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Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean

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Long-Term Goal

Our goal is to develop a comprehensive, verified community model that predicts nearshore hydrodynamics, sediment transport, and seabed morphology changes given offshore wave conditions and initial bathymetry.

Objectives

The basic scientific objective is to synthesize understanding of physical processes in the nearshoreocean by developing a model forwaves and resulting radiation stresses and mass fluxes over evolving coastal bathymetry and currents wave-induced circulation sediment transport and morphological evolution. An additional objective is to test model components and the full community model with field observations.

Approach

Our approach is to develop a tightly-coupled system of individual model components, or modules. We are utilizing a framework where wave processes are distinguished from wave-averaged processes by means of a suitable time average. The resulting set of modules and their functions are: 1. wave module - calculation of second- and third-moment wave properties, including frequencydirectional spectra, radiation stresses, and wave skewness and asymmetry 2. circulation module - calculation of wave-driven circulation and turbulence levels 3. seabed module - calculation of local sediment fluxes and seabed changes resulting from flux divergences, and characterization of bed geometry

A model backbone will allow interaction and feedback between the individual modules and provide an interface to users. Candidate models to be used within each module are being investigated and tested. The model backbone will be constructed as an open architecture with a documented set of required inputs and outputs for each component, allowing users to provide alternative formulations for each module. Wave modules based on energy balances and on frequency domain Boussinesq or mild-slope equations are being investigated. Phase resolving formulations will allow detailed time series of waves to be simulated, and stochastic approaches will allow waves over large nearshore regions to be modeled. Breaking wave dissipation will be included to model waves propagating across the surf zone.

Circulation will be modeled with SHORECIRC (SC) and the Princeton Ocean Model (POM). SC solves the short-wave averaged equations including the 3-dimensional structure of mean and infragravity band currents using forcing and mass flux calculations provided by the wave module. POM is a finite-difference approximation to the hydrostatic primitive equations with a free surface, and includes equations for continuity, momentum, temperature, and salinity.

The seabed module will model the local flux of sediment and the evolution of seafloor sedimentology and morphology. Field observations are being used to develop models for sediment flux driven by nearbottom velocities. Conservation of mass allows sediment flux calculations to be used to predict changes in large-scale nearshore bathymetry. The effects of bedforms such as ripples and megaripples will be incorporated into the modules. Model components and the full community model will be tested by comparison with field observations of waves, currents, sea floor morphology and bathymetric evolution observed at a variety of field experiments.

Work Completed

Three group meetings have been held to organize activities and review results. Working groups have been formed in the areas of (1) surface wave dynamics, (2) wave-induced circulation and turbulence, (3) sediment transport and seabed morphology, and (4) verification and data assimilation. Groups (1)-(3) are pursuing the development and testing of individual modules with the goal of advancing the science in each, as well as defining how each module will interact most effectively with the other model components. Group (4) is testing and calibrating existing models, and assembling a WWW site for field data that can be used by the NOPP partners to test individual modules.

The new time-domain wave driver based on a nonlinear Schrodinger equation (Kennedy and Kirby, 2003) has been coupled to the SHORECIRC model using the prototype model backbone, and is being applied to the study of unsteady currents driven by wave groups.

The effect of nonlinear wave-wave interactions between triads of wave components has been examined for shoaling wave trains. The stochastic model of Herbers and Burton (1997) was extended into the surf zone using a heuristic parameterization of wave breaking dissipation and an improved closure approximation that allows for a relaxation to Gaussian statistics over distances comparable to the surf zone width, while retaining the quasi-normal approximation outside the surf zone. The model was tested through extensive comparisons with data from both laboratory. Work is in progress to extend the model to deeper water and beaches with weak alongshore depth variations.

A curvilinear version of the SC model has been tested against field data obtained at Gray's Harbor, Washington (Shi et al, 2003). A spectral solution of the depth-varying portion of the motion has been implemented in existing Cartesian version of SC, and will allow for the implementation of more accurate turbulence closure schemes.

The Princeton Ocean Model (POM) has been adapted for applications to wave-averaged circulation by adding parameterized forcing represented by gradients in the radiation stress tensor. The appropriate specification of the depth dependence of these forcing terms is an important research issue that remains under study. Additional forcing related to rollers and the effects of wave-induced mass flux is included. Different turbulence closure models, including Mellor-Yamada and k-epsilon schemes, are being used.

Boundary conditions for the turbulence quantities at the surface that include the effects of breaking waves have been implemented. The Styles and Glenn (2000) wave-current bottom boundary layer model that parameterizes the effect of waves on the bottom stress has been embedded. Initial studies have involved the project benchmark applications including comparisons with data from the DUCK94 and SandyDuck field experiments and comparisons with laboratory measurements of rip currents (Haas and Svendsen, 2002). A comprehensive study of the theoretical formulation for wave-averaged equations in acoordinate framework has been conducted (Mellor, 2002).

