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On the formation of streaks on wind-driven water surfaces

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Abstract. Evidence derived from numerical experiments is presented to show that, contrary to the prevalent notion, the generation of elongated wind-induced streaks on water surfaces with spacing of centimeters is not necessarily attributed to interactions between surface waves and the shear current. Although the water surface is artificially designated as a flat boundary in the numerical simulations here, high-speed streaks appear on the surface arising from an underlying shear current. Floating Lagrangian tracers cluster along the streaks and, in accordance with field and laboratory observations, undergo dislocation and amalgamation.

Introduction

The signature of elongated fast-moving streaks on wind-driven water surfaces has been a subject of interest to oceanographers and limnologists since the first seminal observations were made by Irving Langmuir [*Langmuir*, 1938]. The streaks are arranged with somewhat equal spacing ranging from centimeters [*Gemmrich and Hasse*, 1992; *Kenney*, 1993; *Woodcock*, 1941] to kilometers [*Langmuir*, 1938]. The fluids along the streaks converge and downwell, thereby inducing upwellings between the streaks. This structural flow, widely known as Langmuir circulation, is well known to enhance such processes as planktonic activity, air-water gas exchange [*Gemmrich and Hasse*, 1992] as well as the vertical mixing [*Weller and Price*, 1988] and horizontal dispersion [*Thorpe et al.*, 1994] of the upper-ocean boundary layer.

Although the conditions favoring the generation of surface streaks are still not entirely clear, the mechanism involves the nonlinear interaction between wind-generated surface waves and the mean shear current [*Craik and Leibovich*, 1976] may seem the most plausible. However, other observations [*Kenney*, 1993] have shown that geometrically similar windrows form on water surfaces under glassy calm condition without the generation of any significant surface waves. For 'stationary' wall-bounded turbulent flows, low-speed streaks similar in geometry to their high-speed counterparts on water surfaces, have been identified within a sublayer in close proximity to the no-slip wall. These observations raise questions as to whether the presence of surface waves is a necessary component in the process of initiation as well as sustenance of Langmuir circulations and surface streaks, at least for a certain range of length and time scales. Specifically, we concentrate on the processes with lateral and vertical scales of $O(10)$ cm and presence time $\lesssim O(100)$ s [*Gemmrich and Hasse*, 1992; *Kenney*, 1993; *Melville et al.*, 1998; *Woodcock*, 1941]. The significance of these small-scale motions and their relevance to the larger-scale processes have been addressed in *Melville et al.* [1998].

Wind is the primary forcing involved in the production of both surface waves and the underlying shear current. The formation of a shear current always accompanies the inception of the surface waves. Accordingly, in both the real environment and laboratory settings, it is not possible to distinguish various mechanisms, particularly those which are impertinent to surface waves. In the present study, the difficulty encountered in laboratory experiments is resolved by numerical simulation and this reveals an alternative formation mechanism of surface streaks which is not associated with the motion of surface waves.

Numerical Simulation

The approach adopted here is a direct numerical simulation of the wind-driven turbulent shear flow using neither a "vortex force" to initiate the mechanism of wave-current interaction as in the previous simulations [*McWilliams et al.*, 1997; *Skyllingstad and Denbo*, 1995; *Tandon and Leibovich*, 1995] nor any turbulence parameterization to model the subgrid flow processes. Details of the mathematical formulation and the numerical implementation of the simulation resemble those in *Tsai* [1998] except for the tangential stress condition on the interface. In the present simulation the flow is generated and maintained by imposing a wind stress acting on the water surface, which is balanced by interfacial local tangential stress.

The numerical simulation is initiated with a turbulent flow corresponding to the subsequent development of the motion of water which is driven by a wind field accelerating constantly from rest to a final speed of 5 m s^{-1} in approximately 20 s, as in the laboratory experiment of *Melville et al.* [1998]. (We have also performed simulations for the wind speeds of 3 and 4 m s^{-1}. Quatatively identical flow structures were observed for the three wind speeds. We will therefore primarily focus on the computation for the wind speed of 5 m s^{-1} in the following discussion.) The shear stress acting on the water surface is assumed to be constant and invariant over time from the start of the simulation, with the surface velocity developing freely.

