Development of a Highly Efficient and Accurate Wind-Wave Simulation Framework for Operational Data Assimilation

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LONG-TERM GOAL

This research aims at developing a highly efficient yet accurate computational framework for the simulation and prediction of wave and wind coupled motions with wave phases being resolved, which will lead to an advanced data assimilation tool to provide more comprehensive environmental input for naval applications. Our ultimate goal is to pave the way for developing an operational tool for the Navy to use for ocean-wave-atmosphere battlespace sensing and prediction with high resolution.

OBJECTIVES

The scientific and technical objectives of this research are to:

(1) Use the detailed physics revealed in coupled wind-wave simulations to obtain a fundamental understanding of wave surface-layer processes, based on which physics-based advanced wave-layer models can be developed;

(2) Adopt a highly accurate immersed boundary method to perform turbulence-wave simulation on fixed Cartesian grid to achieve superior computation efficiency; and

(3) Use the developments in (1) and (2) to pave the way for the development of a computational framework for data assimilation with a focus on the reconstruction of wavefield and the retrieval of coherent flow structures from field measurements.

APPROACH

This research builds on the combined simulation of wind-wave interaction achieved in a fully dynamical, two-way coupling context. In the simulation, evolution of wavefield is simulated with an efficacious high-order spectral (HOS) method that captures all of the dynamically important nonlinear wave interaction processes. Large-eddy simulation (LES) is performed for the marine atmospheric boundary layer (MABL) in a direct, physical context with wave phases of the broadband wavefield being resolved. In LES, fully resolving the boundary layer at the air-sea interface is prohibitively expensive. We use a wall-layer model to represent the momentum exchange between the flow in the outer layer and the small but dynamically important eddies in the inner layer. The extensive, high resolution data obtained from the coupled LES-HOS simulation provide a unique opportunity to develop, assess, and calibrate wave-layer models.

In this study, we will adopt the immersed boundary (IB) method for turbulence simulation near surface waves, with the constraints of the moving water surface represented by a body force through a discrete force method, which can capture the boundary precisely. We use large-scale high-performance computation on massively parallel computers. Our coupled LES-HOS code is parallelized using massage passing interface (MPI) based on domain decomposition. With the developments of wave-layer model and IB method for turbulence-wave interaction, the computational cost will be reduced significantly. The simulation capabilities developed in this study will be used for data assimilation with a focus on the retrieval of coherent flow structures and the reconstruction of wavefield based on measurements. The simulation results obtained in this study will be compared with and validated against field measurement data.

WORK COMPLETED

During the fiscal year of 2012, substantial progresses have been made in this project, including:

- Theoretical development of dynamic subgrid-scale (SGS) sea-surface roughness models for LES.
- Implementation of dynamic SGS sea-surface roughness into the coupled wind-wave computational framework, i.e. LES with near-surface modeling (LESns-W).
- Performing high-resolution LES with near-surface resolution (LESns-R) to obtain benchmark data for the test of the roughness models.
- *A priori* and *a posteriori* tests of LESns-W with dynamic SGS sea-surface roughness models for a variety of wind and wave conditions.
- Theoretical assessment of the performance of dynamic SGS sea-surface roughness models for a considerably wide range of physical parameters.
- Application of the coupled wind-wave computational framework to offshore wind-wave-structure interaction and offshore wind energy.

RESULTS

In this project, a dynamic sea-surface roughness model has been developed for LES of wind turbulence over ocean wavefield. In the simulations, the surface elevation and the corresponding air pressure variation of the waves are resolved down to grid-scales. As a result, the effects of grid-scale waves on wind turbulence are captured through the wave-induced form drag on the wind turbulence. However, the effects of SGS waves are not resolved explicitly (in LESns-M), and is modeled using a local log-law surface model. In the log-law function, the roughness scale due to the SGS sea-surface waves is modeled by a coefficient α_w (in principle α_w is unknown), multiplied by an effective SGS wave amplitude σ_η^Δ , which is quantified by a weighted integral over the SGS wave spectrum. The total surface stress is expressed as the sum of the grid-scale form drag and the log-law-based SGS shear stress. Based on the physical constraint that the total surface stress is invariant with respect to the grid resolution, the total surface stresses at grid and test-filter scales are equated to form an equation for the unknown coefficient α_w. Such a dynamic approach allows the value of α_w to adjust to particular prevalent wind and wave conditions. An example of the results of LESns-M with the dynamic SGS sea-surface roughness model is show in figure 1.

