Efficient Non-Hydrostatic Modeling of Rotational, Turbulent, Dispersive, and Variable-Density Flows in the Vicinity of River Mouths and Inlets: Development and Field Support

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LONG-TERM GOALS

The long-range goal of this project is to develop a physics framework, and an associated numerical tool, which provides relatively rapid, phase-resolving predictions of wavy environments in the presence of strong currents and vertical stratification. The benefit of this approach, as contrasted with existing models, is that here we are able to more completely represent the nonlinear wave field, without using coarse statistical approximations, and can include the non-hydrostatic physics introduced by these nearshore wind waves.

OBJECTIVES

The scientific objectives of this project are founded on the modeling of currents and coherent turbulent structures generated by tidal or river flow coupled directly, via the same equations, with weakly dispersive wind waves. Integrated with the hydrodynamic model will be a transport module, permitting estimation of the evolution/dispersion of scalar tracers and Lagrangian drifters, in both the depth-averaged sense and with full 3D transport modeling. Finally, modification of the governing physics will include spatial variations in fluid density, in both horizontal and vertical directions, such that fresh and salt water mixing might be captured. Combining this models ability to simulate turbulence and transport in shallow flows with its capacity to include weakly dispersive wind waves, there exists the potential to simulate a wide range of complex and nonlinear processes with a single, practical numerical approach. This project is part of the River Mouth and Inlet DRI, and will be used to both guide the field experiment and interpret the measured data.

APPROACH

The numerical efforts undertaken here implement established aspects of Boussinesq-type modeling, developed by the PI and other researchers. These aspects include wind wave breaking (e.g. Kennedy et al, 2000; Lynett, 2006), accurate moving boundary schemes for shoreline motion (Lynett et al., 2000), and a MPI-based parallellization (Sitanggang & Lynett, 2005). Within this model basis, the project attempts to include physical processes relevant to the hydrodynamic environment near a river mouth or a tidal inlet. The PI and students will work through the theoretical obstacles of including these physics in the Boussinesq-type framework, and then implement in a numerical model. Once this comprehensive model is developed and tested against established experimental data, it will be used to simulate numerous possible wave and current conditions at New River Inlet. These numerical simulation results are expected to help the field teams to best place measurement equipment, as well as provide them with some expectations on the range and scale of phenomena that might be observed at New River.

WORK COMPLETED

In FY13 we have continued the development of a Boussinesq-type formulation that permits the explicit inclusion of small-scale, random turbulent fluctuations. Inclusion of these effects has been demonstrated to be very important for transport and mixing. This work is now published in the journal Physics of Fluids. In addition, the depth-integrated hydrodynamic model has been coupled with a 3D scalar transport model. The goal of this coupling was to permit the modeling of near-field and/or depth-dependent mixing due to combined waves and currents. The results of this effort are currently "in review."

Within the framework discussed in the paragraph above, we have developed a method that allows for the direct coupling of an external current field within a Boussinesq-type wave simulation. Here the current field might be tidal current output from Delft-3D or ADCIRC, for example. The results are now under review in a journal paper. Lastly, we have derived the depth-integrated equations that include the effects of a 3D density field, and tested this theory against experimental data. This work is also under review in a journal paper. Preliminary comparasions with NRI field data has been completed, and presented at the RIVET review meeting this year. Final and complete comparisons with field data are ongoing.

RESULTS

A number of applications of the depth-integrated model specific to New River Inlet have been completed this year. This depth-integrated model includes subgrid scale mixing effects for turbulent transport by long waves and currents and is solved by a fourth-order accurate finite volume method (FVM). In practice, this new approach will permit simulations of very complex turbulent and rotational flows where both nearshore wind waves and currents are important.

An example of the application of this model is given in Figure 1. These images are the significant wave height maps of a 2m, 10-s waves approaching New River Inlet, NC with normal incidence for four different tidal levels: high slack tide, maximum flood tide, low stack tide, and minimum low (maximum ebb in the figure) tide. These images provide useful information regarding where the waves will break, which is similar across the four runs, and how effective the waves are at penetrating into the inlet.

