The Naval Seafloor Evolution Architecture: a platform for predicting dynamic seafloor roughness

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ABSTRACT: Predictions of waves, currents, sediment transport, and the acoustic response of the seafloor depend on reliable estimates of seafloor roughness due to bedform geometry. To predict the spatial and temporal dynamics of seafloor roughness under changing wave conditions, we have developed a modular modelling system, the Naval Seafloor Evolution Architecture (NSEA). NSEA is included in a repository of bottom boundary layer models within a larger modelling framework (Sediment Mobility Regime Estimator – SeaMoRE) developed to ingest regionally simulated wave and current conditions and output near bed hydrodynamics to drive smaller scale models. The near bed wave and current velocity output from SeaMoRE is used to drive a nonequilibrium spectral ripple model within NSEA to estimate the time-dependent power spectrum of the seabed elevation. From the timeseries of the amplitude power spectra, statistical characteristics of the seafloor, such as roughness lengths, can be derived. We illustrate the applicability of this model framework by using it to estimate seafloor ripple evolution during a field experiment off the coast of Panama City, Florida, USA and its potential to forecast seabed roughness variability at other locations using web accessible global models.

1 INTRODUCTION

Seafloor roughness can enhance bottom boundary layer turbulence, is evolved by sediment transported at the seafloor interface, and can have a dynamic feedback between the waves/currents that generate bedforms by also attenuating wave and current energy after formation.

Seafloor roughness is defined here as the unresolved variations in bathymetry at higher resolutions than gridded bathymetric data and/or unresolved in a numerical model. High-resolution models O(1mm-1cm) can directly simulate the interactions between fluid and sediment on the seafloor [Salimi-Tarazouj et al. (2021); Penko et al. (2013)], but are too computationally expensive to couple with regional nearshore wave and current models. Modules to predict roughness within hydrodynamic models are typically empirical in nature and based on the roughness being in equilibrium with the instantaneous forcing, which is not wholly realistic. Coupling (either one- or two-way) a seafloor spectral model to a hydrodynamic model allows for the generation of time-dependent seafloor elevation realizations correlated to the shear stress on the seabed caused by the propagation of surface waves and bottom currents. This method takes into account the time history of the forcing, allowing time for the roughness to adjust to the changing forcing conditions.

Presented here is a modelling framework for estimating seabed boundary conditions given user chosen wave and current models and a one-way coupled spectral seabed model to produce time-dependent realizations of seafloor roughness. The Seabed Mobility Regime Estimator (SeaMoRE) [Penko and Phillip, in review] ingests hydrodynamic information and outputs seafloor boundary layer forcing for input to the Naval Seafloor Evolution Architecture (NSEA) [Kearney and Penko, 2022], which characterizes the spatial and temporal evolution of seafloor roughness.

2 MODEL DESCRIPTIONS

Seabed Mobility Regime Estimator

SeaMoRE is designed to extract and reformat a variety of publicly available meteorological and oceanographic (METOC) data from webservers. Current models (e.g., Navy Global Hybrid Coordinate Ocean Model (HYCOM), Navy Coastal Ocean Model (NCOM)) data are available via NOAA's National Centers for Environmental Information (NCEI) Environmental Research Division's Data Access Program (ERRDAP) server. Python code has been developed to automate the extraction of data needed for calculating the current bottom boundary layer forcing information by SeaMoRE [Penko et al., 2022]. Additionally, NOAA's WaveWatch III (WW3) Production Hindcast multi-grid spectral wave model provides historical and recent global and regional wave data. The WW3 Production Hindcast model can be used to provide the data for SeaMoRE's wave bottom boundary layer calculations. SeaMoRE ingests the wave and current model data along with sediment information (mean grain size and sediment density) and outputs gridded estimations of seabed sediment mobility (based on the critical threshold for sediment incipient motion and sheet flow) and near bed hydrodynamics (bottom current magnitude and direction, wave orbital velocity, wave bottom orbital excursion, and wave direction) (Figure 1).