The Bagnold/Bailard/Bowen sediment transport equations have been examined with respect to the validity of their assumptions in the nearshore environment. These equations were also applied to predict the equilibrium cross-shore profile under simple wave conditions. The model was found to generally be inadequate for the prediction of sediment transport in the nearshore region. Many of the assumptions inherent in this type of model are violated under common environmental conditions. This realization has lead to a significant effort to extend the Bagnold/Bailard/Bowen formulation using additional information from the fluid acceleration.

Two new models for sediment transport under unbroken waves have been developed and are currently being refined. The first is a model for sheet flow based upon a two-phase approach in which granular mechanics are utilized to model the highly concentrated region near the seabed. The model provides qualitative results that are consistent with the observations obtained in SISTEX99. The second model is for suspended sediment concentration under unsteady waves above a rippled seabed. In this model, the recent history of the wave forcing is incorporated into the prediction for suspended sediment concentration.This results in a significant improvement in predictive capability over instantaneous models.

We continue to examine bed load processes in the surf zone using a discrete particle model to explore two phenomena of interest: 1) the effects of local bed slope on bed load transport rates under various waveforms typical of the surf zone; and 2) processes that segregate particles by size and density. Work to date using discrete particle simulations indicates that transport rates for different grain sizes can vary by factors of two to three or more for size distributions which include a wide range of sizes. In particular,distributions including sand and gravel show the largest disparities in transport rates. Visualization of simulation results clearly indicate that as grains are sheared in the bed load layer under sheet flow conditions, larger grains rise to the top of the bed load layer while smaller grains fall into relatively more protected, slower moving regions of the layer. Such ”inverse grading” is commonly observed in nearshore deposits and elsewhere in the geologic record. In addition to the work on the coupled wave driver and circulation model approach, work has been done to extend the Boussinesq model framework as a comprehensive model for coastal processes. Recent work has examined the predictions of longshore currents (Chen et al, 2003) and their low-frequency variability (Kirby et al, 2002), and initial studies of cross-shore sediment transport using accelerationdependenttransport formulas have been carried out.

