

# CCHE2D-Coast: Model Description and Graphical User Interface

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# 1 INTRODUCTION

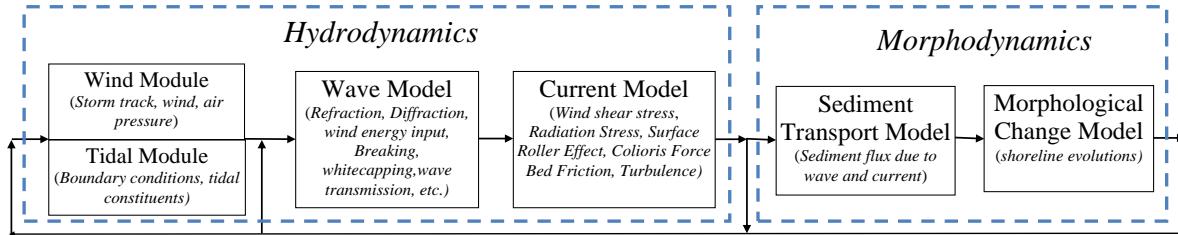
## 1.1 Model Capabilities of CCHE2D-Coast

CCHE2D-Coast is an integrated riverine/coastal/estuarine/ocean processes modeling system, which is developed in the National Center for Computational Hydroscience and Engineering (NCCHE) in the University of Mississippi. It is applicable for simulating multi-scale hydrodynamics and morphodynamics of free-surface water flows such as river flows, tidal currents, waves, storm surges induced by tropical cyclonic wind, sediment transport, and morphological changes over large-scale coastal regions. This modularized application software is developed by using the state-of-art numerical simulation techniques and innovative physical knowledge in river, coastal, and ocean engineering. The model has been validated and verified by using laboratory-scale experimental data and regional-scale field data. It has been applied to solve engineering problems for flooding and inundation management, erosion protection, and infrastructure planning and design in coasts and estuaries. The integrated model is embodied into a user-friendly interface, CCHE2D-GUI, which supports this integrated model for generating computational grids, monitoring computational progress during computations, and visualizing numerical results during and after simulations. CCHE2D-Coast is able to simulate large-scale and long-term problems on a standard PC. The low cost and accurate simulations make this tool specifically attractive to engineers and researchers in the areas.

CCHE2D-Coast has integrated systematically four major submodels for simulating deformations and transformations of irregular/multidirectional waves, tropical cyclonic barometric pressure and wind fields along storm tracks, tidal and wave-induced currents, and coastal morphological changes (Figure 1-1). For computing irregular waves, a multi-directional spectral wave action equation is adopted in the wave spectral module. The following wave deformation/transformation processes are included in the CCHE2D-Coast wave model:

- Refraction
- Diffraction
- Shoaling effect

- Wave breaking
- Wave transmission through coastal structures
- Bottom friction
- Wave-current interaction
- Vegetation attenuation effect
- Wind-induced waves
- Whitecapping



**Figure 1-1 Flow chart of CCHE2D-Coast**

CCHE2D-Coast provides two options for modeling wave actions: a half-plane wave model and a full-plane wave model (Ding et al. 2012b, 2013b). The former is to compute wave fields only from the upwinding direction to the downwind direction, for example, to simulate deformation and transformation processes of swelling waves from deepwater to shallow waters at shore. The latter is the simulation option by which the computations of wave fields are performed by scanning the domain back and forth in wind directions. The full-plane wave simulation can be used for computing waves induced by cyclonic wind fields.

In this model, a nonlinear parametric hurricane cyclonic wind module is integrated to model cyclonic barometric pressure and wind fields along storm tracks by considering the decay effect of landfall and the earth surface resistance (Ding et al. 2013c). By simulating historical hurricanes in the northern Gulf Coast, a database for determining the parameter values for decay and land surface resistance has been established (Ding 2012). By implementing into CCHE2D-Coast, this integrated model has been validated by simulating wind and storm surges in Hurricane Gustav (2008), and used for forecasting wind fields and storm surges induced by Hurricane Isaac (2012) and Sandy (2012).

For the hydrodynamic simulations in coasts and estuaries, the 2-D depth- and shortwave-averaged shallow water equations are employed to simulate the currents driven by wave radiation stresses, tides, storm surges, river inflows, the Coriolis force, and turbulence in surf zones, tidal zones, and ocean waters. This hydrodynamic model provides users with two options to calculate wave radiation stresses: one is the traditional wave stress formulations by means of sinusoidal wave assumption by the linear small-amplitude wave theory; another is the improved radiation stresses formulae derived from the non-sinusoidal wave assumption ([Svendsen 1984](#), [Ding et al. 2006](#)) which enables to take into account the 3-D features of the vertical current structures (e.g. the surface rollers or the undertow currents) in the surf zone. According to [Svendsen et al. \(2003ab\)](#) and [Ding and Wang \(2008a\)](#), the non-sinusoidal wave radiation stresses can produce more accurate nearshore currents in surf zone than the former one. In the morphodynamic submodel, empirical sediment transport models are used to calculate the sediment transport rates contributed from bed materials and suspended sediment under the conditions of combined waves and currents. To compute morphodynamic processes in coasts and estuaries, a unified sediment transport model ([Ding and Wang 2008a](#)) is used to calculate the sediment flux from upstream rivers to estuaries and coasts to consider seamlessly the sediment transport from a non-wave environment at river, to a wave-current interaction area at estuary and a wave-dominant coastal zone. The morphological changes are computed on the basis of the mass balance of sediments in which wetting and drying process is properly modeled to handle tidal variations and bed changes.

This integrated model for simulation of coastal and estuarine morphodynamic processes has been built in a software package called CCHE2D, which is an integrated riverine process simulation model to analyze 2-D shallow water flows, sediment transport, and water quality, with natural flow boundary conditions ([CCHE2D 2011](#)). Similar to the CCHE2D hydrodynamic model, the governing equations of three submodels (modules) in CCHE2D-Coast, i.e., the wave-action equation, the shallow water equations, and the morphological changes equation, were discretized in a non-orthogonal grid system ([Zhang and Jia 2005](#)). Because non-orthogonal meshes have less restrictions for grid shapes than curvilinear grids (orthogonal grids), CCHE2D-Coast has more flexibility to simulate physical variables in complex coastal zones with irregular coastlines. In the process of executing simulations, all the submodels are working with the same computational grid. Therefore, the wave and flow models are running on the same computational

cores, passing information between submodels through local memory/cache, and thus they simulate the propagation of waves from deep water to shallow water in nearshore without any interpolations between the wave and the flow fields. Unlike the so-called model steering operation used in other storm-surge models, CCHE2D-Coast does not need to switch executable codes of the submodels during computations. As a result, CCHE2D-Coast avoids possible errors and loss of information due to interpolation and extrapolation of the results between different grid systems so that simulations by this integrated model are computationally efficient and accurate.

A validated algorithm in the CCHE2D for the treatment of wetting and drying in the computational area was directly used for predicting tidal flat variations and coastal flooding and inundations. An implicit time-marching algorithm proposed by [Jia et al. \(2002\)](#) was used to compute the tidal and wave-induced currents. The simulation time step size, therefore, is not restricted by the CFL (Courant–Friedrichs–Lewy) condition which the explicit schemes have to follow in the hydrodynamic computation. A time step as long as several minutes can be used for computing most large-scale storm-surges driven by tropical cyclones. For a typical one-week storm simulation, CCHE2D-Coast is able to accomplish simulations covering a regional domain (e.g. the Gulf of Mexico or the entire U.S. East Coast) within several CPU hours on a single core standard PC (e.g. [Ding et al. 2012ab, 2013c](#))

As a summary, CCHE2D-Coast has the following principal features for simulating hydrodynamic and morphodynamic processes driven by tropical cyclones:

- Deformation and transformation of multidirectional and irregular waves,
- Tidal currents and River flows,
- Coriolis force,
- Tropical cyclonic wind and atmospheric pressure
- Bottom friction,
- Storm surges and wave setup induced by cyclonic wind and wave fields
- Nearshore currents induced by short-period waves
- Sediment transport due to waves and currents,
- Coastal/estuarine morphodynamic processes
- Morphological changes around coastal structures, e.g., groins, offshore breakwaters, artificial headlands, jetties, artificial reefs, etc.

## 1.2 Mathematical Formulations of CCHE2D-Coast

### 1.2.1 Multi-directional Spectral Wave Model

The spectral wave model is governed by a multidirectional wave action balance equation to compute variations of wave-action density in time, space, wave directions, and frequency. The model formulation is based on the parabolic approximation equation including diffraction terms and energy dissipation due to wave breaking ([Mase et al. 2005](#)). The model can simulate spectral deformation/transformation of directional random waves; and waves can propagate from the seaward boundary toward shore. The model takes into account the effect of an ambient horizontal current or wave-current interaction and solves the wave-action balance equation as follows:

$$\frac{\partial N}{\partial t} + \nabla \bullet (\mathbf{c}N) + \frac{\partial(c_\theta N)}{\partial \theta} = \frac{\kappa}{2\sigma} \left[ \frac{\partial}{\partial y} \left( CC_g \cos^2 \theta \frac{\partial N}{\partial y} \right) - \frac{1}{2} CC_g \cos^2 \theta \frac{\partial^2 N}{\partial y^2} \right] - \varepsilon_b N - Q - Q_v \quad (1)$$

where  $t$  = time,  $x, y$  = two coordinates in two horizontal directions,  $\nabla = (\partial/\partial x, \partial/\partial y)$  the gradient operator in the  $x$ - $y$  plane,  $\theta$  = wave angle relative to the positive  $x$ -direction,  $C, C_g$  = wave celerity and group velocity, respectively; The first term on the left-hand side of (1) represents the local rate of change of action density  $N=N(x,y,\sigma,\theta,t)$  in time, where  $N$  is the ratio  $E(x,y,\sigma,\theta,t)/\sigma$ ,  $\sigma$  is wave angular frequency (or intrinsic frequency), the spectral wave density  $E$  represents the wave energy per unit water surface area per frequency interval. The second term represents propagation of wave action density in a horizontal  $x$ - $y$  plane (with propagation velocities  $\mathbf{c}$ ). The third term represents depth-induced and current-induced refraction (with propagation velocity  $c_\theta$  in  $\theta$  space). The expressions for these propagation speeds are given by the linear wave theory [e.g., [Holthuijsen et al. 1989](#)], i.e.,

$$\mathbf{c} = C_g \mathbf{i}_\theta + \mathbf{u} \quad (2)$$

$$c_\theta = -\frac{1}{k} \frac{\partial \sigma}{\partial h} \frac{\partial h}{\partial n} - \frac{\partial \mathbf{u}}{\partial n} \bullet \mathbf{i}_\theta \quad (3)$$

where  $\mathbf{u}$  =depth-averaged velocity vector;  $k$  = wave number;  $\mathbf{i}_\theta = (\cos \theta, \sin \theta)$ , a unit vector following the wave direction;  $h$  = water depth. The first term on the right-hand side of (1), introduced by [Mase \(2001\)](#), represents the energy dissipation due to the diffraction effect in the alongshore  $y$ -direction, which is implicitly perpendicular to wave direction;  $\kappa$  is an empirical

coefficient. [Mase \(2001\)](#) suggested this empirical coefficient has a possible value within a range of 2.0~3.0. [Ding et al. \(2006b\)](#) found that a wider range of the  $\kappa$  value can be used, which is dependent on problems with laboratory and field scales. To specify an incident wave spectrum in the offshore, the TMA spectrum ([Bouws et al. 1985](#)) and the Bretschneider-Mitsuyasu (B-M) spectrum ([Mitsuyasu 1970](#)) can be selected in this model. The second term in the right-hand side represents wave energy loss due to wave breaking, where  $\varepsilon_b$  is a parameter for wave breaking energy dissipation. The last term in (1),  $Q$ , is source terms of wave energy due to wind forcing, bottom friction loss, nonlinear wave-wave interaction term, etc.  $Q_v$  represents the wave energy loss due to vegetation resistance

Under the circumstance of co-existence of wave and current, wave frequency is changed with water depth and velocities. According to small-amplitude wave theory, the resulting wave number can be calculated by the following dispersion equation with the Doppler frequency shift:

$$\sigma^2 = gk \tanh(kh) \quad (4)$$

$$\sigma = \omega - \mathbf{u} \bullet \mathbf{i}_\theta \quad (5)$$

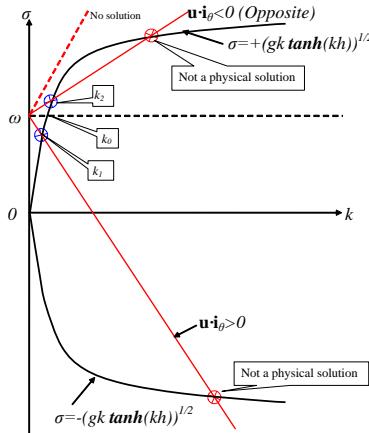
where  $g$  = the gravity acceleration;  $\omega$  = incident (or absolute) wave angular frequency. Two mathematical roots of the equations are illustrated in Figure 1-2, of which the values vary with the relationship between wave and current. By excluding one unphysical root causing a negative angular frequency and a root with large wave number, it is readily found that there are three real roots for solutions of wave numbers:

$k_0$ , no ambient current;

$k_1$ ,  $\mathbf{u} \bullet \mathbf{i}_\theta > 0$ , wave and current traveling in the same direction;

$k_2$ ,  $\mathbf{u} \bullet \mathbf{i}_\theta < 0$ , opposite current, and

$k_1 < k_0 < k_2$ .



**Figure 1-2 Solutions of nonlinear dispersion equation**

If opposite current is strong enough, no solution for wave number exists for the dispersion relation by the linear wave theory. Physically, this effect is associated with wave blocking phenomenon, which prevents wave energy from traveling upstream, and trigger early wave breaking at the offshore of inlets, and causes reflection and energy dissipation. In simulations, the group velocity goes to zero in the case of wave blocked, and the wave action density is set to zero for the corresponding frequency-direction bin. In general, the solutions of wave number under the coexistence of wave and current are obtained iteratively from (4) and (5). Specifically, in the deep water, e.g.,  $kh > 3\pi$ , assuming that  $\tanh kh \approx 1$ , the wave number can be obtained directly from a simplified quadratic equation (Zheng et al. 2008).

According to Takayama et al. (1991), the wave energy dissipation due to wave breaking is calculated by assuming that (1) the probability distribution of breaking wave height can be represented by the Rayleigh distribution (Thornton and Guza 1983); (2) over a computational cell, the local bathymetry can be approximated as shore-parallel contours. Then, the local rate of wave breaking energy dissipation  $\varepsilon_b$  in a computational cell can be calculated as the time-averaged energy loss over a time that an individual wave travels through a cell from the seaward side to the inland side, i.e.

$$\varepsilon_b = \varepsilon'_b C / \sqrt{\Delta x \Delta y} \quad (6)$$

where  $\Delta x, \Delta y$  = the grid size in  $x$ - and  $y$ -directions, respectively. Based on the Rayleigh probability distribution of wave energy, the coefficient  $\varepsilon'_b$  can be obtained as follows:

$$\varepsilon'_b = 1 - \frac{1 - \left[ 1 + \frac{\pi}{4} \left( \alpha \frac{H_{bo}}{H_{1/3}} \right)^2 \right] \exp \left[ -\frac{\pi}{4} \left( \alpha \frac{H_{bo}}{H_{1/3}} \right)^2 \right]}{1 - \left[ 1 + \frac{\pi}{4} \left( \alpha \frac{H_{bi}}{H_{1/3}} \right)^2 \right] \exp \left[ -\frac{\pi}{4} \left( \alpha \frac{H_{bi}}{H_{1/3}} \right)^2 \right]} \quad (7)$$

where  $H_{bo}$ ,  $H_{bi}$  = breaking wave heights at the offshore side and the onshore side of a computational cell, respectively;  $H_{1/3}$  = the local significant wave height;  $\alpha$  = the ratio of the significant wave height to the mean wave height, and  $\alpha = 1.60$  for the Rayleigh distribution of wave heights. The breaking wave height is calculated based on the breaking wave criterion proposed by [Goda \(1970\)](#), or the one extended by [Sakai et al. \(1988\)](#).

The source term  $Q$  in (1) includes the wave energy dissipation due to bottom friction and the wave energy input induced by winds. The energy loss by bottom friction,  $Q_{bf}$ , is calculated by a drag law model ([Collins 1972](#)), i.e.

$$Q_{bf} = -C_f \frac{\sigma^2}{g} \frac{u_{bm}}{\sinh^2(kh)} N \quad (8)$$

where  $C_f$  = bottom friction coefficient, which can be calculated by using bottom roughness coefficient;  $u_{bm}$  = ensemble mean of horizontal wave orbital velocity, i.e.

$$u_{bm} = \frac{1}{2} \sqrt{\frac{g}{h} E_{total}} \quad (9)$$

where  $g$  = gravitational acceleration;  $E_{total}$  is the total energy density at a grid cell.

The energy input by wind forcing,  $Q_{win}$ , can be modeled as separated sink and source terms ([Lin and Lin 2004a,b](#)), i.e.

$$Q_{win} = \frac{a_1 \sigma}{g} F_1 F_2 E_{PM}^* \Phi + \frac{a_2 \sigma^2}{g} F_1 F_2 F_3 N \quad (10)$$

where  $a_1$  and  $a_2$  are two empirical coefficients for wind input energy; the three functions,  $F_1$ ,  $F_2$ , and  $F_3$ , are givens as follows:

$$F_1 = F_1(\vec{W} - \vec{C}_g) = \begin{cases} |\vec{W}| \cos(\theta_{wind} - \theta) - |\vec{C}_g|, & \text{if } |\vec{C}_g| < |\vec{W}| \\ 0, & \text{if } |\vec{C}_g| \geq |\vec{W}| \end{cases} \quad (11)$$

$$F_2 = F_2\left(\frac{\vec{C}_g}{|\vec{W}|}\right) = \begin{cases} \left(\frac{|\vec{C}_g|}{|\vec{W}|}\right)^{1.15}, & \text{if } |\vec{C}_g| < |\vec{W}| \\ 0, & \text{if } |\vec{C}_g| \geq |\vec{W}| \end{cases} \quad (12)$$

$$F_3 = F_3\left(\frac{C_g}{W}\right) = \begin{cases} \log_{10}\left[\left(\frac{|\vec{C}_g|}{|\vec{W}|}\right)^{-1}\right], & \text{if } |\vec{C}_g| < |\vec{W}| \\ 0, & \text{if } |\vec{C}_g| \geq |\vec{W}| \end{cases} \quad (13)$$

where  $\vec{W}$  = wind velocity vector;  $\vec{C}_g$  = wave group velocity vector;  $\theta_{\text{wind}}$  is the angle of wind;  $E_{PM}^*$  is the functional form of the Pierson-Moskowits (PM) spectrum, i.e.

$$E_{PM}^* = E_{PM}^*(\sigma) = \frac{g^2}{\sigma^5} \exp\left(-0.74\left(\frac{\sigma_0}{\sigma}\right)^4\right) \quad (14)$$

where  $\sigma_0 = g/W$ , is the Phillips constant, and  $\Phi$  = the normalized directional spreading function, i.e.

$$\Phi(\theta) = \frac{8}{3\pi} \cos^4(\theta - \theta_{\text{wind}}), \quad \text{for } |\theta - \theta_{\text{wind}}| \leq \frac{\pi}{2} \quad (15)$$

The wave energy attenuation due to the whitecapping effect, which includes current and turbulent viscous effect, can be modeled as a source term ([Lin and Lin 2004a,b](#)),  $Q_{ds}$ , in the wave-action equation, i.e.

$$Q_{ds} = -C_{ds}(a_e k)^{1.5} \frac{\sigma^2}{g} C_g(\sigma, \theta) F_4 F_5 N \quad (16)$$

where  $C_{ds}$  is an empirical coefficient;  $a_e$  is a wave amplitude at a grid cell, which is estimated by

$$a_e = \sqrt{E(\sigma, \theta) d\sigma d\theta} \quad (17)$$

The two functions,  $F_4$  and  $F_5$ , are given as follows:

$$F_4 = F_4(\vec{W}, \vec{U}, \vec{C}_g) = \frac{\nu + |\vec{W}|}{|\vec{W} + \vec{U} + \vec{C}_g|} \quad (18)$$

Where  $\nu$  = the coefficient for turbulent viscous dissipation;  $\vec{U}$  = current velocity vector. According to [Lin et al \(2004a\)](#), the function F4 is set to 1 if the computed value is greater than 1, to consider physical constraint of energy loss for the dissipation and to avoid numerical instability; and

$$F_5 = F_5(kh) = \frac{1}{\tanh(kh)} \quad (19)$$

Boundary conditions for simulating wave deformation over a computational domain covering ocean, coast and estuary are comprised of offshore wave spectra determined by wave heights, periods, and directions. The present wave spectral model supports two kinds of offshore (deepwater) wave spectrum inputs, i.e., the TMA spectrum ([Bouws et al. 1985](#)) and the Bretschneider-Mitsuyasu (B-M) spectrum ([Mitsuyasu 1970](#)).

