Supplementary Materials: Variations in the Wave Climate and Sediment Transport Due to Climate Change along the Coast of Vietnam

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1. Description of Models

1.1. CCAM

The Conformal Cubic Atmospheric Model (CCAM) is a semi-implicit, semi-Lagrangian atmospheric climate model based on a conformal cubic grid [1,2]. Although a global atmospheric model, a variable resolution grid can be used by applying a Schmidt transformation [3], which results in a finer grid resolution over the target area at the expense of a coarser resolution on the opposite side of the globe. In this way, CCAM can be used for regional climate experiments without imposing lateral boundary conditions. An example of variable resolution grid used for these experiments is shown in Figure S1.

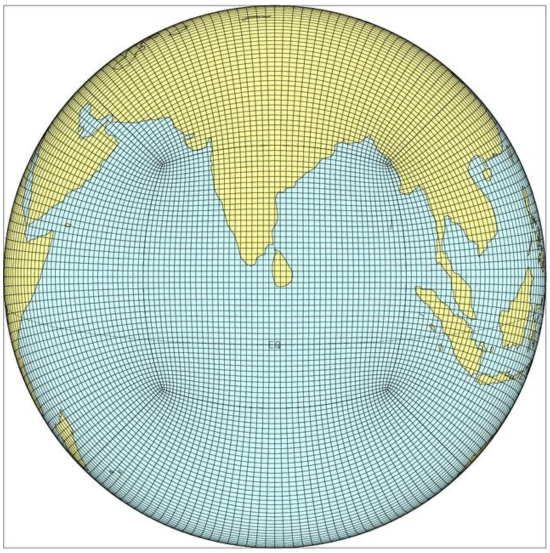

Figure S1. Plot of the variable resolution conformal cubic grid.

The design of CCAM's semi-implicit, semi-Lagrangian dynamical core is discussed in McGregor [1], including the use of a reversibly staggered grid which improves the dispersive aspects of the model [4]. The CCAM physical parameterizations used for this paper include a prognostic cloud scheme [5]. The land-surface scheme supports 6 levels of soil temperature and moisture as well as up to three levels of snow [6]. For these experiments a stability dependent boundary layer scheme was used with non-local vertical mixing and enhanced mixing of cloudy boundary layer air [7]. Gravity wave drag is parameterized following Chouinard et al. [8] Short wave and Long wave radiation for these experiments was parameterized according to Lacis and Hansen [9] and Schwarzkopf and Fels [10], respectively. In this work CCAM employed 18 vertical levels (ranging from 40 m to 35 km), although 27 level and 35 level configurations are also available.

1.2. MIKE21

MIKE 21 SW is a third-generation spectral wind-wave model that simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. It solves the spectral wave action balance equation formulated in either Cartesian or spherical co-ordinates. At each element, the wave field is represented by a discrete two-dimensional wave action density spectrum. The model includes wave growth by action of wind, non-linear wave-wave interaction, dissipation by white-capping, dissipation by wave breaking, dissipation due to bottom friction, refraction due to depth variations, and wave-current interaction.

Transformation of the offshore wave conditions to nearshore could be conveniently carried out using this model. As the model works on a triangular mesh grid, the grids could be varied as per requirement and the accuracy of output desired. Accordingly, a coarser mesh is used for offshore area and very fine mesh in the areas of interest.

The directional decoupled parametric formulation is based on a parameterization of the wave action conservation equation. The parameterization is made in the frequency domain by introducing the zeroth and the first moment of the wave action spectrum as dependent variables [11]. The fully spectral formulation is based on the wave action conservation equation:

$$\frac{\partial N}{\partial t} + \nabla(\vec{v}N) = \frac{S}{\sigma}$$

where, $N(\vec{x}, \sigma, \theta, t)$ is the action density, t is time, $\vec{x} = (x, y)$ are the Cartesian co-ordinates, $\vec{v} = (c_x, c_y, c_\sigma, c_\theta)$ is propagation velocity of a wave group in four dimensional phase space. ∇ is the four dimensional differential operator. More details regarding the wave action balance may be obtained from Komen et al. [12] and Young [13]. The directional-frequency wave action spectrum is the dependent variable. The discretization of the governing equation in geographical and spectral space is performed using cell-centred finite volume method.