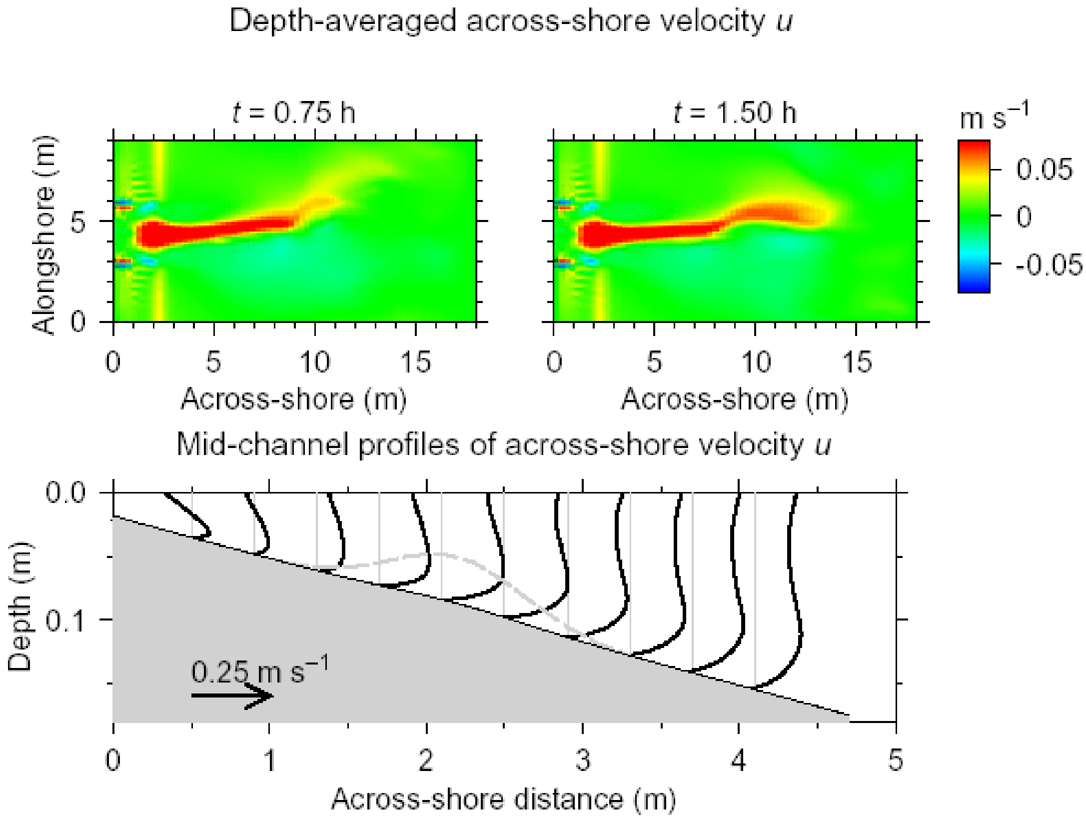
Results

The random wave driver REF/DIF S has been used in conjunction with the curvilinear SHORECIRC model to study undertow during the Duck 94 experiment, yielding successful results for wave heightdistributions and undertow profiles on a cross-shore transect. (Kaihatu et al, 2002)

The phenomenon of shear waves (Oltman-Shay et al, 1989) has been widely studied in the literature by means of numerical modelling. Previous studies have all been conducted using depth-uniform nonlinear shallow water equations or slightly modified version of those equations. An exception is the work by Putrevu and Svendsen (1999) which analysed the effect of the 3-D current structure which has also been found responsible the major part of the lateral mixing in the nearshore (Svendsen and Putrevu, 1994). Inclusion of the 3-D current structure influences the conclusions of earlier investigations on shear wave generation and development. The results are very complex but generally show that the 3-d effects greatly reduce the occurance of instability of the current and play an important role in the development of the shear waves once generated (Zhao et al, 2002).

In the initial applications of POM to DUCK94 and SandyDuck, a two-dimensional approximation (variations across-shore and with depth; uniformity alongshore) has been utilized. Comparisons of model velocities with the 3 hour average velocity measurements from the fixed array of Elgar and Guza show generally good agreement. Comparison of the vertical structure of the model horizontal velocities with the DUCK94 sled measurements of Thornton and colleagues (Garcez Faria et al., 1998; Garcez Faria et al., 2000) likewise shows encouraging agreement. The effects of tidal elevation change on the circulation during DUCK94 are investigated and show variations in the strength of the undertow over the bar and in the trough with tidal height that are in general agreement with velocity measurements from the fixed array. Analysis of the dynamical balances in the model solutions demonstrate the importance of the depth-dependent across-shore circulation, through the across-shore transport of alongshore momentum, in determining basic qualitative features of the wave-averaged circulation.

Three-dimensional experiments for DUCK94 show the development of shear instabilities in the alongshore current that typically take the form of nonlinearly equilibrated shear waves. Initial three-dimensional model runs for the laboratory experiments with rip channel geometry show formation of a narrow, unsteady offshore rip current with largest vertical shear in a relatively thick bottom boundary layer (see Figure 1). Shear wave properties during the SandyDuck experiment were estimated with arrays of current meters deployed for 4 months within 300 m of the shoreline of a sandy beach. Shear wave velocity fluctuations are approximately horizontally isotropic, with root-mean-square values between 10–40% of the mean alongshore current . Cross-shore variations of the time-averaged shear wave momentum flux are consistent with shear wave energy generation close to shore where the breaking-wave driven mean alongshore current and its shear are strong, and shear wave energy dissipation and transfer back to the mean flow farther offshore where and are weak. In case studies where is a narrow jet near the shoreline, the observed strong decay of shear wave energy levels seawards of the jet, and the cross and alongshore structure of shear waves within the jet, are similar to predictions based on the linearly



unstable modes of the observed . Shear wave energy levels also are high in a marginally unstable case with a strong, but weakly sheared, . (Noyes et al, 2002). Mean currents during the SandyDuck ex-

Figure 1: top: Depth-averaged across-shore velocity in the rip channel at t=0.75 and t=1.5 h. bottom: Vertical profiles of the across-shore velocity in the rip channel at t=0.75 h. The vertical gray lines are the zeros for the profiles. The gray dashed line shows the across-shore location and shape of the bar. The rip channel is 3 m wide in the center of the 9 m domain.

periment were found to be alongshore uniform (Feddersen and Guza, 2003). An alongshore momentum balance between wind and wave forcing and bottom stress, cross-shore integrated between the shoreline and approximately 4 m water depth, holds on each of five instrumented cross-shore transects. The corresponding five drag coefficients are similar, consistent with the assumption that terms in the momentum balance associated with alongshore nonuniformity are negligible. In addition, the alongshore nonuniformity of the circulation and bathymetry were examined at five cross-shore locations. Except near the shoreline, the circulation and bathymetry were rarely strongly alongshore nonuniform, and the circulation nonuniformities were usually no larger than expected from current meter noise alone. Near the shoreline, the bathymetry was more irregular and the circulation was often detectably nonuniform, although no relationship between bathymetric and circulation nonuniformities was found. The closure of the alongshore momentum balances on cross-shore transects, and the observed alongshore uniformity of the circulation on four of five alongshore transects, demonstrates that the simplified dynamics of alongshore uniform circulation are valid during the experiment. Initial work on extensions to the Bagnold/Bailard/Bowen sediment transport formulation has given several indications that formulas for transport have an increased capability in predicting cross-shore transport during the recovery phase of nearshore bar evolution. An example may be found in the work of