Two sets of simulations with identical initial velocity field are performed in the numerical experiments. In the first set, the water surface is free to move in accordance with the kinematic and dynamic interfacial conditions, while in the second set, the surface motion is restricted and the surface remains plane throughout the experiment. For such a flow configuration, the generation mechanism due to the interaction between the surface waves and the shear layer is inactivated which means any surface streaks, if they are present, would have to have been produced by other mechanism independent of the motion of the surface waves.

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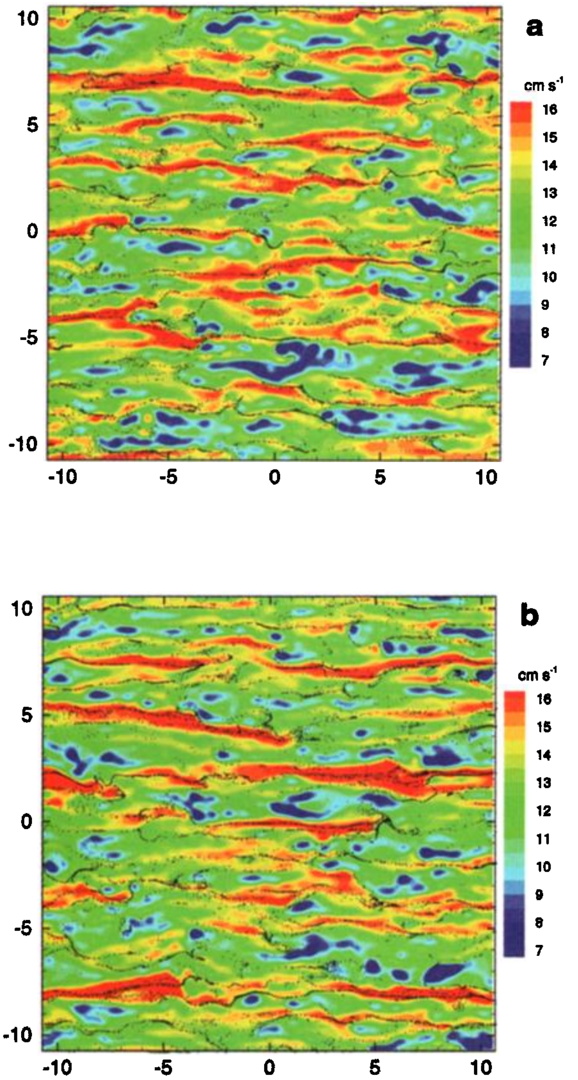

Figure 1. Contours of instantaneous streamwise velocity and the corresponding distributions of surface floating Lagrangian particles on the free-moving (a) and plane (b) surfaces at $t = 5.37$ s after the start of the simulation. In the figures, the flow travels from left to right. The length and width of the computational domain are both 21.5 cm. The streamwise velocity contours reveal predominant high-speed elongated streaks (in red) and localized low-speed spots (in blue). 128^2 uniformly distributed Lagrangian particles are released at time $t = 3.6$ s.

Results

While the simulations are initiated without any prescribed organized flow structures, high-speed surface streaks emerge immediately on both free-moving and plane water surfaces at time approximately 3 s after the start of the simulations (23 s from the onset of the wind). The wave field for the free-moving surface case evolves during the time that the surface streaks are also developing. The wavenumber of the amplitude-spectrum peak reaches an equilibrium value at the time when surface streaks appear though the amplitude of the peak continues to evolves. This was also observed in the laboratory experiments. The Langmuir number after the establishment of the surface streaks as well as the predominant wave is about 0.01 and maintained the same magnitude throughout the simulation.

