AIRFLOW SEPARATION OVER SURFACE GRAVITY WAVES

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Summary: We present experimental results on the details of the airflow above surface gravity waves for a several wind speeds, wave ages and slopes. The bulk of the results presented were obtained from a series of laboratory experiments that took place at the University of Delaware's Air-sea interaction facility. We also present preliminary field data. Airflow properties within and above the viscous sublayer were obtained using PIV, and wave profiles and spectra were measured by laser-induced fluorescence. We observe direct evidence of intermittent separation of the viscous sublayer past the crest of the wind waves. The separation leads to dramatic along-wave variability in the surface viscous tangential stress which in turn may affect wave growth and the air-water momentum balance. Despite the intermittent aspect of this phenomenon, proper orthogonal decomposition (POD) of the wave phase-locked velocity products suggests the airflow separation yield significant flux of vorticity away from the surface thereby generating intense mixing and momentum transport within the airflow. These results hold for wind speeds that would normally be considered low to moderate. Furthermore, the statistics of separation events correlate with surface wave slope parameters, indicating that, while linear and non-separated models might only be adequate for the very initial stages of the wave generation process and in extreme low wind speed conditions, parameterizations of the mean effects of airflow separation on the total air-sea stress based on surface wave spectra products might be successful approaches. We compare the results with available theoretical predictions.

INTRODUCTION

The influence of waves on the flux of momentum is perhaps still the largest uncertainty in determining precise air-sea momentum fluxes for a variety of conditions. Yet, an accurate knowledge of the drag of the ocean on the atmospheric flow is, for example, crucial to both short term forecasting and the modeling of long-term global climate trends. While we know that most the surface stress is supported by the wave-coherent stress carried in large part by the small gravity-capillary wind waves, the role of the airflow separation above these small waves is not well understood. This is due to the difficulty of making measurements within a wave height of the mean water level and consequently, there are to date, very litle direct observations of airflow separation above surface waves, let alone quantitative stress measurements.

Our current understanding of the momentum boundary layers on both sides of the air-sea interface is derived from the well-known "law of the wall". However, the presence of deformable, moving, surface waves influences the structure and dynamics of the marine atmospheric boundary layer (MABL) (e.g. [1]-[7]). As in the familiar flat plate case, there is a viscous sublayer at the surface, where molecular forces are important. A wave boundary layer (WBL), where momentum is exchanged between the air and sea in order to form and to sustain waves, also exists near the surface. The height of this layer depends on the wave length of individual wave modes present. Above the WBL, i.e. away from the influence of the waves, the flow finally resembles that over flat surfaces. Therefore, the stress within the MABL can be decomposed as:

$$\tau = \rho_a u_*^2 = \tau_t + \tau_w + \tau_v = \rho_a \overline{u'w'} + \rho_a \overline{\tilde{u}\tilde{w}} + \mu_a \frac{\partial \overline{u}}{\partial z}.$$

The primes indicate turbulent quantities; the tildes are wave coherent quantities, and the overbars represent ensemble averages. The wave-coherent term also contains a component that leads to wave growth and another component associated with flow separation over breaking waves. While there is currently a large interest in the airflow separation over these waves as it is thought to greatly influence the drag at hurricane-type wind-speeds, the fraction of the wave stress arising from the airflow separation remains arguably the least understood. This is well illustrated by the lack of progress in the past 20 years in predicting hurricane and storm intensity while we have made tremendous progress in predicting their trajectories. Our inability to predict hurricane and tropical storm intensity, besides the obvious drawback in terms of public warning and safety, is in part the consequence of an incomplete understanding and lack of data on the airflow separation effects on the ocean-atmosphere momentum balance.

RESULTS

The laboratory experiments described here were conducted in the large wind-wave-current tank at the Air-Sea Interaction Laboratory of the University of Delaware. The tank is specifically designed and equipped for studies in air-sea interactions. The tank's overall length is 42 m with a working section 37 m long. It is 1 m wide and 1.25 m high. Water depth was kept at 0.71 m to allow sufficient air space above the surface. The tank is equipped with a programmable, computer controlled, recirculating wind tunnel which, for this experiment generated 10-m equivalent wind speeds of between 4.5 and 14.9 ms^{-1}.

