Spatially-coherent Organized Motion in the Upper Ocean Turbulent Boundary Layer: Langmuir Circulation and Ramp-like Structures

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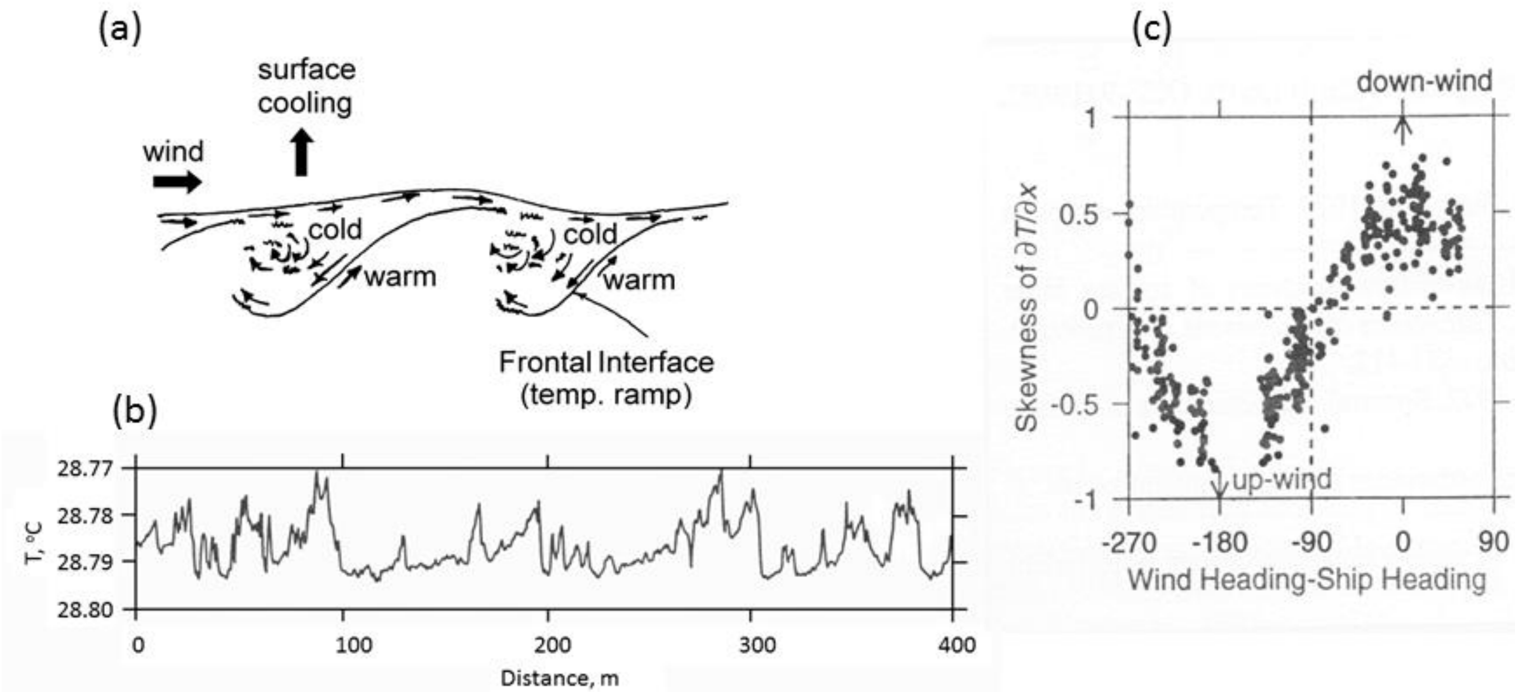
Introduction

- Presence of the free surface significantly complicates the analysis of turbulent exchanges at the air-sea interface including gas fluxes.
- In addition to turbulent motions of chaotic nature, there are also spatially coherent organized types of motion in the upper ocean turbulent boundary layer.
- These coherent structures are not yet completely understood.

