Surface waves and spatially coherent structures in the near-surface layer of the ocean

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Introduction

Spatially coherent organized structures have been recognized as an important part of turbulent boundary layer processes. Langmuir cells and ramp-like structures are believed to transfer an appreciable portion of the momentum, heat, pollutants (e.g., oil), and other substances in the upper layer of the ocean. Presence of the free surface significantly complicates the analysis of turbulent exchanges at the air-sea interface. The coherent structures are not yet completely understood.

A schematic diagram of Langmuir circulation is shown in Figure 1. Langmuir cells are parallel and oriented nearly downwind with alternating longitudinal vorticity, producing convergence and divergence zones. The convergence zones are substantially narrower than the divergence zones. The spacing between the Langmuir vortices ranges from a few meters to a few hundred meters (Pollard, 1977).

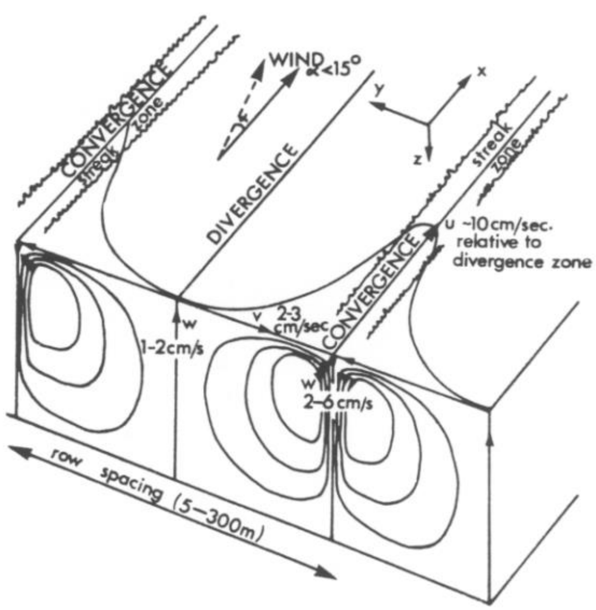

Figure 1. Pollard’s (1977) sketch of Langmuir circulations.

Langmuir circulation can be seen on the sea surface due to collection of flotsam or foam from breaking waves in convergence zones. In Figure 2, Langmuir cells are visualized by an oil spill (Fig. 2a) and foam from breaking waves (Fig. 2b). For developed seas, direction of wind, wave, and Langmuir cells is practically the same. In general, however, they do not necessarily coincide. In the two cases shown in Figure 2, the direction of Langmuir cells is different from the wave direction.

(a)

(b)

Figure 2. Direction of Langmuir cells does not always coincide with wave direction: (a) http://www.nwfdailynews.com; (b) http://www.esoxhunter.com/WalleyeWind.php#eighth

The atmospheric boundary layer above the ground exhibits spatially coherent organized motions in the form of "ramps" (Antonia et al. 1979; Phong-Anant et al. 1980). Ramp-like structures are believed to be a wide spread feature in the upper ocean as well and have been found in the upper layer of the ocean under both stable (Thorpe and Hall 1987) and unstable (Soloviev 1990) stratification. Figure 3 illustrates schematics of ramp-like structures during unstable stratification in the upper layer of the ocean.

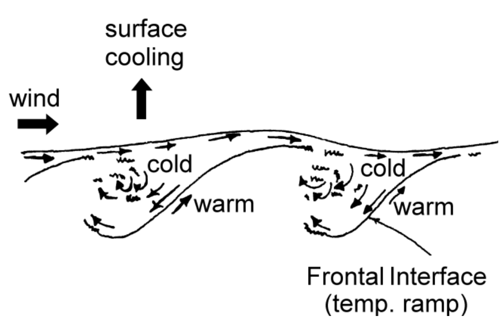

Figure 3. Schematic diagram showing ramp-like structure during nighttime conditions (After Soloviev, 1990).