Perhaps more useful to velocity and sediment observation plans are the predicted time-averaged currents derived from the simulations. Figure 2 shows a series of images from the four tide-level simulations discussed in the previous paragraph. It is clear that the currents are greatest at the offshore limit of the tidal shoal, and these currents are larger during low tidal levels. Interestingly, the simulations show a very strong, nearly-closed loop of circulation just south of the main tidal channel. There are other similar features along the edge of the shoal. For the two tidal stage simulations with tidal flow, the results from a no-waves simulation are also provided (the two subplots at the bottom of the figure). From this output, it is possible to see the wave effect on the current field; while the waves do impact, and largely control, the current field near the ebb shoal, immediately inside the inlet the wave effect is minor.

The simulations shown in Figure 1 and 2 require that the tidal current field be created directly inside the Boussinesq simulation. This is done through the creation of a free surface elevation gradient from offshore through the inlet, which then drives a current; this approach requires tuning of the enforced gradient in order to generate the correct tidal elevations and flow rates. It is not ideal as it requires iterative and manual interaction with the simulation setup. A much more efficient approach would be to take the tidal current field from a different model (e.g. Deflt3D) and enforce that current field at all locations in the Boussinesq domain. This would remove the tedious iteration stage of the previous approach, and would furthermore represent a desirable multi-scale model coupling approach.

Here, we have invented an approach that builds off previous efforts of Kim et al (2009). The external current field is considered to be a second order rotational correction to the wave-driven flow. This correction is permitted to be arbitrary in all three spatial dimensions as well as time; essentially any three dimensional current field can be enforced on the wave field, and the full wave-current interaction effect is included in the model. The expected application of this approach would be composed of two independent steps. First, a tide- or wind-driven circulation model would be run, such as Delft3D or ADCIRC. It is important that the current field from this large-scale simulation does NOT include the effects of waves. Next, the current field from the circulation model would be imported into the Boussinesq model, which would use only the incident wave condition as its boundary condition. The predictions of the Boussinesq model include the effects of wave-current interaction on the wave field, as well as the resulting mean current from these waves.

Finally, once the current field is imported and interacts with the wave field, it is necessary to approximately model the turbulent stress of this wave-current interaction. This turbulent stress is another second order rotational correction. Due to the lack of arbitrary vertical structure permitted by the depth-integrated model, the specification of this stress must rely on highly empirical closure. Specifically, the shape function of the vertical profile of the Reynolds stress must be specified. There has been much work on this general topic in the past, and it is possible to use experimental results to generate the vertical shape function. Figure 3 shows the typical stress profile for the three general cases of (1) without waves, (2) waves on a following current, and (3) waves on an opposing current (adapted from Umeyama, 2005).

Based on these vertical profiles, the stress is given as $\tau = \tau_b \left[\left(\frac{\zeta - z}{\zeta + h} \right) + b \left(\frac{z + h}{\zeta + h} \right) \right]$ where b is calculated following You (1996). The vertical profile of the horizontal velocity becomes:

$$\mathbf{U} = \underbrace{\mathbf{U}_{W\alpha} + \mathbf{U}_{C\alpha}}_{\mathbf{U}_\alpha} + \mu^2 \underbrace{\left\{ \frac{1}{2} \left(z_\alpha{}^2 - z^2 \right) \nabla S + \left(z_\alpha - z \right) \nabla T \right\}}_{\mathbf{U}_1{}^\phi}$$

$$+ \mu^2 \underbrace{\boldsymbol{\psi} \left\{ \frac{(1-b)}{2} \left(z_\alpha{}^2 - z^2 \right) + \left(\zeta + bh \right) \left(z - z_\alpha \right) \right\}}_{\Omega 1} + \mu^2 \underbrace{\left[\mathbf{U}_C(z) - \mathbf{U}_{C\alpha} \right]}_{\Omega 2} + O(\mu^4)$$