Ramp-like structures

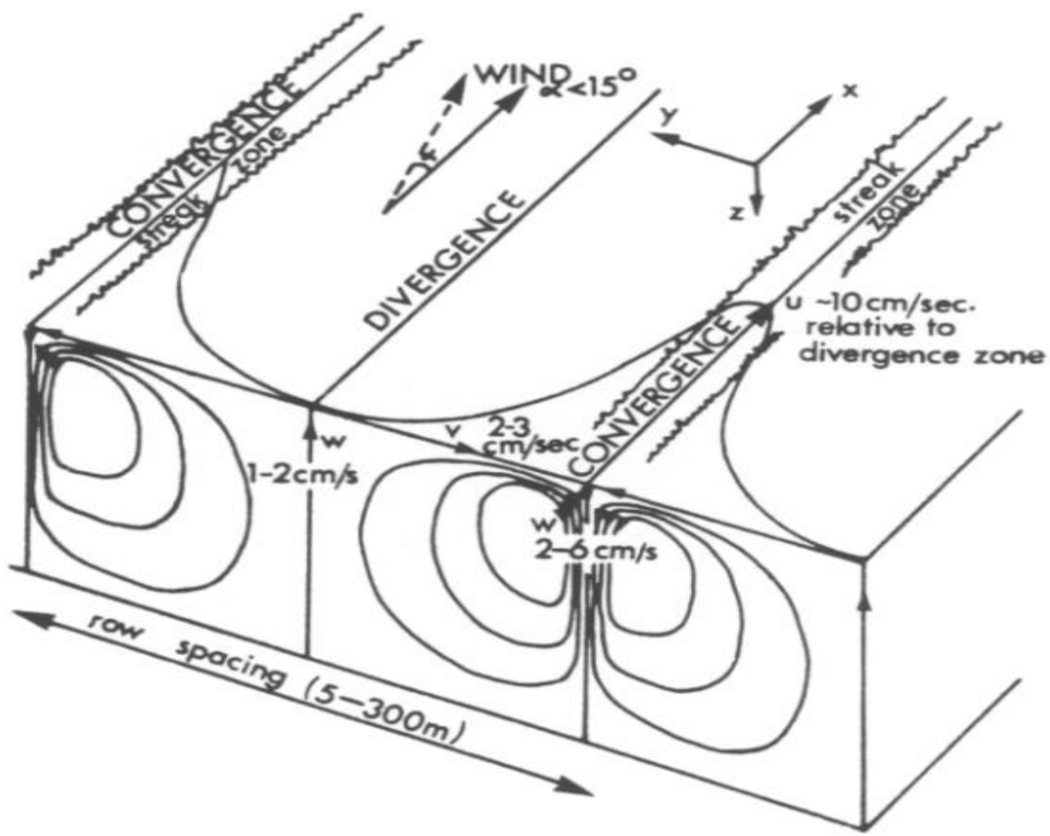


Ramp-like structures (RLS) are associated with vortices with axes approximately perpendicular to wind direction and non-zero skewness of the temperature derivative

$\mu_3(z) = \left\langle M_3(z) / M_2(z)^{3/2} \right\rangle$, where $M_3(z) = \left\langle \left(\partial T / \partial x - \langle \partial T / \partial x \rangle \right)^3 \right\rangle$, $M_2(z) = \left\langle \left(\partial T / \partial x - \langle \partial T / \partial x \rangle \right)^2 \right\rangle$

(Thorpe and Hall 1987, Soloviev 1990, Wijesekera et al. 1999.)

Langmuir circulation



Pollard's (1979) sketch of LC

In the "traditional" (Craik & Lebovich) theory, Langmuir circulation (LC) is driven by the Stokes vortex force and is oriented along the wave direction.

Langmuir circulation does not always coincide with the wave direction

Photo taken during an oil spill in the Gulf of Mexico
http://www.aolcdn.com/photogalleryassets/kol/896579/Gulf-Oil-Spill-1040sv3-061010.jpg