Wijesekera et al (1999) collected large statistics on ramp-like structures during TOGA COARE (Fig. 4a). These data suggested that the direction of frontal interfaces produced by ramp-like structures is approximately perpendicular to wind direction (Fig. 4b). According to the field study performed by Thorpe et al. (2003) using an autonomous underwater vehicle, both types of coherent structures could coexist. Vortices associated with ramp-like structures have transverse axes, while Langmuir circulations have longitudinal axes, relative to the wind direction. How can two organized motions with perpendicular axis coexist in 3D space?

(a) (b)

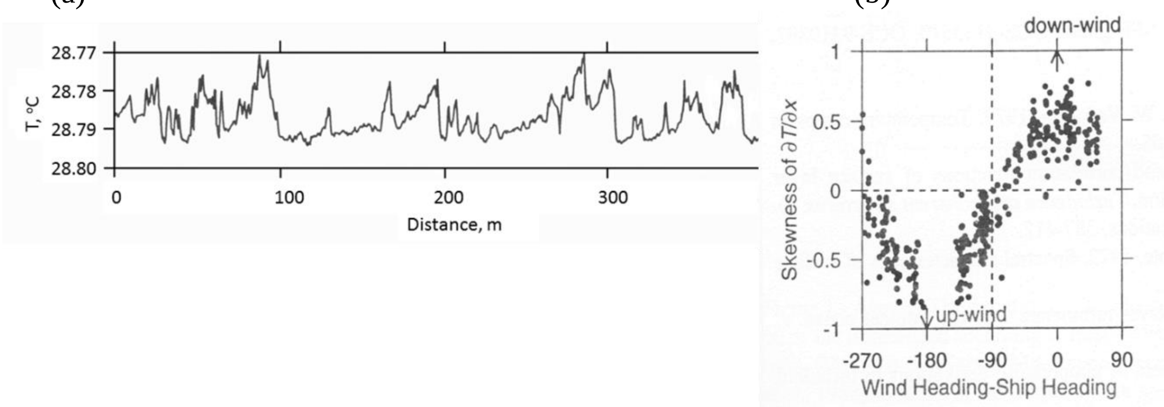

Figure 4. A horizontal temperature profile observed at 2 m during the night of December 31, 1992 from the R/V *Wecoma* moving downwind at 4 m s^{-1}. Wind stress (westerly) is about 0.1 N m^{-2}, net surface cooling about 250 W m^{-2}, the stability parameter, $|z_s|/L_O = -0.1$, where L_O is the Oboukhov length scale, and average bow sensor depth $|z_s| = 2$ m. (After Wijesekera et al. 1999.)

Wave breaking is a powerful mechanism producing significant energy flux to small scale turbulence. Benilov and Ly (2002) conditionally divided the upper ocean turbulent boundary layer into the following three sublayers (Fig. 5):

1. *The wave-stirred layer (a layer of intense mixing by breaking waves).* The turbulent kinetic energy (TKE) production by wave breaking substantially exceeds the mean shear production.

2. *The turbulent diffusion layer*. The turbulent diffusion of TKE from the wave stirred layer exceeds the wave (as well as the mean shear) effect.

3. *The wall layer.* The mean shear production of turbulent energy dominates over wave breaking turbulence. A logarithmic layer can form but stratification and rotation can also be important.

