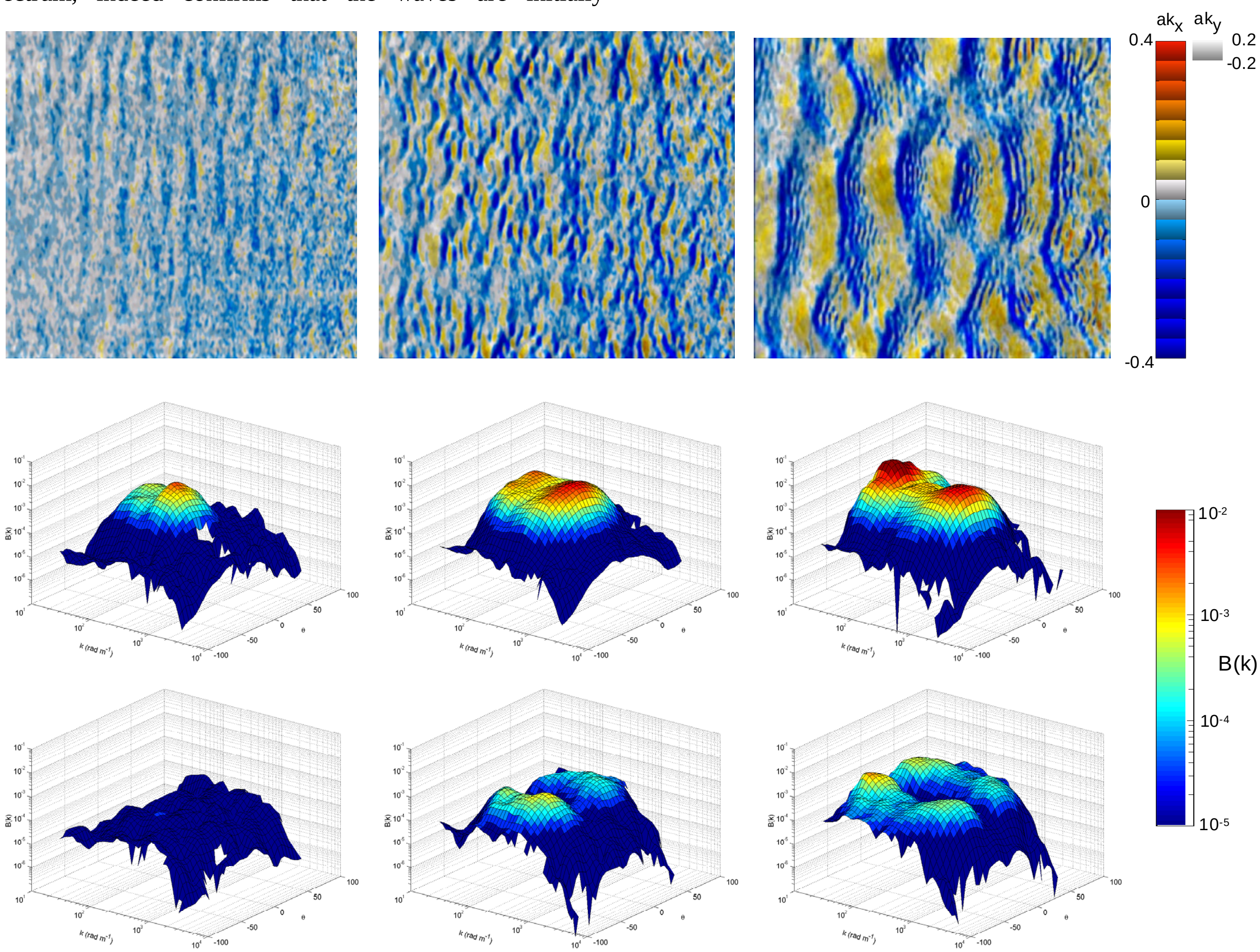

Fig. 2 Surface slope images for a final wind speed of 5ms^{-1} Image size is 26.5 x 36 cm. Time shown are t=15, 25, and 35s. The color code shows the along-wind slope and the shading corresponds to the cross-wind slope. Below each slope image is the corresponding directional saturation spectrum for the along-wind slope and cross-wind slope respectively.

downshift of the dominant surface wavenumber as the wave field grows.