Fig. 1 depicts the contours of instantaneous streamwise velocity on both free-moving and plane surfaces at $t = 5.37$ s and shows a prominent elongated high-speed streaky structure aligned with the wind direction. The surface streaks consist of major fast-moving strips with several narrower and shorter ones between the major streaks. Regardless of the restriction in the surface wave generation, i.e. the possible wave-current interaction mechanism, the streaky surface signature which appears on the plane surface is quantitatively identical to that on the free-moving surface. The distributions of the streamwise and vertical velocities as well as the streamwise vorticity on a cross-wind vertical plane in the plane surface case, as shown in Fig. 2, reveals flow structures beneath the water surface. The fast-moving streaks penetrate underneath and form an array of streamwise jets. Beneath these jets, downwellings occur and longitudinal counter-rotating vortices are observed among other dominant streamwise vortices. Between the fast-moving jets, slowly-moving "tongues" form. These tongues are associated with upwellings which bring the slowly-moving underneath fluids up towards the water surface.

The spacing of the streaks is estimated by examining the spanwise spectrum of the streamwise-averaged surface velocity, as shown in Fig. 3. The simulation begins with a spectrum of streamwise velocities with no predominant

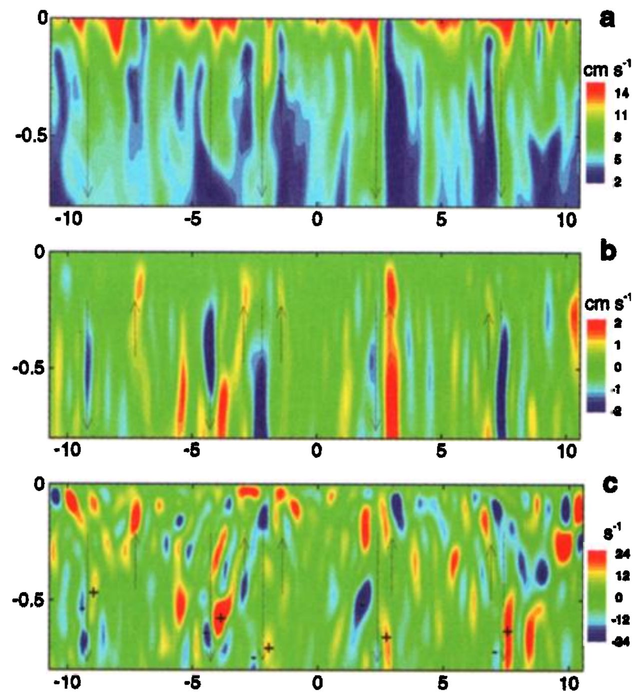

Figure 2. Contours of instantaneous streamwise velocity (a), vertical velocity (b) and streamwise vorticity (c) on a vertical plane perpendicular to the wind direction at $t = 5.37$ s after the start of the simulation for the case of flat surface. The direction of wind is out of the page. The upwellings, which bring the slowly-moving submerged waters towards the water surface where they consequently induce localized low-speed spots, are denoted by upward arrows. The spanwise positions of the high-speed stremawise, beneath which downwellings occurs, are indicated by vertical lines with downward arrows. The locations of the counter-rotating streamwise vortex cells on the two sides of the upwellings are marked with plus and minus signs.

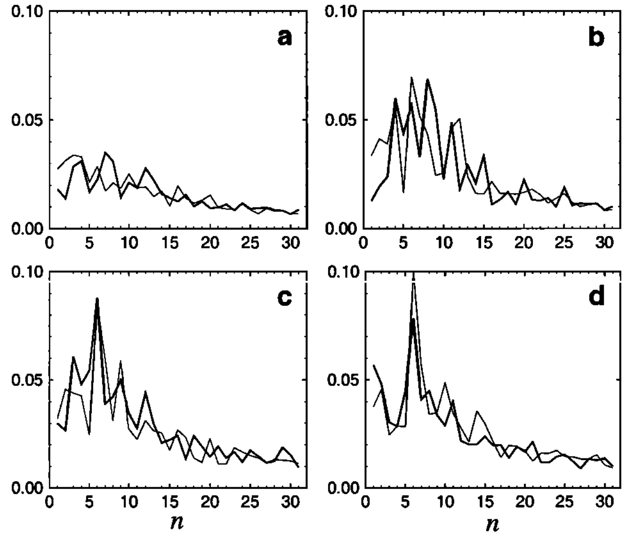

Figure 3. Spanwise spectrum of the x-averaged streamwise surface velocity, $\int \hat{u}(x,n,0)dx$, where n is the spanwise modal number, at times $t = 2.68$ s (a), 5.37 s (b), 7.38 s (c) and 8.94 s (d) from the start of the simulation. The thick and thin lines denote the spectrum of free-moving and flat water surfaces respectively.

