11.10 DEEPENING OF THE OCEAN MIXED LAYER BY LANGMUIR AND SHEAR TURBULENCE

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1. Introduction

When the wind blows across a stratified ocean, a surface mixed layer develops in which the density is approximately uniform. The lower boundary is marked by a strongly stratified transition region. In a wind-driven upper ocean, both shear turbulence and Langmuir turbulence can cause the deepening of the ocean mixed layer.

Most mixed layer models are one-dimensional and assume that the mean temperature and horizontal velocity are quasi-uniform within the layer but have a jump at the lower boundary. To close the model, the entrainment velocity at the mixed layer base is prescribed empirically in terms of the wind stress and/or the difference of the velocity and density between the mixed layer and the water below it (Niiler & Kraus 1977; Price et al. 1986). These bulk models, as well as more elaborate higher-order turbulence closure models (e.g. Mellor & Yamada 1982, Large et al. 1994), do not explicitly incorporate the key turbulent processes in the ocean surface layer that are responsible for the mixed layer deepening.

Neither is it clear if these mixed-layer models implicitly parameterise the turbulent mixing processes correctly. Although the empirical formulae developed for shear-induced deepening are based on physically-sound dimensional analysis and laboratory experiments, they were not derived from process studies of shear-driven turbulent mixing in the upper ocean. Using a 2D DNS model, Li & Garrett (1997, hereafter LG97) investigated the mixed-layer deepening due to Langmuir circulation. Langmuir cells engulf the stratified water and create a homogeneous surface layer. The mixed-layer deepening is arrested when a Froude number reaches a critical value. From the numerical results, LG97 obtained a parameterisation scheme based on a bulk Richardson number in which the maximum downwelling velocity in Langmuir circulation is the velocity scale. However, LG97's results are sensitive to the unknown eddy viscosity used in their 2D DNS model.

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In this paper we shall use a 3D LES model to investigate how wind-driven shear and Langmuir turbulence interact with a linearly stratified water and generate a surface mixed layer. As demonstrated in Li et al. (2004a), shear and Langmuir turbulence have markedly different turbulence characteristics. Langmuir turbulence has a vertical turbulence intensity twice as much as that in shear turbulence. The ordering of turbulence intensities in three directions is also different. In Langmuir turbulence, the crosswind and vertical components are of similar magnitude but both are much greater than the downwind component. In shear turbulence, however, the downwind component is the largest, followed by the crosswind and vertical components. It is thus interesting to examine how these two different types of turbulent large eddies interact with stratified fluid and cause the deepening of the surface mixed layer.

2. Model nondimensionalization

In order to obtain a parameterization scheme, we have nondimensionalized the LES equations. We have identified two controlling dimensionless parameters: (1) turbulent Langmuir number $La_t = (u_* / U_s)^{1/2}$ which is the ratio of water friction velocity to the Stokes drift velocity (McWilliams et al., 1997); (2) a Richardson number $R_{LN} = N^2 / (u_*^2 \beta^2)$ which compares the strength of stabilizing buoyancy force to the wind shear. Here u_* is the friction velocity, U_s and β are the surface velocity and e-folding depth of the Stokes drift current, N is the buoyancy frequency in stratified water. As discussed in Li et al. (2004a), Langmuir turbulence falls into a range La_t<0.7, whereas shear turbulence falls into a range La_t>0.7. We shall run the LES model for a range of buoyancy frequency or R_{LN} values. We shall compare numerical results at two different values of turbulent Langmuir number: one representing Langmuir turbulence and one representing shear turbulence.

3. Deepening of Langmuir turbulence

In the first numerical experiment, the water is linearly stratified with buoyancy frequency N=0.0032 1/s, the wind stress is 0.16 N/m^2, the surface velocity and e-folding depth of the Stokes drift current are 10.6 cm/s and 4.77 m, respectively. In nondimensional terms, this corresponds to La_t=0.34 and R_{LN}=0.35. According to Li et al. (2004a), turbulence at La_t=0.34 falls into the Langmuir regime and corresponds to a fully-developed sea state.

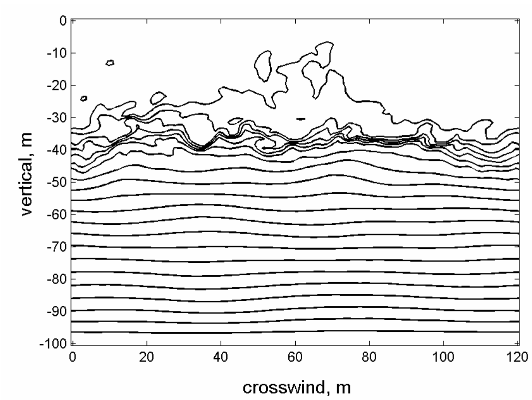

Figure 1. Temperature contours in a crosswind section, showing engulfment of stratified water into the mixed layer by upwelling plumes in Langmuir turbulence.