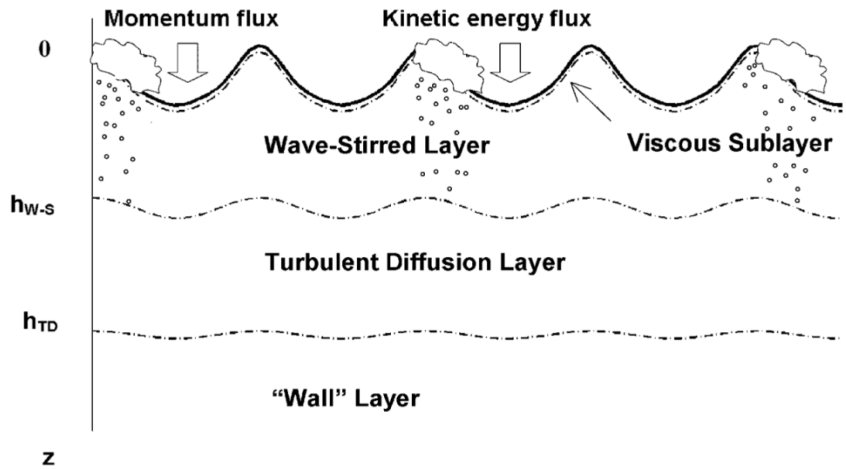

Figure 5. Structure of the upper ocean turbulent boundary layer below breaking surface waves (Soloviev and Lukas, 2014).

Figure 6 summarizes the results of field and theoretical studies of wave-breaking turbulence. In Figure 6, only the data obtained during high wind speeds are presented in order to minimize the influence of thermohaline stratification effects on near-surface turbulence characteristics. Most of the turbulent energy dissipation takes place within one significant wave height, while the turbulent diffusion layer extends to approximately ten significant wave heights.

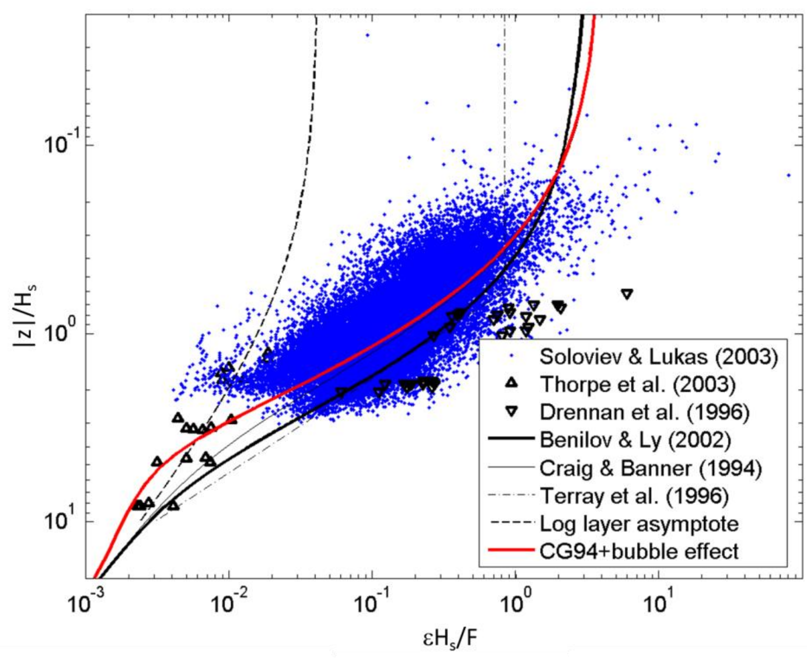

Figure 6. Turbulence dissipation in the upper ocean. Normalized dissipation rate $\varepsilon H_s/F$ versus dimensionless depth $|z|/H_s$ according to field and theoretical results. Here ε is the dissipation rate of the TKE, F the flux of the kinetic energy from wind to waves, and H_s is the significant wave height. Wind speed range is from 7 to 19 m s^{-1}. (After Soloviev and Lukas, 2014).

Modeling Langmuir circulation and ramp-like structures

Large eddy simulation (LES) models of Langmuir circulation are now very sophisticated but still pose some questions (Soloviev and Lukas, 2014). From the basic principles of nonlinear dissipative systems, the process of self-organization reduces chaos and dissipation in the system and increases the effectiveness of property transport. In contrast, existing LES models of Langmuir circulation demonstrate significant increase of turbulent dissipation. Also, the traditional models of Langmuir circulation do not account for ramp-like structures, which are widespread features in the upper ocean turbulent boundary layer.