In CCHE2D-Coast, using a general non-orthogonal quadrilateral computational grid, the wave action balance equation (1) is numerically discretized in a geophysical domain by means of finite difference schemes which taking into account non-uniform grid size and general quadrilateral mesh shape. In addition, the wave spectra are discretized into a number of frequency bins, based on the equal energy dividend, by which each frequency bin represents an individual wave. The bins for wave directions are also discretized to cover a half-plane wave direction ( $\theta$ ) domain from  $+\pi/2$  to  $-\pi/2$ . A first-order upwinding finite difference scheme is applied to discretize the second, third, and fourth terms which represent the propagation of wave action in the horizontal plane and wave refraction due to varying water depth. The central difference scheme is applied to discretize the first term in the right-hand side for the diffraction term. A semi-implicit treatment is applied to the source terms for wave breaking and bottom friction in order to increase the stability of the numerical model. Finally, the discretized wave action balance equation is solved by means of the parabolic approximation, in which the waves are assumed to have a principal propagation direction from offshore toward onshore. An iterative solver, the Gaussian-Seidel algorithm, is used to solve the linear algebraic equations of the wave action balance equation in every  $y$ - $\theta$  plane arranged from offshore to onshore. The computed wave actions in all the frequency bins add up to the total wave energy, which can be used to calculate statistical wave parameters such as wave heights, mean wave directions, and peak/mean periods.

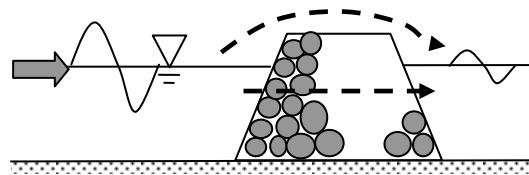
Based on the monochromatic linear wave theory and an assumption of impermeable bottom proposed by [Dalrymple et al. \(1984\)](#), [Mendez and Losada \(2004\)](#) established a relationship between the wave energy loss and vegetation parameters under a condition of random wave incidence. The Reyleigh probability density distribution function ([Thornton and Guza 1983](#)) is assumed to model random wave actions. As a result, the source term of the wave energy loss due to vegetation,  $Q_v$ , is obtained as follows:

$$Q_v = \frac{1}{\sigma 2\sqrt{\pi}} \rho C_D b_v N_v \left( \frac{kg}{2\sigma} \right)^3 \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{3k \cosh^3(kh)} H_{rms}^3 \quad (20)$$

where  $\rho$ =water density ( $\text{kg/m}^3$ ),  $b_v$  = the plant area per unit height of each vegetation stand normal to horizontal velocity (m),  $N_v$  = number of vegetation stands per unit horizontal area ( $\text{m}^{-2}$ ),  $C_D$  = drag coefficient for random waves,  $g$ =the gravitational acceleration ( $\text{m/s}^2$ ),  $\alpha$ = relative vegetation height,  $H_{rms}$  = root-mean-square wave height (m). Because the random wave energy can be defined as  $E = \frac{1}{8} \rho g H_{rms}^2$ , the source term can be written as the local linear form of the wave action density, i.e.,  $Q_v = \varepsilon_v N$ . Then the coefficient  $\varepsilon_v$  can be given as follows:

$$\varepsilon_v = \frac{4}{g\sqrt{\pi}} C_D b_v N_v \left( \frac{kg}{2\sigma} \right)^3 \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{3k \cosh^3(kh)} H_{rms} \quad (21)$$

Another important wave transformation phenomenon for coastal structures, which has been considered in the CCHE2D-Coast model, is wave transmissions in case that offshore incident waves penetrate through a permeable coastal structure which has water in the lee side (see Figure 1-3). Wave run-up and overtopping can cause wave transmissions by regenerating the waves on the lee side. In addition, waves passing through the structures, if it is sufficiently permeable, can transmit energy from the front side to the lee side. The portion of wave transmission has been taken into account in the calculations of the wave energy in (1) (Ding et al. 2006a).



**Figure 1-3. Transmission through and over a rubble mound breakwater.**

The radiation stresses for random waves can be calculated by the numerical integration of the following expressions:

$$R_{xx} = \iint E(\sigma, \theta) [n(\cos^2 \theta + 1) - 0.5] d\sigma d\theta \quad (22)$$

$$R_{xy} = R_{yx} = \iint E(\sigma, \theta) [n \sin \theta \cos \theta] d\sigma d\theta \quad (23)$$

$$R_{yy} = \iint E(\sigma, \theta) [n(\sin^2 \theta + 1) - 0.5] d\sigma d\theta \quad (24)$$

where  $R_{xx}$ ,  $R_{xy}$ ,  $R_{yx}$ , and  $R_{yy}$  are the four components of the radiation stresses  $\mathbf{R}$ , and

$$n = \frac{1}{2} + \frac{kh}{\sinh 2kh} \quad (25)$$

These radiation stresses are used to calculate wave stresses which in turn are used in the momentum equations of hydrodynamic model described in the following section.

### 1.2.2 The Hydrodynamic Model

The hydrodynamic model contains the depth-averaged 2-D continuity and momentum equations to simulate flows driven by hydrological forcing such as tides, waves, river inflows, surface winds, and turbulence flows in a large-scale coastal and estuarine region, namely

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (h\mathbf{u}) = 0 \quad (26)$$

$$\frac{\partial h\mathbf{u}}{\partial t} + \nabla \cdot h\mathbf{u}\mathbf{u} = -gh\nabla\left(\frac{P_s}{\rho g} + \eta\right) + \frac{1}{\rho}(\nabla \cdot h\boldsymbol{\tau}^t - \nabla \cdot \mathbf{R} + \boldsymbol{\tau}^s - \boldsymbol{\tau}^b) + hf_{cor} \quad (27)$$

where  $\eta$  = water elevation relative to mean sea level (MSL);  $h$  = water depth;  $\mathbf{u} = (U, V)$ , depth-averaged velocity vector with two components in the horizontal coordinates;  $P_s$  = atmospheric pressure on the free surface, which accounts for the variation of air pressure during a storm;  $\rho$  = water density;  $\boldsymbol{\tau}^t$  = the depth- averaged Reynolds stress;  $\boldsymbol{\tau}^s$  = wind shear stress;  $\boldsymbol{\tau}^b$  = bottom friction stress;  $f_{cor} = (fV, -fU)$ , the Coriolis force term;  $f = 2\Omega \sin \varphi$  is the Coriolis parameter, wherein  $\Omega$  = angular frequency of earth rotation and  $\varphi$  = latitude of the study area.

For random waves, the radiation stresses (22), (23), and (24) can be added into the momentum equations (27) for simulations of wave-induced nearshore currents. However, the drawback of these expressions for calculations of radiation stresses is lack of consideration of complex nearshore flow structure such as undertow and difference in volume flux between offshore and onshore due to non-sinusoidal wave shapes. It is known that these sinusoidal formulations could not generate accurately currents inside surf zone when especially wave breaking occurs ([Svendsen et al., 2003a,b](#)). Therefore, based on a concept for surface roller due to breaking waves, the following expression of the radiation stresses proposed by [Svendsen \(1984\)](#) represents the net (shortwave-averaged) force that the shortwave exert on a water column is defined as:

$$\mathbf{R} = S_m \mathbf{e} + S_p \mathbf{I} - \rho \frac{\mathbf{Q}_w \mathbf{Q}_w}{h} \quad (28)$$

where  $\mathbf{I}$  = the identity matrix;  $\mathbf{Q}_w$  = the wave volume flux induced by the short wave motion; the tensor  $\mathbf{e}$  is

$$\mathbf{e} = \begin{bmatrix} \cos^2 \theta & \sin \theta \cos \theta \\ \sin \theta \cos \theta & \sin^2 \theta \end{bmatrix} \quad (29)$$

The scalar  $S_m$  and  $S_p$ , as well as the wave volume flux are calculated respectively according to the different formulations suitable for the region inside and outside the surf zone (Table 1-1).

**Table 1-1. Terms of radiation stresses inside and outside surf zone.**

	Inside surf zone	Outside surf zone
$S_m$	$\rho g H^2 \frac{C^2}{gh} \left[ \frac{1}{8} + \frac{Ah}{H^2 L} \right]$	$\frac{1}{16} \rho g H^2 \left( 1 + \frac{2kh}{\sinh 2kh} \right)$
$S_p$	$\frac{1}{16} \rho g H^2$	$\frac{1}{16} \rho g H^2 \frac{2kh}{\sinh 2kh}$
$\mathbf{Q}_w$	$\frac{gH^2}{C} \frac{c^2}{gh} \left( \frac{1}{8} + \frac{Ah}{H^2 L} \right) \mathbf{i}_\theta$	$\frac{gH^2}{8C} \mathbf{i}_\theta$

Note:  $H$  is wave height;  $A$  is the surface roller area,  $=0.9H^2$ ;  $L$  is the wavelength.

Most existing hydrodynamic models only adopt the radiation stresses derived from the sinusoidal wave theory to calculate the wave-induced forcing terms over the entire coastal domain. The hydrodynamic model in CCHE2D-Coast provides several options for calculation of the radiation stresses (Ding et al. 2006b). Those options are based on (1) the radiation stresses by the integration of wave energy in (22), (23), and (24), (2) the conventional radiation stresses driven by sinusoidal waves, and (3) the radiation stresses with consideration of non-sinusoidal waves and surface roller assumption. For the third option of the radiation stresses, this hydrodynamic model needs to identify the coastal surf zone, and then uses the non-sinusoidal radiation stresses for the region inside the surf zone, and the sinusoidal wave formulation for the region outside the surf zone (deep water region), respectively. The significant wave height can be used as the representative wave height  $H$  for the case of irregular wave incidence. Table 1-1 summarizes the different radiation stress formulae inside and outside the surf zone. Because the radiation stresses used for the surf zone take into account the vertical variations of wave breaker

structures, some 3D features of the cross-shore movement mechanisms, e.g. undertow and mass flux, are reflected accordingly in the hydrodynamic model ([Ding et al. 2006b](#)).

By taking into account the influence of combined wave and current on the bottom friction stress  $\tau^b$ , the friction law of the combined wave and current proposed by [Tanaka and Thu \(1994\)](#) is used to estimate the friction coefficient, namely

$$\bar{\tau}^b = \rho C_f \overline{|\mathbf{u} + \mathbf{u}_b|(\mathbf{u} + \mathbf{u}_b)} \quad (30)$$

where the overbar means the time-averaged integration over a shortwave period;  $C_f$  = friction coefficient;  $\mathbf{u}_b$ =the wave orbital velocity at the bottom. The friction law of the combined wave and current is used to estimate the friction coefficient in the different flow regimes, including rough turbulent flow, smooth turbulent flow, and laminar flow. The combined friction coefficient  $f_{cw}$  ( $=2C_f$ ) is given as follows,

$$f_{cw} = f_c + 2\sqrt{f_c \beta f_w} |\cos \phi| + \beta f_w \quad (31)$$

where  $f_c$  and  $f_w$  are the friction coefficients due to current and wave, respectively;  $\beta$  is the coefficient due to nonlinear interaction of waves and currents;  $\phi$  is the angle between wave orthogonal and current vector.

Surface wind stresses are given by the following empirical wind shear stress formulations

$$\bar{\tau}^s = \rho_a C_d |W| \mathbf{W} \quad (32)$$

where  $C_d$  = wind drag coefficient,  $\rho_a$  = density of air,  $\mathbf{W}$ = wind speed vector measured at 10.0-m above the sea level.

As far as the depth-averaged Reynolds stress  $\tau^t$  in Eq. (27) is concerned, the present hydrodynamic model provided users with two eddy viscosity turbulence models pertaining to the characteristics of waves ([Ding et al. 2006b](#)), and a  $k-\varepsilon$  model ([Jia et al. 2002](#) ).

### 1.2.3 Hurricane Track Model

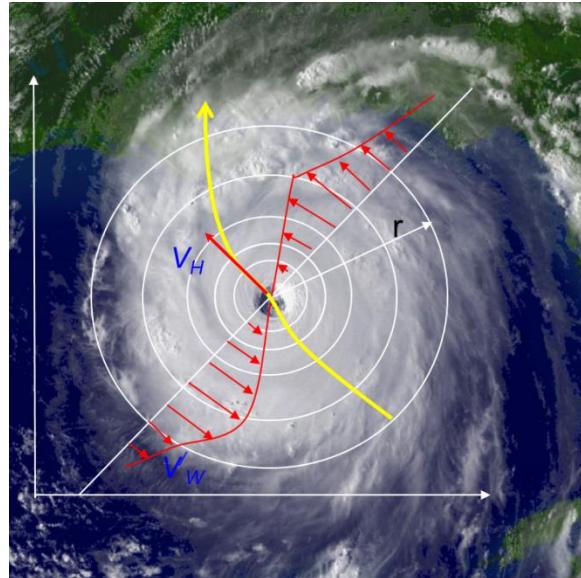
A parametric cyclonic hurricane wind model proposed by Holland (1980) has been integrated in the CCHE2D-Coast model, which is to simulate variations of wind and atmospheric pressure along a given storm track. Provided that central pressure and maximum wind speed, [Holland \(1980\)](#) proposed a parametric wind model to reconstruct hurricane wind fields as depicted in Figure 1-4. The atmospheric pressure field and tangential wind velocity induced by the pressure gradient are expressed respectively as follows:

$$P_s = P_c + (P_\infty - P_c) \exp\left(-\left(\frac{R}{r}\right)^B\right) \quad (33)$$

$$V'_w = \left[ \frac{B}{\rho_a} \left( \frac{R}{r} \right)^B (P_\infty - P_c) \exp\left(-\left(\frac{R}{r}\right)^B\right) \right]^{\frac{1}{2}} \quad (34)$$

where  $P_s$  is the atmospheric pressure at radius  $r$ ,  $P_c$  is the hurricane central pressure,  $P_\infty$  is the ambient pressure,  $R$  is the radius of maximum wind,  $\rho_a$  is the air density,  $B$  is scaling parameter and  $V'_w$  is the tangential velocity induced by the pressure gradient of cyclonic wind. The resultant wind speed used here is the combination of Eq. (34) and hurricane translation speed  $V_H$  (Figure 1-4):

$$\vec{W} = \vec{V}'_w + \vec{V}_H \quad (35)$$



**Figure 1-4: Tangential wind field induced by a hurricane**

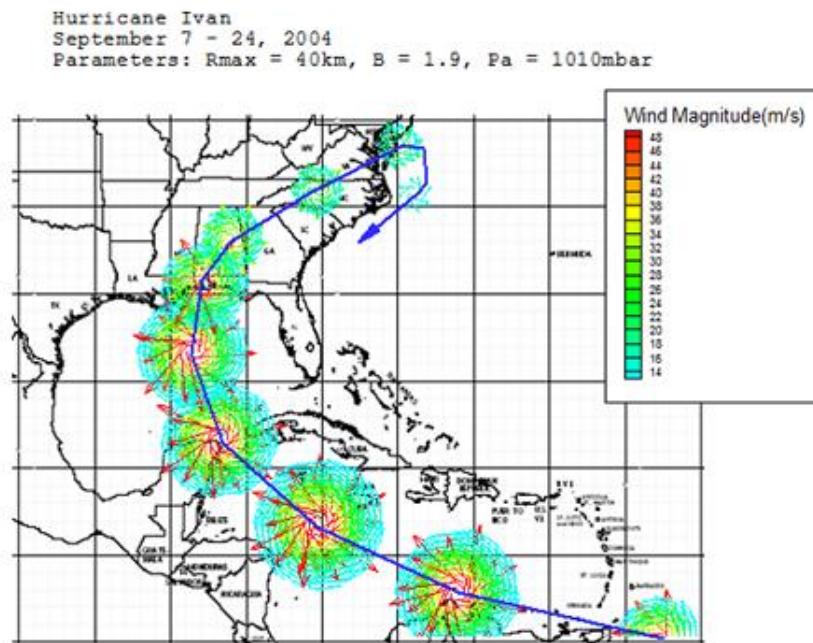
The surface wind stresses induced by cyclonic wind can be also calculated by using the conventional bulk formulation of Eq. (32): But the drag/friction coefficient  $C_d$  may vary with wind speed. [Large and Pond \(1981\)](#) proposed the following equation to estimate this wind drag coefficient, which is used in CCHE2D-Coast:

$$10^3 C_d = \begin{cases} 0.49 + 0.065 |\vec{W}| & |\vec{W}| \geq 10 \text{ m/s} \\ 1.14 & 3 \leq |\vec{W}| < 10 \text{ m/s} \\ 0.62 + 1.56 |\vec{W}| & 1 \leq |\vec{W}| < 10 \text{ m/s} \\ 2.18 & |\vec{W}| < 1 \text{ m/s} \end{cases} \quad (36)$$

The hurricane pressure field given by Eq. (33) is applied as a forcing term in the momentum equation (27). A typical simulation track of hurricane Ivan in the Gulf of Mexico is shown in Figure 1-5. The simulated wind field is shown in Figure 1-6.