where the first group of terms on the right hand side are the leading order velocities composed of the wave velocity and external current velocity, the second group is the second order correction due to wave dispersion typical of the Boussinesq formulation, the third group is the correction due to the wave-current stress, and the fourth term is the vertical profile of the external current field. Following the Boussinesq-type derivation, the above profile is substituted into the Navier-Stokes equations. The resulting equations are not presented here, but do not add any particularly difficult terms to model as compared to the previous Boussinesq type models, and thus the same numerical scheme can be employed.

In this report, two of the model-data comparisons are provided. In Figure 4, the vertical profile of horizontal velocity for four different wave heights propagating with the current is shown. The experimental data is from Kemp and Simons (1982). The model-data agreement is better with smaller wave heights, but even for the larger heights the agreement is quite good. Note here that the without-waves current profiles, given by the green curves in each subplot, are the corresponding measured profiles from the Kemp and Simons (1982) experiment. Figure 5 shows a similar set of comparisons, but for waves with an opposing current using the data of Kemp and Simons (1983). The model accuracy for this case is reasonable, with again agreement degradation for larger wave heights. In summary, the developed wave-current interaction module derived within the Boussinesq approach allows for the inclusion of current effects on the wave field as well as the modification of the vertical structure of the mean flow.

To extend upon the wave-current applications, we have also developed the ability to include the effects of a 3D density field on the wave evolution. We consider the change in fluid density in a depth-integrated long-wave model. By allowing horizontal and vertical variation of fluid density, a depth-integrated model for long gravity waves over a variable-density fluid has been developed, where density change effects are included as correction terms. In particular, a two-layer fluid system is chosen to represent vertical density variations, where interfacial wave effects on the free surface are accounted for through direct inclusion of the velocity component of the interfacial wave. For the numerical implementation of the model, a finite-volume scheme coupled with an approximate Riemann solver is adopted for leading order terms while cell-centered finite-volume methods are utilized for others. Numerical tests in which the density field is configured to vary either horizontally or vertically have been performed to verify the model. For horizontal variation of fluid density, a pneumatic breakwater system is simulated and fair agreement is observed between computed and measured data, showing that the current induced by the upward bubble flux is responsible for wave attenuation to some degree. To investigate the effects of internal motion on the free surface, a two-layer fluid system with monochromatic internal wave motion is tested numerically. Simulated results agree well with the measured and analytical data. Lastly, nonlinear interactions between external- and internal-mode surface waves are studied numerically and analytically, and the model is shown to have nonlinear accuracy limitations similar to existing Boussinesq-type models.

IMPACT APPLICATIONS

This project aims to develop a depth-integrated nearshore hydrodynamic model which explicitly includes a number of currently neglected physical forcings. In particular, this will make the model uniquely applicable near inlets and river mouths where wind waves are present. In addition, the option to import an external tidal current field from a circulation model such as Delft3D allows for model coupling with nested, multi-scale capability.

RELATED PROJECTS

This effort is one of a large number of projects that make up the River Mouths and Inlets DRI.

