

Massively Scalable Mixture Model for Small-scale Sand Ripples

Joseph Calantoni
Marine Geosciences Division
Naval Research Laboratory
Code 7440.3, Building 1005
Stennis Space Center, MS 39529
phone: (228) 688-4435 fax: (228) 688-4853 email: joe.calantoni@nrlssc.navy.mil

Allison M. Penko
Marine Geosciences Division
Naval Research Laboratory
Code 7440.3, Building 1005
Stennis Space Center, MS 39529
phone: (228) 688-4823 fax: (228) 688-4853 email: allison.penko@nrlssc.navy.mil

Award Number: N0001410WX20018
<http://www7400.nrlssc.navy.mil/index.htm>

LONG-TERM GOALS

Our long-term goal is to develop a modeling framework to predict sediment transport, the evolution of seafloor roughness, and acoustic propagation through the seafloor in the nearshore and littoral battlespace environment.

OBJECTIVES

Our primary objective is to develop and validate a massively parallel version of an existing mixture model, SedMix3D (Penko et al., *in press*), for simulating small-scale ripple dynamics in shallow littoral environments. Applicability of the serial version of SedMix3D is severely hampered by physical limitations (memory and CPU speed) of typical desktop workstations. The scalable version of SedMix3D developed here will be able to simulate prototype size domains as found in the center of a laboratory U-tube (up to 1 m in length), for example. The parallel version of SedMix3D is a powerful research tool that will be used to study the details of small-scale sand ripple dynamics including (1) the effects of suspended sediment concentration on turbulence modulation, (2) the dynamics of ripple transitions from 2D to 3D (and back to 2D) under changing forcing conditions, and (3) the role of terminations and bifurcations on ripple migration and growth rates.

APPROACH

SedMix3D solves the unfiltered Navier-Stokes equations for the fluid-sediment mixture with the addition of a sediment flux equation that considers the balance between gravitational settling, advection, and diffusion. The capability of SedMix3D to simulate small-scale sand ripple dynamics has been illustrated both qualitatively and quantitatively (Penko and Slinn, 2006; Penko et al., 2008;

Penko et al., *in press*). These initial quantitative comparisons between the model and existing laboratory data were performed using simulation domains that were essentially two-dimensional. Our approach here has been to use the message-passing interface (MPI) to develop a parallel and massively scalable version of SedMix3D to utilize existing HPC hardware and ultimately perform quantitative comparisons with existing laboratory data using three-dimensional simulation domains.

WORK COMPLETED

We successfully parallelized SedMix3D using the message-passing interface (MPI). Typical simulations involving multiple ripple wavelengths now run on 128 – 512 cores. Recent speed up tests indicate that the parallel version of SedMix3D is 93.3% parallel resulting in approximately a 15 times speedup over the serial code when running on 512 cores. Further refinement and optimization of the MPI version of SedMix3D is still ongoing.

Laboratory measurements of velocity obtained from particle image velocimetry (PIV) were used to compute phase averaged velocity, vorticity, and swirling strength through a vertical slice in the water column (Rodriguez-Abudo and Foster, 2010; Rodriguez-Abudo and Foster, *in prep*). Measured velocity time series from a laboratory ADV (acoustic doppler velocimeter) located outside the wave bottom boundary layer was used to drive simulations. Fully three-dimensional simulations of the laboratory experiments were run and direct comparisons from a vertical slice in the simulation domain show remarkable agreement with the laboratory measurements (see results below). Additionally, we have performed extensive testing of model parameterizations for the effective viscosity, the bulk hindered settling velocity of sediment, and the particle pressure.

RESULTS

To validate the parallelized version of SedMix3D we made comparisons with laboratory measurements of flow velocity obtained from PIV (Rodriguez-Abudo and Foster, 2010; Rodriguez-Abudo and Foster, *in prep*). In Figure 1, snapshots from the simulation and experimental data are shown. The model is driven by the free stream velocity acquired from an ADV over the 20 wave periods examined. The simulated bed profile is initialized with the observed bed profile averaged over the first wave period in the observation time series. The fluid ($\rho = 0.998 \text{ g cm}^{-3}$, $\mu = 1 \times 10^{-2} \text{ g cm}^{-1} \text{ s}^{-1}$) and sediment ($d = 0.054 \text{ cm}$, $\rho_s = 1.198 \text{ g cm}^{-3}$, $w = 1.7 \text{ cm s}^{-1}$) properties used in the simulation matched those from the experiments.