In traditional models, Langmuir circulation is driven by the vortex force due to Stokes drift (Craik and Lebovich, 1976):

$$F_v \sim u_s du / dz \tag{1}$$

where u_s is the Stokes drift and u is the horizontal velocity component. Due to wave stirring, the near surface layer becomes almost homogeneous, like a "slab" layer (Fig. 7). As a result,

$$du / dz \to 0 . \tag{2}$$

Thus, the vortex force F_v may vanish in that layer due to wave-breaking mixing.

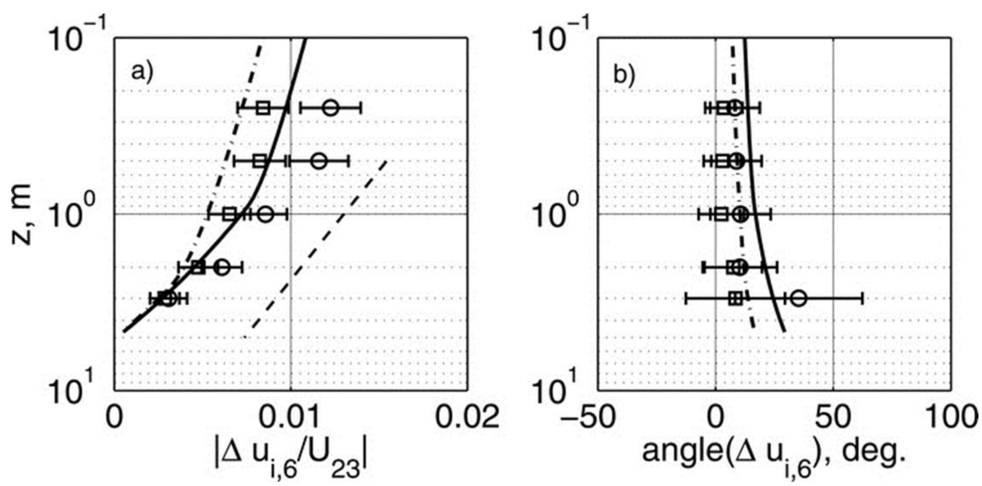

Figure 7. The near-surface ocean is almost uniform below breaking waves. The velocity gradients beneath the surface are found to be 2 to 5 times weaker than in the "wall" boundary and the near-surface ocean is almost uniform due to wave-breaking stirring. Mean profiles of (a) magnitude and (b) direction of relative current velocity with respect to a 5-m depth $\Delta u_{j,6}$ normalized by wind speed in the wind speed ranges U^{23} from 4 to 8 m s^{-1} (open circles) and from 8 to 12 m s^{-1} (open squares). Dashed line indicates log layer velocity profile. (After Kudryavtsev et al., 2008.)

Li et al. (2013) simulated the observations collected at the Martha's Vineyard Coastal Observatory's Air-Sea Interaction Tower during the CBLAST experiment in 2003 (Fig. 8) using an LES model. The model showed that breaking waves dominated turbulence generation near the ocean surface over the Stokes term production. In fact, diagnostic analysis of the TKE budget in the model of Li et al. (2013) shows a dominant balance between turbulent transport and dissipation near the surface and a dominant balance between shear production and dissipation at deeper depths. Although the Stokes production is a significant term in the TKE budget balance near the surface, it is smaller than shear production. Langmuir circulation could develop deeper in the water column; though, according to Figure 8, the Stokes production is much smaller than shear production and dissipation term also below the wave stirred layer. It is therefore not obvious that large eddies reproduced by this LES model below the layer of wave breaking turbulence were driven by Stokes drift.