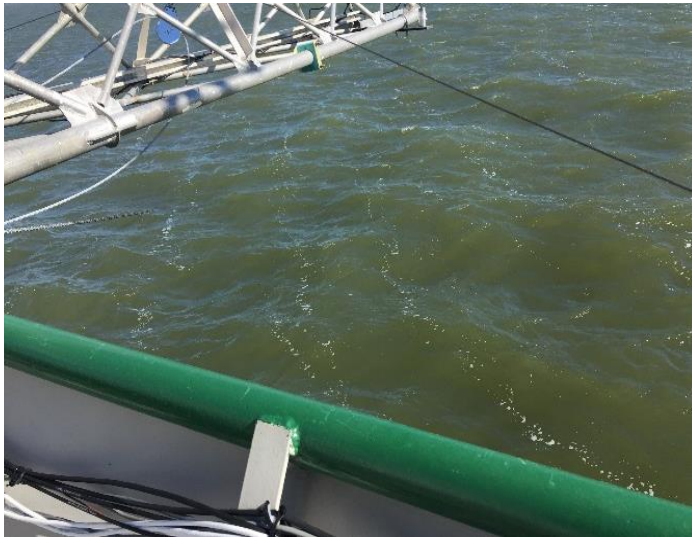
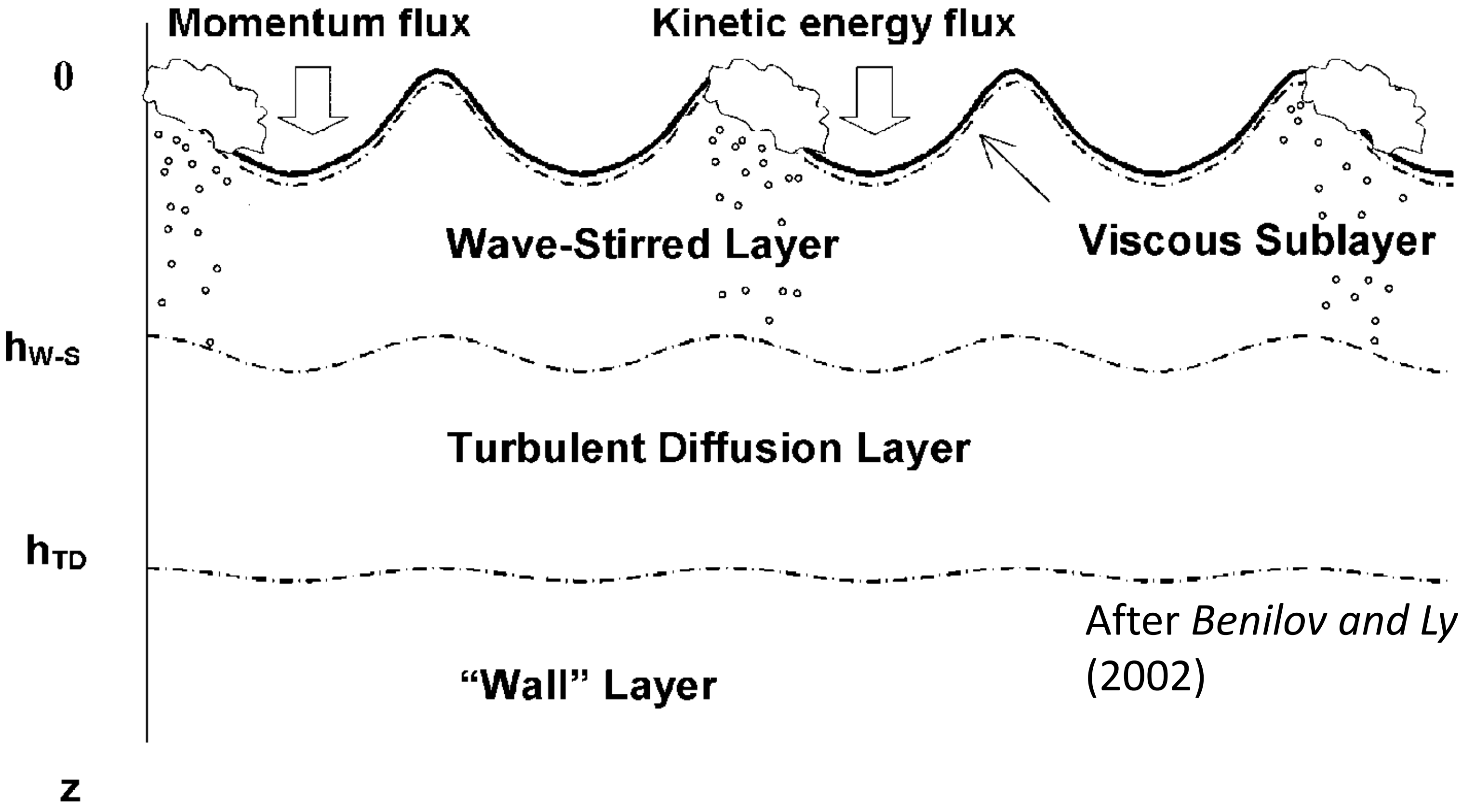


Photo taken in coastal waters of the Gulf of Mexico in February 2016 during a cruise (LASER/CARTHE) of the *R/V Walton Smith*.