The simulations are turbulent and fully three-dimensional. The three-dimensional structures in the flow field are primarily responsible for entraining and advecting suspended sediment. We examine the ability of SedMix3D to accurately produce such three-dimensional structures by looking at the vorticity field generated at different phases of the wave compared to the measured vorticity field (Figure 2). Additionally, we compared the simulated and measured swirling strength (Figure 3). The swirling strength is a scalar quantity that identifies locations where streamlines are closed, which are typically associated with vortex cores. In both cases for the vorticity and swirling strength SedMix3D accurately reproduces both the timing, location, and intensity of vortical structures. SedMix3D may now be used as a research tool to improve existing parameterizations for vortex sand ripple dynamics.

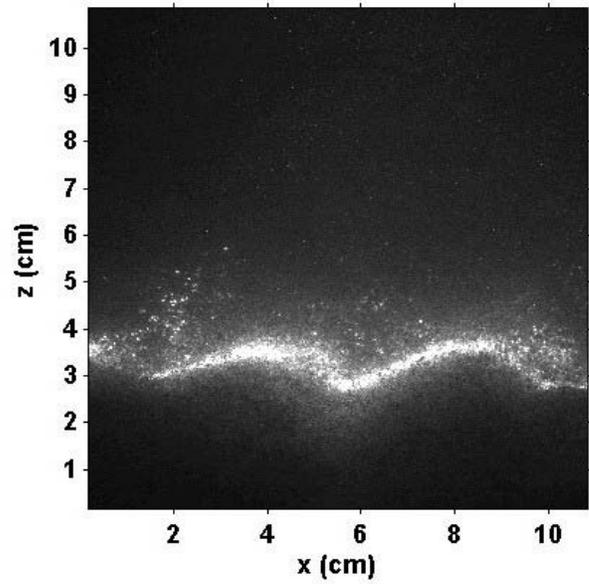
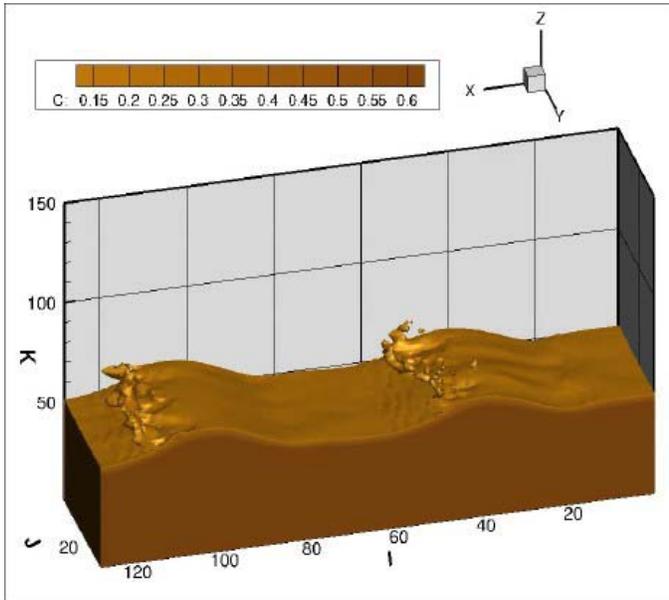


Figure 1. Shown (left) is a snapshot of the concentration output from SedMix3D at maximum horizontal velocity. Isosurface of suspended sediment is contoured at 10% concentration by volume. Axis labels indicate number of computational grid points with domain size, $I = 10.6$ cm, $J = 2.6$ cm, $K = 10.8$ cm. Shown (right) is a raw image from the laboratory used to extract two-dimensional velocity vectors for comparison (courtesy of Dr. Diane Foster, University of New Hampshire).