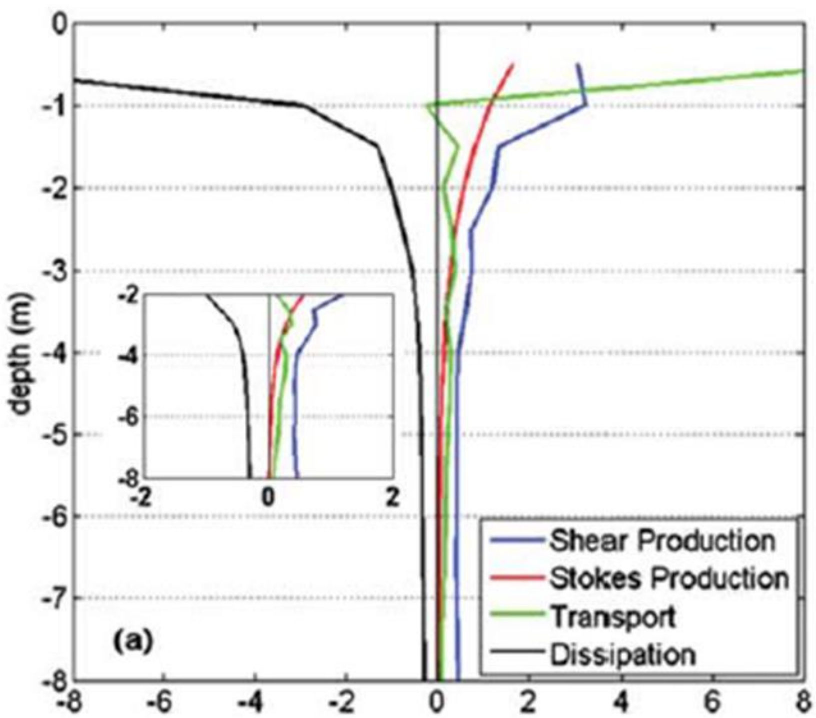

Figure 8. Comparison of TKE budget terms including wave breaking and Langmuir circulation (Li et al., 2013).

How can Langmuir circulation exist under breaking waves? In this work we consider a new mechanism for creation of Langmuir cells and ramp-like structures, which can help to address this question. Based on the analysis of the turbulence and Stokes production terms, we have found that in certain conditions the Stokes drift may not be the main driving mechanism for Langmuir circulation.

We have completely eliminated the Stokes drift from the LES model but added injection of mixing due to wave breaking in the near surface layer of the ocean (Fig. 9). The model is able to reproduce both Langmuir cells and ramp-like structures coexisting in space though intermittent in time. This model does not require the Stokes drift term and thus is not locked to the wave direction. It may explain the observations similar to those shown in Figure 2 when the Langmuir cell direction does not coincide with the wave propagation direction.