Figure 1 shows temperature contours in a crosswind vertical section at 4 hours after the initiation of wind and waves. Temperature becomes homogeneous in a surface layer, indicating the formation of a surface mixed layer. As shown by uplifting temperature contours, stratified water is being engulfed into the surface layer by upwelling plumes in Langmuir turbulence. Internal waves appear to be generated below the surface layer and propagate into the deeper stratified water.

In Figure 2 we plot vertical profiles of horizontally-averaged temperature at t=4, 8, 12 hours. Clearly, the surface mixed layer gets progressively deeper as Langmuir turbulence penetrates into the stratified water below. In the mean time, the density (temperature) gradient below the mixed layer increases as the mixed layer deepens. We define the mixed-layer depth to be the depth of maximum temperature gradient.

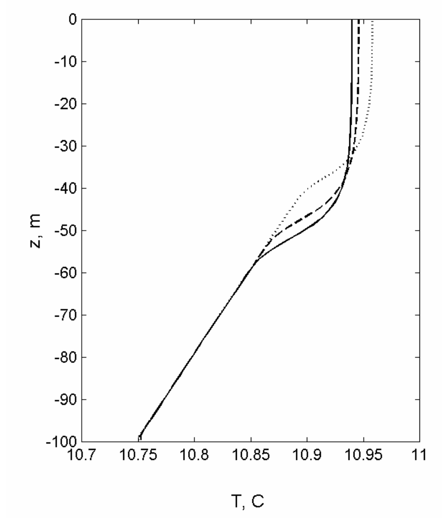

Figure 2. Vertical profiles of mean temperature at t=4 (dotted), 8 (dashed), 12 (solid) hour, showing the deepening of the mixed layer due to Langmuir turbulence.

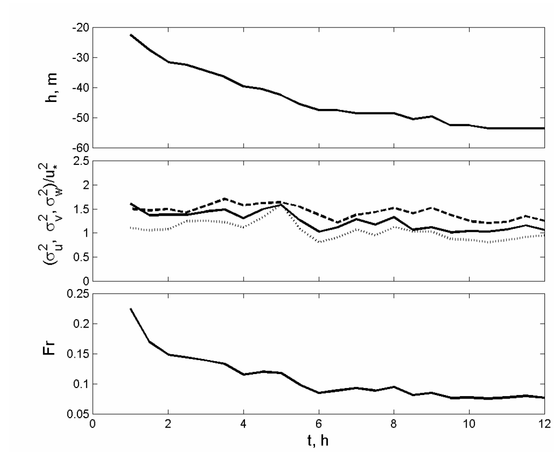

Figure 3. Time series of mixed-layer depth (a), three components of turbulence intensity (dashed-crosswind, solid-vertical; dotted-downwind) (b) and Froude number (c) in Langmuir turbulence.

Next we examine how the mixed-layer depth evolves in time. As shown in Figure 3a, it first increases rather rapidly but then approaches a quasi-steady limit. We also calculate the averages of turbulence intensities over the mixed layer depth and examine their temporal evolution. The turbulence intensities decrease slightly as the mixed layer deepens but then level off when the mixed layer deepening stops. As expected in Langmuir turbulence, the turbulence intensities have the ordering of crosswind > vertical > downwind components. In addition, we plot the time series of a Froude number. We define Fr to be $Fr = \sigma_w/(Nh)$ where σ_w is the rms of depth-averaged vertical turbulence intensity and h the mixed layer depth. Figure 3c shows that the Froude number settles down to a constant value of about 0.1 when the mixed-layer deepening is arrested.

4. Deepening of shear turbulence

In the second numerical experiment, the initial stratification has a buoyancy frequency N=0.0032 1/s, the wind stress is 0.43 N/m^2, the surface velocity and e-folding depth of the Stokes drift current are 0.66 cm/s and 4.77 m, respectively. In nondimensional terms, this corresponds to La_t=1.76 and R_{LN}=0.53. According to Li et al. (2004a), turbulence at La_t=1.76 should fall into the shear regime and corresponds to a fetch-limited sea state.