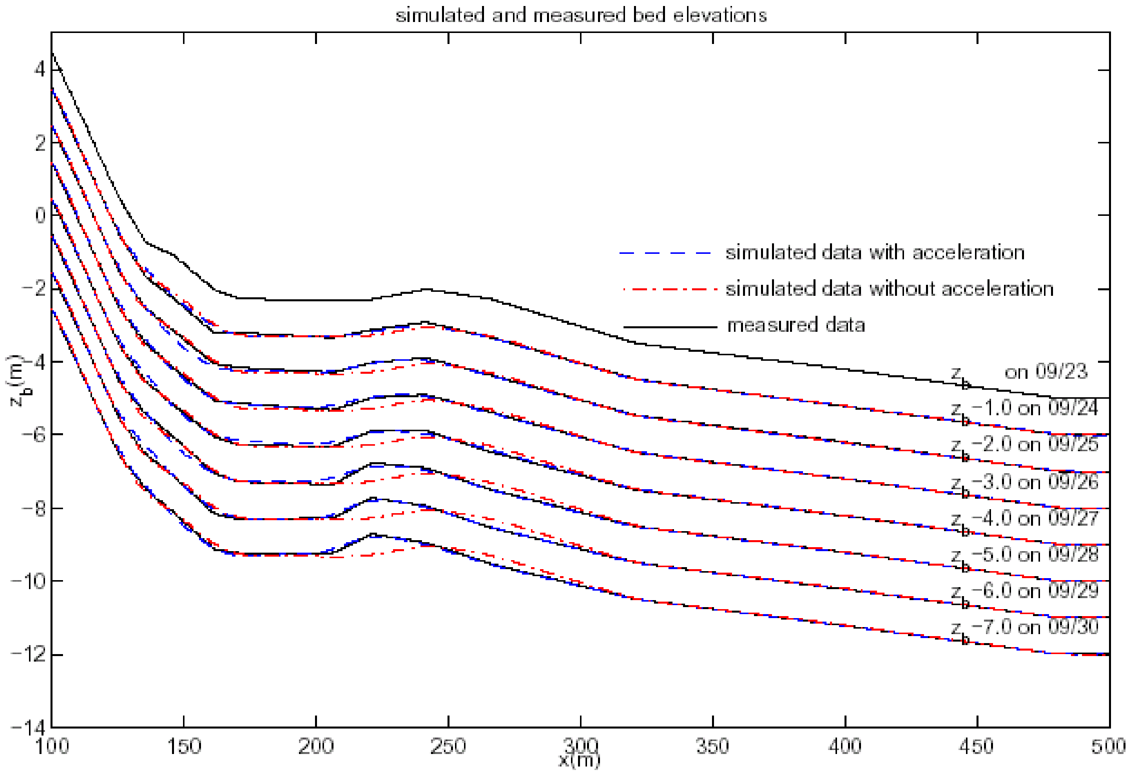


Figure 2: Profile evolution during 9/23/94- 9/30/94, Duck 94. The dashed line shows profile evolution with an extended transport formula including acceleration, indicating an enhanced predictive capability during accretion. The dash-dot line represents the originalBagnold/Bailard/Bowen relation.

Long and Kirby (2003), who have implemented an acceleration-dependent transport formula in a timeresolving Boussinesq model, and have calibrated the formula using data from Duck 94. Figure 2 shows a comparison of profile evolution for an 8 day period during which a shore-parallel bar moved 30m landward in moderate wave conditions. The figure compares results from the Bagnold/BailardBowen model as calibrated by Gallagher et al (1998), where littel bar evolution is noted, and an extended formula incorporating acceleration effects, which recovers the bar motion quite well. The formulas utilized in this and related calculations are still very ad hoc in nature, and a focus of the next year’s work will be the attempt to provide a theoretical basis for such a formulation.

IMPACT/APPLICATION

The model system under development will provide a comprehensive predictive tool for nearshore processes, and will have a wide range of uses in the scientific community, as well as in DoD and civil planning and operations.

Related Projects

The investigators in the NOPP project have a range of individual projects with closely related science and modeling objectives. The NOPP effort benefits these other ongoing studies by increasing collaboration and exchange of results and data among the partners. The NOPP project allows results from individual investigations to be synthesized into a community-wide model for nearshore processes.

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Publications

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