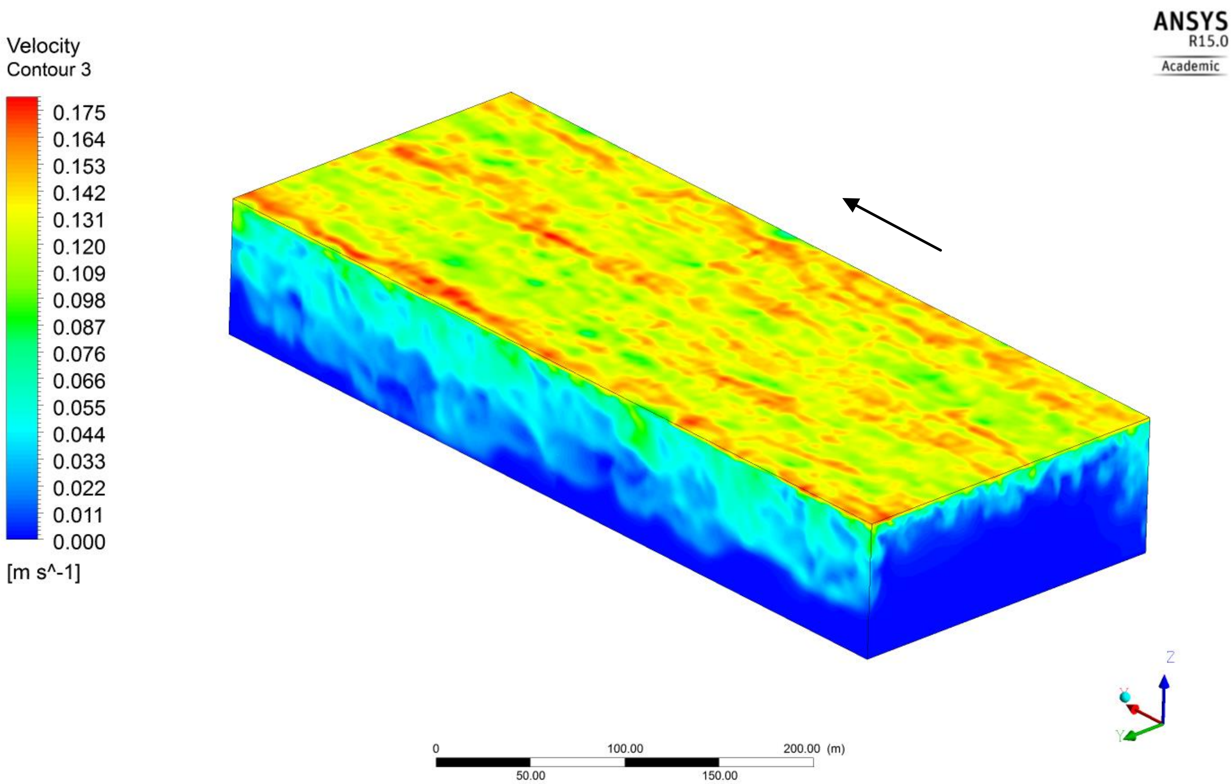

Figure 9. Langmuir circulation and ramp-like structures reproduced by accounting for mixing due to wave-breaking turbulence in the near-surface layer of the ocean. Langmuir cells and ramp-like structures coexist in space, but are intermittent in time. The numerical domain is 500 m long, 200 m wide and 80 m deep. The vertical resolution of the mesh near the surface is 0.1 m, gradually increasing with depth. A periodic boundary condition is set along the tank. A 0.1 N m^{-2} wind stress (indicated by a vector) was applied to the top of the domain and was equivalent to approximately 8 m s^{-1} wind speed at a 10 m height.

The proposed model of Langmuir circulation may compete with that of Craik and Leibovich (1976) within a certain range of depths and wind/wave conditions (in particular, under high wind speed conditions when the vortex force term including Stokes drift can be suppressed due to strong near-surface turbulence).

Discussion

A plausible mechanism for the generation of ramp-like structures in the near-surface layer of the ocean has been proposed by Soloviev and Lukas (2014). It is based on the analysis of ramp-like structures in the atmospheric boundary layer over the ground by Smith and Walker (1997) and McNaughton and Brunet (2002).

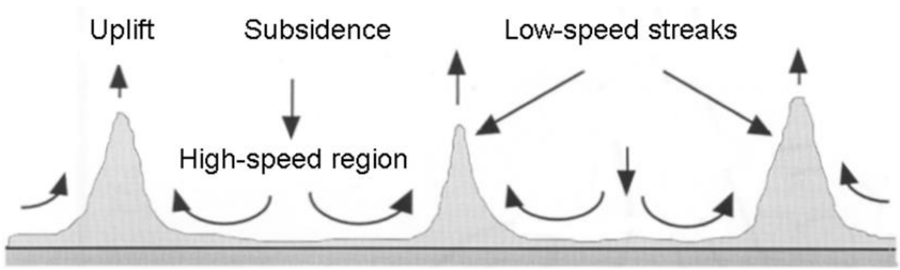

Figure 10. Schematic cross-flow section of the low-speed streaks near the ground (Smith and Walker, 1997).