Traditional (Craik & Leibovich) model of Langmuir circulation:

- **replaces free surface with a rigid lid**
- **introduces Stokes vortex force to compensate for this replacement**
- **based on an assumption of weak ambient turbulence in the upper ocean.**
- **However, the assumption of weak ambient turbulence may not work well in the presence of breaking surface waves.**

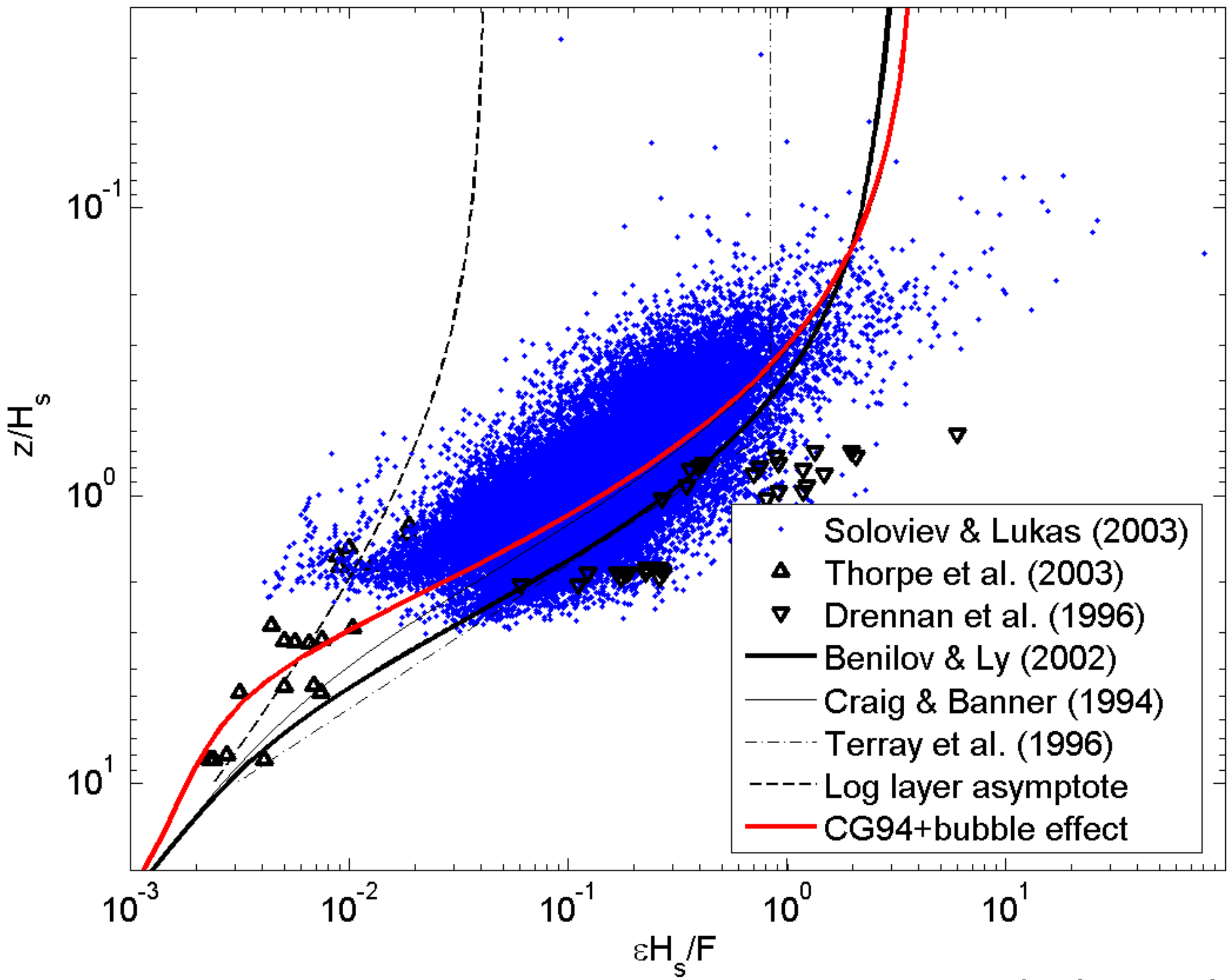
Structure of the ocean below breaking surface waves



After *Benilov and Ly* (2002)