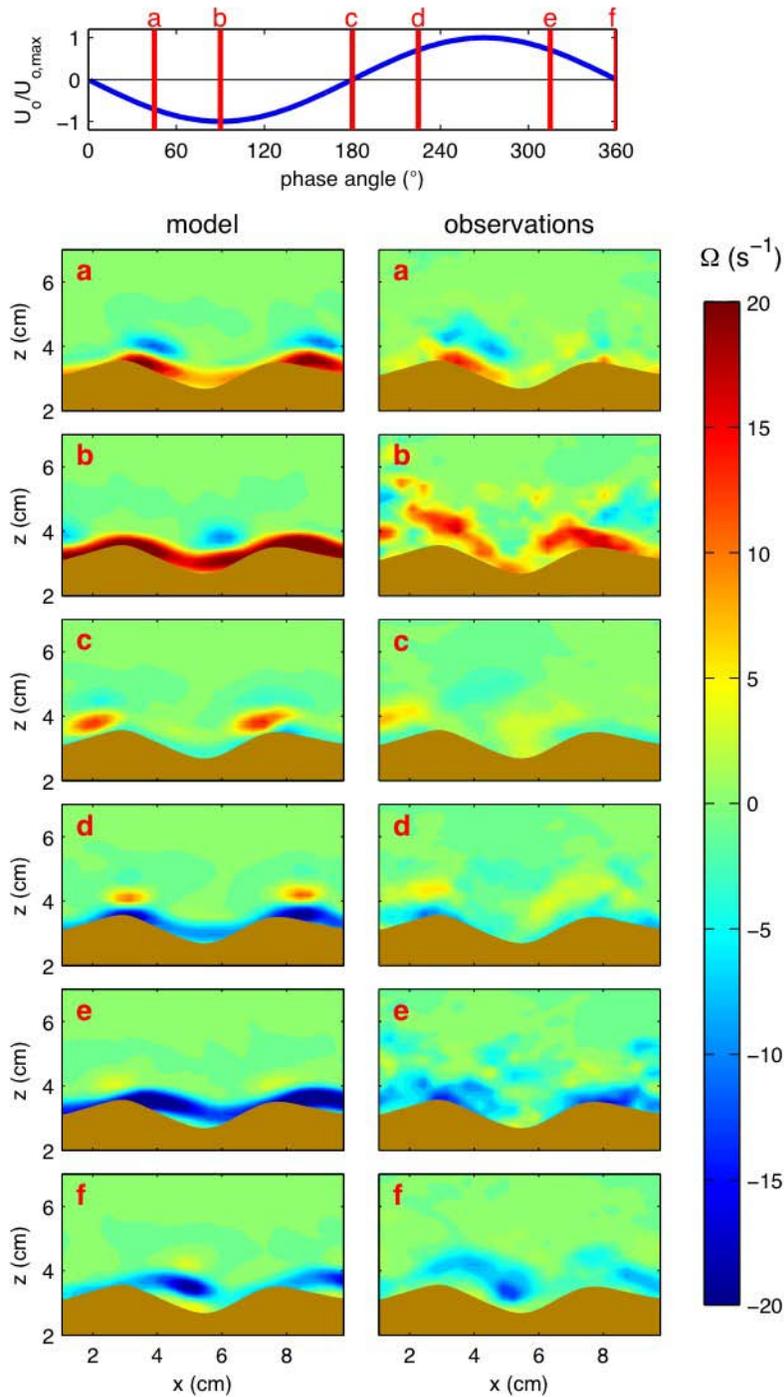


Figure 2. Shown above are phase-averaged modeled and observed vorticity fields at six different phases of the wave. Flow is initially directed to the left. Positive (red) contours indicate counter-clockwise rotation. A time-average of the observed bed profile is plotted for reference. The free stream velocity is plotted in the top panel where the red lines indicate the phase locations.