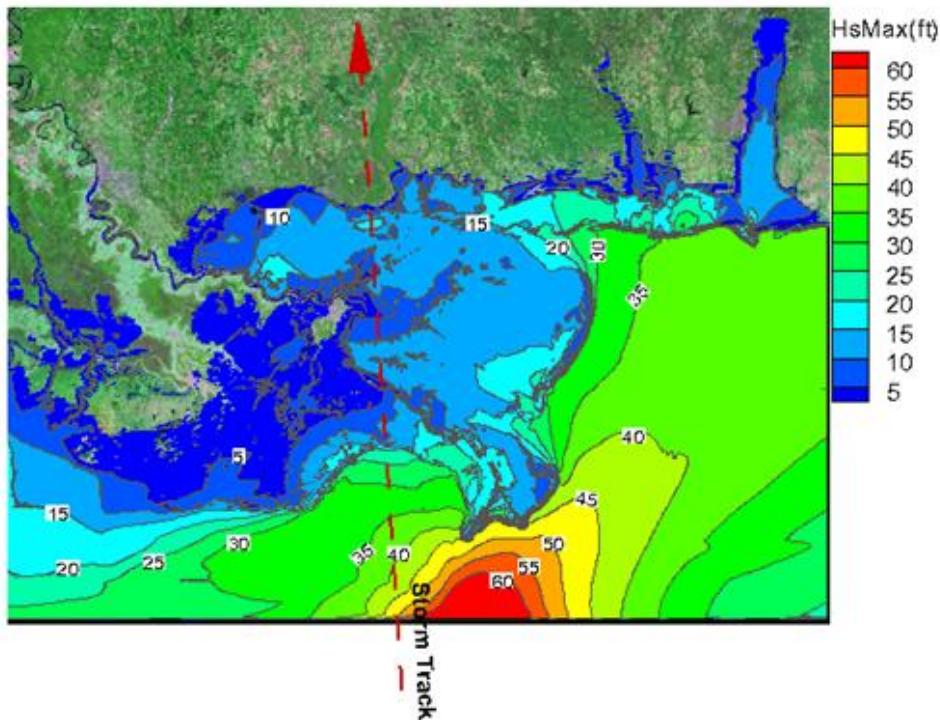


**Figure 1-5 Tracking of Hurricane Ivan by NOAA**



**Figure 1-6 Simulated Wind Fields**

When the model is applied to simulate storm waves generated by hurricanes, the waves at the deepwater can be calculated by a deepwater wave model, such as WAM. However, the CCHE2D-Coast wave model can work within the deepwater zone, if the boundary conditions for the wave spectral distributions at the offshore can be given. To do so, Young's ocean wave model, which is a parametric wave model, is usually employed to create the wave spectral boundary conditions at the offshore (Young 1988, Young and Burchell 1996). The significant wave heights are calculated based on JONSWAP spectrum. Figure 1-7 shows a snapshot of storm wave field (significant wave heights) computed in the Gulf of Mexico.



**Figure 1-7 A simulated storm wave field by CCHE2D-Coast (contour lines indicate computed significant wave height in feet)**

#### 1.2.4 Morphodynamic Model

The morphological changes, or the variations of seabed elevation  $Z_b$ , is calculated by considering the local sediment balance and the downslope gravitational transport:

$$\frac{\partial Z_b}{\partial t} = -\nabla \bullet \mathbf{q} + \frac{\partial}{\partial x} \left( \varepsilon |q_x| \frac{\partial Z_b}{\partial x} \right) + \frac{\partial}{\partial y} \left( \varepsilon |q_y| \frac{\partial Z_b}{\partial y} \right), \quad (37)$$

where  $\mathbf{q}=(q_x, q_y)$  is the local sediment transport rate, and  $\varepsilon$  is an empiric coefficient. The bed evolution is described by a divergence term at the right hand side and the other two terms for the anisotropic downstream gravitational effect. According to [Watanabe et al. \(1986\)](#), the local sediment transport rate has two contributions from wave and current:

$$\mathbf{q} = \mathbf{q}_w + \mathbf{q}_c = \frac{\tau_m - \tau_c}{\rho g} (A_w F_D |\mathbf{u}_b| \mathbf{i}_\theta + A_c \mathbf{u}), \quad (38)$$

where  $\mathbf{q}_w$  and  $\mathbf{q}_c$  are the local sediment transport rates due to wave and current, respectively, which includes bed load and suspended sediment load;  $\tau_m$  is the maximum bottom shear stress which has been modified to consider the difference of the stress in river flow and nearshore current (see [van Rijn \(2007\)](#) for more details);  $\tau_c$  is the critical shear stress;  $A_w$  is an empirical coefficient related to grain size and fall velocity;  $\mathbf{u}_b$  is the wave orbital velocity at the bottom;  $A_c$  is an empirical coefficient for sediment transport rate due to current.  $F_D$  represents the direction function ( $=+1$  for onshore,  $=-1$  for offshore).

### 1.2.5 Numerical Approaches

This integrated coastal process model (CCHE2D-Coast) has been built in a well-established numerical software package called CCHE2D ([Jia et al. 2002](#)), which is an extensively verified and validated tool to analyze 2-D shallow water flows, sediment transport, and water quality, with natural flow boundary conditions. Similar to the CCHE2D hydrodynamic model, the wave and hydrodynamic models in CCHE2D-Coast were discretized in a non-orthogonal grid system so that the models have more flexibility to simulate physical variables in complex coastal zones with irregular coastlines. A time-marching algorithm proposed by [Jia et al. \(2002\)](#) was used to compute tidal and wave-induced currents. A validated algorithm in CCHE2D for the treatment of wetting and drying processes was directly used for predicting the tidal flat variations and coastal inundations. This coastal process model has been extensively validated by simulating waves, wave-induced currents, and morphological changes in coastal applications in various laboratory and field scales (e.g., [Ding et al. 2004](#), [Ding and Wang 2005](#), [Ding et al. 2006b](#), [Ding et al. 2008](#)).

### 1.2.6 Boundary Conditions

In general, a typical computational domain in a coastal and estuarine region is surrounded by four types of boundaries: shoreline, offshore boundary, two open cross-shore boundaries, and river inflows at upstream. Inside the domain, island shorelines or offshore structure boundaries may exist. In order to compute wave fields in the computational domain, by means of the parabolic approximation for wave propagation, incident wave parameters (i.e. wave heights, directions, and periods) are needed to specify the incident wave spectra on the offshore boundary. The TMA spectrum ([Bouws et al. 1985](#)) and the Bretschneider-Mitsuyasu (B-M) spectrum ([Mitsuyasu 1970](#)) are two choices provided by the wave model. In simulation of hydrodynamic processes, the known values of velocities or discharges can be imposed on the corresponding cross-shore boundaries. The impermeable condition of currents is used on shorelines. The known tidal elevations are specified at the offshore boundary to generate tidal flows. The hydrographs of river inflows can be given as the time series of discharge  $Q_{in}(t)$  ( $\text{m}^3/\text{s}$ ) at the inlets of rivers.

As for the boundary conditions of sediment transport rate, CCHE2D-Coast allows users to specify sediment transport concentration of sediment supply at the inlets of rivers. For a simulation case, if the total sediment transport flux  $Q_{s,in}(t)$  ( $\text{m}^3/\text{s}$ ) through an inlet crosssection is given, then the cross-section averaged sediment transport concentration  $\bar{C}_{in}(t)$  can be obtained as follows:

$$\bar{C}_{in}(t) = \frac{Q_{s,in}(t)}{Q_{in}(t)}, \quad (39)$$

The graphic user interface (GUI) of the model can help users prepare the data of the concentration, and then link the conditions to the river inlets.

### 1.2.7 Initialization of Simulation

For the initial conditions for velocities and water elevations, there are two ways to initiate numerical simulations, cold start and hot start.

The cold start (starting from a static state) is generally utilized to initiate the simulations of the tidal and wave-induced currents. For preparing a well-established tidal sea, user may need to run tidal flow simulations for several days in a local-scale computational domain (typically a domain including a moderate-scale estuary with a coastal zone), and for at least two weeks in a regional computational domain such as a domain including the Gulf of Mexico. Starting from a

static state, CCHE2D-Coast manages the tidal elevations to gradually ramp up the tidal levels to the given tidal conditions. The ramp duration at the beginning of the transient start-up is approximately 4 tidal cycles.

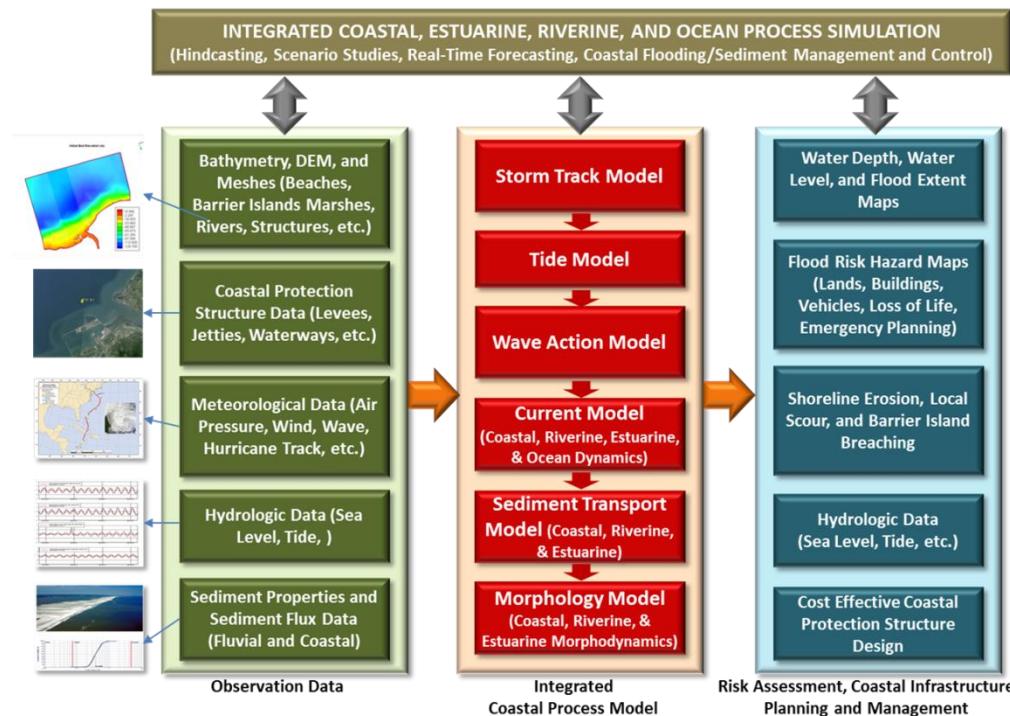
The hot start of simulation is to continue simulations from a given flow field. This existing flow results could be a simulation result of the cold start or any previous simulated flow field.

### 1.3 Validation and Application of Model

CCHE2D-Coast has been extensively verified and validated by simulating riverine, coastal, estuarine, and ocean processes driven by tides, waves, river flows, and sediment transport (e.g. Ding et al. 2006, Ding and Wang 2008ab, Ding and Wang 2011). It has been successfully applied to simulate a variety of coupled coastal hydrodynamic and morphodynamic processes such as coastal flooding and inundations, beach erosion, coastal inlet channel sediment refilling, local scour around structures, and sand bar breaching due to extreme hurricane/storm waves, surges, and river floods (e.g. Ding et al. 2013a). It has been demonstrated that this model is effective and efficient for managing and planning coastal disasters due to severe flooding and inundation, and for designing and planning coastal infrastructures such as levees, dikes, breakwaters, waterways, and harbors, by considering both hydrodynamic and morphodynamic impacts due to disastrous storm events (hurricanes and typhoons) (e.g. Ding et al. 2012ab, Ding et al. 2013bc). It also has been used to forecast storm surges and waves during tropical cyclone seasons such as Hurricane Isaac (2012) in the Gulf of Mexico (Ding et al. 2013b) and Hurricane Sandy (2012) in the U.S. East Coast (Ding et al. 2013c). It has been used to assess both hydrological and morphological impacts of sea level rise and climate change under tropical cyclonic weather conditions on river mouths, shorelines, and coastal communities (Ding et al. 2013b). This model has been also used for post-disaster investigation in the Mississippi Gulf coast by investigating the impacts of the new coastal protection systems of New Orleans on the flood levels along the Mississippi coastline and the inland areas (Ding et al. 2012a). Moreover, an ad-hoc GIS-application tool has been developed by the NCCHE to connect CCHE2D-Coast simulation results with FEMA’s risk assessment tool (HAZUS-MH) to provide a quick assessment tool to map risks of hazards and damage of properties due to storm surges and waves

(Hossain et al. 2013). In summary, CCHE2D-Coast is a comprehensive simulation-prediction-analysis tool for forecasting, planning, and investigating coastal disasters induced by tropical cyclones.

For various engineering application purposes of predicting, investigating, and planning coastal hazards such as flooding, inundations, and erosion, CCHE2D-Coast has been applied to simulate a variety of coupled coastal hydrodynamic and morphodynamic processes such as coastal inundations, beach erosion, coastal inlet channel sediment refilling, local scour around structures, and sand bar breaching due to extreme hurricane/storm waves, surges, and river floods (Ding et al. 2006; Ding and Wang 2008ab; Kuiry et al. 2010, Ding et al. 2012abc, Ding et al. 2013abc). It also has been used to forecast storm surges and waves during tropical cyclone seasons such as Hurricane Isaac (2012) in the Gulf of Mexico and Hurricane Sandy (2012) in the U.S. East Coast (Ding et al. 2013c), and to assess the impacts of storm surges under sea level rise scenarios due to the future climate change (Ding et al. 2013b). Figure 1-8 shows a flow chart for using the model to acquire hydrological, geomorphic, infrastructural, and meteorological data, to execute the model, and to analyze simulation results by mapping flooding and inundation.



**Figure 1-8 Integrated modeling system based on CCHE2D-Coast for planning and management of flood and inundation**

## 1.4 About Using This Manual

The manual provides a quick start guide for users to use CCHE2D-Coast for simulating coastal/ocean processes such as tide flows, wind-induced waves, nearshore currents, river inflows, and theirs combinations.

Chapter 1 gives a brief description on the capabilities of this integrated coastal/ocean/riverine/estuarine process model. It also provides mathematical formulations for four major modules for simulating (1) multidirectional and irregular waves, (2) flows, (3) cyclonic winds, and (4) sediment transport. Numerical approaches used in the model are also presented. Since these approaches are the same as CCHE2D, users may refer to the technical manual of CCHE2D for the details of numerical methods ([CCHE2D 2011](#)).

Chapter 2 introduces the user interface functions of CCHE-GUI for simulations of waves and flows by using CCHE2D-Coast. It includes the methods for generating computational meshes covering coastal areas and structures, setup of boundary conditions, and visualization of computed results.

From Chapter 3 to 6, four simulation examples are given to compute (1) tidal flows, (2) tidal flows and waves, (3) storm surges driven by tropical cyclonic winds, and (4) storm surges and waves. Please note that the capability for computing sediment transport and morphological changes is not available in this version.

A list of references is finally provided in the manual.

## 2 GRAPHIC INTERFACE FOR SIMULATIONS USING CCHE2D-COAST

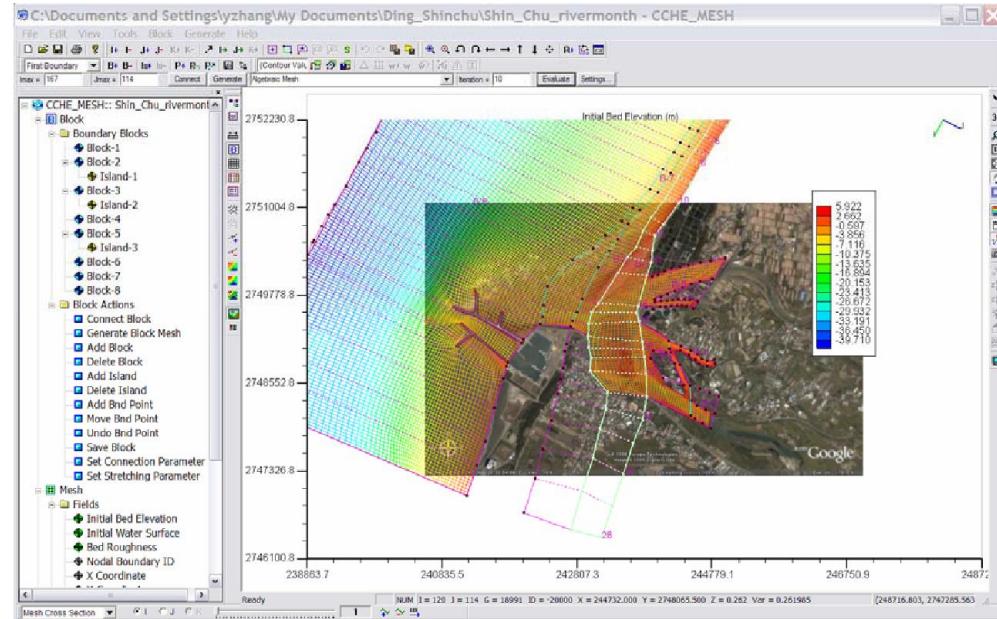
CCHE2D-Coast is an integrated coastal/riverine/estuarine/ocean process model which is capable of simulating deformation and transformation of irregular waves, tidal flows, storm surges, wave setup, river flows, and sediment transport through rivers, estuaries, and coasts. It consists of four major modules (submodels): (1) **wave action model** for computing deformation and transformation of multidirectional/irregular waves from deepwater in oceans to shallow water at coasts and estuaries, (2) **tropical cyclone parametric wind model** with landfall effect for simulating atmospheric pressure and wind fields along storm tracks, (3) **flow (current) model** for simulating hydrodynamic processes including astronomical tides, storm surges, wave setup, river inflows, nearshore currents, and the Coriolis effects, and (4) **sediment transport model** for computing sediment transport rates and morphological changes in river beds, coastal zones, and estuaries. This process-based model has been embedded into CCHE-GUI – the Graphical Users Interface for CCHE2D modeling systems, through which the users can set model parameters, initial conditions, and boundary conditions, launch simulations, and view and analyze simulation results.

This section gives a brief description on mesh generation, parameter specification, setup of initial/boundary conditions, execution of coastal modules, simulation process monitoring, and visualization of numerical results.

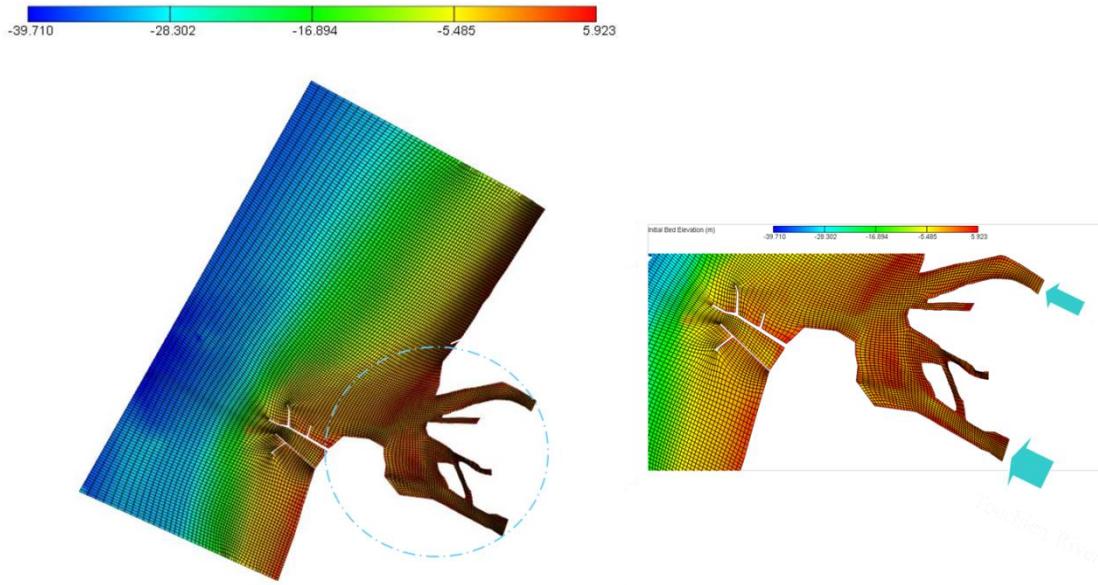
### 2.1 Mesh Generation

CCHE2D-Coast adopts the same mesh system as CCHE2D, so CCHE-MESH ([Zhang and Jia 2009](#)) can be used to generate computational meshes for it as well. A typical CCHE2D computational mesh is formed by constructed orthogonal quadrilateral grids. The multi-block mesh generation provided in CCHE-MESH is commonly used to create a computational mesh covering coastal structures such as breakwaters, dikes, and submerged reefs and irregular coastlines. Figure 2-1 shows a computational mesh covering an estuary and adjacent coasts which is being built by using CCHE-MESH. It indicates at least two structural mesh blocks are used for creating the orthogonal grids in the sea and on the land. Figure 2-2 presents a

computational mesh and a zoom-in of the parts in the estuary where two rivers are located. For the detailed guide to generate this mesh, please refer to Zhang and Jia (2009).



