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Numerical study on the effects of progressive gravity waves on turbulence*

Anqing (Elliott) XUAN, Bingqing DENG, Tao CAO, Lian SHEN
Department of Mechanical Engineering and Saint Anthony Falls Laboratory, University of Minnesota, Minneapolis, MN, USA, E-mail: xuanx004@umn.edu

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Abstract: The wind-wave-ocean system, which contains complex interactive processes, is of great importance for the momentum, heat and mass transport in the atmosphere and ocean and at their interface. In this work, we perform wave-coupled phase-resolved numerical simulations to investigate the effect of progressive gravity waves on wind and ocean turbulence. Initially homogeneous turbulence under a finite-amplitude monochromatic surface wave is simulated to reveal how the wave influences the subsurface turbulence. For the interaction between wind-driven waves and shear turbulence in the ocean, new wave-phase-resolved simulation approaches are developed to capture Langmuir cells. Lastly, wind turbulence over one and two progressive waves is simulated to elucidate the dynamics of turbulence coherent structures impacted by surface waves for improved understanding of wind-wave growth mechanism.

Key words: wave-ocean interaction, Langmuir circulation, wave-wind interaction, numerical simulation

Introduction

Turbulence in the wind-wave-ocean system involves many complex processes. Waves can substantially modify the turbulent flows, resulting in many distinct features, such as, Langmuir cells on the ocean side and critical layer on the air side. The turbulence can in turn affect ocean currents and waves. The coupling dynamics plays an important role in the momentum, heat, and mass fluxes at sea surfaces and the transport and mixing in the oceanic mixed layer and marine atmospheric boundary layer. Despite its importance, the dynamics of turbulence in the wave environment has largely been elusive due to the complexity of the physical problem.

Considerable studies have been performed to investigate the subsurface turbulence in the presence of surface waves. It has been found that turbulence intensity can be enhanced by wave-turbulence interaction[1,2]. Waves can also contribute to the stretching and tilting of turbulence vortices[3,4]. Meanwhile, turbulence has been shown to become wave-phase dependent under the modulation of waves[1,4-6]. It is therefore desirable to study the wave-turbulence interaction using wave-phase-resolved simulations, which have been made possible with the increase in computing resources and the recent development of numerical methods[7-9].

The interaction between surface waves and wind-driven turbulence can generate Langmuir cells[10-12], which is one of the most important turbulence processes in the upper ocean. Langmuir cells can be manifested by windrows on the surface, which are the amalgamation of buoyant materials driven by pairs of counter-rotating vortices aligned with the wind. The downward and upward convection by the vortices can significantly affect the mixing and transport processes in the mixed layer. Traditionally, numerical simulations of Langmuir cells have been limited to a wave-phase-averaged description using a Craik-Leibovich equations with a rigid-lid approximation[13-15]. The wave effect on the long-term evolution of the turbulent flow is modeled through a vortex force involving the Stokes drift. However, such model may oversimplify the complex system by overlooking the wave phase information and the correlation between waves and turbulence fluctuations. This limitation motivates us to develop and perform large-eddy simulation (LES) of Langmuir turbulence with explicitly resolved waves

* **Biography:** Anqing (Elliott) XUAN (1991-), Male, Ph. D. Candidate
Corresponding author: Lian SHEN,
E-mail: shen@umn.edu

to capture more accurately the wave-turbulence interaction dynamics.

Wind-wave interaction is important in many applications and critical for the fundamental understanding of the wind wave growth mechanism. It has been found that the turbulent coherent structures and the related Reynolds stresses over progressive surface waves are characterized by wave-phase-correlated turbulence fluctuations. Belcher and Hunt[16] and Cohen and Belcher[17] proposed a non-separated sheltering mechanism to relate the wave-phase-correlated turbulent stress to the growth of the waves. As a consequence, a detailed understanding of turbulent structures in the vicinity of surface waves was obtained. The turbulence over two progressive surface waves is far more complicated than that over one surface wave, because the wave-phase-correlated turbulent motions induced by two different surface waves can interact with each other. Chen and Belcher[18] performed a theoretical analysis at extremely high Reynolds numbers, and showed the importance of the sheltering effect with a decrease of the form drag on short waves due to the reduction of the turbulent stress over the short waves in the presence of a long wave. This theory shed lights on the understanding of the generation of surface waves in the presence of long waves, but still needs more study to be validated. In our study, one of the tasks is to perform numerical simulations for wind turbulence over one and two surface waves to improve the understanding of the effect of progressive waves on turbulent structures.