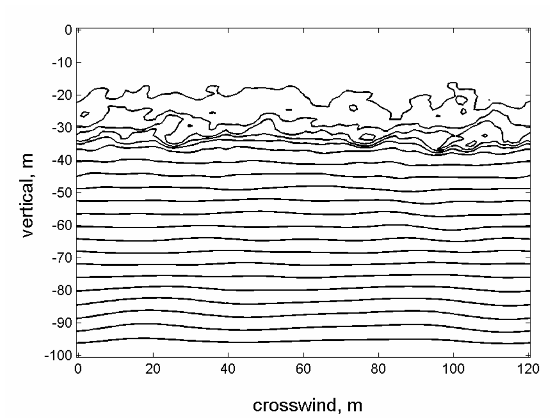

Figure 4. Temperature contours in a crosswind section, showing turbulent mixing due to Kelvin-Helmholtz billows in shear turbulence.

Figure 4 shows temperature contours in a crosswind section at 4 hours. Temperature becomes homogeneous in a surface layer, indicating the generation of a surface mixed layer. Turbulent mixing now appears to be in the form of Kelvin-Helmholtz billows, as expected in shear turbulence. To examine how the surface mixed layer evolve in time, we plot the vertical profiles of horizontally-averaged temperature at t=4, 8. 12 hours, as shown in Figure 5. The surface mixed layer deepens as the shear turbulence penetrates into the stratified water below.

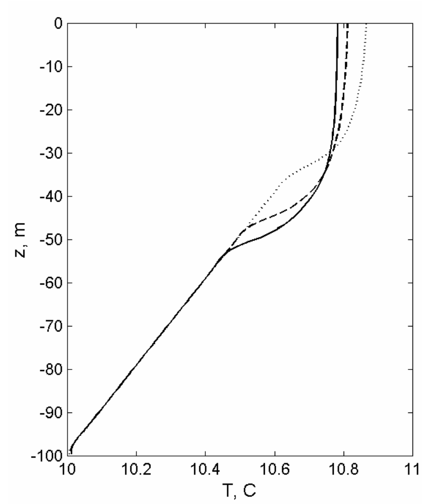

Figure 5. Vertical profiles of mean temperature at t=4 (dotted), 8 (dashed), 12 (solid) hour, showing the deepening of the mixed layer due to shear turbulence.

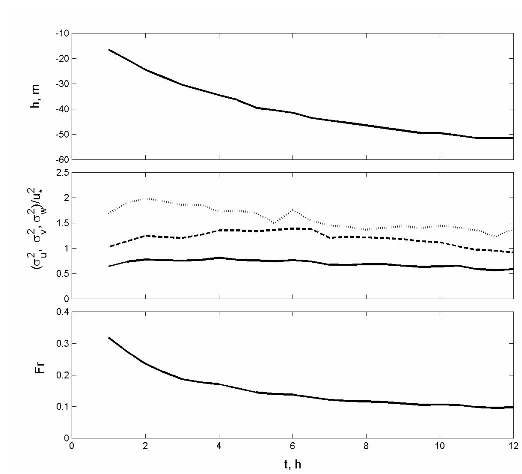

Figure 6. Time series of mixed-layer depth (a), three components of turbulence intensity (dashed-crosswind, solid-vertical; dotted-downwind) (b) and Froude number (c) in shear turbulence.

Next we examine the time series of the mixed-layer depth, depth-averaged turbulence intensities and the Froude number. As shown in Figure 6, the mixed layer depth increases gradually and then approaches a quasi-steady limit. The three turbulence intensities show an ordering of crosswind > vertical > downwind components, as expected in shear turbulence. Finally, the Froude number settles down to a constant value of about 0.1 when the mixed-layer deepening is arrested.

5. Interpretation by a Froude number

As shown in the previous two numerical experiments, the mixed-layer deepening can be interpreted in terms of the Froude number. Both Langmuir or shear turbulence generate vertical velocity with vertical penetration inhibited by stratification. The turbulence penetration depth thus depends on the competition, between vertical motion and stratification, as represented by the Froude number. We have run the LES model over a range of R_{LN} values for both Langmuir and shear turbulence. As shown in Figure 7, the critical values of Fr_c, at which the mixed layer deepening is arrested, hovers around about 0.1. This has a physical interpretation in terms of kinetic energy conversion into potential energy: Langmuir or shear turbulence generates kinetic energy that is used to raise water particles from their initial equilibrium positions. Penetration stops if the potential energy required is more than the kinetic energy available.

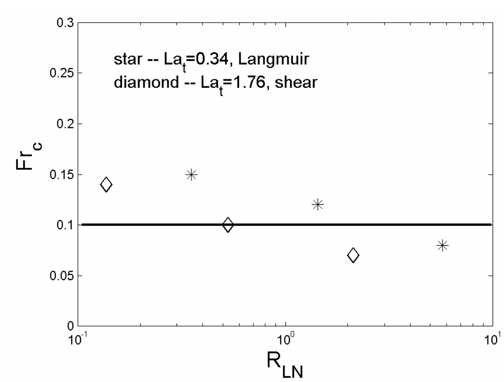

Figure 7. Summary of critical Froude number Fr_c in La_t and R_{LN} parameter space. Symbol * corresponds to Langmuir turbulence and symbol diamond corresponds to shear turbulence.