Five candidate models for σ_η^Δ based on different aspects of the wave characteristics are evaluated. They are named the RMS model, geometry model, steepness-dependent Charnock model, wave-kinematics-dependent model, and combined kinematics-steepness model. They are tested for different wind-wave conditions. The performance of the models is evaluated by means of *a priori* tests using the benchmark data from high-resolution surface-resolving simulations (LESns-R), as well as *a posteriori* test by implementing the approach in surface-modeled LES (LESns-M). The LESns-R has a grid resolution of (128*256*64), with evenly spaced grid points in the horizontal directions and clustered grid towards the wave surface in the vertical direction. The Reynolds number based on the friction velocity and the peak wavelength is $\mathrm{Re} = u_* \lambda_p / \nu = 4096$. In terms of wall units, the horizontal grid sizes are $\Delta x^+ = 64.0$ and $\Delta y^+ = 16.0$. The vertical grid size is $\Delta z^+ = 2.0$ near the wave surface and gradually increases to $\Delta z^+ = 118.6$ towards the top of the simulation domain. Such grid resolutions ensure the resolving of the vertical structure of the turbulence boundary layer near the sea surface. And the results of LESns-R are used as the benchmark data for model testing. On the other hand, the LESns-M has the same physical parameters as the LESns-R but using a lower grid resolution of (48*64*64), with evenly spaced grid points in all three directions. This gives a grid resolution of $\Delta x^+ = 170.7$, $\Delta y^+ = 64.0$, and $\Delta z^+ = 64.0$ for LESns-M. The results of the *a posteriori* test using LESns-M are reported here.

Figure 2 shows the vertical profiles of mean (time- and horizontal-averaged) streamwise velocity for $U_{10} = 12$ m/s and $c_p / u_* = 6$. Here, U_{10} is the mean wind velocity at the height of 10m above the sea surface; c_p is the wave phase velocity at the wave spectrum peak; and u_* is the wind friction velocity. The results from LESns-M using the dynamic sea-surface roughness model are compared with the filtered result of LESns-R. Results from the various models for σ_η^Δ are shown. It can be seen that the mean velocity profile from the LESns-M using the wave-kinematics-dependent model agrees best with the benchmark results obtained from the high-resolution LESns-R. The RMS model and the geometry model underestimate the sea-surface roughness, resulting in a slightly larger value for the streamwise velocity. On the other hand, both the steepness-dependent Charnock model and the combined-kinematics-steepness model overestimate the sea-surface roughness, which leads to reduced mean velocity.

Figure 3 shows the vertical profiles of mean streamwise velocity for $U_{10} = 12\ \text{m/s}$ and $c_p / u_* = 10$. Similar to the result for $c_p / u_* = 6$, the RMS and geometry models overestimate the mean velocity in the case of $c_p / u_* = 10$, but with even more appreciable deviations. The steepness-dependent Charnock model and combined-kinematics-steepness model underestimate the mean velocity for $c_p / u_* = 10$, as they did for $c_p / u_* = 6$. The wave-kinematics-dependent model still has the best performance among the five σ_η^Δ models.

Figure 4 shows the vertical profiles of mean streamwise velocity for $U_{10} = 12$ m/s and $c_p / u_* = 18$. In this case, the energy-containing waves in the wavefield propagate faster than in the cases of $c_p / u_* = 6$ and 10, and the wave surface for $c_p / u_* = 18$ is thus effectively smoother than those for $c_p / u_* = 6$ and 10. The smaller total surface roughness for case CU18 is indicated by the larger value of mean streamwise velocity near the wave surface in figure 4 compared with figures 2 and 3. Furthermore, the difference between LESns-R and LESns-M with various σ_η^Δ models is also found to be less obvious compared with the results in figures 2 and 3.