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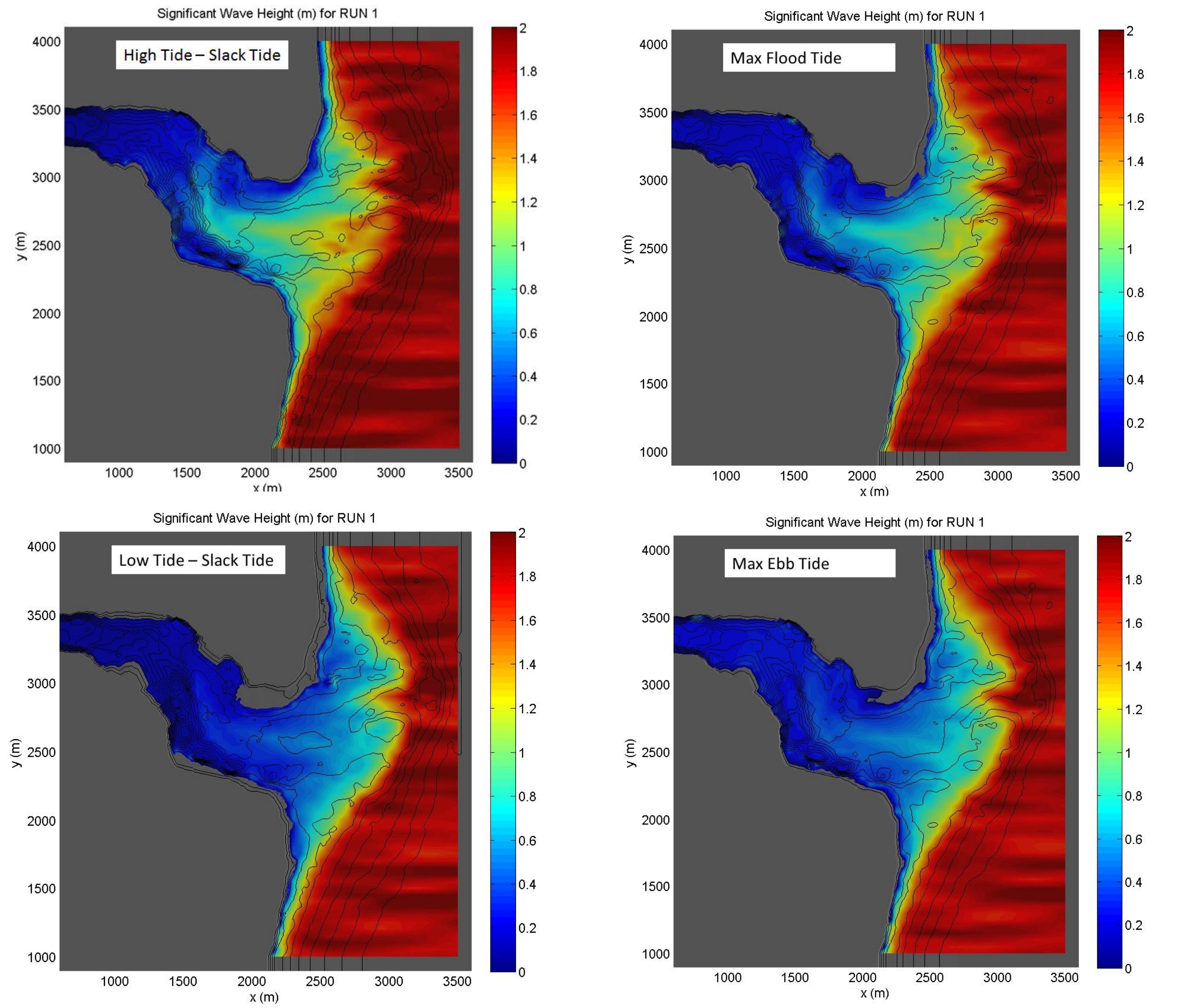

Figure 1. Significant wave height predictions at NRI for 4 different tidal stages, where the stage is given in the white box in each subplot.