spanwise wavelengths. As time progresses, the streaks appear and several dominant scales of spanwise spacing coexist (see, e.g., 5.37 s in Fig. 3). The spectrum evolves such that the streamwise streaks with small wavelengths of spacing diminish, whereas those with larger spacing grow. Later on in the simulation, the spectrum is dominated by components with streak spacing of 3.58 cm, which approximates laboratory measurements of *Melville et al.* [1998]. This upscale cascade of the streak spacing wavelength has also been clearly demonstrated in previous laboratory experiments [*Faller and Caponi*, 1978]. Again, such cascade can be observed at both the plane and free-moving water surfaces in the numerical experiments here.

In addition to the elongated high-speed streaks, other characteristic surface signatures in our simulations are localized low-speed spots which randomly emerge on the water surface, as shown in Fig. 1. A high-speed streak bifurcates when it encounters a localized low-speed surface spot. This bifurcation feature of high-speed streaks has commonly been observed in nature [*Thorpe et al.*, 1994] and laboratory experiments [*Melville et al.*, 1998]. The velocity field around a low-speed spot on the surface and underneath reveals that a local upwelling flow carries the submerged slowly-moving fluids up (see Fig. 2) and induces a divergent velocity spot on the surface. This three-dimensional flow is attributed to the formation and upward movement of coherent Ω-shaped horseshoe vortices in the turbulent shear layer [*Tsai*, 1998]. The underlying coherent horseshoe vortices move upwards and impinge on the water surface. During impingement, these vortices induce upwelling flows and consequently enhance the renewal of water in contact with the surface.

To further visualize the structures and also the inception and evolution of the fast-moving streaks and slowly-moving spots, uniformly distributed floating Lagrangian particles are released at time $t = 3.6$ s and their trajectories are tracked. The corresponding distributions of the particles for the velocity contours at $t = 5.37$ s (about 1.8 s after the release of the particles) are plotted in Fig. 1. Immediately after the particles are released, they aggregate and form several elongated streaky groups traveling along the high-speed streaks. The formation of this surface streaky pattern takes place as rapidly as in the laboratory [*Melville et al.*, 1998] and field [*Woodcock*, 1941] experiments. Viewing the animations of the particle movements, we see that some streets of the aligned particles suddenly divide into separated branches. The positions of bifurcation of the aligned particles coincide with the intermittently appearing low-speed spots. Some particles of the individual bifurcated streaks diverge and join other streaks, a feature which is identical to the dislocation and amalgamation of surface streaks observed in the experiments [*Melville et al.*, 1998; *Thorpe et al.*, 1994].

Discussion

The simulated flow field, which is maintained by applying a constant shear stress on the water surface, may not be identical to the actual flow of water driven by the boundary forcing of a developing wind field. The focus of the simulation, however, is on the inception and initial development of the coherent surface signatures, which occur within a few seconds [*Melville et al.*, 1998; *Woodcock*, 1941] as well as on the possible underlying generation mechanisms. For such purposes, the present free-surface flow driven by a constant surface shear should be sufficient. It would, nevertheless, be invalid to describe the longer-term evolution of an actual wind-driven flow. In fact, as we have discussed, the present numerical simulation results reproduce all the surface features observed in the experiments.

