Vortical motions under short wind waves

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Abstract
The flow structures under ocean wind waves are of great significance in matters relating to the near surface mixing of water, mass, heat, and momentum, and their transfer across the air-sea interface. However, there are hardly direct observations (Okuda 1982a,b,c, Banner and Peirson 1998) on structures and distribution of micro-scale vortical subsurface motions under wind waves. Our recent laboratory fluid visualizations clearly showed that vortices within top centimeter water are a consistent feature. The surface boundary layer is intermittently viscous and turbulent relating to these vortices attached to the surface. The consistent small-scale wave breaking is quantitatively observed. The surface boundary layer can be separated at different phase of short wind waves even near the short wave troughs. These surface vortices no doubt contribute greatly to the small scale mixing at the air-sea interface.

1 Introduction
The exchanges of mass, heat, and momentum between atmosphere and ocean are controlled by the air-sea boundary processes. The experiments and observations all indicate that the presence of short wind waves greatly enhances the gas and heat exchange across the air-sea interface. However, since the wave motion itself is not that efficient in mixing before wave breaking at high wind, the mixing mechanism is not well understood. The vortical flow motion immediately under the surface is capable of enhancing mixing at sea. It is critical to observe flow structures near the water surface.

From IR studies of ocean cool skin layer, McAlister (1964) suggested that within this boundary layer there must be a conductive sub-layer. The existence of a conductive sub-layer also implies a viscous sub-layer of momentum transport by the molecular process. The averaged profiles of velocity in the top millimeter of water were found from cine photographs of clouds of microscopic hydrogen bubble tracers (McLeish and Putland 1975). The viscous sublayer was found considerably thinner than a solid boundary. The flow structures under wavy surface were studied by Okuda (1982a, 1982b, 1982c) from the observation of flow distorted hydrogen bubble lines. The viscous sub-layer is further carefully measured by PIV techniques (Banner and Peirson 1998). The superior PIV method can overcome bias from the bubble measurements. This study here with particle imaging of high seeding density enable us to visualize and quantify the entire components of boundary structures, waves, viscous layer, vortices, surface separations, and small-scale wave breaking.

2 Experiment set-up
A wind wave experiment is carried out at the wind wave facility of Scripps Institution of Oceanography examining the flow structures immediately below a wind blow wavy water surface. The wind tank is closed at the top and has a width, depth and length of 2.4m, 2.4m and 44m respectively. The channel is filled with fresh water to a depth of 1.2m. The tank size and wind fetch are much bigger than those of early surface layer observations. More details on the structure of the channel, wind speed profiles, and short wave distributions can be found in Zhang (1994 and 1995).
To observe the flow motions, a vertical water section along the wave direction is illuminate from below by a sheet of light (about 2mm thin) from a diode array laser (Cox and Zhang 1997). A highly sensitive CCD camera focused on the 6x6 cm$^2$ water surface section from a window of side-wall at about a fetch of 24m. The camera is tilted upward 10° to avoid imaging interference from the near field wavy surface. The water is seeded with minute particles (particle size is around 10 µm and seeding density is about 300 particles/cm$^3$). The subsurface flow motion is revealed by the trajectories of particles within the section lighted by the laser light sheet. The light sheet is pulsed at 1 to 10 ms in our experiments. The flow speed in the water varies from about 90 cm/s at high wave crests down to a few cm/s away from surface, which is difficult to be measured at any single fixed pulsing rate.

More than 400 particle images are collected at each of wind speeds with different light pulsing sequences. An example of particle image is shown in figure 1. All the image data acquired in the experiments are under steady wind wave conditions. The motion of the flow is marked by the trajectories of particles. In comparison with other early observations, one of superior advantages of such a high seeding density and pulsing sequences is that the detailed streamlines are visible showing flow spatial micro-structures as a whole. The flow velocity can be estimated from the direction and length of particle trace on the images knowing the light pulse length. However, it has to be very careful in these measurements. The particles can move in and out of the light sheet during the exposure pulses. In order to reduce this ambiguity, for example, three consequent light pulses of 1ms, 10 ms and 1ms, of 1ms apart, can be given in each of camera exposures. For a particle moving within the light sheet during the exposure, it leaves a dot-line-dot pattern. Otherwise, only part of the pattern is shown, and velocity is still can be measured if there is a dot-line or line-dot pattern. The time interval between the dot and line is 1ms. Since the orbital motion of waves is dominant, there is little difficulty in distinguishing between dot-line and line-dot patterns for the direction of the flow. When flow is slow, the interval of pulses has to be increased to separate pulse images.
3 Wave motions

Orbital wave motions are the dominant first order phenomenon. On the water surface, flow velocity appears differently in direction from the flow immediately below due to the existence of the surface boundary layer. The surface orbital velocities of the wind wave motions are measured immediately below surface boundary layer, and are shown in figure 2. For a progressive sinusoidal water wave, a water particle moves in a circle at the free surface. As the amplitude increases, the circle is opened indicating a slow Stokes drift. Water particles move forward faster near the crests and move backward slower near the trough. Over a whole period of a wave, the water particle is drifted forward due to the asymmetry of the orbital velocity. Characteristically, measured wind waves are resembled to the theoretical one. The measurements are taken from succeeding waves, which can vary in wave heights. The maximum surface slope of dominant wind waves is around 20°.