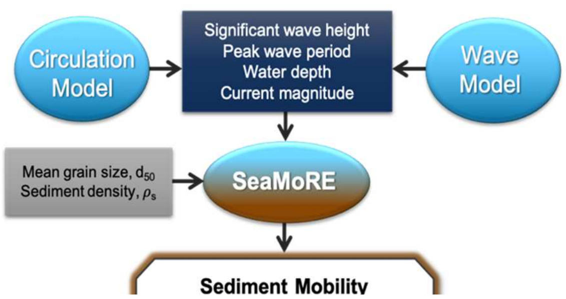

Figure 1: Flow chart depicting SeaMoRE's inputs and outputs.

Data is written in both NetCDF and CSV formats for reading into one-way coupled bottom boundary layer models (e.g., NSEA). For validation purposes, observational data can also be input to SeaMoRE, and the output from the sediment mobilization estimations can be compared to local observations of sediment transport as presented here.

Naval Seafloor Evolution Architecture

NSEA consists of four modules: forcing, seafloor evolution, seafloor synthesis, and observations. Information naturally flows from one module to the next (i.e., the seafloor evolution module uses the forcing information and its outputs are used by the seafloor synthesis module). The forcing information is directly provided by SeaMoRE at the location of interest. The seafloor evolution model [Penko et al., 2017, Kearney and Penko, 2022], approximates the evolution of the amplitude spectrum of the seafloor elevation by modelling the relaxation of the amplitude spectrum toward its equilibrium value calculated from an equilibrium ripple predictor method [e.g., Nielsen, 1981; Nelson et al., 2013] with a time scale based on the instantaneous ripple geometry and sediment transport rate [Traykovski, 2007]. Under strong forcing conditions, sheet flow conditions are expected to exist, in which case the entire bed is mobilized and any ripples present are washed out. In the absence of hydrodynamic forcing, bioturbation will slowly modify the roughness, leading to a decay of ripple amplitude and is modelled as a diffusive process [Jackson et al., 2009]. The output of the seafloor evolution model is the amplitude spectrum, which characterizes the statistical properties of the random seafloor elevation field. statistics of seafloor roughness such as the root-mean-square elevation or the peak ripple wavelength can be computed from the spectrum. Random realizations of seafloor elevations can then be generated from the output spectrum through a Fourier synthesis approach. Finally, the seafloor realization

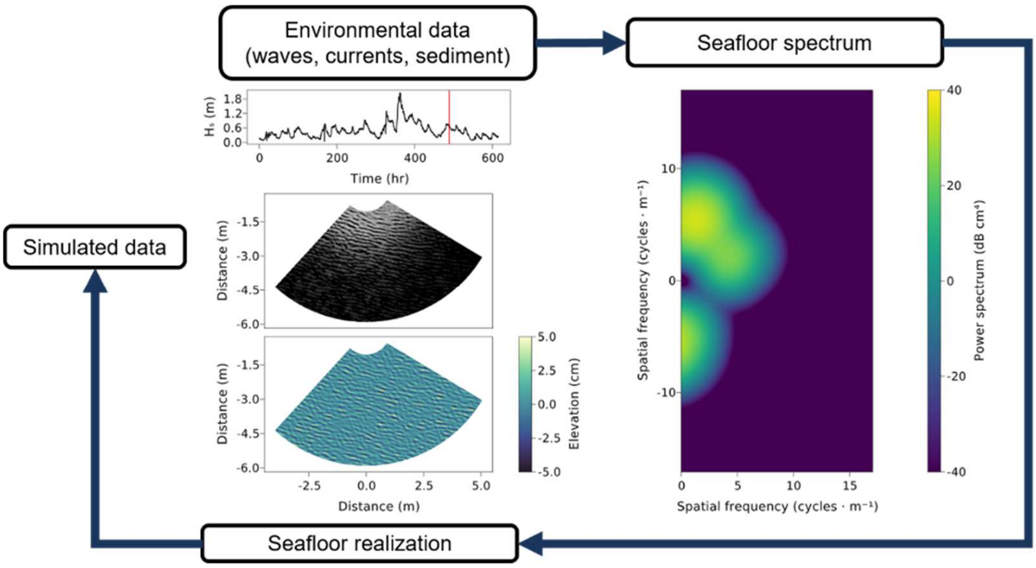

Figure 2: Flow chart of the input and output of the modules in NSEA.

elevations can be used to simulate a timeseries of acoustic data A flow chart depicting the inputs and outputs of the NSEA modules is shown in Figure 2. For complete model description see Kearney and Penko [2022].