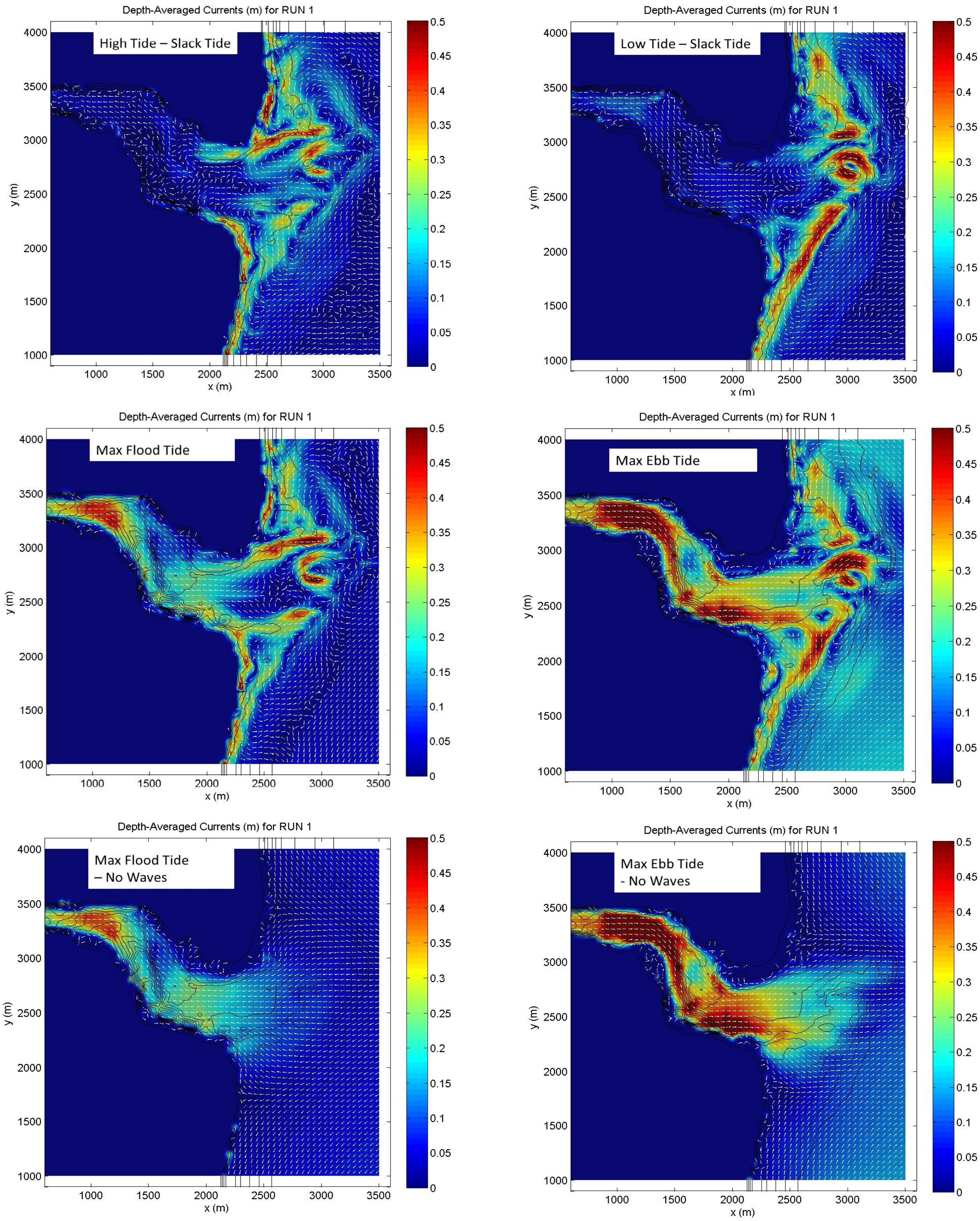

Figure 2. Depth-averaged mean currents at NRI for 4 different tidal stages, with the stage given in the white box. Note that the lower two subplots are from a simulation with no waves – only tides – and can be used to see the wave effect on the currents.