IMPACT/APPLICATION

This project addresses the basic physics of wave surface layer, which will lead to better understanding of turbulence-wave interaction dynamics. It is expected to improve simulation efficiency significantly, which will lead to a powerful computational capability for direct comparison between measurement and modeling and for data fusion in field experiments.

RELATED PROJECTS

None

PUBLICATIONS

Yang, D. & Shen, L. 2011a "Simulation of viscous flows with undulatory boundaries. Part I: Basic solver," *J. Comput. Phys.* **230**, 5488-5509.

Yang, D. & Shen, L. 2011b "Simulation of viscous flows with undulatory boundaries. Part II: Coupling with other solvers for two-fluid computations," *J. Comput. Phys.* **230**, 5510-5531.

Yang, D., Meneveau, C. & Shen, L. "Dynamic modeling of sea-surface roughness for large-eddy simulation of wind over ocean wavefield," submitted to *J. Fluid Mech.* (current status: reviewed and revision invited).

Yang, D., Shen, L. & Meneveau, C. "An assessment of dynamic subgrid-scale sea-surface roughness models," submitted to *Flow Turbul. Combust.*.

CONFERENCE PRESENTATIONS

Meneveau, C., Anderson, W., Yang, D. & Shen, L. "A dynamic surface roughness model for LES & applications to turbulent flow over static and moving multi-scale surfaces," invited talk at KAVLI Institute for Theoretical Physics China (KITPC) workshop entitled "New directions in Turbulence",
March 28, 2012, Beijing, China.

Yang, D., Meneveau, C. & Shen, L. "Dynamic modeling of sea-surface roughness for large-eddy simulation of wind over ocean surface waves," Ocean Science Meeting, February 20, 2012, Salt Lake City, Utah, USA.