This paper aims at using high-fidelity and high-resolution data from wave-coupled phase-resolved simulations to obtain an improved understanding of the fundamental mechanisms of wave effects on the wind and ocean turbulence. First, the interaction between sur-face progressive waves and initially isotropic turbulence underneath is studied using direct numerical simulation (DNS). We focus on the mechanistic study of the effect of a finite-amplitude monochromatic wave on the subsurface turbulence. Then, Langmuir turbulence is studied with two advanced wave-phase-resolved numerical simulation approaches. Finally, the effects of progressive waves on the wind turbulence are investigated.

1. Mechanistic study of wave-turbulence interaction

In this section, we focus on the interaction of initially homogeneous turbulence with surface progressive waves. To capture the sea-surface boundary effects and wave nonlinearity, we perform DNS on a wave-surface-fitted curvilinear grid that moves with the dynamically-evolving wave surface subject to fully nonlinear kinematic and dynamic free-surface boundary conditions[9]. As a result, the wave profile and orbital motions are explicitly resolved, in contrast to the rigid-lid approximation and Stokes drift treatment used in previous studies. Fourier-based pseudo-spectral method in the horizontal directions and finite-difference method in the vertical direction are used for spatial discretization, and a second-order fractional-step scheme is used for temporal integration. Statistically steady isotropic homogeneous turbulence is generated in the bulk flow by a random forcing method[19,20]. The turbulence is then distorted by surface waves with various wave steepness and frequency. The turbulence-to-wave length ratio is 0.109, and the turbulence-to-wave time ratio ranges from 2.58 to 11.5, corresponding to immediate to rapid distortion regimes. A gentle pressure is applied on the surface to dynamically adjust and maintain the progressive waves to obtain a statistically steady state. Detailed problem setup and parameters can be found in the works of Guo and Shen[6,21].

The statistics of our simulation data show that the magnitude and orientation of turbulent vortices vary with the wave phase. The vertical vortices are tilted toward the wave propagating direction under the wave crest, and are tilted backwards under the wave trough. In other words, as a wave passes by, vertical vortices are tilted back and forth. However, it is found that there exists a net tilting of vertical vortices to the wave propagation direction, which can be attributed to the Stokes drift of waves and the correlation between turbulence and wave strain rate[21]. The tilting of vortices is closely related to the role of waves in the initial formation of Langmuir cells. Horizontal vortices also experience periodic tilting, but the net effect is close to zero.

The intensities of turbulence velocity fluctuations are also found to vary with wave phases. Take phase-dependent averaged streamwise velocity fluctuations intensity $<u'^2>$ as an example. Away from the surface, $<u'^2>$ reaches its maximum under the wave trough and minimum under the wave crest. This result is consistent with previous theoretical analysis using the rapid distortion theory[4]. The variation near the surface, however, is opposite to the theoretical prediction. Our analysis of the budget of $<u'^2>$ shows that the variation of velocity fluctuations is dominated by the normal production associated with the mean wave strain rate, pressure-strain correlation, and pressure transport. The production term in the budget equation, $-2<u'^2>\partial<u>/\partial x$, increases $<u'^2>$ under the forward slope, and the opposite process happens below the backward slope. Near the surface, both the pressure-strain correlation $2<p'\partial u'/\partial x>$ and pressure transport $-2<\partial(p'u')/\partial x>$ terms are negative under the forward slope and positive under the backward slope. Therefore, near the surface, the