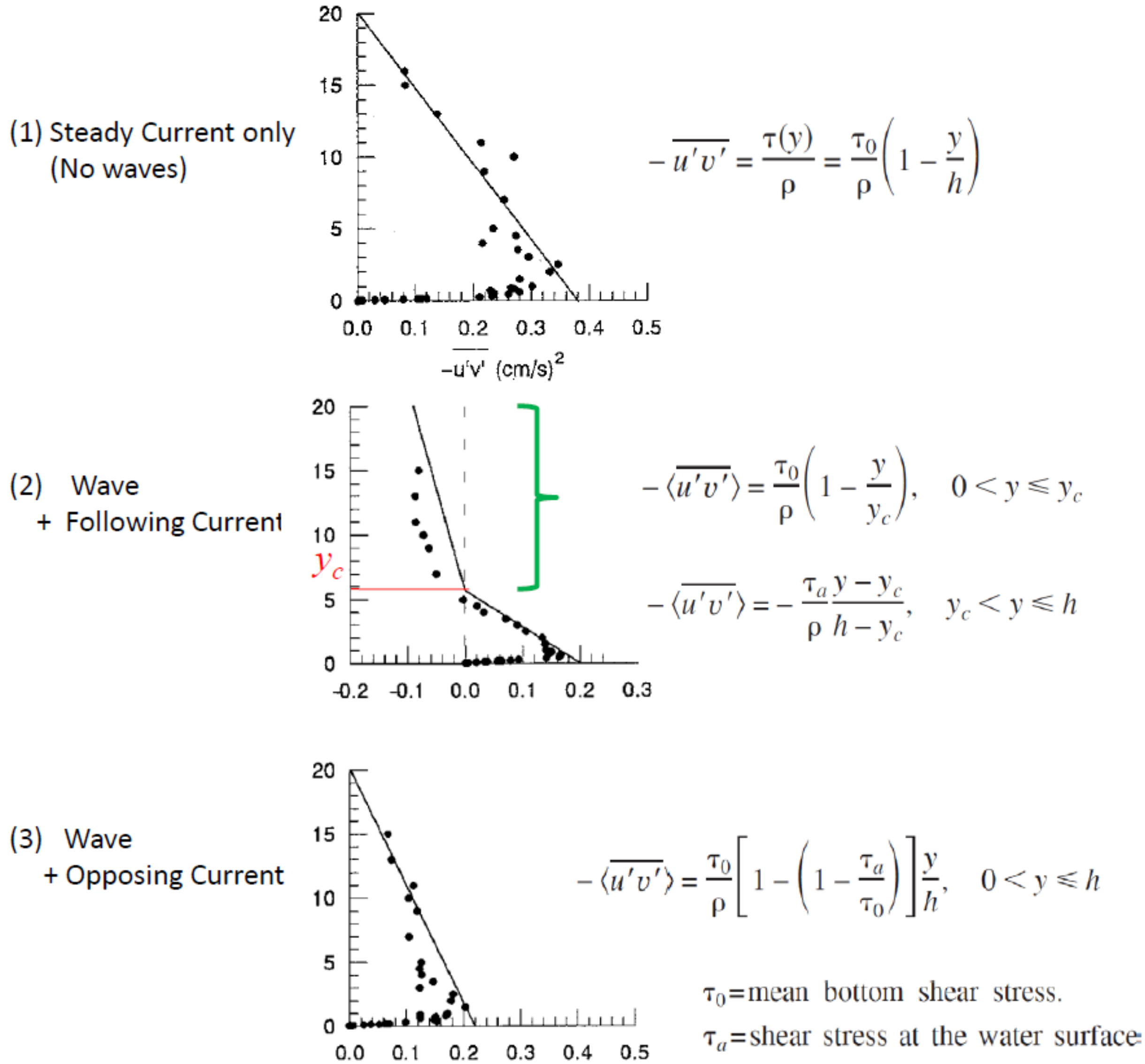

Figure 3. Reynolds stress profiles for three different situations. The shape of these profiles is used to approximated the vertical stress in the Boussinesq-type model.