4 Surface shear layer

With a 1024x1024 pixel CCD chip, our camera can spatially resolve into the sub-millimeter scale which comparable with thickness of the viscous wind shear layer. The surface boundary structures can be clearly seen from the picture data. At not very high wind speeds, the surface boundary layer is intermittently viscous shear and vortex-turbulent patches.

The viscous shear is direct result of local tangential wind stress, or the difference in local wind speed and wave orbital velocity. There are a few attempts of measuring tangential stress on the backward face of short wind waves aimed at wind forcing mechanism. These results are somewhat in disagreement with each other. In our observation from the images (at a much longer wind fetch...
than Okuda 1982a,b,c, Banner and Peirson 1998), the drift speed varies a lot on different wavelets (more than a order magnitude). The variations in boundary layer further infer a strong spatial and temporal variation in the surface wave motions and air flow structures. Figure 3 shows the tangential surface drift speed verse the surface orbital speed on different phase of waves under different wind conditions. This ratio is a very accurate estimation in a sense that it depends only on the measured directions of particle trajectories at the surface and below the surface, and surface slope rather than the length of the particle trajectories.

There is a tendency that minute particles attach the surface if they are getting close enough to the surface. To ensure that particles that we used for measuring surface speed are on the surface, we only chose those particles have a cluster of surrounding surface particles with the same speeds. The surface viscous drift current can be as large as wave orbital velocity, which is very significant. On the average, the drift is proportional to the wave orbital velocity regardless the phase of the waves. The viscous boundary layer is in an order of a half millimeter; thus the surface tangential stress can be roughly estimated from the surface drift. The mean viscous wind drift and wave orbital drift at different wind speeds are shown in figure 4. The total drift is an about 2.5% of wind speed which is lower the 3.5% measured by Wu (1968).

Figure 3 The viscous surface drift verses the dominant wave phase. (a) a wave profile. (b), (c), (d), (e), and (f) are the viscous surface drift normalized by the phase speed at the wind speeds of 4.0 m/s, 5.1 m/s, 6.3 m/s, 7.6 m/s, and 8.5 m/s respectively.

Figure 4 Surface drifts at different wind speeds. The symbols of +, o, and * denote wave, viscous, and total drift respectively. The turbulent surface component is not included here.
5 Observed vortices in the surface layer

Vortices of size of a half-centimeter or so can be frequently seen in the top two centimeters surface layer. Near the troughs, the wave orbital motions are relatively weak, and the motions of vortices are at the same order of magnitude. There, the motions of vortices can be easily visualized (figure 5). There are vortices attached to the free surface being observed near the wave troughs. However, the wave motions are much stronger than the motions of vortices elsewhere. The vortical motions can still be identified from the local distortion of streamlines of wave motions, as it is shown in figure 1, the wiggled stream lines under surface at forward face (left).

Even at low wind speeds, the well defined surface viscous shear layer can be disrupted by those vortices attached to the free surface. Vortices can be observed either as isolated single or double vortices or as a vortex patch. There is usually some smaller scale turbulence wakes around vortex patches. The size of the individual vortices is around 0.5 cm, and does not change with wind speeds. At high wind speeds, both the number of vortex patches and the number of vortices in a patch increase. In some cases, the vortices in a patch all attached to the free surface, forming a street of vortices as a vortex-turbulent boundary layer about only one centimeter or less thick. When a patch partially attached to the surface, the patch extends into the flow at an angle from vertical to the windward. The angle can be 0° to 90°. The angle may indicate where the vortices separated from the surface, since they are advected under the orbital velocity of waves.

Figure 5 Near surface vortices under a wave trough. Wind is at a speed 8.5 m/s to the left.