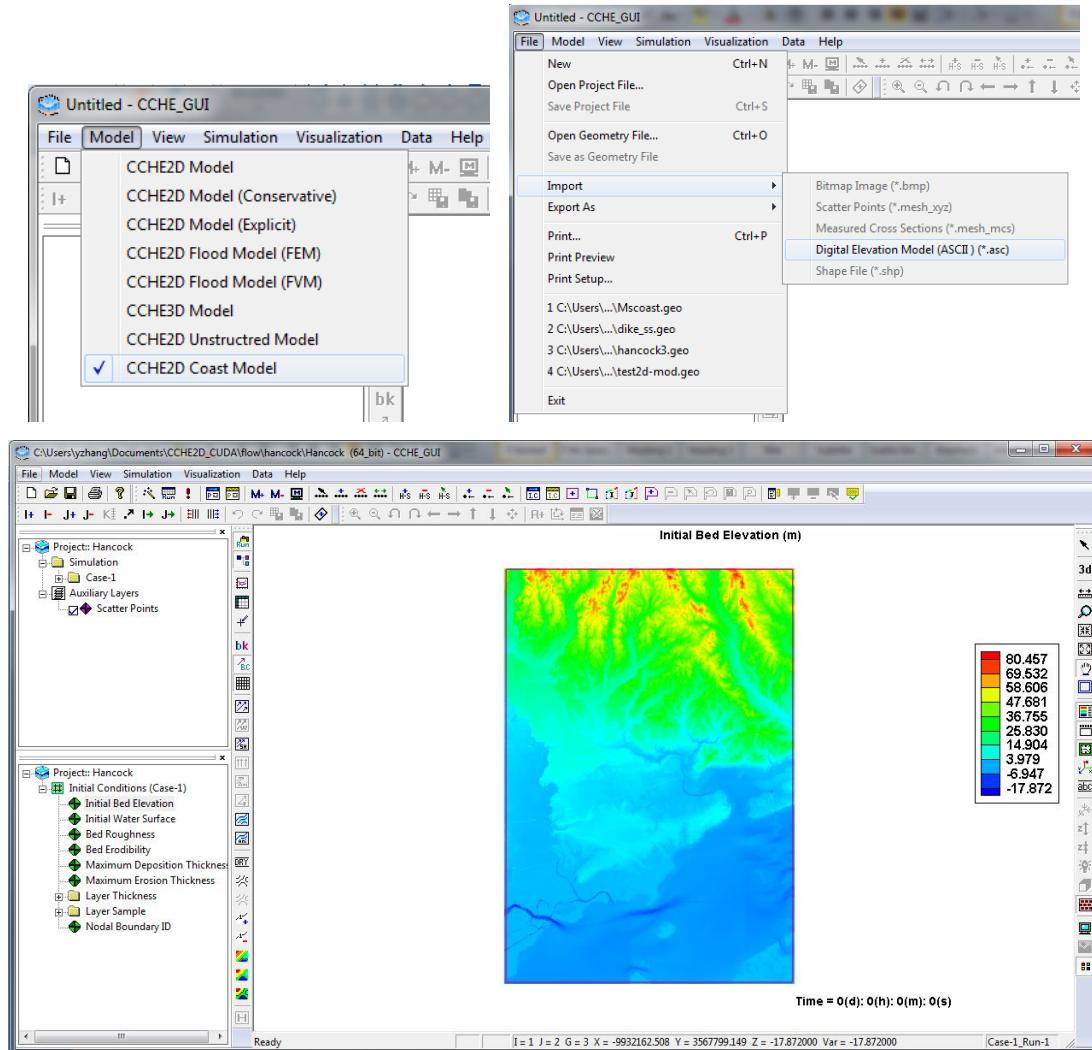
**Figure 2-1 A computational grid covering a domain with rivers, estuary, and adjacent coasts created by CCHE-Mesh**



**Figure 2-2 A computational mesh and close-up view of coastal structures and rivers in an estuary**

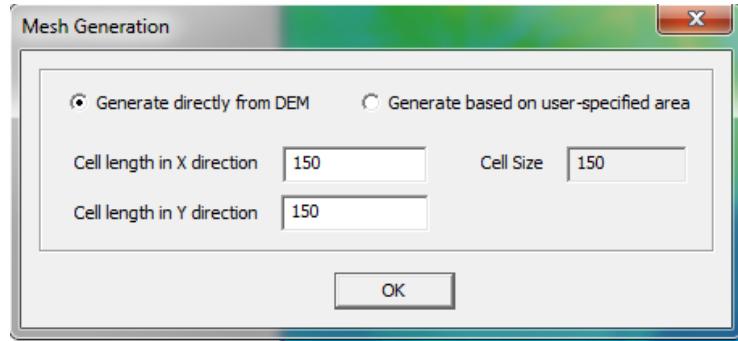
Alternatively, when the DEM (Digital Elevation Model) data is available, the users can directly generate rectangle meshes through CCHE-GUI efficiently.

To generate a mesh based on a DEM file, start CCHE-GUI and select “CCHE2D Coast Model” from “Model” menu, and then select “Digital Elevation Model (ASCII) (\*.asc)” from “Import” submenu of “File” menu to load a DEM file (see Figure 2-3).

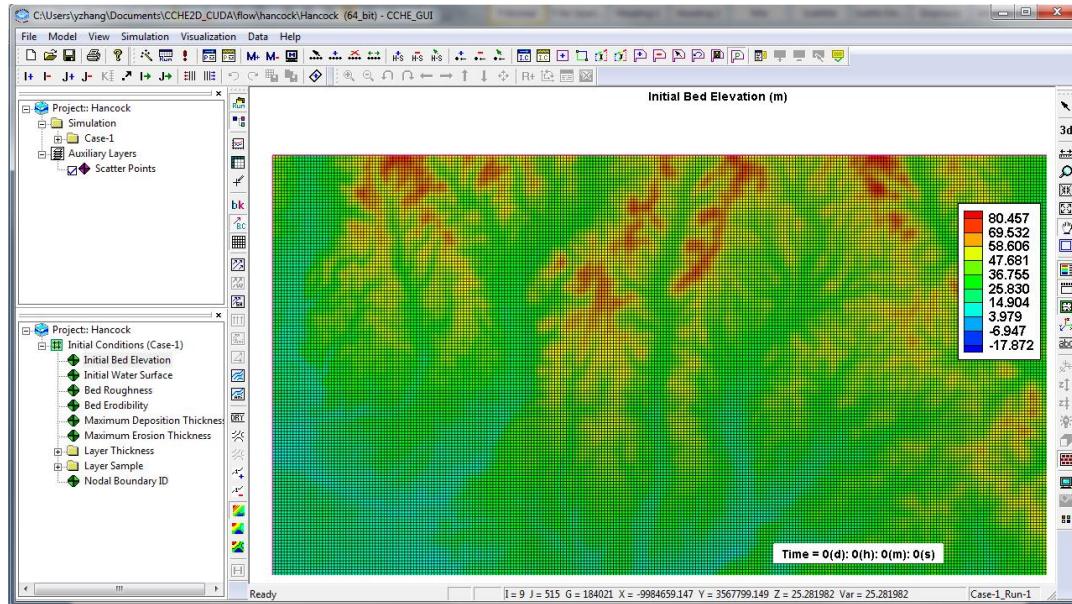


**Figure 2-3 Select CCHE2D Coast Model to Import a DEM File**

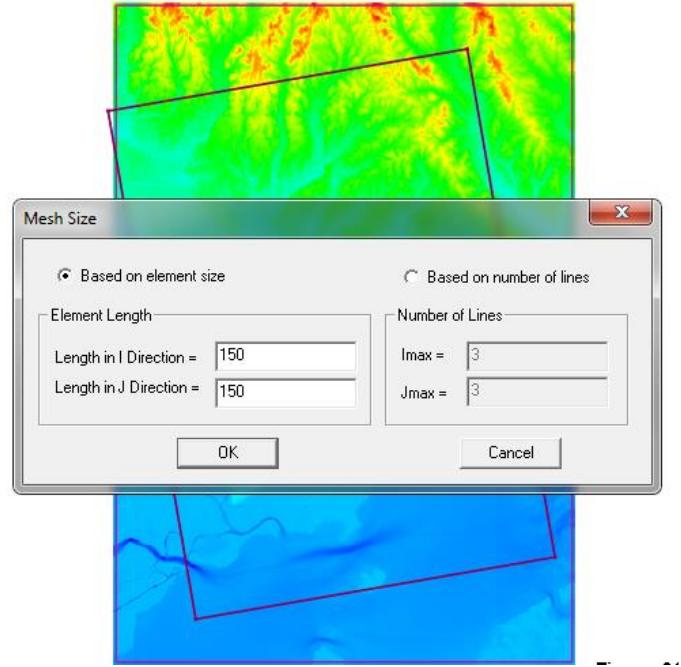
To generate a mesh, select on mesh editing Toolbar. In the dialog window “Mesh Generation”, two methods, namely, “Generate directly from DEM” and “Generate based on user-specified area”, are available (Figure 2-4).

**Figure 2-4 Mesh Generation Methods**

For the first method “Generate directly from DEM”, a Cartesian rectangle mesh covering the whole domain will be generated based on the cell length in x and y directions provided by the users (see Figure 2-5).

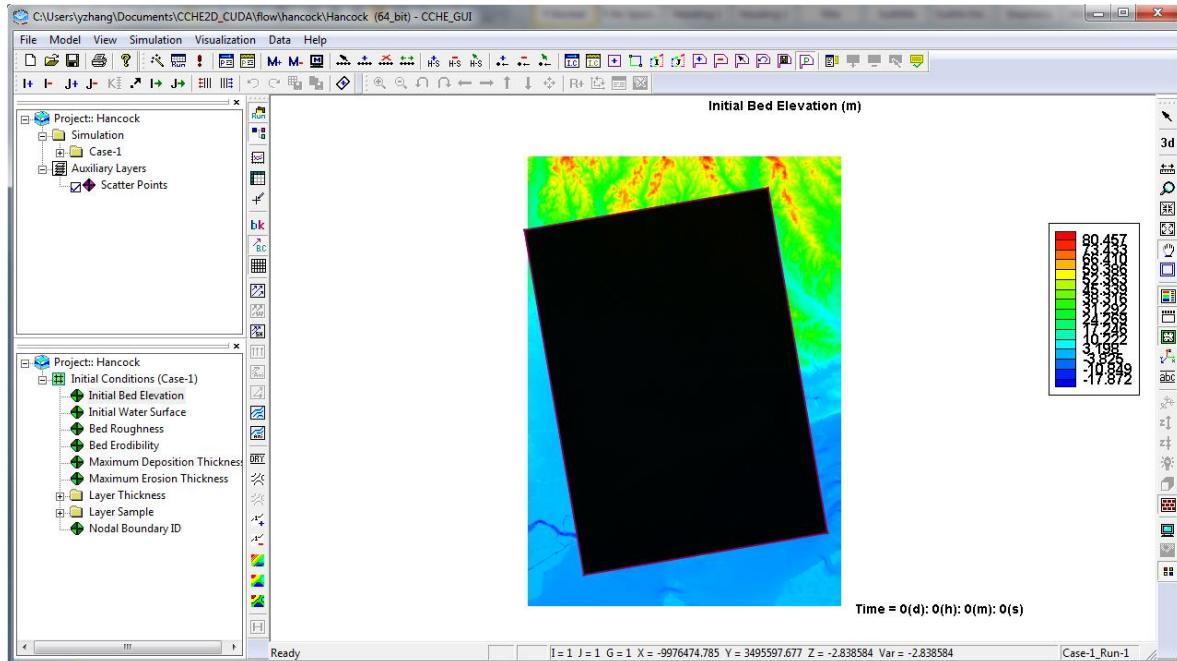
**Figure 2-5 Cartesian mesh generated directly from DEM**

If the second method “Generate based on user-specified area” is selected, the user can define a quadrilateral area by clicking four points on DEM data either clockwise or anti-clockwise. This quadrilateral will be automatically corrected and transformed into a rectangle (see Figure 2-6). In the popup window “Mesh Size”, the users can choose to generate mesh based on cell size or number of lines.



**Figure 2-6 Define a quadrilateral area as study domain**

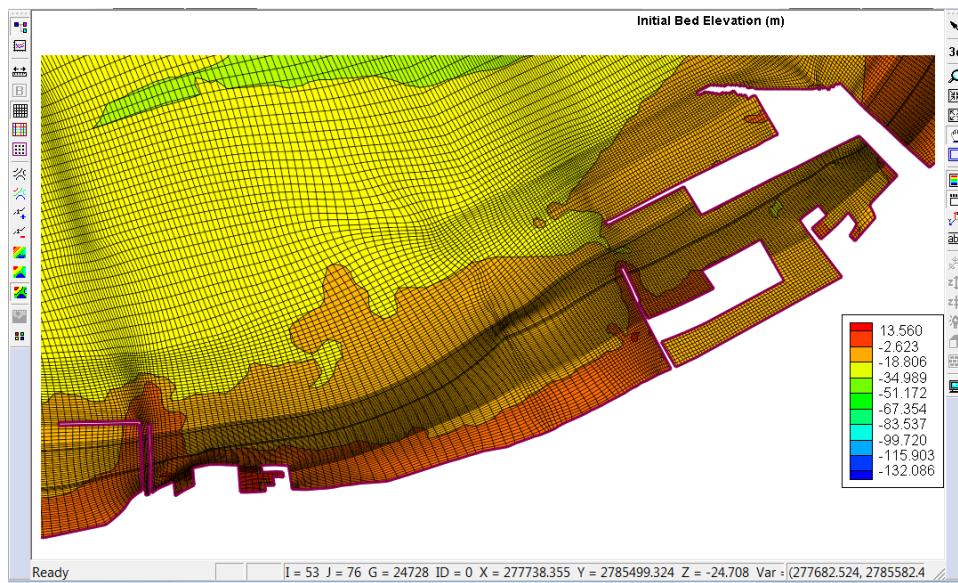
For this second method, the generated mesh can be inclined and not necessarily a Cartesian mesh, so that more precise definition of the study domain may be obtained (see Figure 2-7).



**Figure 2-7 Generate mesh based on user-specified area**

## 2.2 Define Permeable Coastal Structures

During processes of mesh generation, several in-stream structures such as breakwaters, dikes, and irregular coastlines can be modeled by arranging grid lines to fit the shapes of the structures and then changing the properties of the covered nodes to “external nodes”. Figure 2-8 presents an example grid with coastal structures such as dikes, breakwaters, and coastlines, of which the shapes are identified by the internal boundaries of those structures. Apparently, those coastal structures are impermeable, which do not allow waves to penetrate through. The user manual of CCHE2D (Zhang 2013) has provided a technical guide for modeling those in-stream structures. For the details of generating a grid covering structures, one may refer to this CCHE2D manual.



**Figure 2-8 Coastal structures in CCHE2D-Coast**

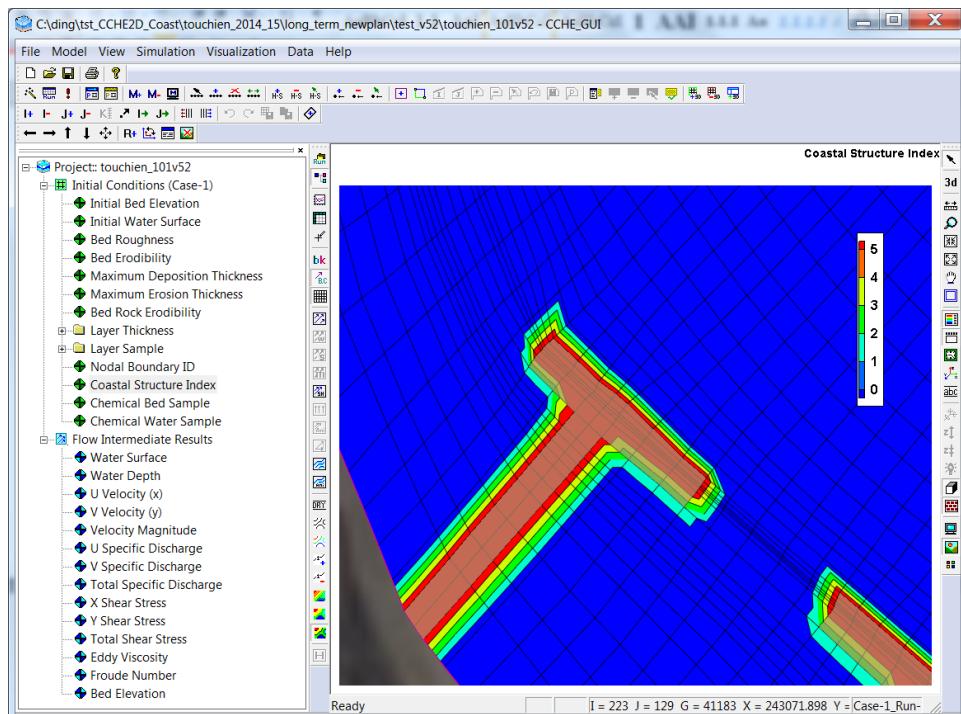
In addition to the above-mentioned impermeable structure, the CCHE2D-Coast GUI provides one more option for determining the properties of coastal structures in the model such as wave transmission and erodibility, which allow certain waves to transmit through the structures.