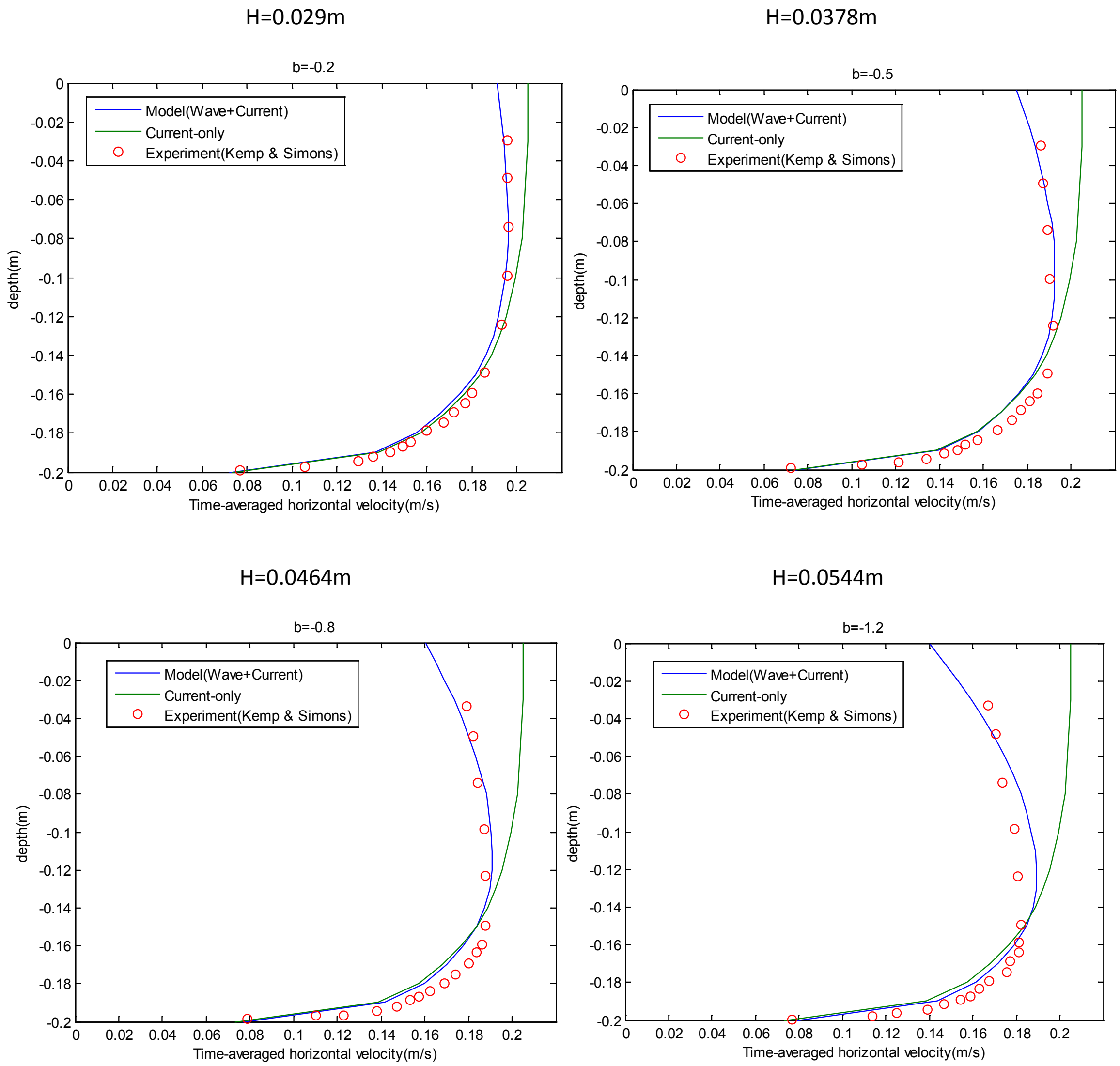

Figure 4. Model-data comparisons for the mean current profile under the wave + following current situation. The four subplots are for 4 different incident wave heights.