Figure 6. Vortex distributions. (a) vorticity distribution. (b) size distribution.
6 Small-scale short wave breaking

Large-scale ocean wave breaking revealed as whitecaps is generally known to be rather infrequent. In the meantime, the concept of small-scale breaking without air entrainment was proposed (Banner and Phillips 1974; Phillips and Banner 1974) but has not attracted its proper share of attention. It is believed some of the spiky features of radar sea return and surface temperature features are closely associated with the small-scale breaking. The wave breaks near the wave crest when its fluid elements are moving forward faster than the propagation phase speed and tumbling on the forward phase forming a local steep slope near the crest. In the existence of surface wind drift, the speed of the top thin surface boundary layer can be considerably fast than the orbital velocity. Thus the small-scale breaking can be induced before the wave gets to the limiting form. Figure 7 shows an image of such very small-scale breaking. The surface speed is very close to the phase speed that was estimated from the wind wave spectral peak through the linear dispersion relation. The nonlinear wave speed is a little less than linear phase speed. However, the orbital velocity immediately below the surface is considerably less than the surface speed. Without the surface drift, the surface flow will not be separated from the wave profile. The surface drift near the wave crest is stronger and approximately proportional to the wave orbital velocity (reference to a fixed observer) due to the orbital convergence. The small-scale breaking is consistently observed at low wind speed as it is shown here. There is no visible large-scale wave breaking at this wind speed.

Figure 7 An example of small-scale wave breaking at a wind speed of 5.1 m/s. The moving surface is indicated by brighter particle trajectories of dot-line pattern. Velocity near the surface is given in numbers normalized by the wave phase speed.
The breaking process is more complicated due to the existence of the parasitic capillaries on the forward phase closed to the crest. The first few wavelets of parasitic capillaries are steep and the wave length is about a half cm. They are all involved and then destroyed in the process. The last few shorter parasitic capillaries at the end parasitic patch, about 2 cm of wave length, can prevail in the process, and, most unlikely, they were dynamically involved. A time sequence of surface feature change during a small-scale breaking event is shown in the figure 8. The whole breaking process happened in about only 1/10 sec. The irregular three dimensionality of the parasitic capillaries was first developed. Then, the first couple of capillaries were overtaken by the breaking turbulent patch. The turbulent patch, featured as a rough surface pattern, tumbles forward near the phase speed. Gradually, it detached from the surface and a capillary wave train was building up again.

7 Discussions and Conclusions
Okuda (1982) reported the most detailed study so far on internal flow structures under very short fetch wind waves with the use of hydrogen bubble line and strobe lights. Our technique of high particle seeding and long-short light pulses is extremely efficient in capturing the whole picture of flow spatial structures of water motions under the surface, which differs from the early wind wave observations. The wave and non-wave motions are effectively separated. The wind wave drift and viscous drift are, for the first time being separated, about 1% and 1.5% of wind speed. The sum is less than the early measurements (Wu 1968) which we contribute to the better particle tracers and excluding of turbulent drift. Coherent structures, such as small-scale vortices in the top surface layer and small-scale wave breaking, are observed.

The vortices near the surface that uncovered in the experiments have not been reported in any early wind wave experiments to the best of our knowledge. It is no doubt these vortical motions play an
important rule of enhancing surface mixing in wind wave environments. There is a much intense mixing in the top 2 cm water layer in the wind wave tanks. Our camera imaging speed is currently unable us to trace the vortices in time and pin point the sources of these vortices. Based on the vortex size distribution, there are a few of possible surface mechanisms that capable of generating these vortices: 1) steep ripples with high surface curvature, such as parasitic ripples (Longuet-Higgins 1992), 2) small-scale wave breaking induced by surface share (Banner and Phillips 1974), 3) surface boundary share layer separations, and 4) Reynolds ridge of surface films.

Early study of airflow separation (Banner and Melville 1976) indicated that form drag was an important contribution to the flux of momentum between the airflow and the surface waves. About the same time, Okuda et al (1977) conducted a surface boundary layer experiments through visualization hydrogen bubble lines. It was concluded that the wind stress was predominantly supported by the skin friction at a short fetch. A future experiment study with PIV (Banner and Peirson 1995, 1998) shown that tangential stress in the aqueous viscous sub-layer does not account for the entire wind stress in the presence of large-scale waves. Our study here revealed the intermittent viscous shear and vortical patch spatial structure in the top water boundary. In the viscous shear part surface, the surface tangential draft can change by an order of magnitude, which partly conforms the recent PIV observations, although at a quite different wind fetch. Our imaging area is bigger which limited for the accurate stress estimation. Beside the variation in the air flow, the large variation in surface drift is the result of a constant surface breaking down. The aqueous viscous sub-layer is in a dynamic equilibrium of building up and breaking down. The weak phase dependency of surface drift normalized by the orbital velocity can be well explained by the surface drift kinematics equation governed by wind viscous stress and orbital wave motion (see eq. 2.5 in Phillips and Banner 1974).

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