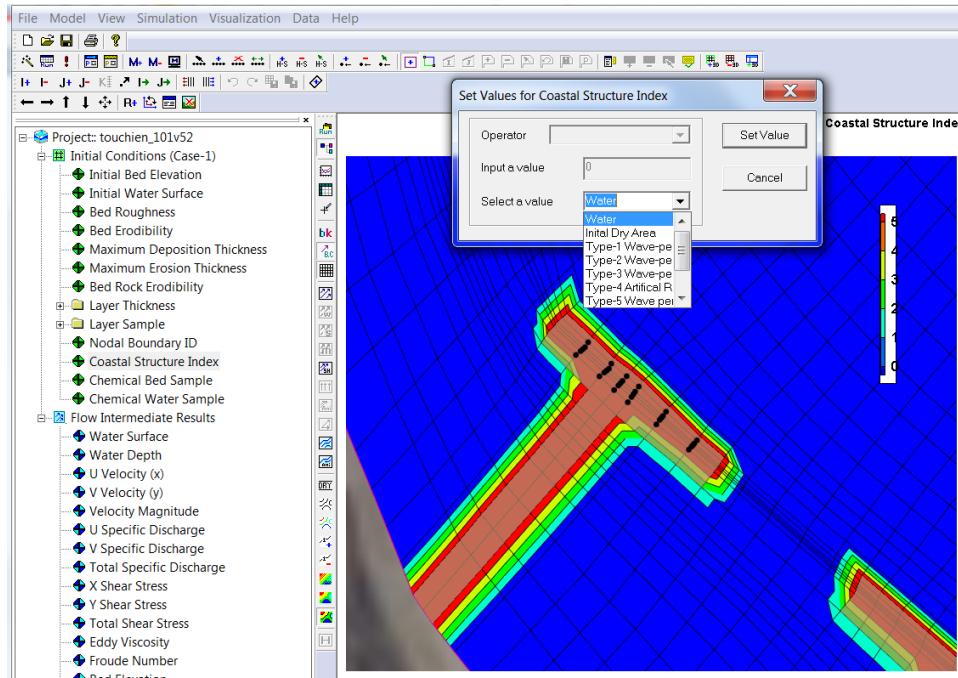
First, to identify different types of structure, the model has defined a Coastal Structure Index (CSI). As shown in Figure 2-9, a headland (a T-shape breakwater) was identified by visualizing the distribution of the CSI in a grid, in which the CSI is equal to 5, corresponding to the fourth type of the structures (its permeability similar to an artificial reef). To define the CSI through the GUI, one has to select the layer called “Coastal Structure Index” at the left hand side

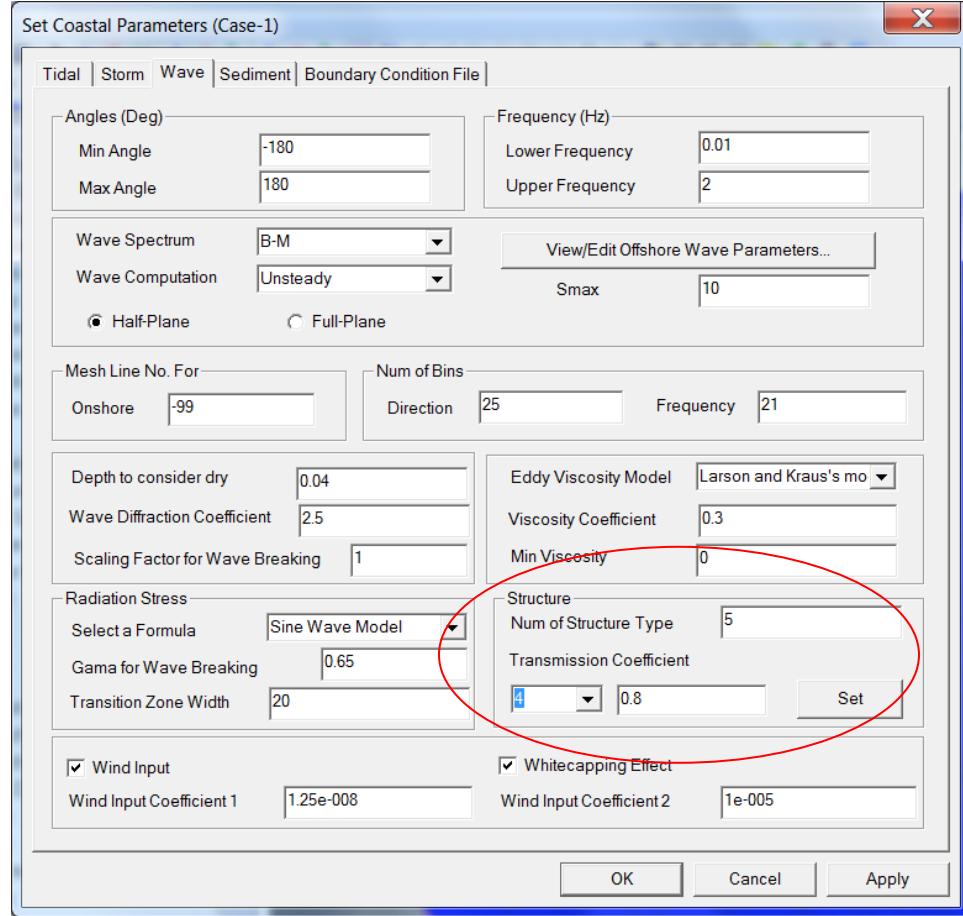
of the GUI (Figure 2-10), and then uses the button “

To simulate the wave transmission effect of a permeable structure (e.g. Figure 1-3), it is required to specify a wave transmission coefficient for each permeable coastal structure in the computational domain. For this purpose, use has to use the “Wave” window in the “Set Coastal Parameters” from the drop-down menu “Simulation”. As demonstrated in Figure 2-11, the wave transmission coefficient was set to 0.8 for this Type-4 structure. After inputted a coefficient value for each type, one has to push the button “Set” to save the value in the simulation project. As an example, Figure 2-13 plots a snapshot of computed significant wave heights and mean wave directions around a set of headlands. Finally, before running the simulation for considering those wave transmission effects, the button called “Input Structure Information” in the menu “Tidal” has to be checked (Figure 2-12).

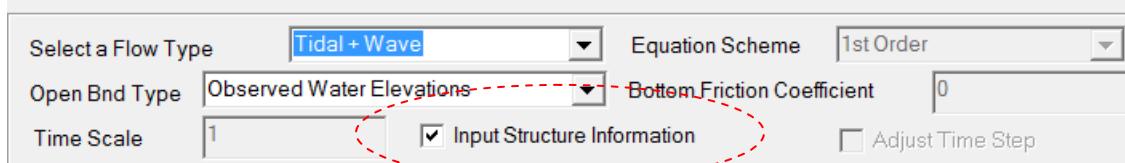
By CCHE2D-Coast, the surface of the permeable coastal structures is assumed to be non-erodible. It means that the sediment load may go through the structures, but it won’t cause any morphological changes on the areas of the structures.



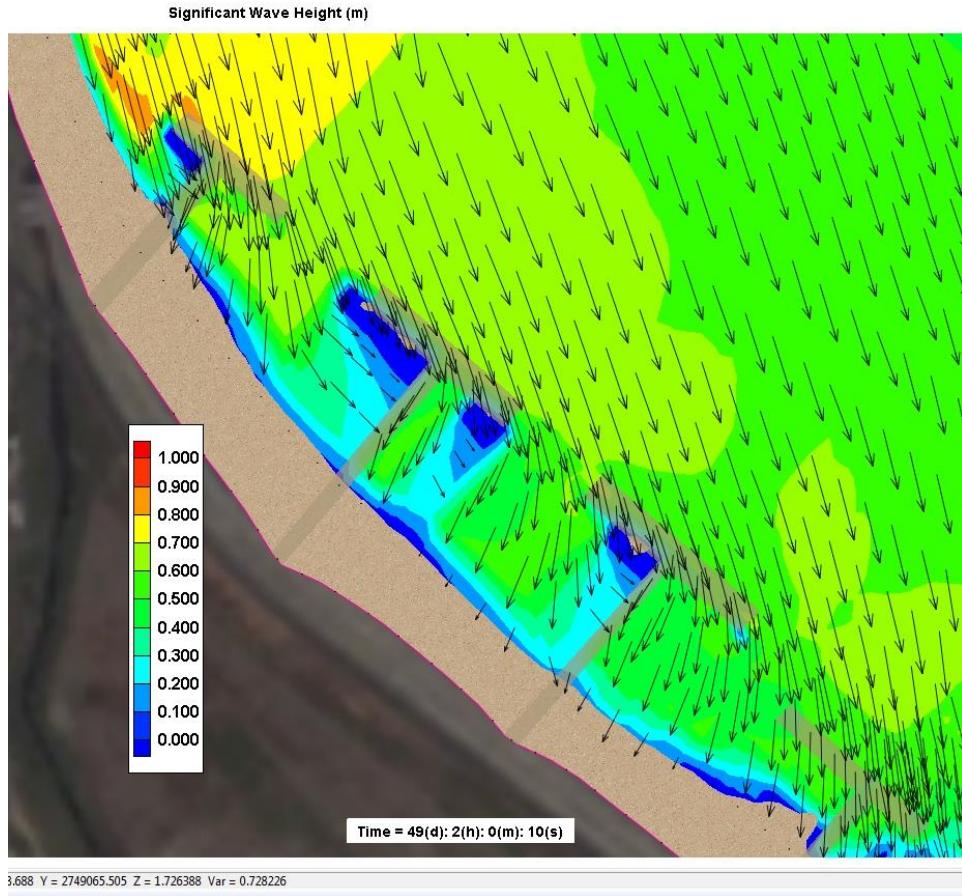
**Figure 2-9 Coastal structure index (CSI) for defining structures in CCHE2D-Coast****Figure 2-10 Change coastal structure index**



**Figure 2-11 Specify wave transmission coefficients for coastal structures (The number of Structure Types has to be given before the values are set up)**



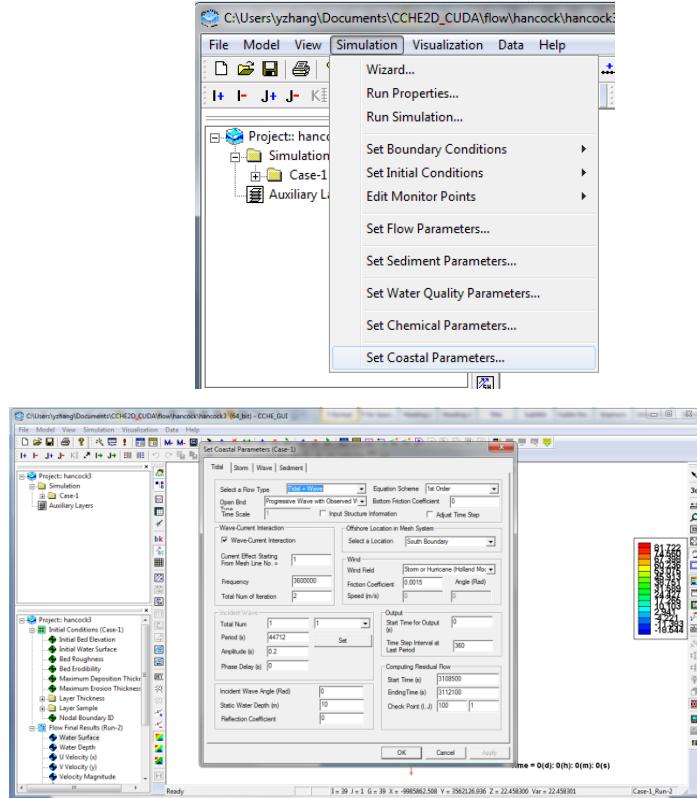
**Figure 2-12 Input structure data through the menu “Tidal”**



**Figure 2-13 An example of computed significant wave heights and mean wave directions around structures**

## 2.3 Set Parameter Values for Computing Coastal Processes

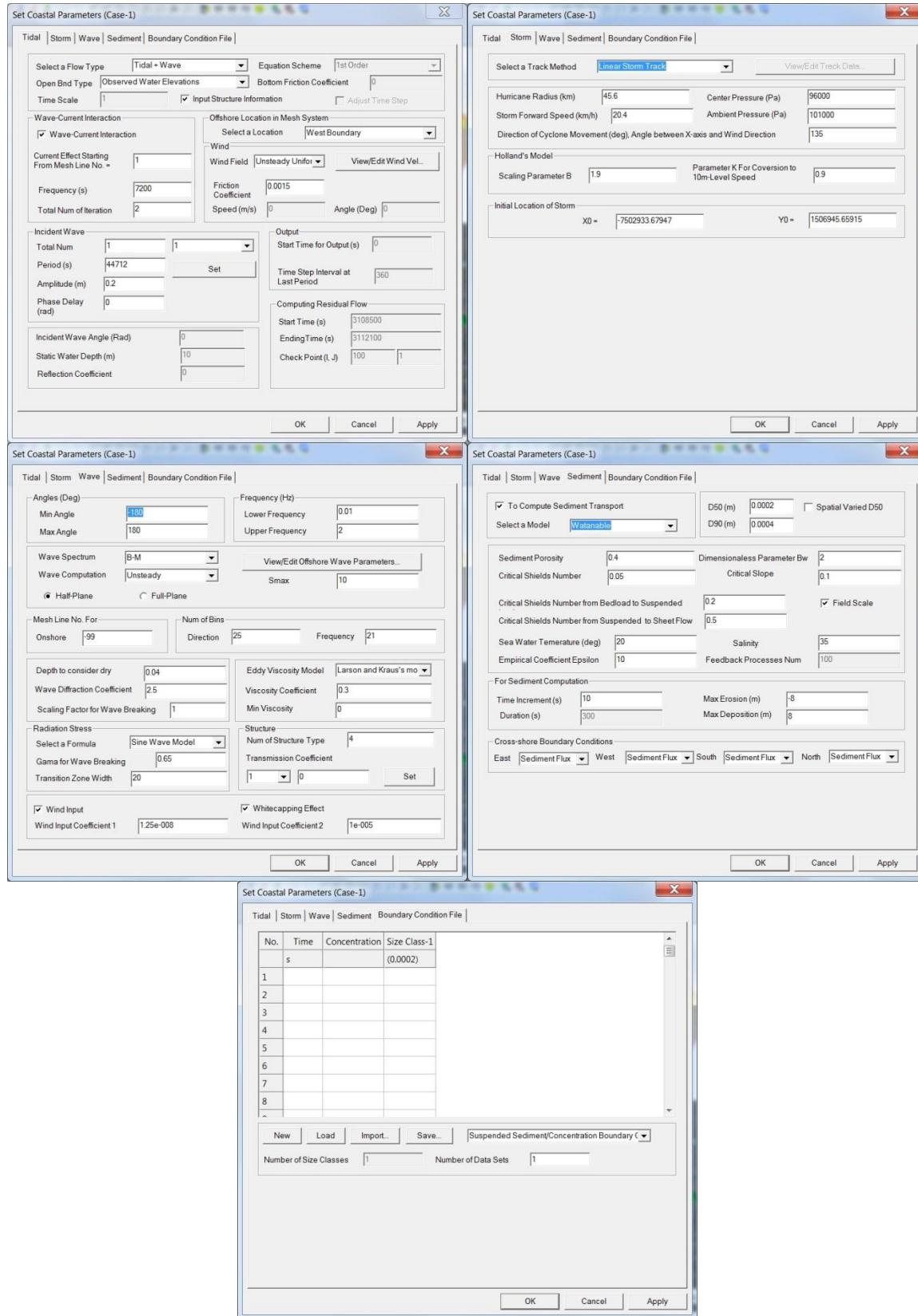
After generated a mesh, user can set the coast parameters by selecting the “Set Coastal Parameters...” window from “Simulation” menu (see Figure 2-14).



**Figure 2-14 Set parameter values**

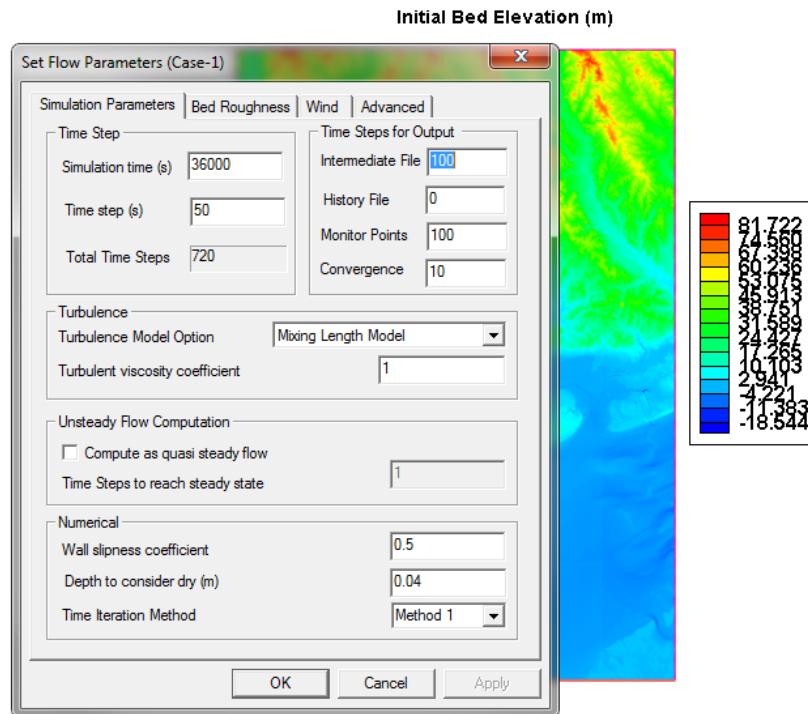
In the window “Set Coastal Parameters”, the coastal parameters are grouped into five pages, namely, “Tidal”, “Storm”, “Wave”, “Sediment”, and “Boundary Condition File” (see Figure 2-15). For illustration purpose, the physical definitions of all the parameters will not be covered here. The specifications of the coastal model parameters will be discussed in Sections 3 – 6 in the tutorial examples.

## Graphical User Interface for CCHE2D-Coast-Quick Start Guide



**Figure 2-15 Five windows for specifying parameters in the coastal model**

Because the hydrodynamic model of CCHE2D-Coast was developed by using the same numerical approaches as the CCHE2D model has utilized, and the governing equations of the hydrodynamic process model are the same, the depth-averaged shallow water equations. Therefore, for running the coastal model, user needs to use the “Set Flow Parameters” window from “Simulation” menu (Figure 2-16) to specify the computational control parameters such as the time step size of flow model, simulation time, output frequency of simulations results, and to select turbulence models.



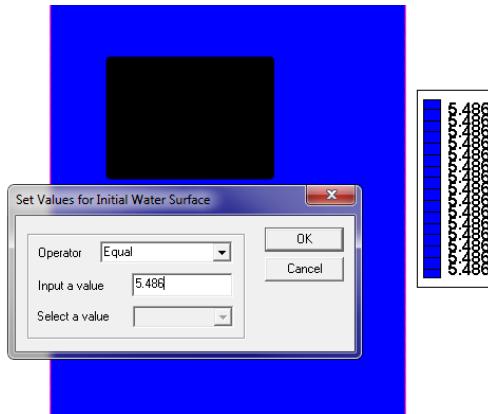
**Figure 2-16 Set Flow Parameters**

## 2.4 Set Initial Conditions

The user is required to set “Initial Water Surface” and may set other initial conditions, such as “Initial Bed Elevation”, “Bed Roughness”, and “Bed Erodibility”, etc., when necessary.

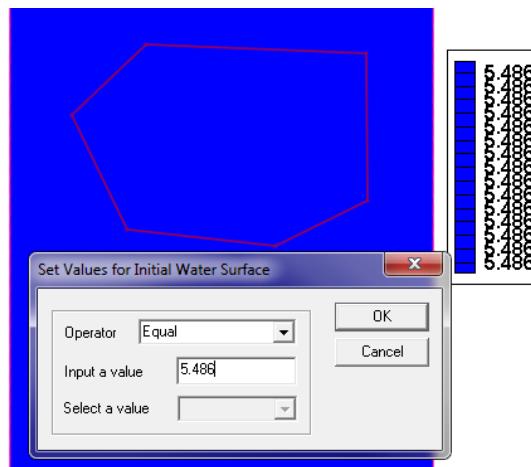
To set “Initial Water Surface”, select “Initial Water Surface” from “Initial Conditions” group in “Variable View”. The user can set a constant value in either a rectangle area or arbitrary polygon area or the whole domain.

- Select  from Simulation Toolbar, and then click two diagonal points to define a rectangle area in the mesh (see Figure 2-17).