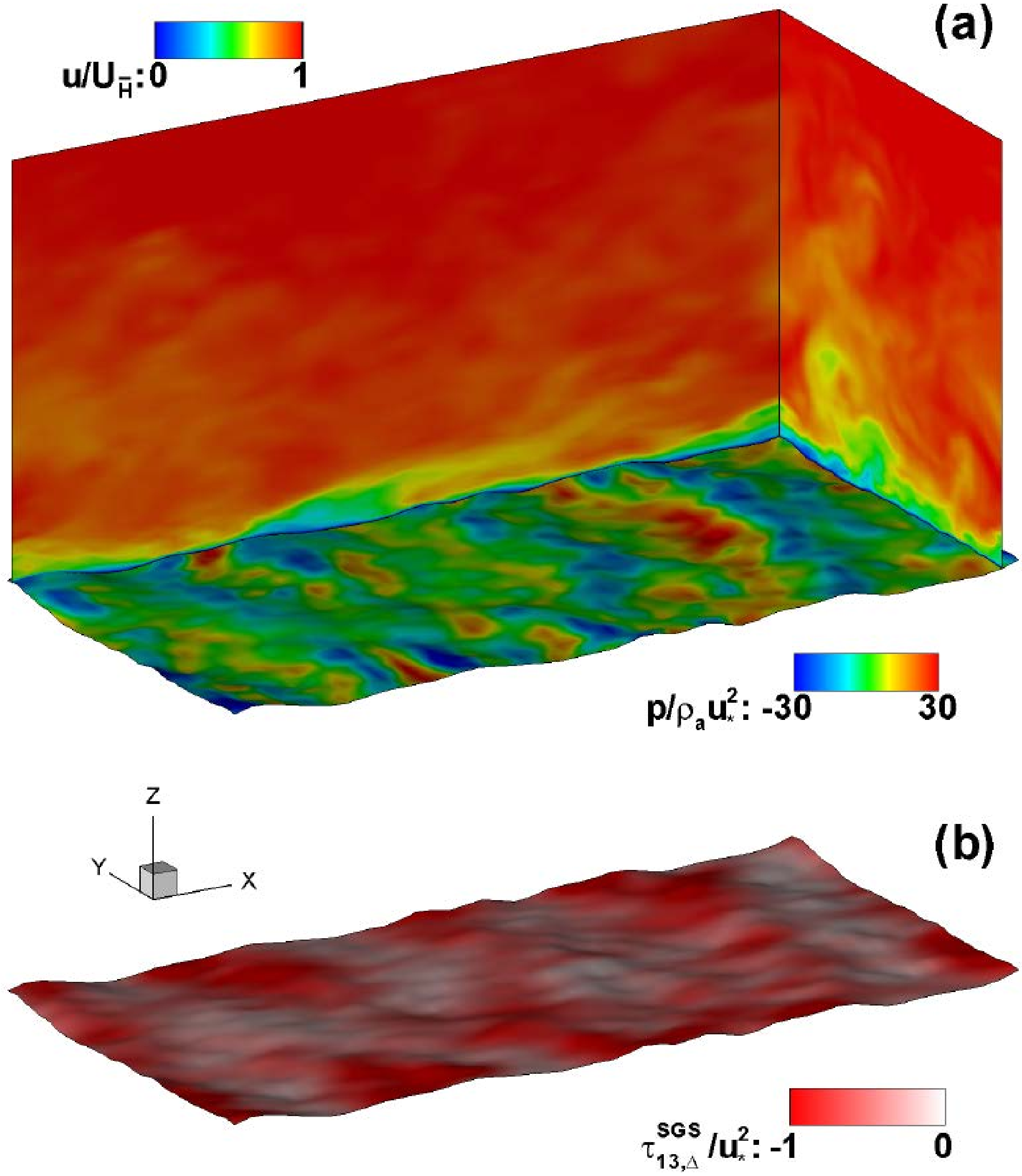

Figure 1. Illustration of LESns-M of wind turbulence together with HOSM simulations of wavefield for $U_{10} = 12$ m/s and $c_p / u_* = 6$. Here, U_{10} is the mean wind velocity at the height of 10m above the sea surface; c_p is the wave phase velocity at the wave spectrum peak; and u_* is the wind friction velocity. In (a), contours of streamwise velocity (normalized by the mean velocity at the top of the simulation domain $U_{\overline{H}}$) are plotted on two vertical planes, and contours of air pressure are plotted on the wave surface. In (b), contours of the instantaneous SGS surface shear stress $\tau_{13,\Delta}^{SGS}$ calculated by the wave-kinematics-dependent model are shown on the same wave surface as in (a).