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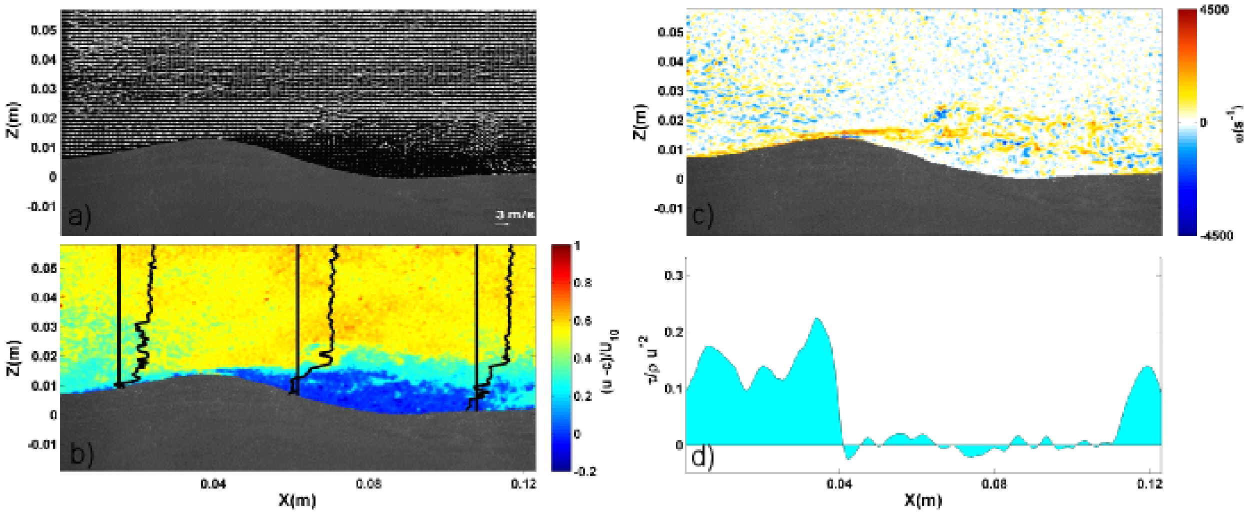

Figure 1. (a) Velocity field above a wave for a wind speed of 5 ms^{-1}. (b) Velocity magnitude for the same data set. The velocity has been moved to a frame a reference moving with the wave crest and normalized by the wind speed. (c) shows the vorticity field and (d) shows the near surface tangential viscous stress.

Figure 1a shows a vector plot of air velocity for a typical airflow separation event for a wind speed of U_{10}=5 ms^{-1} at a fetch of 21 m. The data has a resolution of approximately 300 μm in both directions, and for clarity, only shows a fifth of the available data in each direction. It shows that the airflow is attached to the wave on the windward side where the viscous sublayer is very thin but visible in the velocity magnitude on figure 1b. Past the wave crest, the flow starts decelerating and on the leeward side of the wave, there is a large turbulent region, presumably generated by the boundary layer separation. On figure 1b) we also show instantaneous velocity profile showing that the intense shear originally located in the viscous region near the interface is transported into the bulk airflow with the separation (also visible in the vorticity). The detached region exhibits low velocity, as it is dominated by turbulence where the air velocity is significantly lower than the free stream velocity above the wave crest. As the flow separates, the vortical/shear layer leaves the surface. This vortical/shear layer remains coherent and clearly visible for some distance past the wave crest (figure 1c). In fact, the turbulent detached region and the remaining undisturbed flow above are relatively well segregated by this shear layer. Finally, figure 1d shows the near surface tangential viscous stress measured at 154 μm from the surface. Once the flow detaches, estimates of the near-surface viscous stress abruptly drop and collapse to approximately 0, indicating the loss of shear and the loss of the classical linear viscous velocity profiles near the surface. We note here that these data are quite typical and that there are no significant qualitative differences in the data taken for other wind speeds.
Modal decomposition (POD) of the phase-locked averaged velocity products shows that, while intermittent, airflow separation participates significantly in the production of Turbulent Kinetic Energy (TKE) and in the transport of vorticity and momentum over the surface waves.

CONCLUSIONS

We present direct measurements of the velocity field over surface gravity waves. From these we deduce estimates of the tangential viscous stress above the wavy surface and within the viscous sublayer. The near surface velocity show that the air-flow separates above wind waves under wind speed conditions that would normally be considered benign. The viscous stress exhibits extreme along wave variability where it locally (at the wave crest) exceeds the average total stress and drops to nearly zero in the separated region. Wave phase averaged fields reveal the balance in the production and transport of TKE and statistics of the airflow separation correlate with the surface slope parameters. We will compare these data with available theoretical estimates.

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