The time discretization can be applied as quasi-stationary or non-stationary formulations. In the quasi-stationary mode, time is removed as an independent variable and a steady state solution is calculated at each time step using modified Newton-Raphson iterative procedure or iteration in the time domain. In the non-stationary formulation, time integration is based on a fractional step approach where each time step involves calculation of solution for the source function as well as propagation function. An unstructured mesh technique is used in the geographical domain [14].

1.3. SWAN

The SWAN model, which is an acronym for Simulating WAves Nearshore, is a spectral third-generation wave model (see e.g., [11,15]). The SWAN model is the successor of the stationary second-generation HISWA model [16] and has the great advantage, compared to HISWA, of having the physics explicitly represented with state-of-the-art formulations and a model that is unconditionally stable (fully implicit schemes). Moreover, the SWAN model can perform computations on a curvilinear grid and it can—for instance—generate output in terms of one- and two-dimensional wave spectra. In addition, the wave forces, as computed by SWAN on the basis of the gradient of the radiation stress tensor (instead of the dissipation rate as in HISWA), can be used as a driving force to compute the wave-induced currents and set-up in the flow module. The SWAN model is based on the discrete spectral action balance equation and is fully spectral (in all directions and frequencies). This implies that short-crested random wave fields propagating simultaneously from widely different directions can be accommodated. SWAN computes the evolution of random, short-crested waves in coastal regions with deep, intermediate and shallow water and ambient currents. The SWAN model accounts for (refractive) propagation and represents the processes of wave generation by wind, dissipation due to white-capping, bottom friction and depth-induced wave breaking and non-linear wave-wave interactions (both quadruplets and triads) explicitly with state-of-the-art formulations. The SWAN model has successfully been validated and verified in laboratory and (complex) field cases (see e.g., [15,17]). It is noted that the SWAN model does not account for diffraction effects. The SWAN model was developed at Delft University of Technology (The

Netherlands), where it is undergoing further enhancements. It is specified as the new standard for nearshore wave modelling and coastal protection studies [18].

1.4. GENESIS

GENESIS, developed by Coastal Engineering Research Center (CERC), US Army Corps of Engineers, is designed to simulate long-term shoreline change on an open coast, as produced by spatial and temporal differences in longshore sand transport [19]. The name GENESIS is an acronym that stands for GENEralized model for Simulating Shoreline Change. The modelling system is founded on considerable research and applications of shoreline change numerical models. Wave action is the mechanism producing the longshore sand transport, and, in GENESIS, spatial and temporal differences in the transport rate may be caused by such diverse factors as irregular bottom bathymetry, wave diffraction, boundary conditions, line sources and sinks of sand. There are also constraints on transport (such as seawalls and groins). These factors are interrelated and may work in different combinations at different times.

The GENESIS model is generalized in that it allows simulation of a wide variety of user-specified offshore wave inputs, initial beach plan shape configurations, coastal structures, and beach fills. Input to the model is comprised of the shoreline position, beach profiles and a time series of significant wave height, significant wave period, and the direction. Based on these data, the model calculates wave breaking properties, longshore sediment transport rates, and shoreline positions.

The empirical predictive formula for the longshore sand transport rate used in this model is:

$$Q = \left(H^2 C_g\right)_b \left[a_1 \sin\theta_{bs} - a_2 \cos\theta_{bs} \frac{\partial H}{\partial x}\right]_b$$

where H is the wave height (m), C_g is the wave group speed given by linear wave theory, *b* subscript denoting wave breaking condition and θ_{bs} is the angle of breaking waves to the local shoreline and the non-dimensional parameters a_1 and a_2 are given by:

$$a_1 = \frac{k_1}{16\left({\varrho_s}/{\varrho} - 1\right)(1-p)\left(1.416^{5/2}\right)}$$

$$a_2 = \frac{k_2}{8\left({\varrho_s}/{\rho} - 1\right)(1-p)\tan\beta\left(1.416^{7/2}\right)}$$

where k_1 and k_2 are the empirical coefficients treated as the calibration parameters, ϱ_s is the density of sand (assumed 2.65 × 103 kg/m^3 for quartz sand), ϱ is the density of water (assumed 1.03 × 103 kg/m^3 for sea water), p is the porosity of sand on the bed (assumed to be 0.4) and $\tan\beta$ is the average bottom slope from the shoreline to the depth of active longshore sand transport.

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