6. Coupling between surface and bottom boundary layers

To interpret turbulence measurements collected at the CBLAST-low site, we have also investigated the interaction between turbulent large eddies and stratification in shallow water. We examined how turbulence generated in the bottom boundary layer interacts with turbulence in the surface mixed layer. In addition to surface forcing due to wind stress, waves and heat flux, we impose an oscillating body force to generate a tidal current. We carried out numerical runs to investigate stratification conditions under which the surface and bottom boundary layers are coupled together or decoupled from each other.

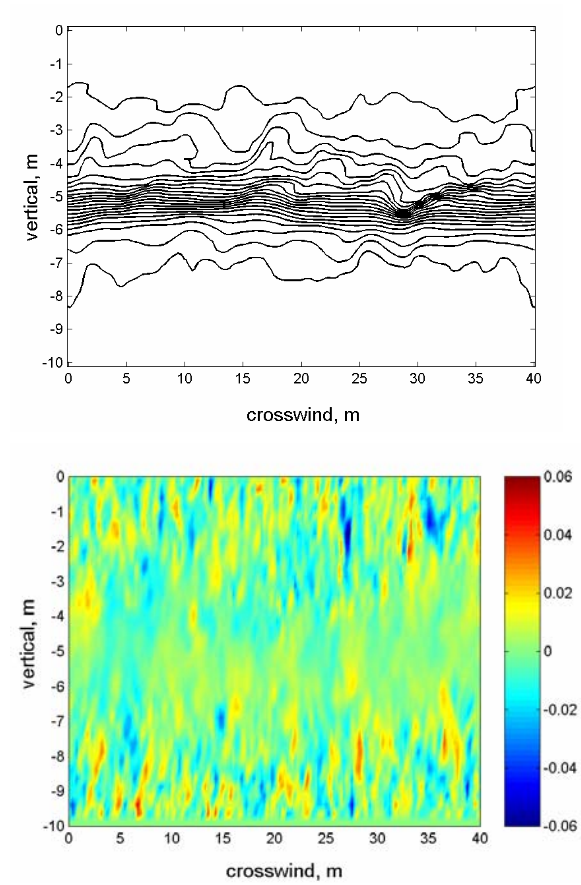

Figure 8. Temperature contours (a) and vertical velocity (b) in a vertical cross-section perpendicular to the wind and the mean tidal flow. A strongly-stratified thermocline is established to separate the surface boundary layer generated by Langmuir turbulence from the bottom boundary layer generated by tidal currents.

We have carried out a preliminary investigation into the coupling between the surface and bottom boundary layers in water of 10 m depth. Initially water is linearly stratified with buoyancy frequency N=0.05 1/s. We then switch on a wind stress of 0.16 N/m^2, a monochromatic wave field with wave height of 2 m and wavelength of 60 m, a surface heating rate of 200 W/m^2. In addition, a tidal current with M_2 frequency and a peak velocity of 0.5 m/s moves over the bottom boundary with a roughness height of 3 mm (Li et al, 2004b). Figure 8 shows the vertical distributions of temperature and vertical velocity near the peak flood tide. A surface boundary layer is generated by Langmuir turbulence, whereas a bottom boundary layer is generated by the tidal current. They are separated by a strong thermocline. Under much weaker stratification, however, temperature is homogenized everywhere after a couple of tidal cycles. With the bottom stress three times larger than the wind stress, bottom-generated turbulence was able to overcome the stratification and penetrate to the sea surface. In this case momentum and heat fluxes measured near the sea surface cannot simply be related to the air-sea fluxes.

7. Conclusion

We have conducted numerical simulations of the interaction between Langmuir/shear turbulence and a linearly stratified water. In Langmuir turbulence, the mixed-layer deepening occurs through direct engulfment of stratified water into the mixed layer. In shear turbulence, however, the deepening occurs through the Kelvin-Helmholtz billows. In shallow water environment such as the CBLAST-low site, stratification is needed to separate the surface mixed layer from the bottom boundary layer. Under weak stratification condition during the fall, bottom-generated turbulence may reach the surface layer so that the surface and bottom boundary layers might be coupled. Although the preliminary results on coupled boundary layers are encouraging, many questions remain unanswered. Under what stratification condition (magnitude and profile) will the surface and bottom boundary layers be coupled or uncoupled? How does this condition change with changing surface wave field or wave age? We plan to carry out LES simulations and compare the model results with turbulence measurements collected during CBLAST-low experiments.

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