**Figure 2-17 Define a rectangle area**

- Select  from Simulation Toolbar, and then click more than three points on the mesh to define a polygon area (see Figure 2-18).
- 



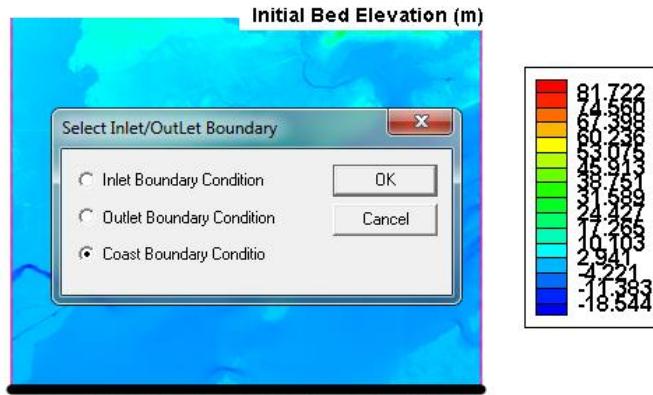
**Figure 2-18 Define a polygon area**

- Select  from Simulation Toolbar to choose the whole domain.

A similar procedure may be performed for setting the other initial conditions.

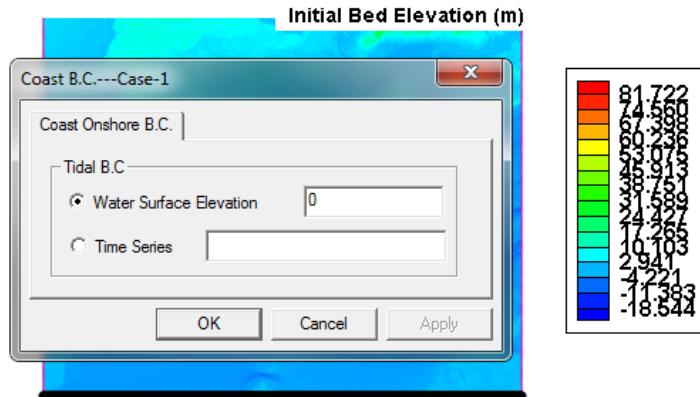
## 2.5 Set Boundary Conditions

To set the coastal boundary conditions, select  from Simulation Toolbar and the click two boundary points on a I line or J line to define a boundary node string (see Figure 2-19). In the popup window, select “Coastal Boundary Condition” and the click OK.

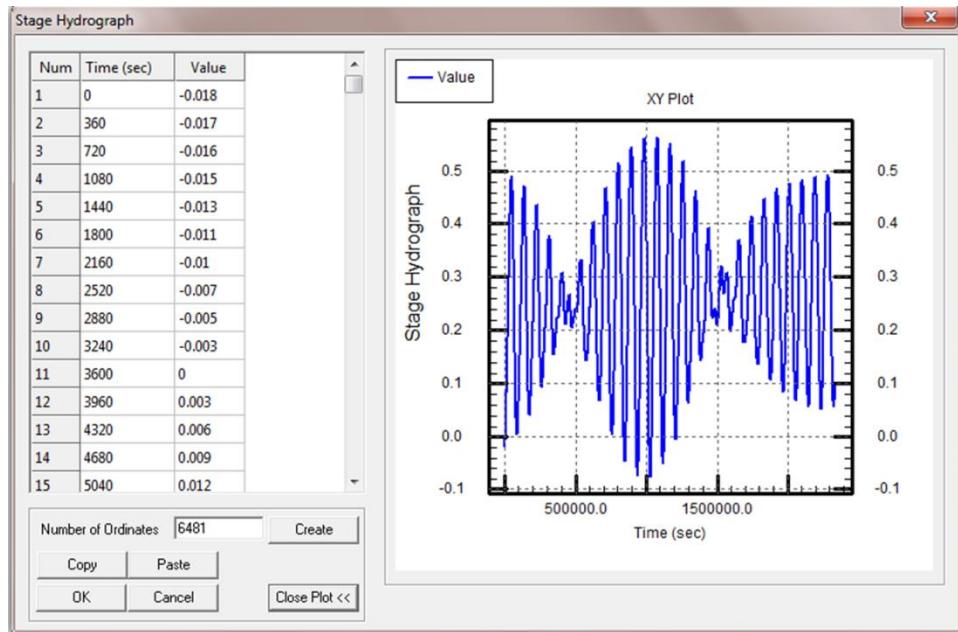


**Figure 2-19 Define coastal boundary node string**

In the window “Coastal B.C”, the user may set a constant water surface (Figure 2-20) or a time series stage hydrograph (Figure 2-21) at the current boundary node string (typically the offshore boundary node strings).



**Figure 2-20 Set coastal boundary conditions**



**Figure 2-21 A time series of tidal elevations created and visualized in the GUI**

## 2.6 Set Parameters for Sediment Transport Simulation

When sediment transport and morphological changes needed to be computed, user can utilize the “Sediment” window in the “ Set Coastal Parameters” menu to set the parameter values of sediment transport model and the types of boundary conditions of sediment transport rates (Figure 2-22).

First, one has to check the option “to Compute Sediment Transport” to request for coupling computation of flows and morphological changes. For the sediment transport rate formulation, the current coastal model only provide the Watanabe model (Eq. (38) in Watanabe et al. (1986)) for computing the total sediment transport rates driven by the combined wave and current. For computing the sediment transport rates from river to coast, this formulation has been modified by Ding et al. (2008a).

If the bed composition is uniform over the computational domain, the representative sediment sizes D50 and D90 can be given in the window, of which the unit is meter. If the bed composition is not uniform, after checking the option “Spatial Varied D50”, user has to prepare an additional data file for the node-defined values of D50 which is a list of D50 at all the nodes as demonstrated in Figure 2-23. The sequence of the data is the same as the CCHE grid file (i.e.

\*.geo). The file name of the D50 data is \*\_d50.dat, in which “\*” is the project name. This data file has to be located in the project folder where all the project files are stored.

For many other parameters such as sediment porosity, Bw, critical Shields numbers, user can specify general values of them as suggested in Figure 2-22. But one has to validate the “Time Increment” case-by-case. The maximum deposition height and the maximum erosion depth can be given through the window. However, the two values are constant over the domain, which are not varying in space.

The model provides two types of boundary conditions for cross-shore sediment transport rate, one is for no sediment supply through the cross-shore section, another the gradient of the sediment rate equal to zero (in other words, an open boundary condition for the sediment flux). Figure 2-24 displays the two options: “No Sediment” for the first type of the boundary condition, and “Sediment Flux” for the second boundary condition.

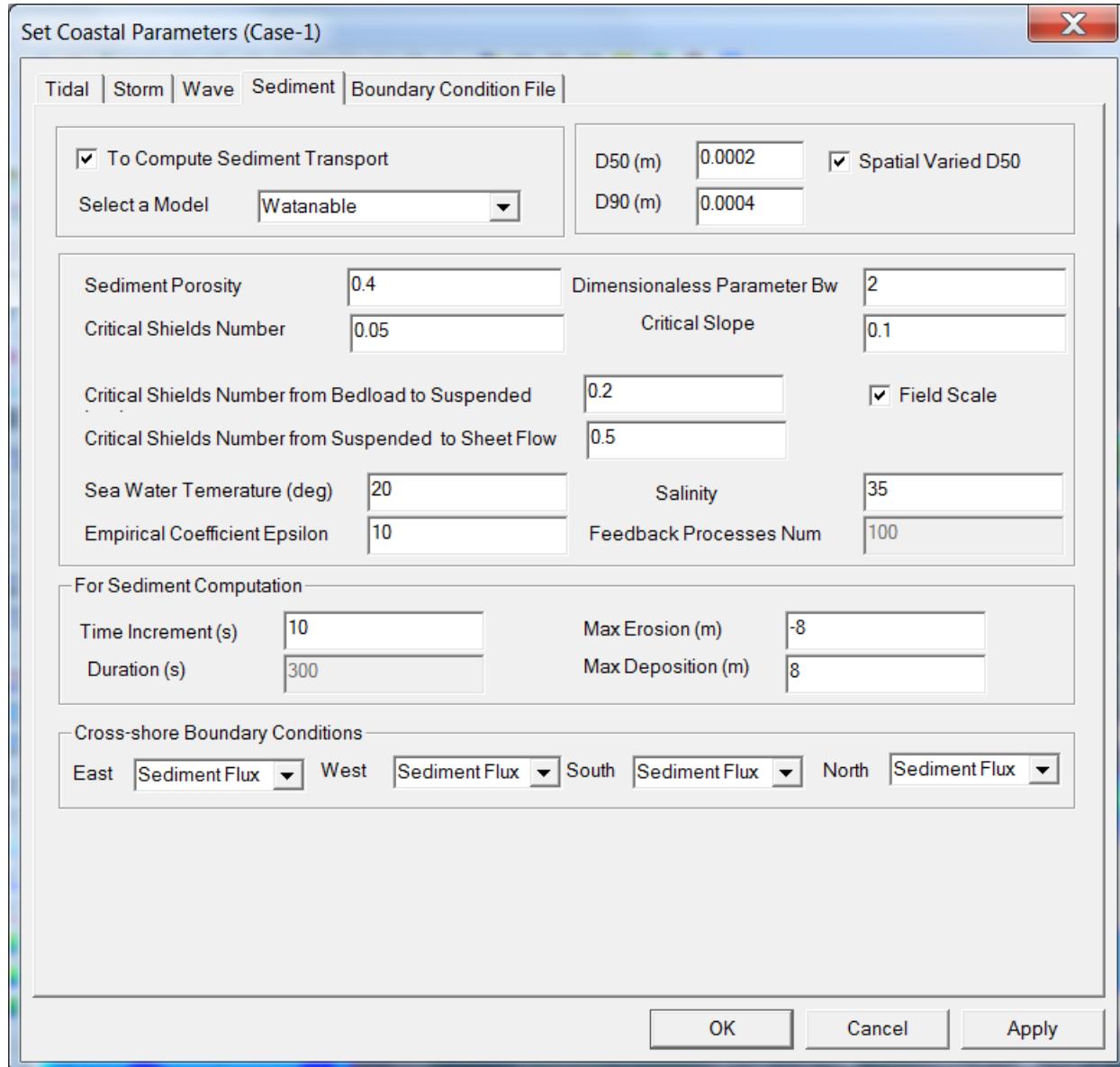
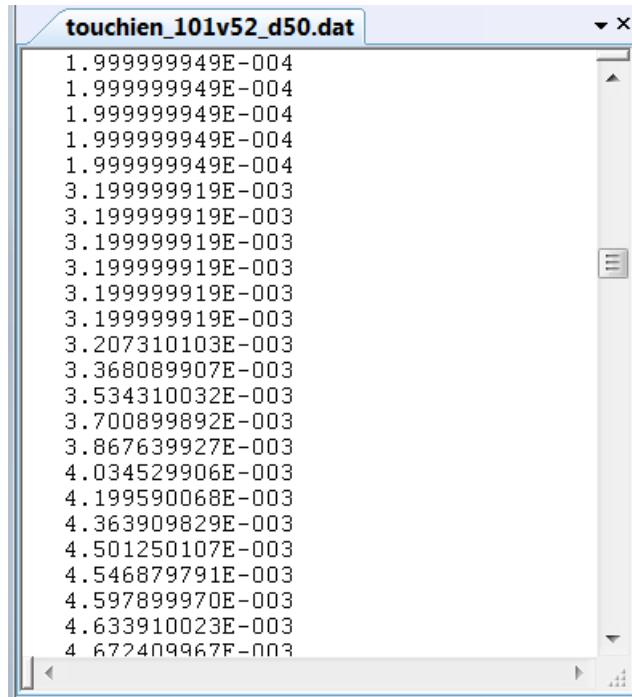
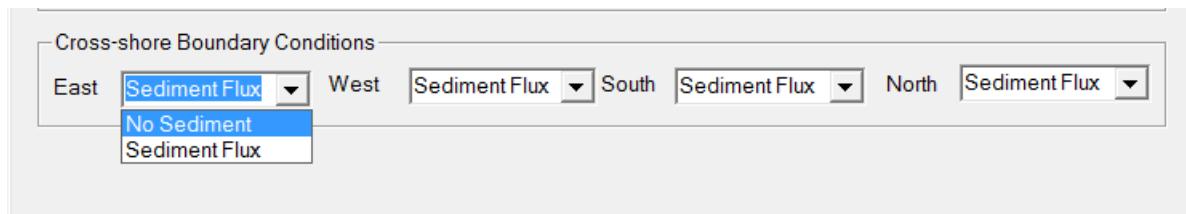


Figure 2-22 “Sediment” window for setting up parameters of sediment transport model



**Figure 2-23 Data structure for inputting spatially-varying D50**

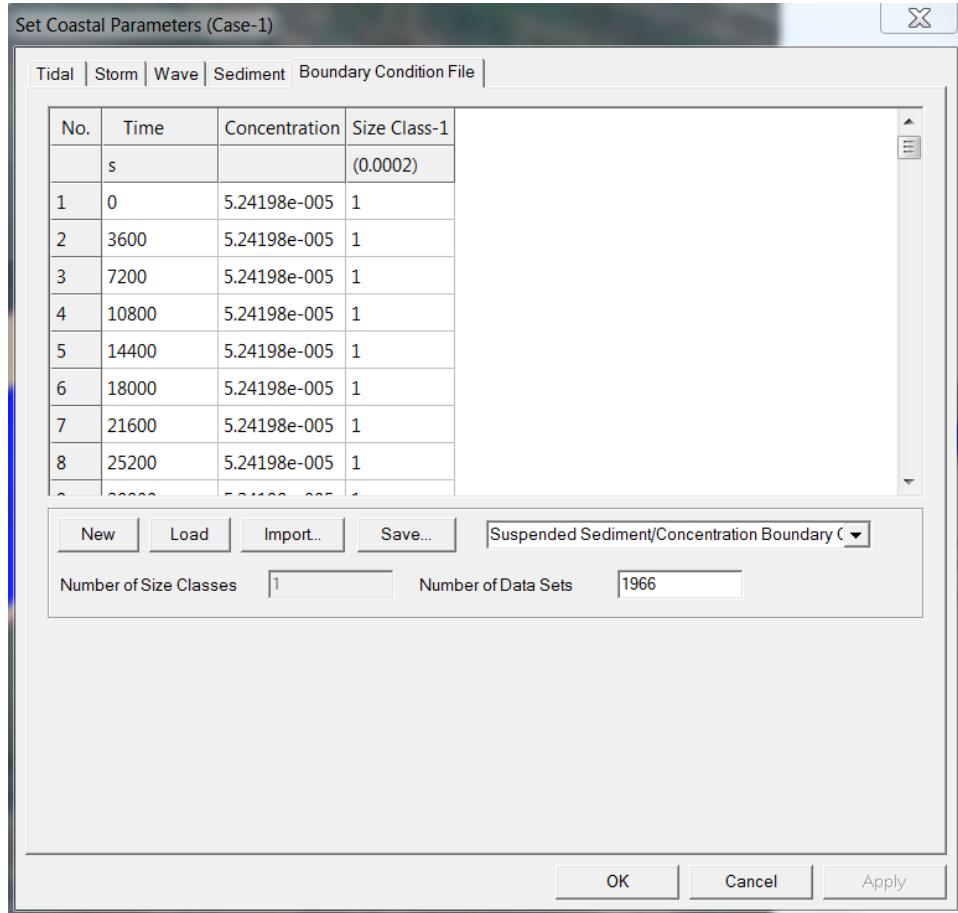


**Figure 2-24** Cross-shore sediment transport boundary conditions

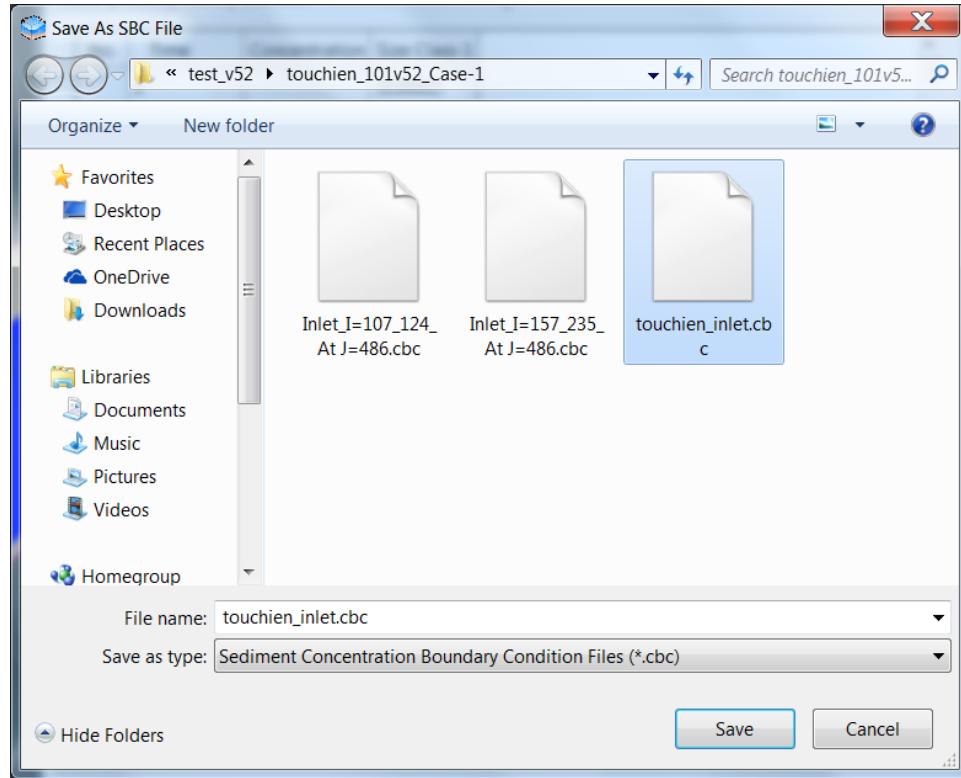
## 2.7 Specify Boundary Conditions for Sediment Concentration from River Inflows

In case that a time series of sediment supply through river inflows is needed to be specified, in the first step, user is suggested to prepare a set of data for the cross-section averaged sediment concentration (for total load) according to Eq. (39). Then, using the window “Boundary Condition File” from the menu “Set Coastal Parameters” as shown in Figure 2-25, user can specify the total number of the data record, and input the data for time, concentration, the number of sediment size class. In the current version of CCHE2D-Coast, only single sediment

size class is allowed. Finally, the sediment concentration data is saved to a file with a “cbc” file extension. One may refer to Figure 2-26 as an example for saving a data file.

