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Wavelets and Turbulence on the Sea Surface

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FINAL REPORT ON ONR CONTRACT

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Introduction

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This contract was first awarded for fiscal year 1988, renewed for 1989, and extended without funds for 1990. Goals were to understand the physical processes determining the small scale structure of the sea surface, identify the "roughness elements" acting on the air side, explore the character and dynamics of short breaking wavelets on the water side, and quantify their role in the transfer of momentum, heat and mass across the air-sea interface. Analytical model studies were carried out on the dynamics of short, breaking wavelets, their momentum balance, interaction with the wind-induced shear flow at the surface, and the action of shear stress concentrations ("spikes") on the upwind face of such wavelets. The conceptual model of the breaking wavelets developed in these studies ("roller" riding an irrotational wave) was applied to the important problem of air-sea gas transfer, and was shown to account for otherwise puzzling observations on gas transfer. A graduate research assistant supported by this contract applied a matrix inversion technique to explore the hydrodynamic instability of the coupled air-water shear flow at the sea surface. This method allowed the exploration of various physical effects on wavelet generation, and supported the construction of a new conceptual model for the small scale structure of the sea surface.

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Scientific Results

The principal result of this project is the clear recognition that the small scale wavelets of the sea surface (which act as the "roughness elements") arise from the instability of the coupled air-water shear flow, and draw their momentum and energy from that shear flow primarily on the *water* side. This process differs fundamentally from the generally accepted idea of long-wave generation by wind, which relies on forces exerted by the *air flow* on waves. Initial wavelet growth is similar to the growth of Tollmien-Schlichting waves in a boundary layer, except that the eddies growing near the free surface have some wave-like characteristics.

This striking conclusion was arrived at through a convergence of ideas from several different investigations carried out under this contract during the last three years. A study of the dynamics of breaking wavelets showed that the breakers transfer momentum to the underlying shear flow at an unexpectedly high rate, so that they rapidly disappear without a similarly high rate of momentum gain. A study of momentum transfer from the air to the water surface via shear stress spikes revealed that most of the momentum goes into shear flow, not wave motion. Pressure forces on incipient waves have long been known to be too feeble to counter the high rate of momentum loss in breakers. Therefore the ubiquitous presence of wavelets on the sea surface can only be understood if another momentum source exists for them. A detailed numerical investigation of the stability of the air-water shear flow indeed showed that the initial growth of wavelets is governed entirely by water-side parameters, such as the depth of the viscous shear flow, water viscosity, and surface current speed. The wavelets propagate with a celerity close to that of free waves of the same wavenumber, but their internal structure is different, the near surface motion being strongly vortical. One may conjecture that wavelets of finite amplitude have a flow structure similar to the initial infinitesimal wavelets, making them a blend of wave motion and turbulence ("wavulence" has been whimsically suggested).

On the basis of laboratory investigations at Tohoku University in Japan and elsewhere, the structure of finite amplitude wavelets was modeled as a "roller" (separated flow region, in a wave-following frame) riding an essentially irrotational wave. Apart from the momentum transfer studies already mentioned, this model was also used to account for the properties of diffusion boundary layers at the sea surface, which control the transfer of gases of low diffusivity in water, such as CO_2. The essential physical effect exerted by the rollers is to generate sharp surface divergences and convergences, the former keeping the diffusion boundary layer thin, the latter conveying gas-charged fluid from the surface into the fluid interior. The model accounts for the observed Schmidt number dependence of gas transfer, and supplies a rigorous alternative for the intuitive notion of "surface renewal", as well as a tentative explanation for the puzzling differences between laboratory and field observations.

The notion that the small scale structure of the sea surface is determined by viscous disturbances on the free surface shear flow opens the door for innovative investigations of surface structure and air-sea transfer processes.

Presentation of Results and Documentation

The results briefly summarized here have been presented to the scientific community in several lectures and seminars at conferences and visits to other institutions. Also, they are described in detail in a series of publications in the open literature, and in a Ph.D. thesis, list follows.

Csanady, G.T. 1990: The role of breaking wavelets in air-sea gas transfer, J. Geophys. Res. 95, 749-759.

Csanady, G.T. 1990: Momentum flux in breaking wavelets, J. Geophys. Res. 95, 13,289-13,299.

Csanady, G.T. 1990: Wavelets and air-sea transfer. Proc. 2-nd Intern. Symp. on Gas Transfer at Water Surfaces. To be published by Amer. Soc. of Civil Engineers.

Wheless, Glen 1990: An Investigation of the Hydrodynamic Stability of the Coupled Shear Flow at the Air-Sea Interface. Ph.D. Thesis, Old Dominion University, Norfolk, VA.

It is expected that the results contained in Wheless's thesis will be published in the open literature in due course.

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