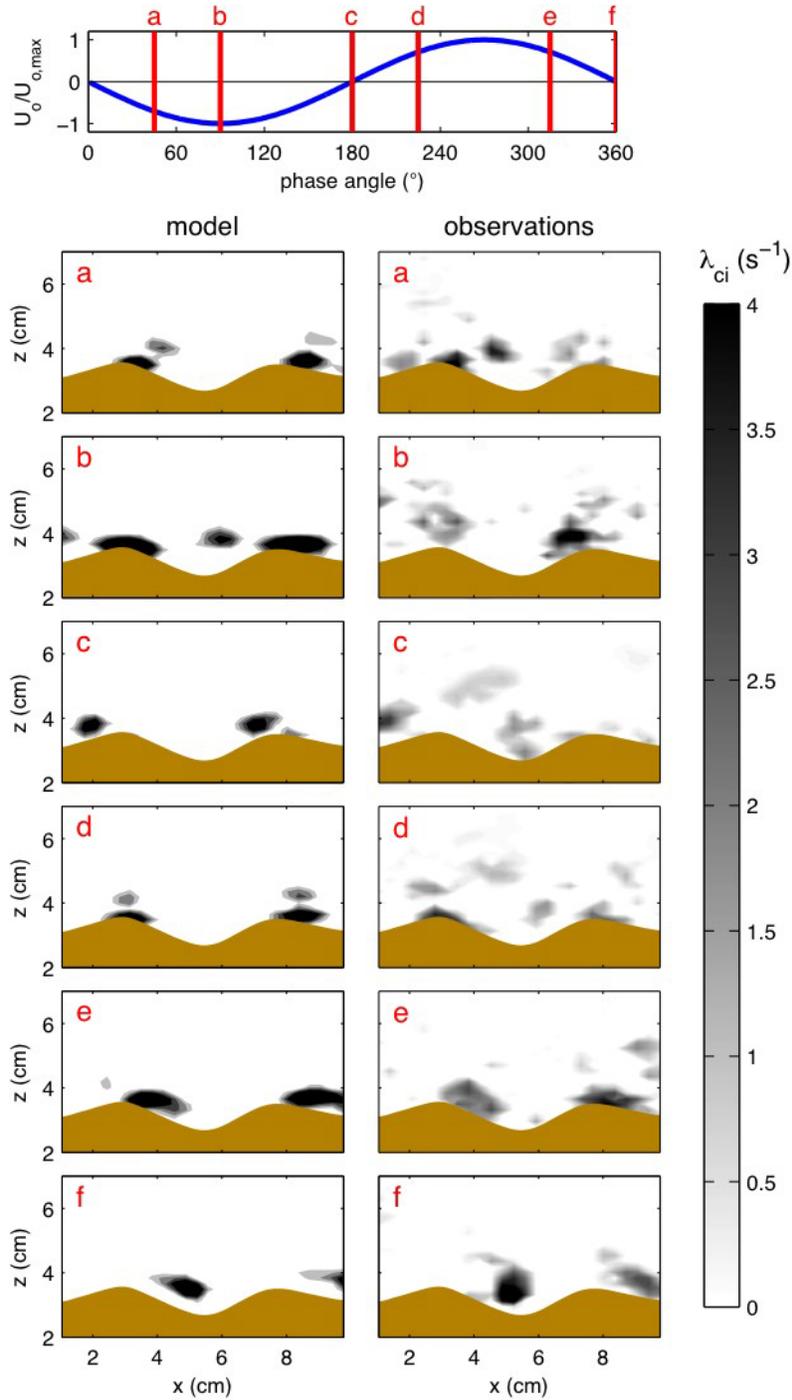


Figure 3. Shown above are phase-averaged modeled and observed swirling strength at six different phases of the wave. Swirling strength is a scalar measure of the magnitude of coherent, closed vortex structures excluding the influence of boundary-layer generated shear. A time-average of the observed bed profile is plotted for reference. The free stream velocity is plotted in the top panel where the red lines indicate the phase locations.

IMPACT/APPLICATIONS

The research tool developed here will be used to improve understanding of bedform dynamics, and more generally, bottom boundary layer physics in shallow sandy environments. We expect the results to impact broadly both Naval operations (e.g., littoral navigation and trafficability including surf zone breaching, MCM, and characterization of both the air-sea boundary layer and the seafloor boundary layer in the battlespace environment) and commercial activities (e.g., coastal restoration procedures and design of coastal infrastructure).

RELATED PROJECTS

The PI is the lead investigator for an NRL 6.1 base project (FY08 – FY10), titled “Direct Numerical Simulation of Small-scale Sand Ripples”. The parallel version of SedMix3D developed here was used in direct support of the NRL base project. Likewise, all HPC resources used to perform the work funded by ONR were provided by NRL. Additionally, the model and simulation results produced here form the basis for the Ph.D. dissertation (defense scheduled 28 October 2010) of co-PI, Allison M. Penko, University of Florida. Presently, Ms. Penko is working at NRL under the Student Temporary Employment Program (STEP).

REFERENCES

- Penko, A.M., and D.N. Slinn (2006), Modeling sand ripple evolution under wave and current boundary layers, *Proceedings of the 30th International Conference on Coastal Engineering*, ASCE, San Diego, CA.
- Penko, A.M., Slinn, D.N., and D.L. Foster (2008), Model-Data Comparison of Sediment Transport over Evolving Rippled Beds, *Ocean Sciences Meeting*, Orlando, FL.
- Penko, A.M., Slinn, D.N., Calantoni, J., and G.M. Burdick, *in press*, Model for direct numerical simulation of vortex sand ripple dynamics, *Journal of Waterway, Port, Coastal, and Ocean Engineering*.
- Rodriguez-Abudo, S. and D.L. Foster (2010), Characterization of the wave bottom boundary layer over movable rippled beds, *Eos Trans. AGU*, 91(26), Ocean Sci. Meet. Suppl., Abstract PO21B-05.
- Rodriguez-Abudo, S. and D.L. Foster, *in prep*, Observations of the wave bottom boundary layer over a movable rippled bed, *to be submitted to Journal of Geophysical Research*.

PUBLICATIONS

- Penko, A.M., Calantoni, J., and D.N. Slinn (2009), Mixture theory model sensitivity to effective viscosity in simulations of sandy bedform dynamics, *Proc. IEEE Oceans 2009, OCEANS*, Biloxi, MS.
- Penko, A.M., Calantoni, J., and D.N. Slinn (2010) Direct numerical simulation of sediment transport and seabed morphology at laboratory scales, *Proc. International Conference on Multiphase Flow*, Tampa, FL.

Penko, A.M., Slinn, D.N., Calantoni, J., and G.M. Burdick, *in press*, Model for direct numerical simulation of vortex sand ripple dynamics, *Journal of Waterway, Port, Coastal, and Ocean Engineering*.

HONORS/AWARDS/PRIZES

Allison M. Penko received Third Place Award in the MTS/IEEE OCEANS '09 Student Poster Competition at the Oceans '09 Conference in Biloxi, MS (October 2009).