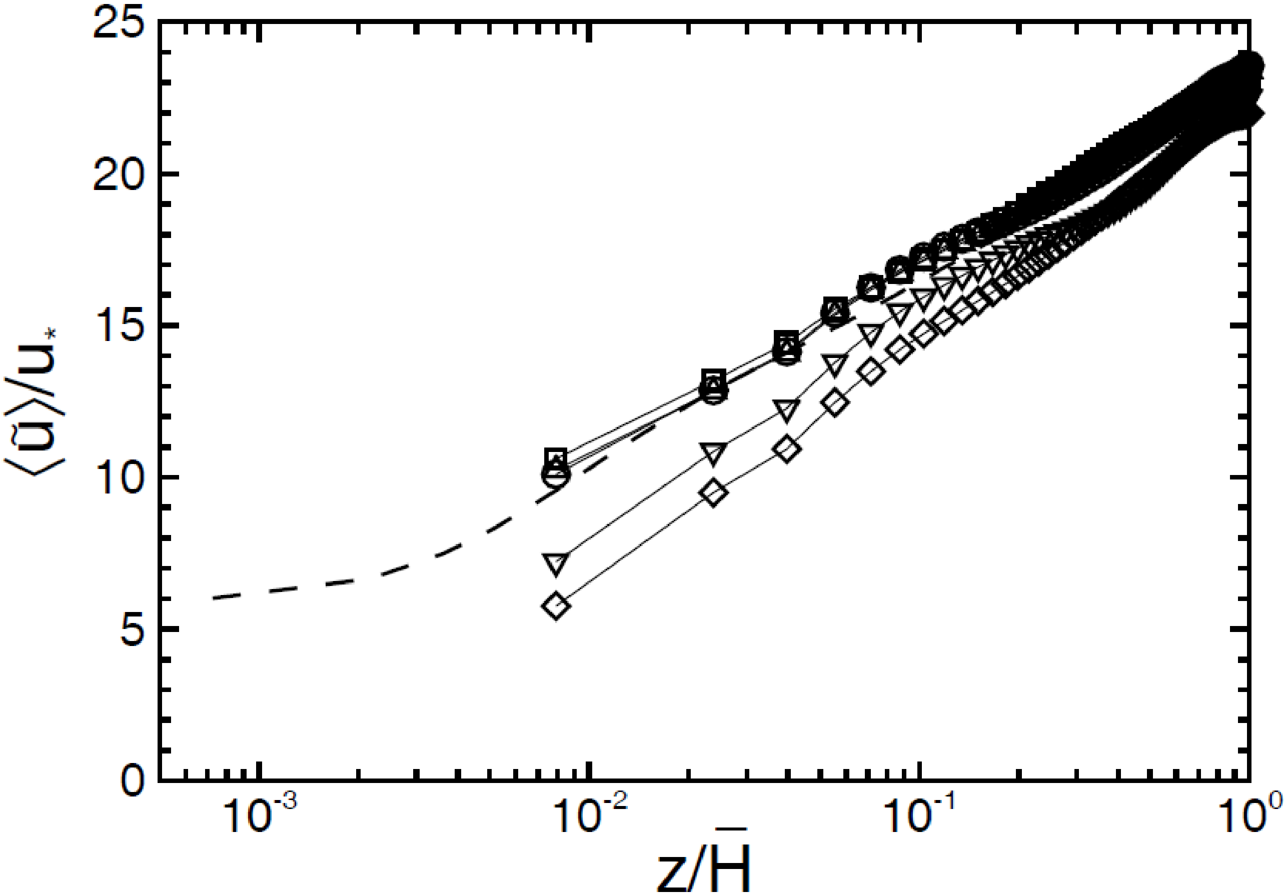

Figure 2. Normalized mean streamwise velocity profiles in semi-logarithmic scale for the case of $c_p / u_* = 6$. Here, c_p is the wave phase velocity at the wave spectrum peak; and u_* is the wind friction velocity. The result of LESns-R is indicated by dashed line. The results from LESns-M with various sea-surface roughness models are indicated by solid lines with different symbols: square, RMS model; up-triangle, geometry model; down-triangle, steepness-dependent Charnock model; circle, wave-kinematics-dependent model; and diamond, combined-kinematics-steepness model.