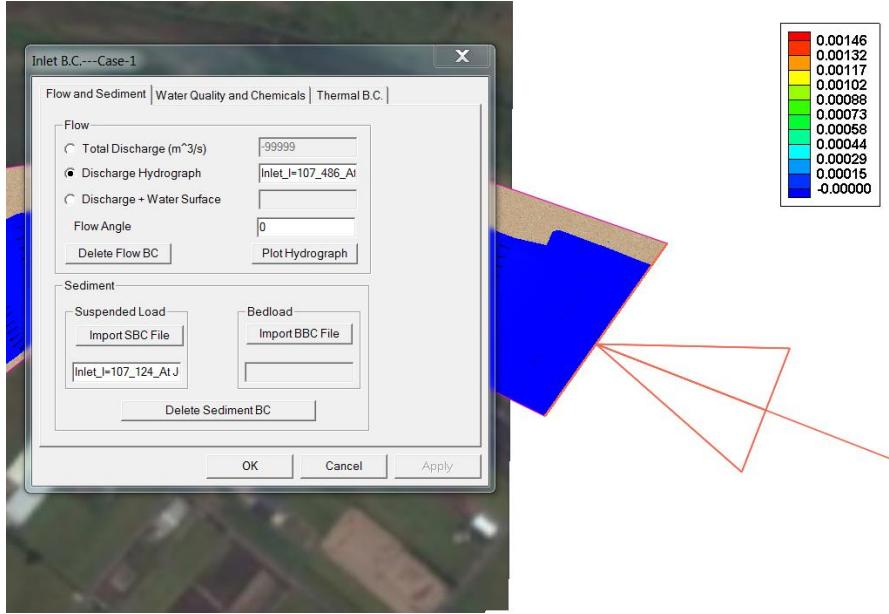


**Figure 2-25 A time series of cross-section averaged sediment concentration created by the GUI**



**Figure 2-26 A data file for time series of cross-section averaged sediment concentration is saved**

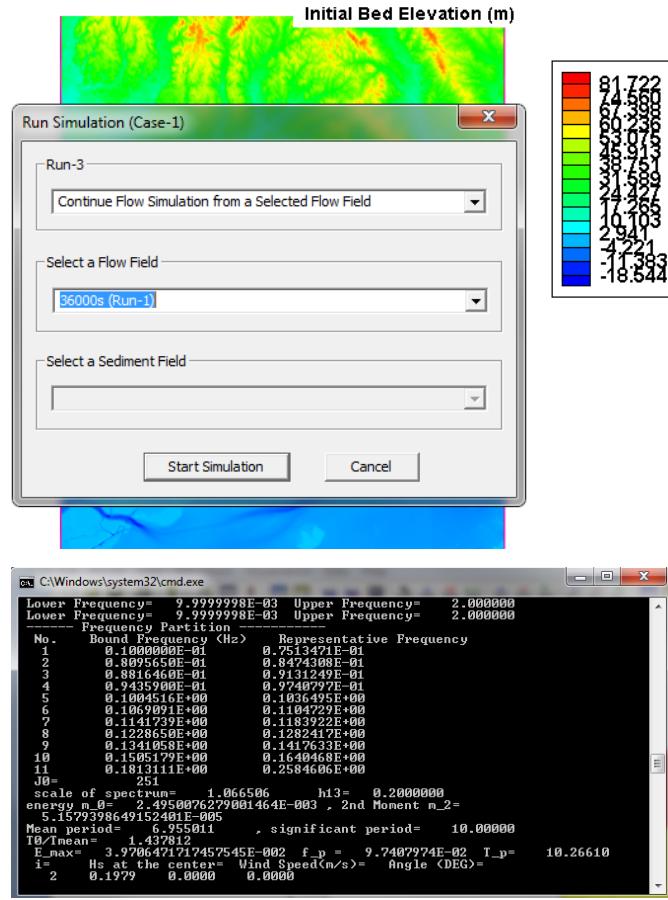
To specify this time series data file as the boundary conditions of the sediment concentration of total load at an inlet, user needs to pre-define a nodal string at the inlet boundary which is the same as the one for a hydrograph at the inlet crosssection of a river. The details for defining a nodal string for boundary conditions, one may refer to the user manual of CCHE2D (Zhang 2013). Once user has defined a nodal string for an inlet boundary, user can import the prepared file name by using the window “Inlet B.C.” through “Set Boundary Conditions” to “Select Node String” (Figure 2-27). Finally, user needs to save the entire project through the GUI.



**Figure 2-27 Link the data file for sediment concentration to the inlet boundary**

## 2.8 Launch Simulation

CCHE2D-coast model starts with an initial flow field, so a steady flow simulation is required before launching the simulation for coastal processes. To run simulation of coastal processes, select from Simulation Toolbar, and in the window of “Run Simulation”, select “Continue Flow Simulation from a selected Flow Field” and select a desired flow field (see Figure 2-28). Finally, click “Start Simulation” and a simulation will be carried out in a console window.



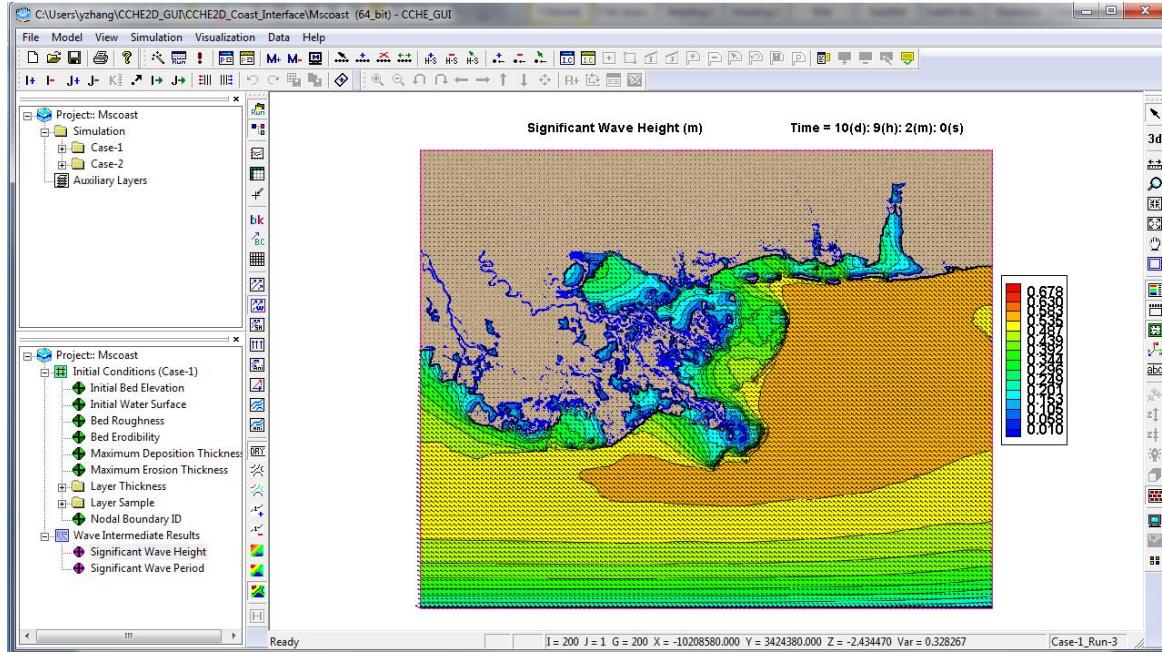
## **Figure 2-28 Run coastal simulation**

## 2.9 Visualize and Analyze Simulation Results

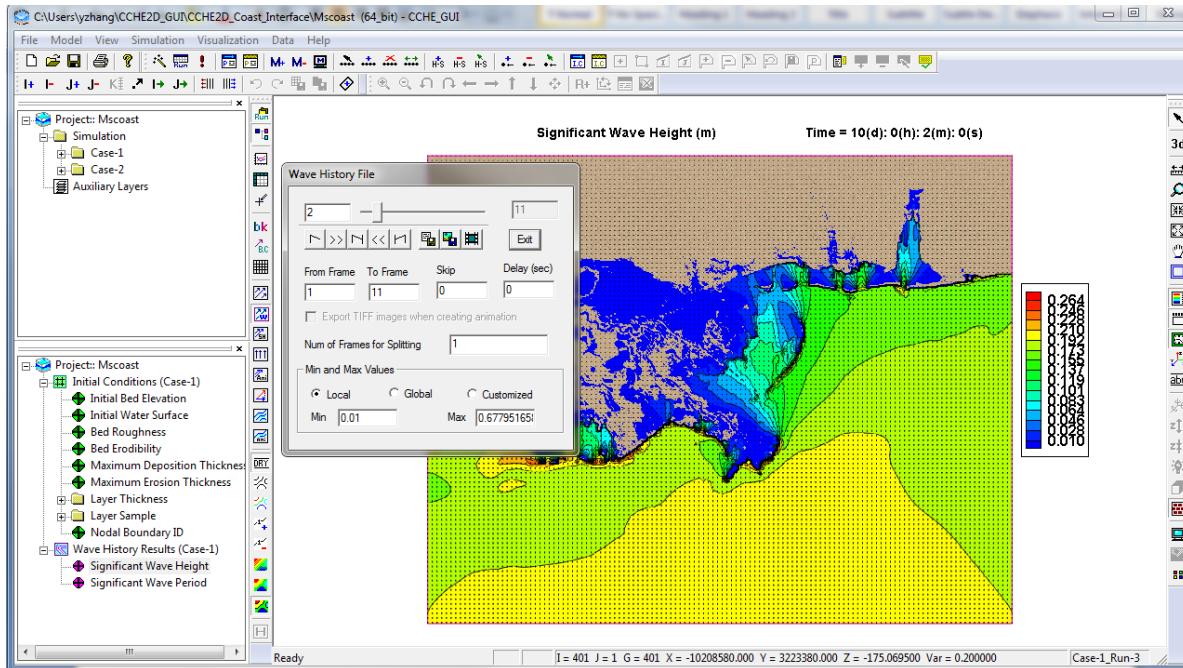
### 2.9.1 Visualization of Wave Results during and after a Simulation

During a simulation, user can visualize intermediate results of flows and waves in the GUI such as flow velocity fields and spatial distributions of wave parameters (i.e. significant wave heights, significant wave periods, and wave mean directions). After the simulation is finished, user can visualize history of wave fields as well. Currently, the “Significant Wave Height” and “Significant Wave Period” are available to view and analyze.

To load and visualize the wave results, select “Wave Intermediate File” (see Figure 2-29) or “Wave History File” (see Figure 2-30) from “Visualization” menu.



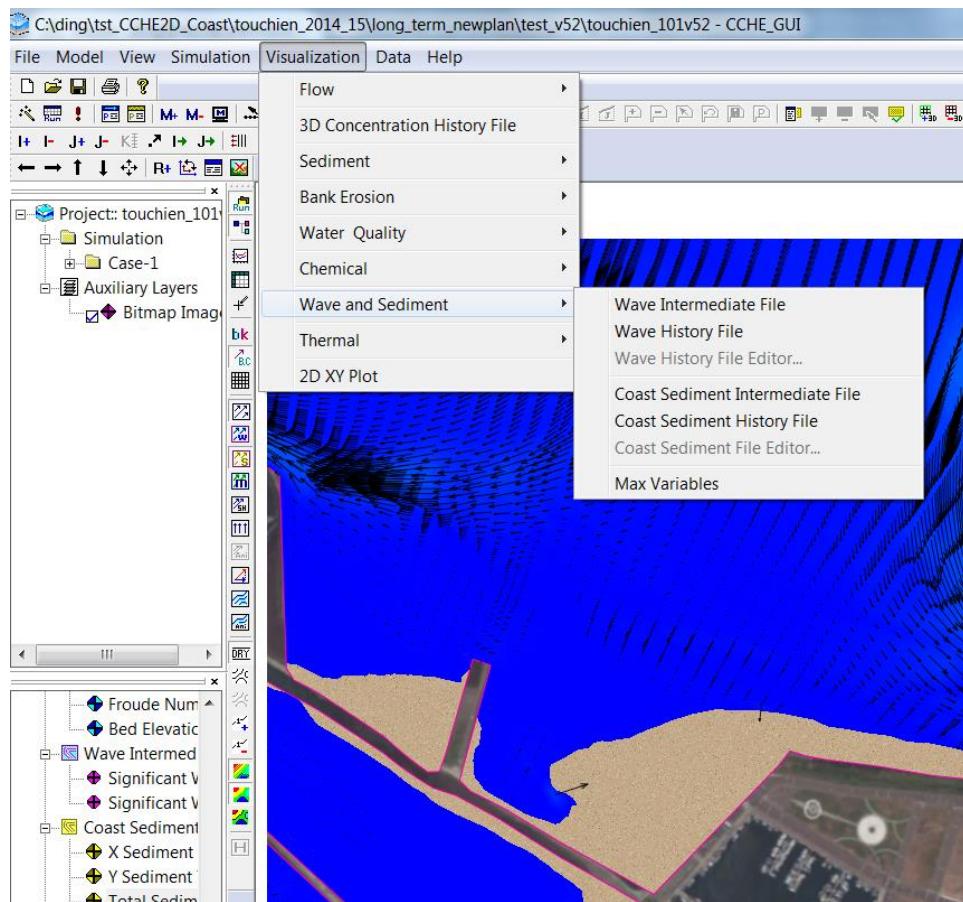
**Figure 2-29 Visualize wave intermediate results**



**Figure 2-30 Visualize wave history results**

## 2.9.2 Visualization of Sediment Transport Results during and after a Simulation

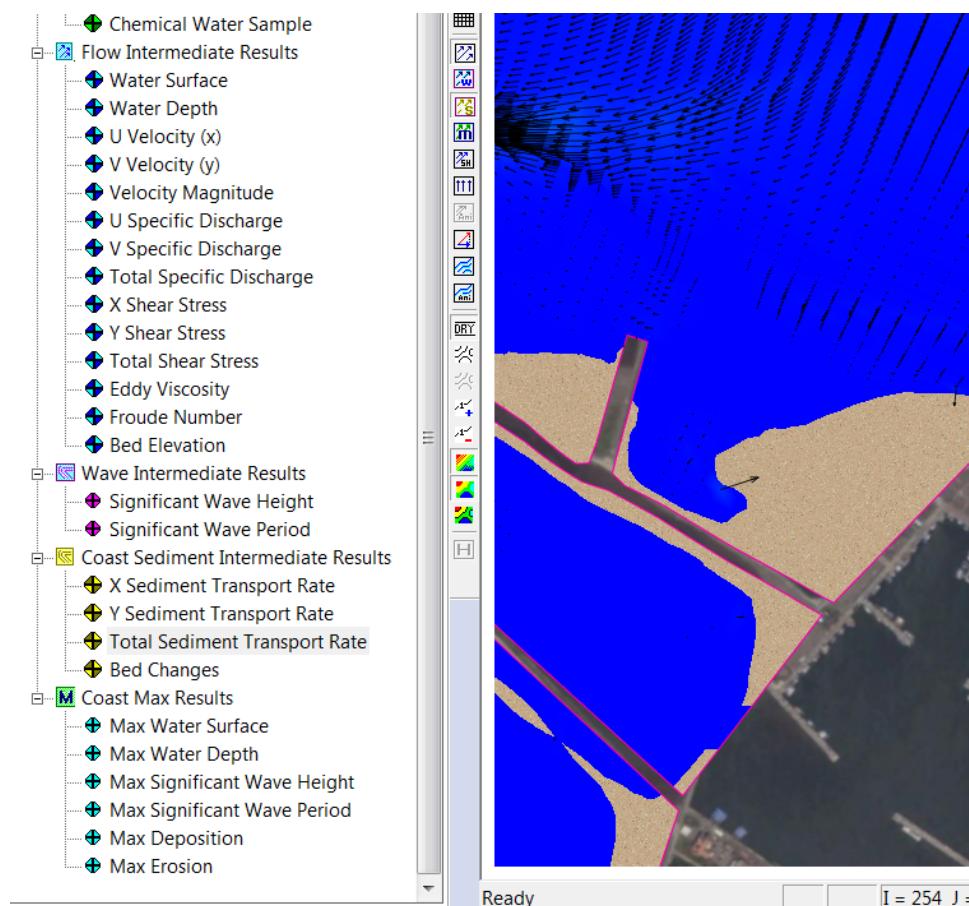
Similar to monitoring results of flows and waves during the simulation, the GUI also provides the corresponding visualization capabilities to plot an intermediate result of sediment transport rates and bed changes. Figure 2-31 shows the expanded menu for loading the simulation results of intermediate wave data, sediment transport rate, and the history data files of these variables. At the same time, the maximum values of flows, waves, and morphological changes will be loaded into the GUI.



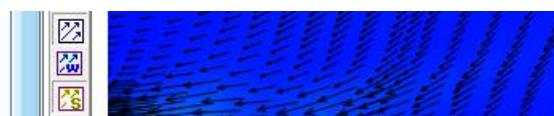
**Figure 2-31 Visualize results of waves and sediment transport**

In addition to the computed hydrodynamic variables such as water surface elevations, depths, etc. this GUI can display the computed results of significant wave heights ( $H_s$ ), significant wave periods ( $T_s$ ), mean wave directions, sediment transport fluxes ( $q_s$ ), bed change, and the maximum values for water elevations, depths, wave heights, and bed changes (maximum depositions and erosions). Figure 2-32 gives an overall view of the menu for displaying these

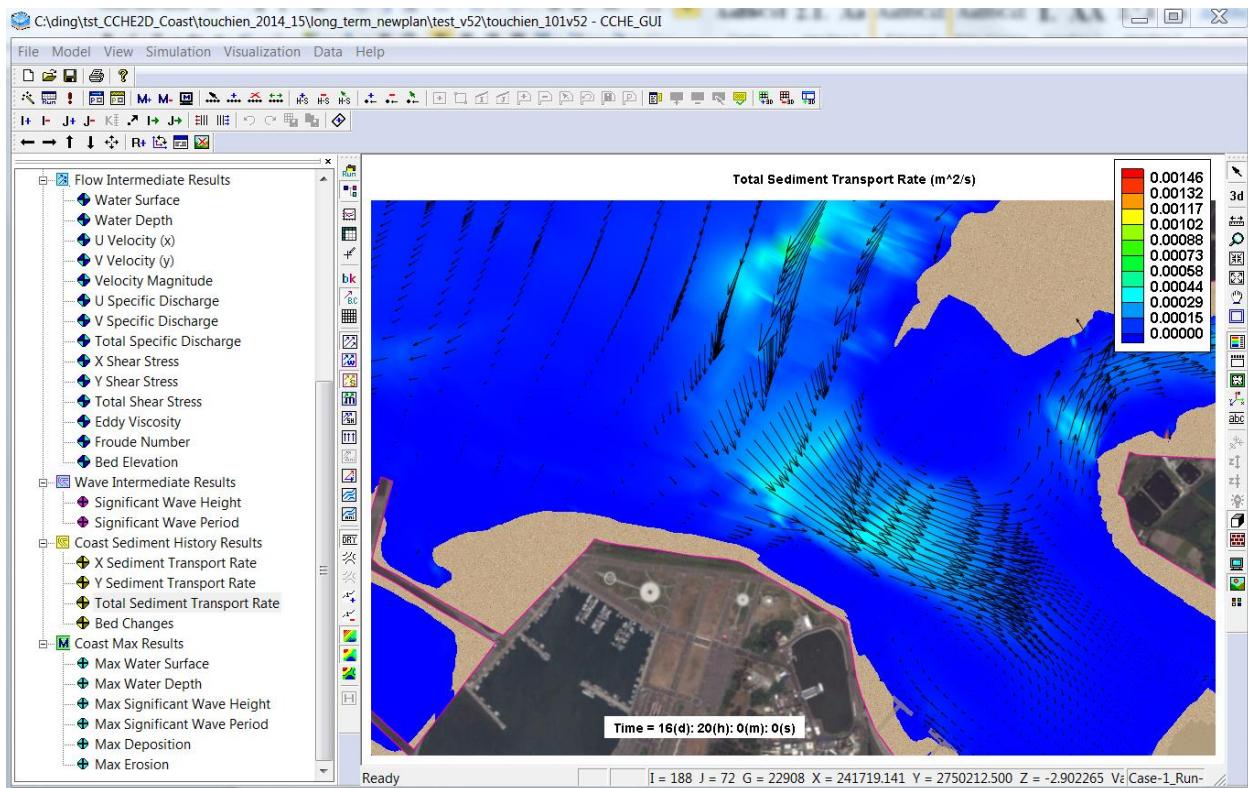
variables at the left hand side. The three buttons with arrows as shown in Figure 2-33 are for displaying velocity vectors, wave directions, and sediment transport fluxes. In case of plotting the maximum wave heights, the button of wave directions will draw the vectors for mean wave directions of the maximum significant waves. The vector field of computed sediment transport fluxes/rates can also be readily displayed (Figure 2-34). After the history files of sediment transport are loaded into the interface, the animations of those variables (sediment transport flux and bed changes) can be generated by the GUI (Figure 2-35).