Townsend (1961) divided the near-wall turbulence into the active part (transporting momentum) and the inactive part (not transporting momentum). According to McNaughton and Brunet (2002) inactive motions could initiate active, coherent ejection motions, which carry much of the momentum. These authors concluded that the inactive motions take the form of streak patterns of faster and slower air (Fig. 10), and the streaks are aligned with the surface wind. The narrow convergence lines of uplifted, slower air are formed due to the high-speed streams of subsiding and laterally spreading air.

“The difference in speeds of the various parts of the flow thus creates convergence zones where the high-speed streams overtake the slower moving streaks. In each of these zones, the faster air stream at first simply passes about the slower streak, creating a zone of strong shear between the faster and slower air streams. The velocity profile along normals to this interface is strongly inflected, forming a classic source of instability in the flow. It initiates a series of transverse roll vortices, just as similar inflections do in plane mixing layers, but here the roll vortices are draped across the spine of the engulfed streak. These vortices describe gentle arcs where the streak is low and board, but become croissant- or horseshoe vortices over taller, more upright parts of streaks. Well-formed horseshoe vortices can then assume a life of their own, continuing to grow by taking vorticity and turbulent kinetic energy (TKE) from the mean flow itself. The mean shear also rotates these coherent vortices forward until, by a combination of growth and rotation, they contact the ground to form a dam with strong inflows along the ground produced by the rotation of the vortex arms and the main flow presenting pressing in from behind. With nowhere else to go, the trapped air squirts backward and outward into the flow. This squirt is usually described as an ejection/sweep event." (Soloviev and Lukas 2014.)

Figure 11a illustrates a schematic of the first ejection formation on a streak. McNaughton and Brunet's mechanism is consistent with a wide range of results from laboratory and atmospheric boundary-layer experiments.

(a) (b)

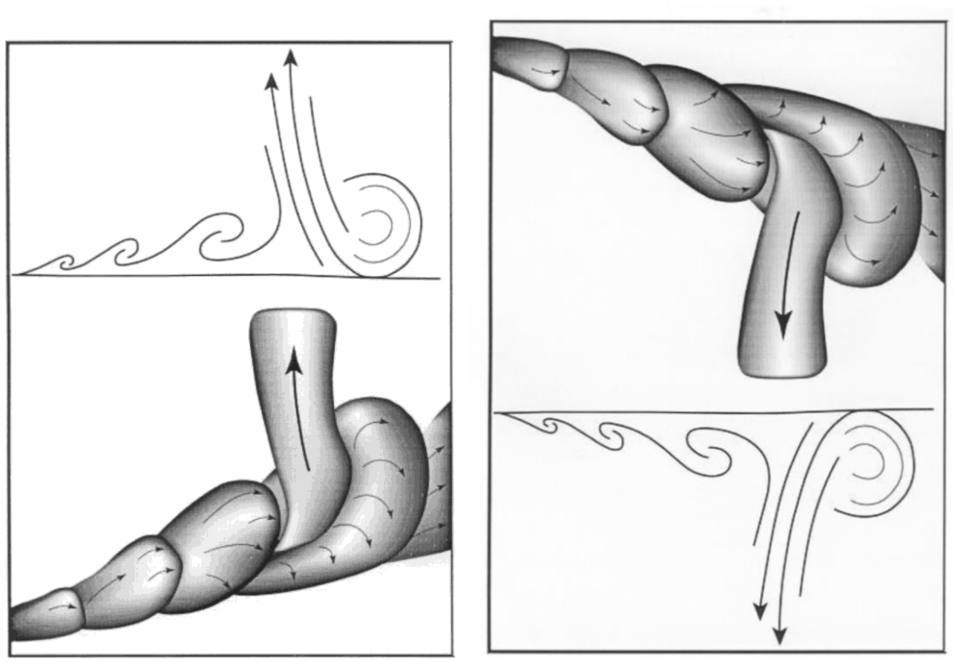

Figure 11. (a) The vortices lying across the spine of the streak take on a 'horseshoe' or 'hairpin' shape and can grow to the point where they contact the ground and cause a vigorous ejection of fluid (McNaughton and Brunet, 2002). The "hairpin" shape initiates a pair of counter rotating vertical vortices when touches the ground. (b) In application to the near-surface layer of the ocean, a pair of counter rotating vertical vortices is formed when the "hairpin" shape touches the sea surface, from below.