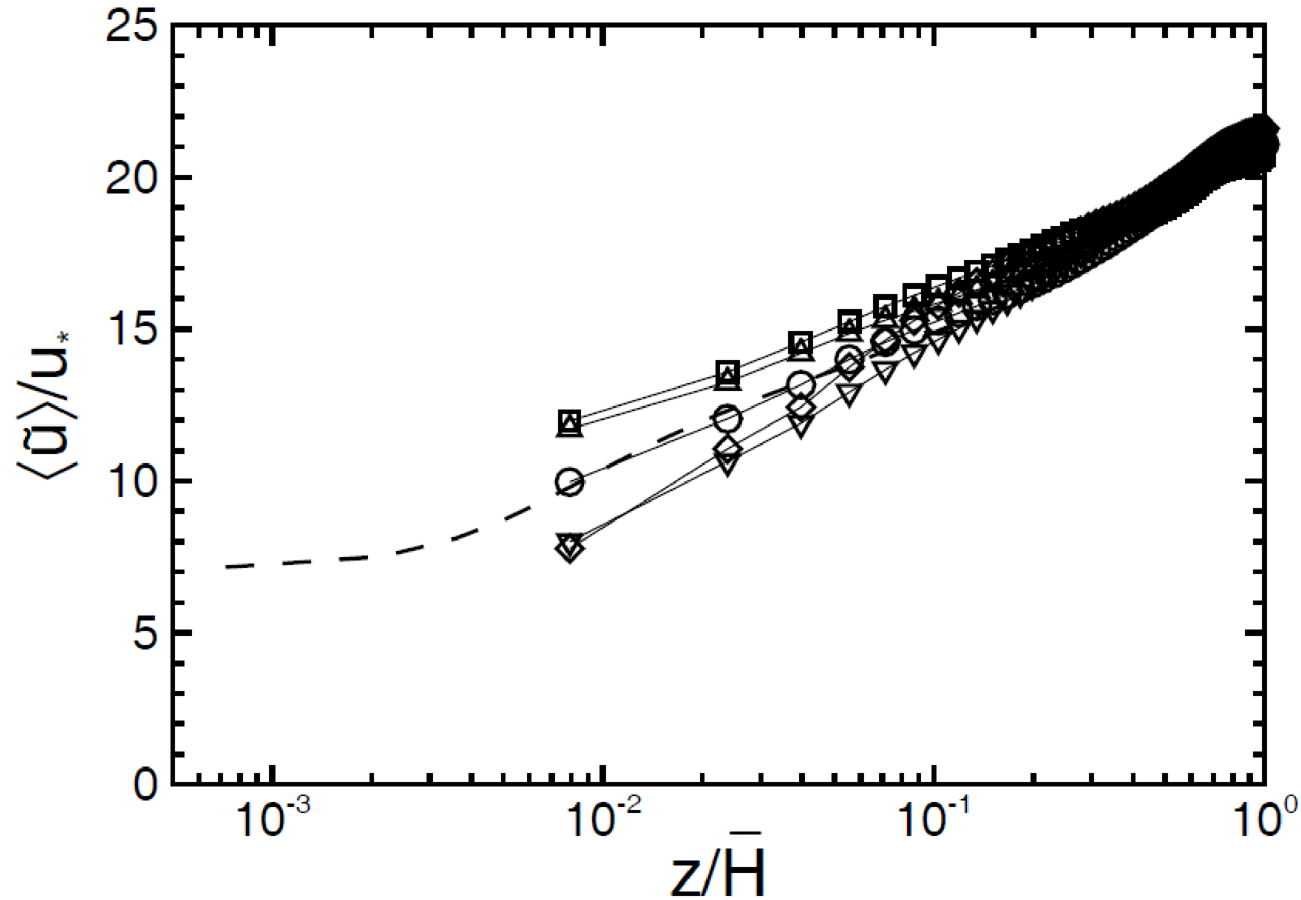

***Figure 3.** Normalized mean streamwise velocity profiles in semi-logarithmic scale for the case of $c_p / u_* = 10$. Here, c_p is the wave phase velocity at the wave spectrum peak; and u_* is the wind friction velocity. The result of LESns-R is indicated by dashed line. The results from LESns-M with various sea-surface roughness models are indicated by solid lines with different symbols: square, RMS model; up-triangle, geometry model; down-triangle, steepness-dependent Charnock model; circle, wave-kinematics-dependent model; and diamond, combined-kinematics-steepness model.*