3 RESULTS & DISCUSSION

The applicability and validation of this model architecture is presented by estimating seafloor roughness during the Target and Reverberation Experiment (TREX13) deployed off the coast of Panama City, FL, USA in 2013. Instrumentation on a quadpod in 8m water depth collected data for 34 days.

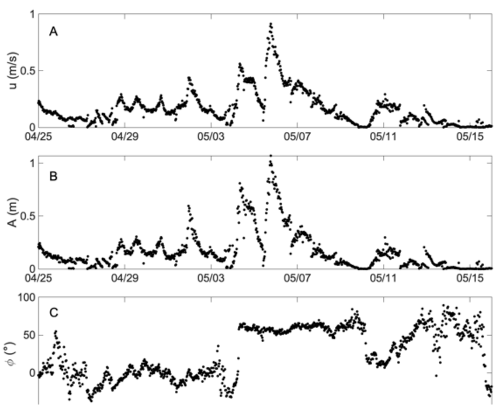

Figure 3: (A) Bottom orbital velocity, (B) bottom semiorbital excursion and (C) wave direction (0° North) from the TREX13 field experiment.

Wave height, period, and direction were recorded by a Nortek AWAC-AST at 2 Hz for 1,024 s every 30 minutes. Linear wave theory was used to estimate the bottom orbital velocity and the semiorbital excursion from the observed significant wave height. The forcing data input to NSEA included the bottom orbital velocity (u), wave semiorbital excursion (A), and the wave direction (ϕ) (Figure 3). A 2.25 MHz rotary sonar (Imagenex 881b) installed at a height of 1.05 m above the seafloor imaged approximately a 6 m × 6 m area under the quadpods every 12 minutes. A fast Fourier transform of a 3 m × 3 m patch of the backscatter image was computed and the wavenumber corresponding to the maximum Fourier amplitude was extracted and converted into an estimate of the ripple wavelength.

The SeaMoRE-NSEA coupled framework was validated with observations of the ripples generated on the seafloor recorded with the rotary sonar (Figure 4). SeaMoRE ingested the wave observations and estimated whether the seafloor was in a stable state (the estimated bottom shear stress was below the critical shear stress for sediment incipient motion), an active ripple state (the estimated bottom shear stress was between the critical threshold for sediment incipient motion and the critical threshold for sheet flow), or turbulent (the estimated bottom shear stress was above the critical threshold for sheet flow). The contours in the top panel of Figure 4 shows the times when SeaMoRE predicts the stable (white), rippled (blue), and turbulent (red) regimes for the entire TREX experiment. The observed ripple wavelengths extracted from the rotary sonar backscatter image are plotted with black dots also in the top panel. The middle panels (a-d) are 3 m x 3 m images of the rotary sonar backscatter at four different times of the experiment showing the variability of the ripples.

At time (a), the seafloor is stable; however, ripples are present due to being generated by a previous forcing condition. NSEA predictions of a random seafloor realization at the same time as the sonar image is plotted in the bottom panels. The ripple geometry predicted in the seafloor realization in (a) is qualitatively similar to the sonar image. The ripple wavelengths and orientations are in good agreement with the observations. Note that the white color blocks in the top panel generally correspond to times when the ripple wavelengths are constant, indicating that SeaMoRE is in good agreement with the observations for the stable regime.

The blue shading indicates that sediment is predicted as being mobilized and/or ripples are actively evolving. At times (b) and (d), SeaMoRE predicts that the seafloor roughness is evolving, which is also observed in the sonar images. Note that the blue shading generally corresponds to times when the ripple wavelengths are observed as changing, showing that SeaMoRE is in good agreement with the observations for the ripple regime. At both times (b) and (d), NSEA predicts that the ripples are actively evolving and the wavelengths are increasing; however, it doesn't quite capture the three-dimensionality or the orientation of the ripple fields. The complex and three-dimensional ripple field could be a result of interacting waves and currents of varying directions which is presently not resolved in the model.