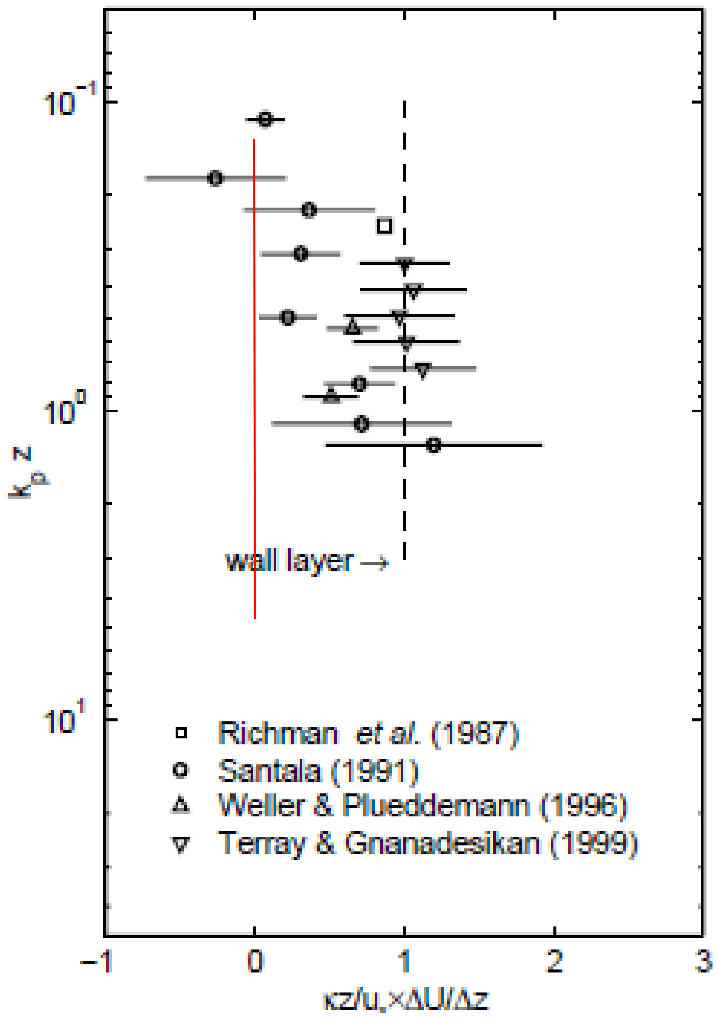
h_{TD} is on the order of 10 significant wave heights (*Terray et al*. 1996)

Turbulence below breaking waves



Soloviev and Lukas (2014)

Mean shear below breaking waves



$\Delta U/\Delta z$ - near-surface shear

z - depth

u_* - friction velocity in water

k_p - wavenumber of the dominant wave

Mean downwind shear practically vanishes below breaking waves (Terray et al. 1999, Kudryavtsev et al. 2008).

Langmuir circulation and Stokes drift

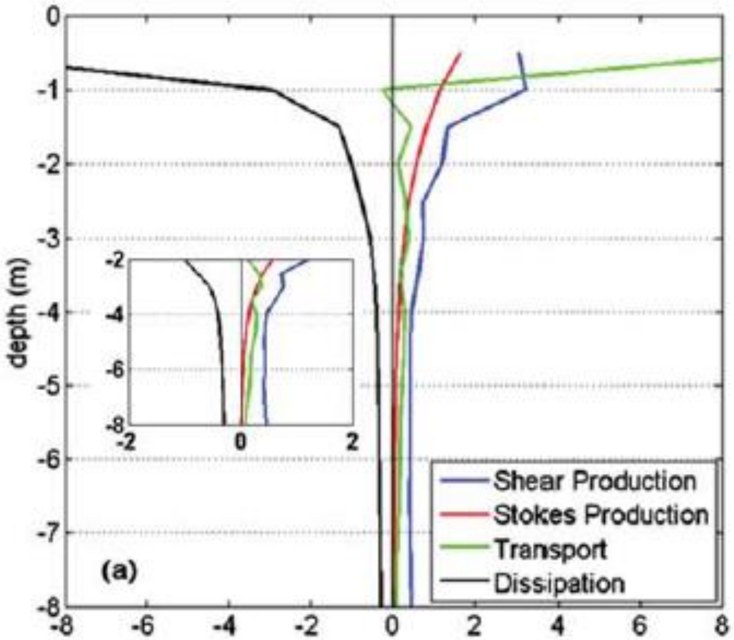
In traditional models, LC is driven by the Stokes vortex force:

$$F \sim u_s du / dz$$

Due to wave stirring, the near surface layer behaves like a “slab” layer

$$du/dz \rightarrow 0$$

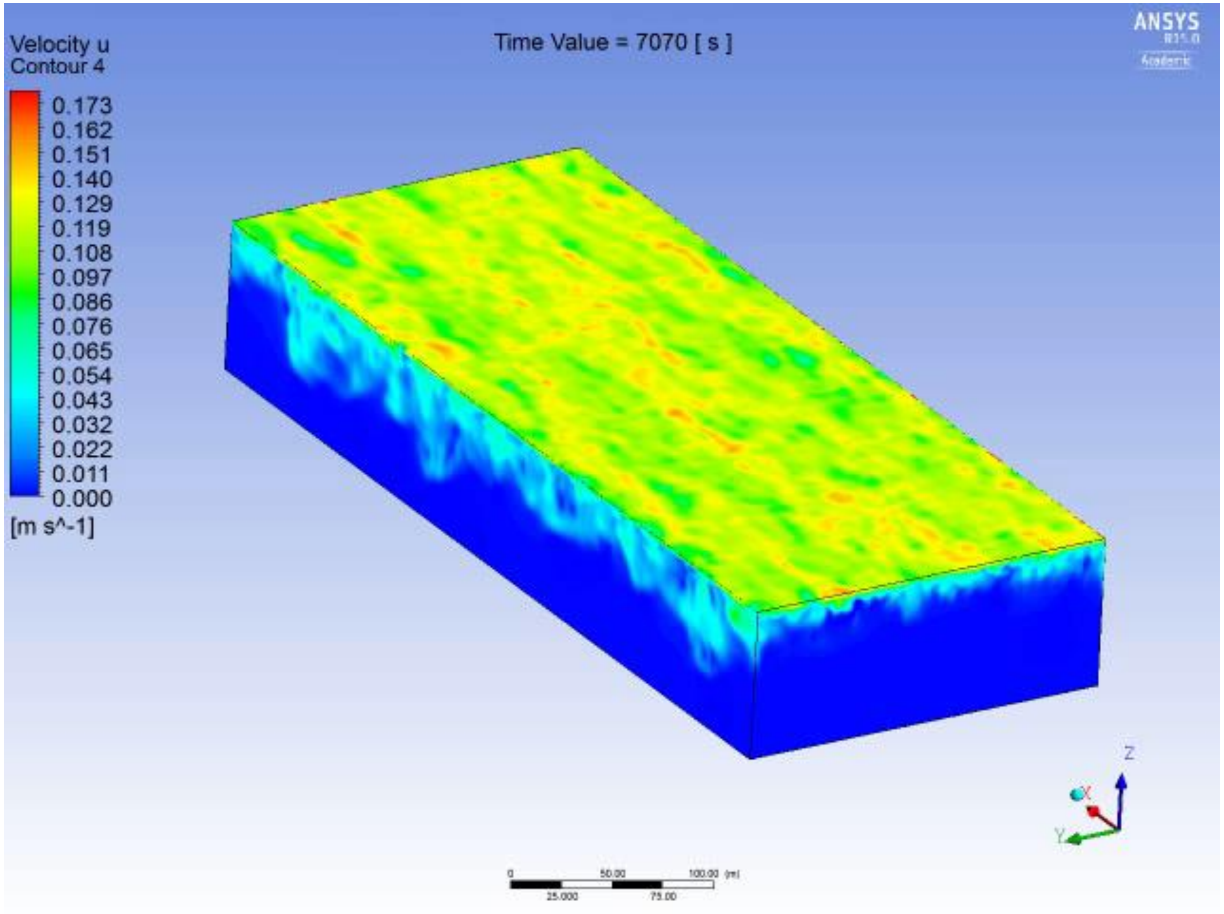
Thus, the vortex force may vanish under breaking waves (Terray, Williams III, & Brumley, private communication)



TKE budget terms by Li et al (JGR 2013):

Can LC exist under these conditions?