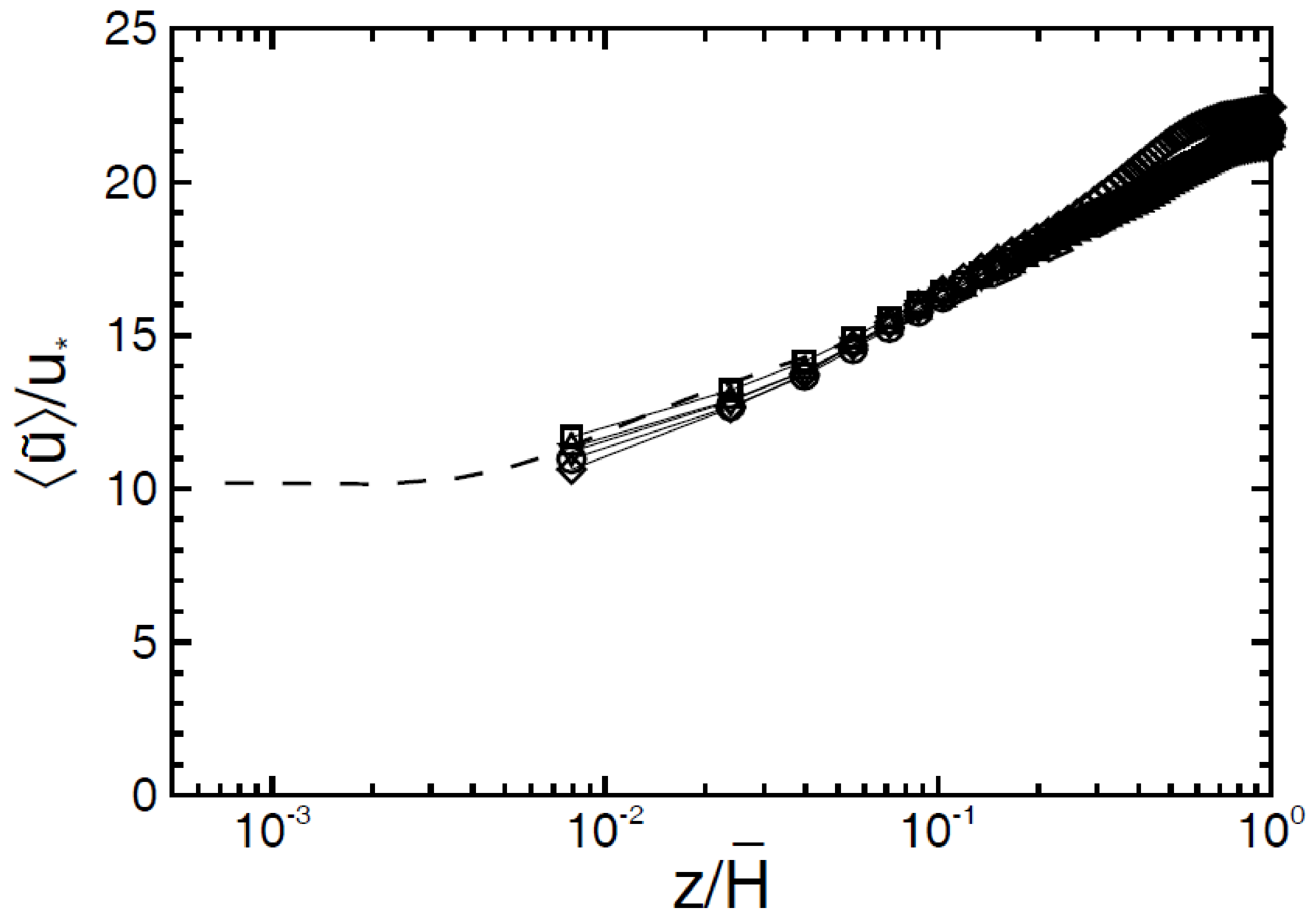

Figure 4. Normalized mean streamwise velocity profiles in semi-logarithmic scale for the case of $c_p / u_* = 18$. Here, c_p is the wave phase velocity at the wave spectrum peak; and u_* is the wind friction velocity. The result of LESns-R is indicated by dashed line. The results from LESns-M with various sea-surface roughness models are indicated by solid lines with different symbols: square, RMS model; up-triangle, geometry model; down-triangle, steepness-dependent Charnock model; circle, wave-kinematics-dependent model; and diamond, combined-kinematics-steepness model.