It is found from our simulation results that the mean near-surface current exhibits a two-layer (linear viscous sublayer and logarithmic buffer layer) velocity profile, analogous to that of a turbulent wall layer. The high-speed streaks are within the viscous sublayer and undergo a self-sustaining process. Similar to the wall-bounded turbulence, the velocity field adjacent to a wind-blown water surface is subjected to a mean shear prescribed by wind stress. The major difference between a wind-sheared surface current and wall-bounded turbulence is that the surface-tangential fluctuating velocities are free to evolve at the water surface whereas they are not at the no-slip wall. A recent numerical study on near-wall turbulence [*Jiménez and Pinelli*, 1999], however, indicates that the presence of a no-slip wall only seems to be necessary to maintain the mean shear in the formation of velocity streaks. This finding further supports the hypothesis that both wind-sheared and wall-bounded turbulent layers share the same mechanism in forming the sublayer streaks.

The primary objective of the present numerical experiment is to demonstrate that the formation of surface streaks, particularly those with spacing of centimeters, can be independent of surface waves. The results do not imply that the mechanisms associated with the wave-current interactions are inactive in the generation process of surface streaks. The findings do, however, demonstrate the possibility that other mechanisms, similar to the ones which generate geometrically-alike low-speed streaks within a sublayer next to a no-slip wall, can also produce streaks on natural water surfaces.

In a similar numerical experiment, but for an oceanic current in the surface planetary boundary layer with a spatial scale of hundreds of meters, *McWilliams et al.* [1997] performed computations both with and without the gravity-wave effect in the generalized Craik-Leibovich equations. They found significant differences in the turbulent structures between the two cases. In particular, the longitudinal vorticity in Langmuir turbulence was found to be much stronger and more elongated than that in shear turbulence. In comparison with the present experiment, their conclusions indicate the potential that wave-current interaction process may still be the dominant mechanism in forming surface streaks on the planetary boundary layer scale.

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References

Craik, A. D. D., and S. Leibovich, A rational model for Langmuir circulations, *J. Fluid Mech.*, *73*, 401-426, 1976.

Faller, A. J., and E. A. Caponi, Laboratory studies of wind-driven Langmuir circulations, *J. Geophys. Res.*, *83*, 3617-3633, 1978.

Gemmrich, J., and L. Hasse, Small-scale surface streaming under natural conditions as effective in air-sea gas exchange, *Tellus*, *44B*, 150-159, 1992.

Jiménez, J., and A. Pinelli The autonomous cycle of near-wall turbulence, *J. Fluid Mech.*, *389*, 335-359.

Kenney, B. C., Observations of coherent bands of algae in a surface shear layer, *Limnol. Oceanogr.*, *38*, 1059-1067, 1993.

Langmuir, I., Surface motion of water induced by wind, *Science*, *87*, 119-123, 1938.

McWilliams, J. C., P. P. Sullivan, and C.-H. Moeng, Langmuir turbulence in the ocean, *J. Fluid Mech.*, *334*, 1-30, 1997.

Melville, K., R. Shear, and F. Veron, Laboratory measurements of the generation and evolution of Langmuir circulations, *J. Fluid Mech.*, *364*, 31-58, 1998.

Skyllingstad, E. D., and D. W. Denbo, An ocean large-eddy simulation of Langmuir circulations and convection in the surface mixed layer, *J. Geophys. Res.*, *100*, 8501-8522, 1995.

Tandon, A., and S. Leibovich, Simulations of three-dimensional Langmuir circulation in water of constant density, *J. Geophys. Res.*, *100*, 22,613-22,623, 1995.

Thorpe, S. A., M. S. Cure, and A. Graham, Sonar observations of Langmuir circulation and estimation of dispersion of floating particles, *J. Atmos. Oceanic Tech.*, *11*, 1273-1294, 1994.

Tsai, W.-T., A numerical study of the evolution and structure of a turbulent shear layer under a free surface, *J. Fluid Mech.*, *354*, 239-276, 1998a.

Weller, R. A., and J. F. Price, Langmuir circulation within the oceanic mixed layer, *Deep-Sea Res.*, *35*, 711-747, 1988.

Woodcock, A. H., Surface cooling and streaming in shallow fresh and salt waters, *J. Marine Res.*, *4*, 153-161, 1941.

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