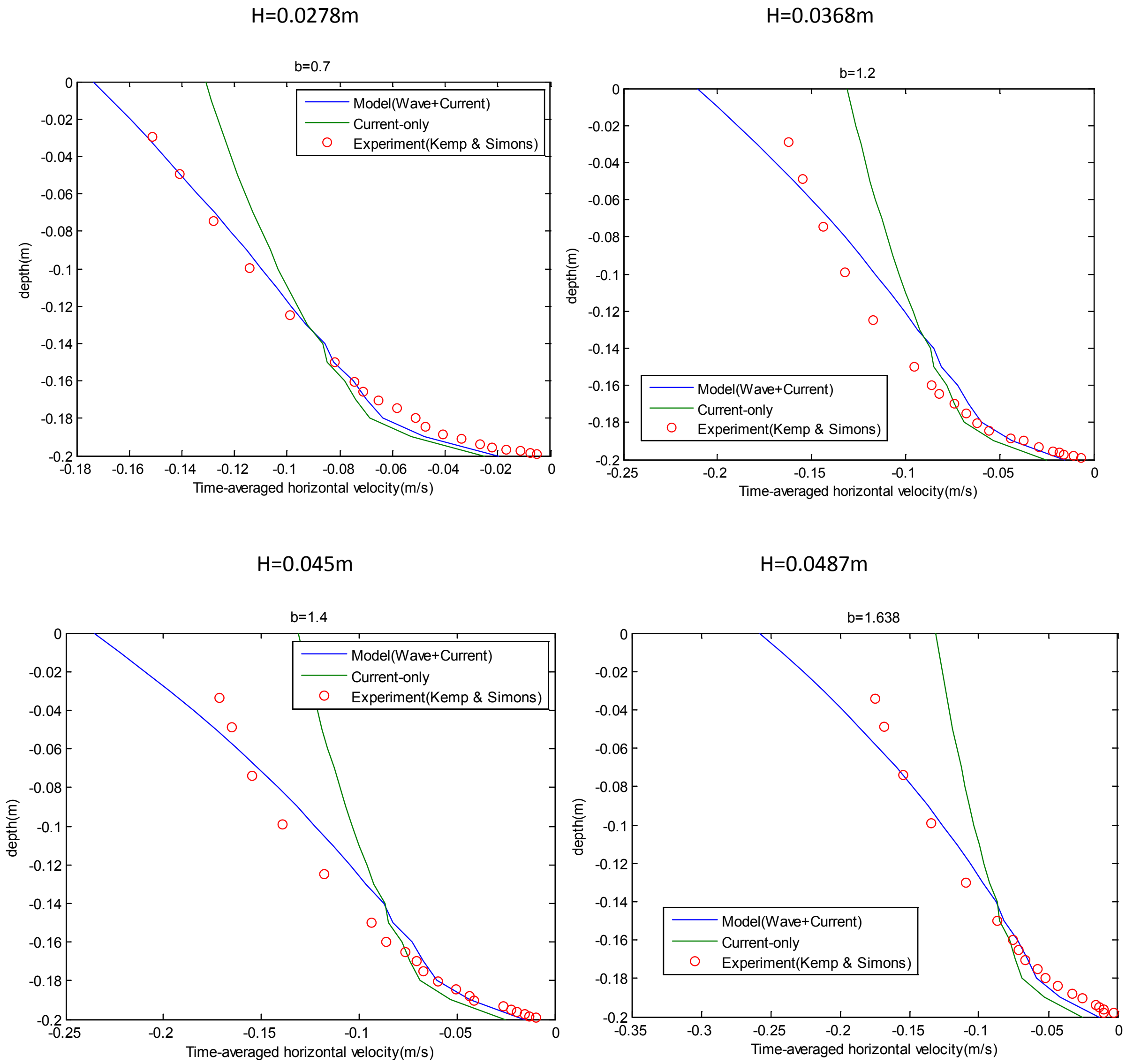

Figure 5. Model-data comparisons for the mean current profile under the wave + opposing current situation. The four subplots are for 4 different incident wave heights.