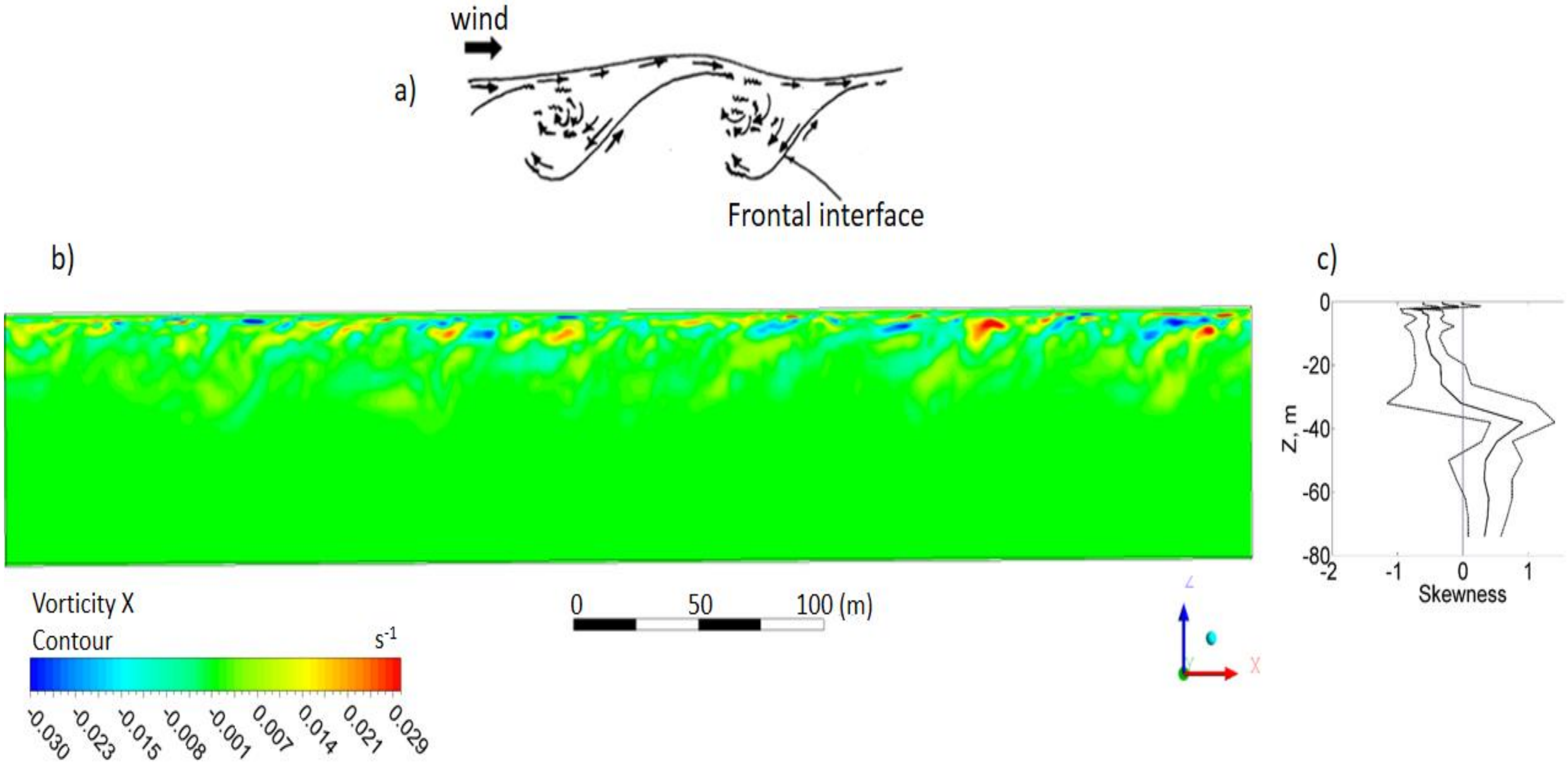
Model of Langmuir circulation and ramp-like structures



$U_{10} = 8\ ms^{-1}$

This LES model doesn't include Stokes terms; instead, the shear-free turbulence from breaking waves has been added. LC is locked to the wind (rather than wave) direction. LC and ramps coexist in space but are intermittent in time.

Coupling between the Langmuir cells and ramp-like structures



(a) Schematic diagram showing ramp-like structures. (b) Center-plane contour plot of the vorticity component along wind direction from the CFD simulation, and (c) corresponding vertical profile of the skewness coefficient (+/- one STD).

Conclusions

- We report a previously unknown mode of LC, which is coupled with RLS.
- This coupled mode is locked to the wind (but not wave) direction.
- Computational fluid dynamics model incorporating the wave-breaking turbulence has been able to reproduce both LC and RLS, coexisting in space but intermittent in time.
- Under developing seas (including high wind speed conditions), the new model can complement or compete with the traditional model of LC.

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