Soloviev and Lukas (2014) analyzed the effect of a similar pattern but developing from the water side of the air-sea interface. In the same way, a pair of counter rotating vertical vortices is formed when the "hairpin" shape touches the sea surface and ejects fluid from the boundary layer (Fig. 11b). The vertical vortices initiate a converging streak via the Craik-Leibovich 2 mechanism (Fig. 12). This mechanism resembles convective initiation of longitudinal rolls in the atmospheric boundary layer (Brown, 1991).

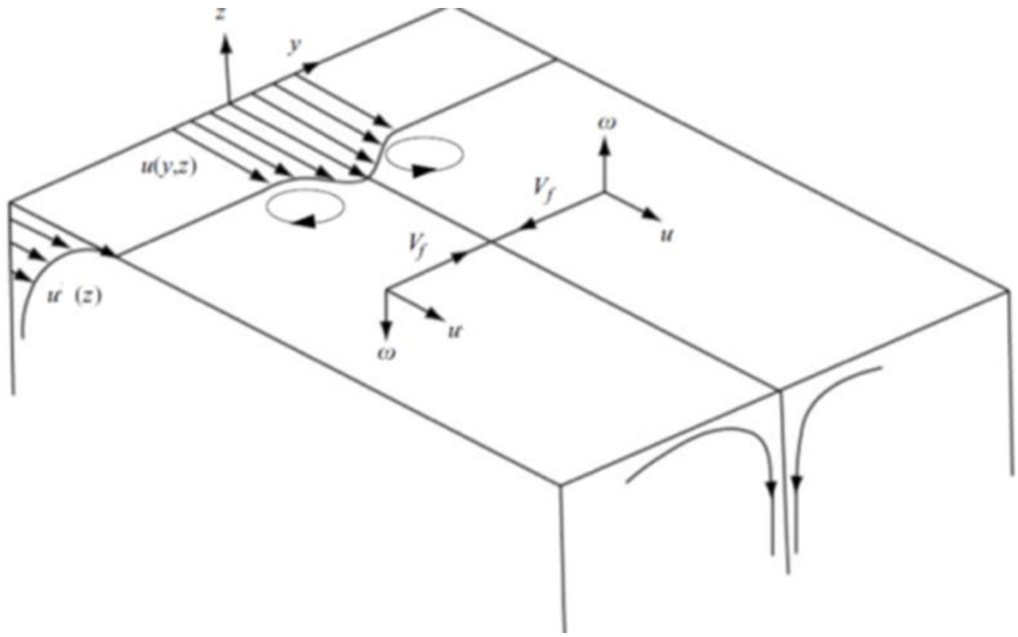

Figure 12. The vertical vortices in the near-surface layer of the ocean produced by the "hairpin" shape initiate a converging streak via the Craik-Leibovich (CL2) mechanism. Diagram adopted from Sullivan et al. (2007), though no Stokes vortex force is required.

Conclusions

We have developed a concept, which links the Langmuir circulation and ramp-like structures to wave stirring of the near-surface layer of the ocean. This mode of Langmuir circulation does not require Stokes drift and is locked to the wind (but not wave) direction. Using computational fluid dynamics LES model, we have been able to reproduce both Langmuir cells and ramp-like structures coexisting in space though intermittent in time. This mechanism for generation of Langmuir circulation may be explained with the CL2 theory but without the Stokes drift term. This is a coupled mode of Langmuir circulation and ramp-like structures. This mode can dominate over the traditional model within a certain range of wind/wave conditions (in particular, when the waves are not fully developed). The process has some resemblance to the formation of longitudinal rolls in the atmospheric boundary layer.

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