C. *Surface wave – current interactions Transition to three-dimensional wave field.*

We previously established that the waves and currents from the Langmuir circulations were coupled [8]. In fact, Fig.3 shows the surface temperature field (modulated by the sub-surface currents) co-located with the along-wind slope image of the wave field at t=19.8 s and for a wind speed of 5 ms^{-1}. It appears indeed that the wave field is also modulated by the velocity associated with the Langmuir circulations. In agreement with wave action conservation, the waves propagating on warmer, slower, recently upwelled water are steeper and slower. A close look at the slope image however reveals that the wave fronts are bent by the surface velocity gradient (arrow). Therefore, as we expect from wave action conservation and geometrical optics, the wave front bend around regions of vertical vorticity, thereby forcing the waves to propagate in a direction different from that of the wind. This is emphasized by the saturation spectra which show that cross-wind waves appear at t=19.8 s

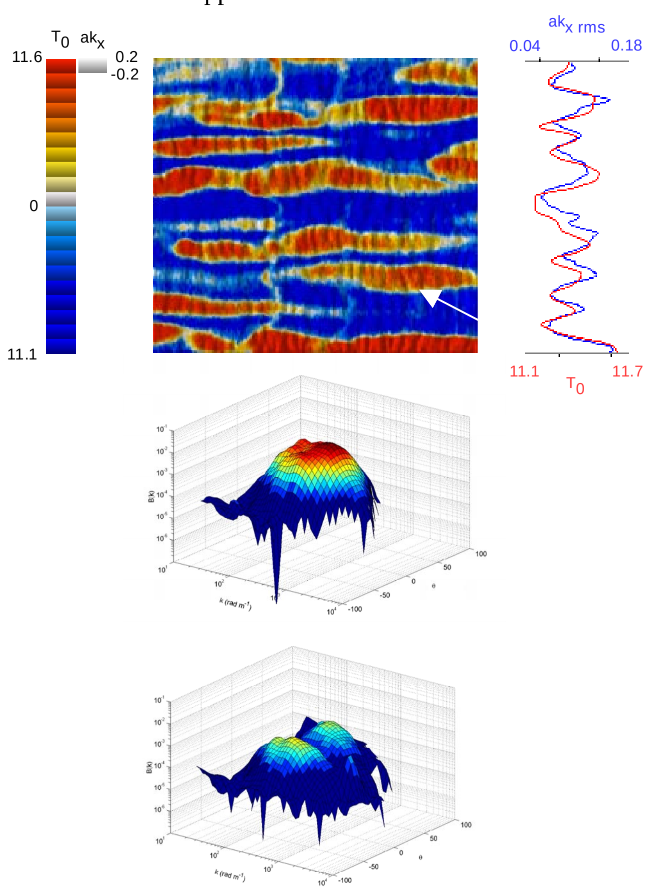

Fig. 3 Co-located surface temperature (color) and wave slope (shading) at t=19.8 s for a final wind speed of 5 ms^{-1}. The surface temperature (modulated by the sub-surface velocity) is clearly coupled with the surface waves which consequently develop slopes in the cross-wind direction as shown in the spectra.

IV. CONCLUSION

While we had previously observed and studied the turbulent transition of the surface velocity field through the instability to Langmuir circulations of the surface shear current [8], it appears that this transition also affords the transition from a two to three dimensional surface wave field.

During the transition, we observed a cross-wind modulation of the surface waves which is qualitatively consistent with wave action conservation and correlates with the wavelength of the Langmuir circulations. This has some important implications for radar remote sensing of the ocean surface.

The Langmuir circulations appear shortly after the first waves are generated [8] and since it seems that the Langmuir circulations, in turn, modulate the wave field, it follows that the wave field evolves on a time scale of a few seconds at most. This rapid evolution from 2D to 3D surface wave patterns in the early stages of the wave generation implies that 2D models for wind-wave generation might only apply in the very early stages of wave growth.

This work was supported by NSF grant OCE 9633794.

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