The red shading indicates that the bottom boundary layer is in a sheet flow regime, and

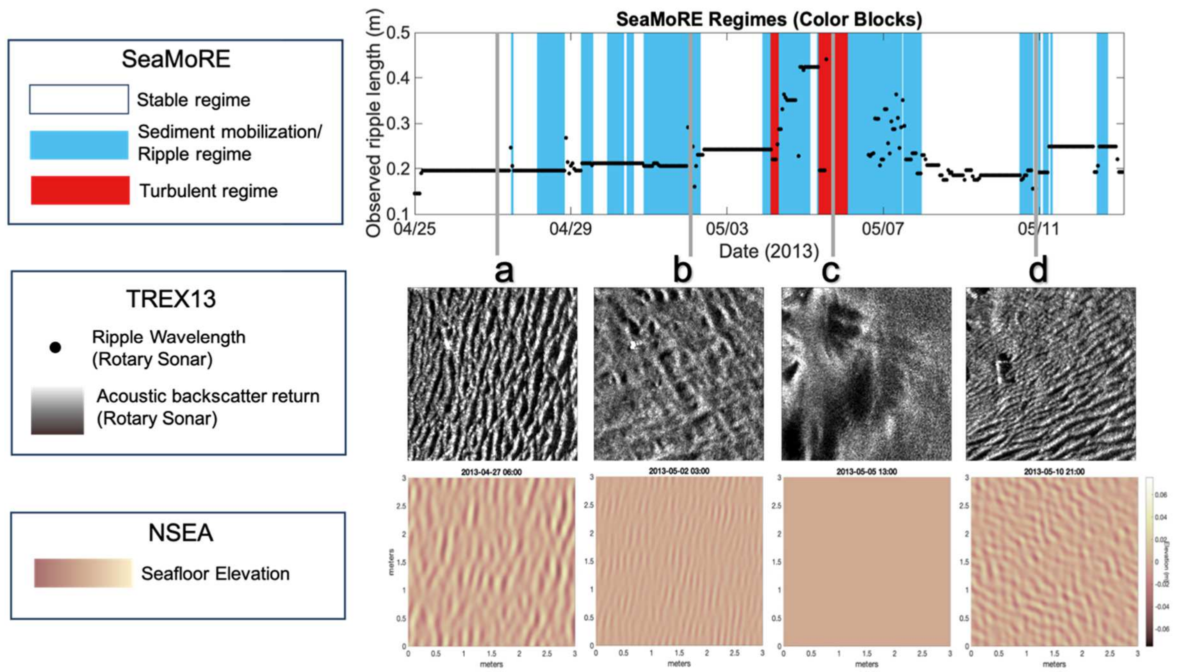

Figure 1: Output from SeaMoRE (color blocks in top panel) indicating the instantaneous seafloor regime and random seafloor elevation realizations output from NSEA (bottom panels) plotted with the rotary scanning sonar images (middle panels) and the peak ripple wavelength extracted using Fourier analysis on the sonar images (black dots in top panel). The grey lines in the top panel indicate the times of the four sonar images and NSEA model realizations.

the ripples are being washed out. SeaMoRE accurately predicts the two times in the time series that the ripples are sheared off completely by the flow and a smooth, flat bed results. NSEA also accurately predicts this result at time (c) as shown as no variations in seabed elevations in the bottom panel.

In general, both SeaMoRE and NSEA are in good agreement with observations of ripple fields as observed from rotary sonar backscatter images in 8 m of water depth. While both models compare well qualitatively, a more quantitative analysis and sensitivity testing is needed before the models can be applied at other locations.

4 CONCLUSIONS

A near bed hydrodynamic and sediment mobility model (SeaMoRE) was coupled with a seafloor roughness architecture (NSEA) to provide predictions of seabed regime (stable/evolving/turbulent) and random realizations of seabed elevations generated by local wave and current conditions. The models agreed well with observations made at the Target and Reverberation Experiment off the coast of Panama City, FL, USA, in 2013. Future work will include a sensitivity analysis on the models and validation at other field sites to determine the applicability of the models to other locations and conditions.

5 ACKNOWLEDGEMENTS

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