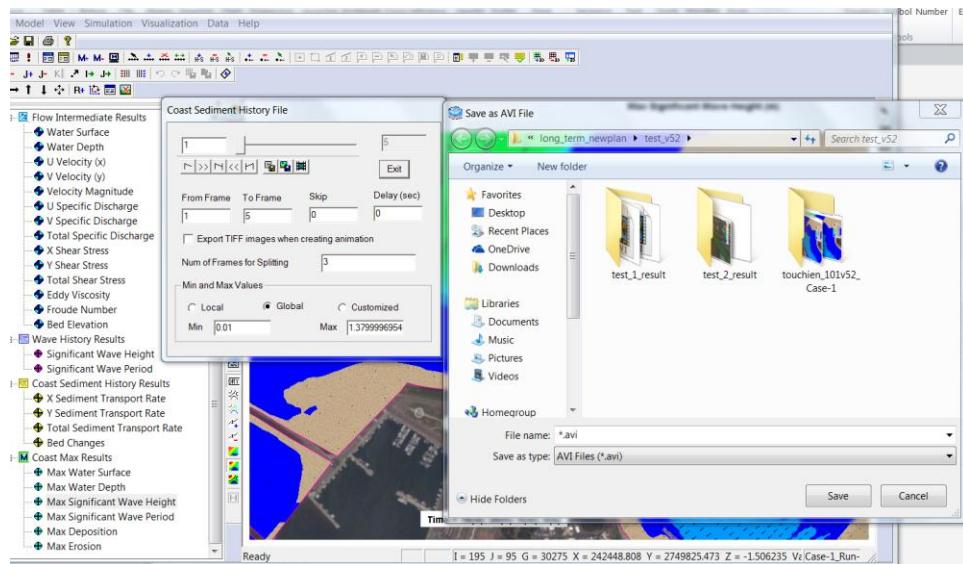
**Figure 2-32 Menu for displaying simulation results**



**Figure 2-33 Buttons for displaying velocity vectors, wave directions, and sediment transport fluxes**



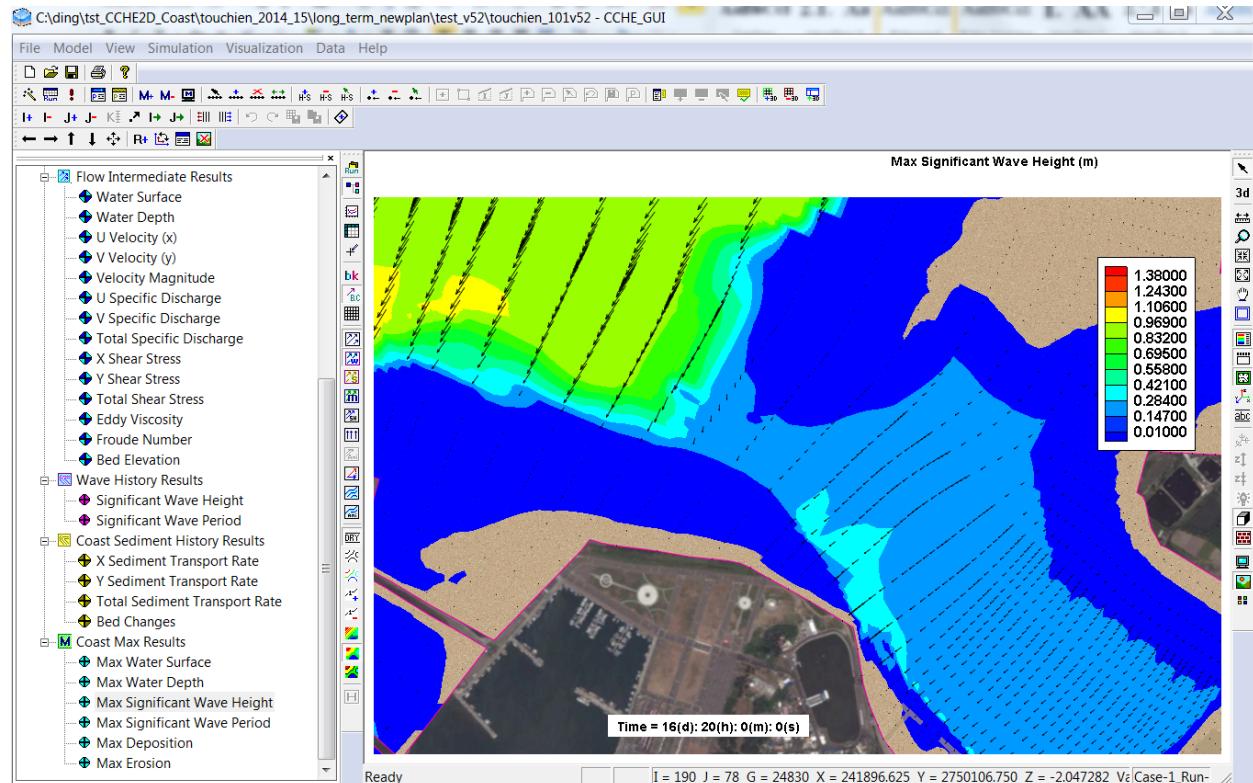
**Figure 2-34 Displaying the sediment transport rate**



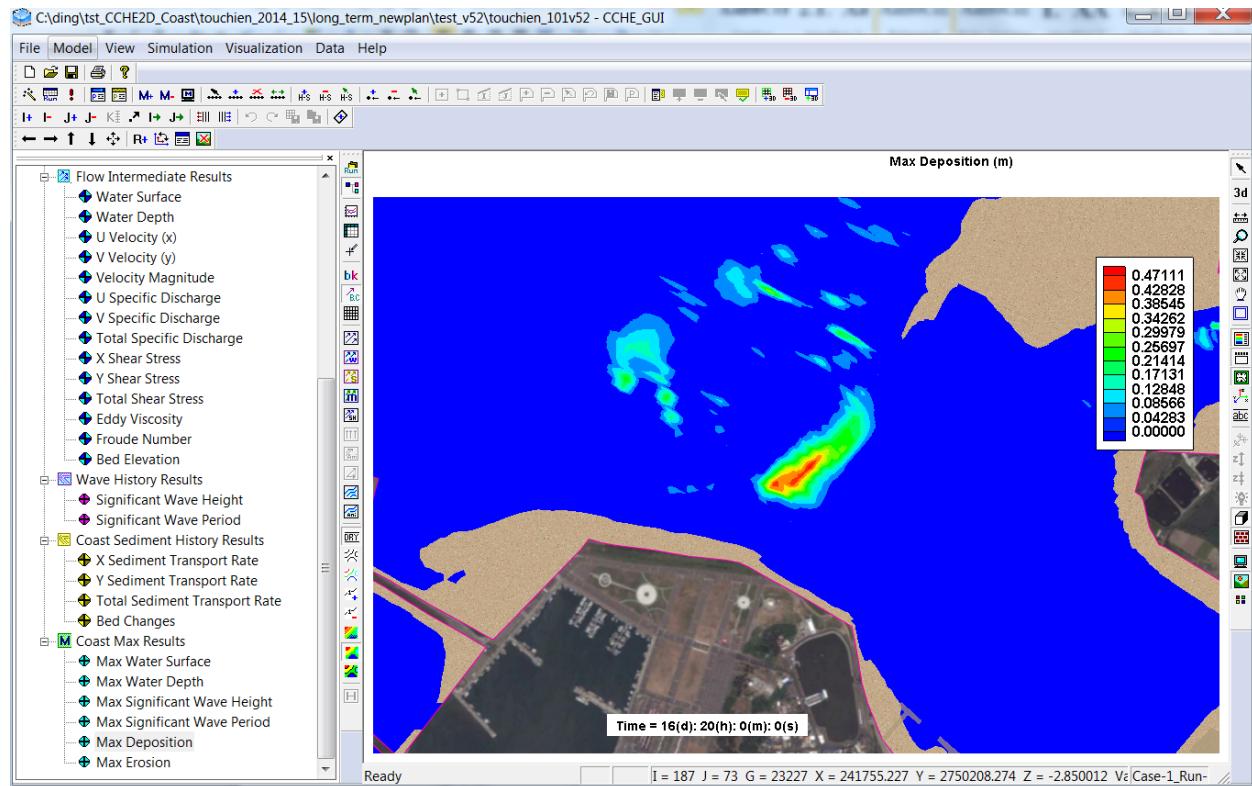
**Figure 2-35 Generating a video clip for displaying the history of sediment transport rates**

### 2.9.3 Visualization of Maximum Values of Water Levels, Depths, Wave Heights, and Morphological Changes

After loaded the data file for maximum values of flows, waves, and sediment transport, the visualization of the maximum values of each physical variable can be readily drawn by directly selecting the name of the variable. For example, Figure 2-36 plots the maximum significant wave heights and the mean directions of the maximum waves by selecting the “Max. Significant Wave Height” and clicking the button of the wave directions. By choosing the “Max. Deposition”, Figure 2-37 shows a spatial distribution of maximum deposition heights in a simulation duration. If selecting the “Max. Erosion”, the GUI will visualize the distribution of maximum erosion depths occurring in the simulation duration. Moreover, by selecting the “Max. Water Surface” or “Max. Water Depth”, user can generate a flooding and inundation extent map for a flood event in the simulation period.



**Figure 2-36 Visualization of maximum significant wave heights and the mean directions of the maximum waves**



**Figure 2-37 Maximum deposition in a simulation duration**

### 3 EXAMPLE CASE NO. 1: SIMULATION OF A TIDAL FLOW

This section is to briefly describe the procedure for creating a simulation case of tidal flow by means of the user interface: CCHE-GUI and the simulation engine: CCHE2D-Coast. It presents how to set up tidal boundary conditions by using tidal constitutes or measured tidal elevations. Hereafter, a computational mesh covering the northern Gulf Coast is used in the demonstration. Several examples are included in the CCHE2D-Coast software package, which can be found in a folder named “examples\tidal\_flow”.

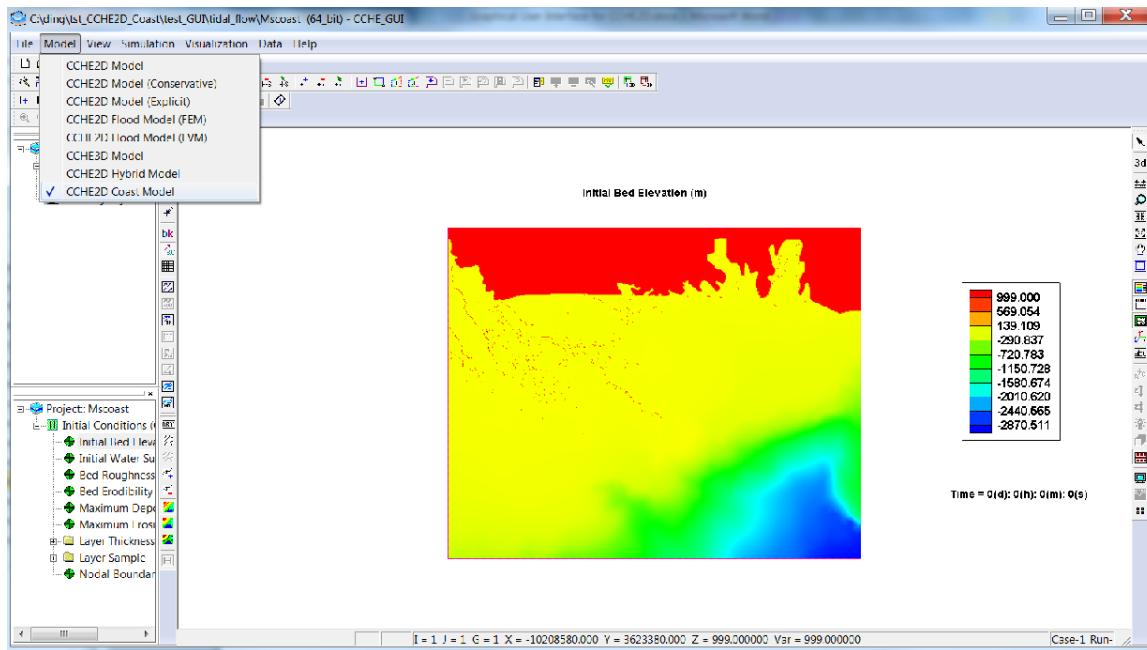
#### 3.1. Step 1: Load mesh and create boundary nodal strings

Suppose that the computational mesh has been already generated by the mesh generator, CCHE-Mesh, or the GUI by using bathymetrical and topographic data, user can launch CCHE-GUI from user’s computer. For the mesh generation, the datum of geodetic data should be unified, for example, into the North American Vertical Datum of 1988 (NAVD88) if one simulates a tidal flow over an area in North American.

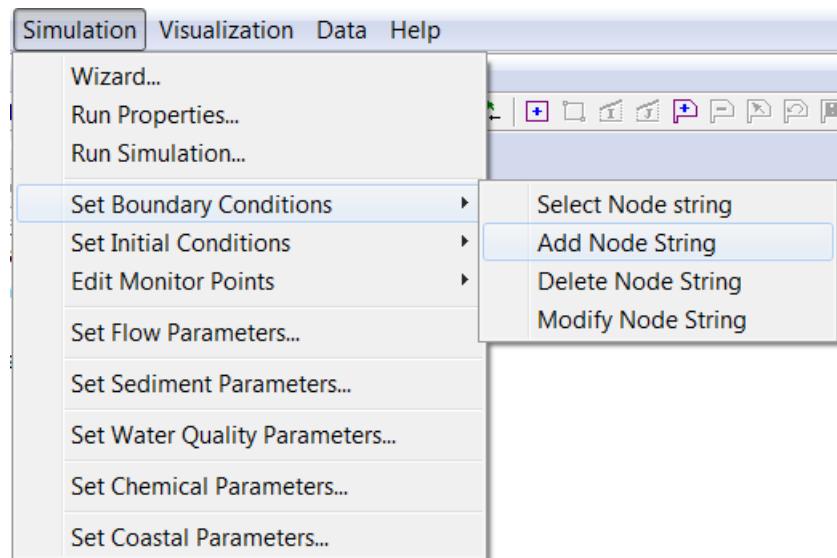
To load a pre-generated mesh for the domain in the northern Gulf Coast, Mscoast.geo, which can be found in the folder of examples in the model package, select “Open Geometry File” from the drop-down menu “File”, then select the geometry file from the folder where the file is stored. Figure 3-1 displays the bathymetry of a computational mesh in the area of the northern Gulf Coast, in which the geodetic datum is the NAVD88.

After having loaded the mesh, user has to select computational model for simulations. Herein, select “CCHE2D Coastal Model” from the drop-down list “Model” in the upper left corner of the GUI (Figure 3-1). To create a tidal boundary at the offshore, as shown in Figure 3-2, click the drop-down menu “Simulation”, then move the mouse cursor to “Set Boundary Conditions”. Then, from the pop-up menu on the right, select “Add Node String”. By clicking the first node of the offshore boundary and the last node on the tidal boundary, a nodal string will be highlighted, and immediately a menu for “Select Inlet/Outlet Boundary” will pop up. As shown in Figure 3-3, user has to select “Coast Boundary Condition” to define this nodal string as a tidal boundary. In the following pop-up menu called “Coastal Offshore B.C.”, as shown in

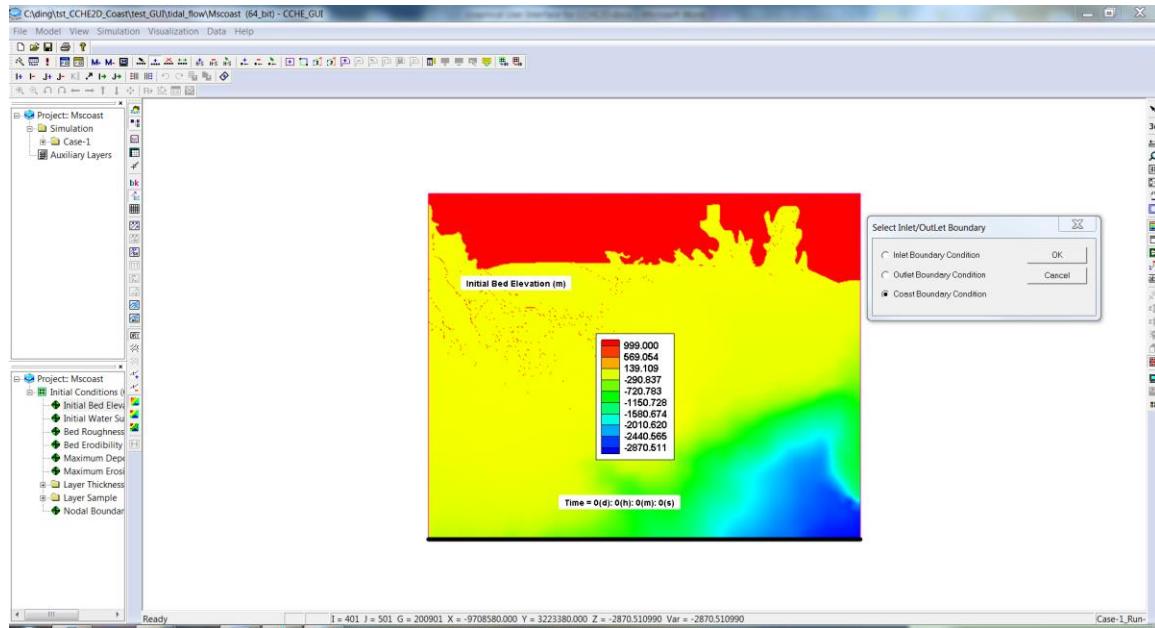
Figure 3-4, to specify tidal elevations given by a tidal table (i.e. a combination of tidal constituents), one can select “Water Surface Elevation”, and leave the value of 9999 as is. If measured time series of tidal elevations at the offshore are given, user can click “Time Series”. More details about this option are given in the following paragraph.



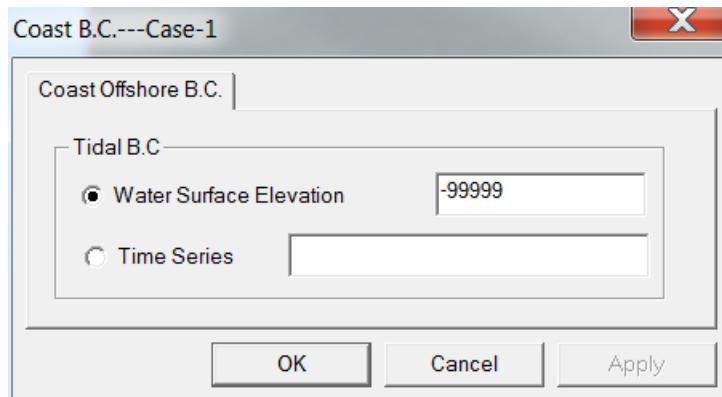
**Figure 3-1 A computational mesh loaded into CCHE-GUI**



**Figure 3-2 Set boundary nodal strings**



**Figure 3-3 Create boundary nodal strings**



**Figure 3-4 Set tidal boundary condition**

### 3.2. Step 2: Specify model parameters, boundary conditions, and wind conditions

First, let us set up the numerical parameters related to the coastal model, by selecting “Set Coast Parameters” from the bottom of the drop-down menu, “Simulation” (Figure 3-2). This will come up with a pop-up menu as shown in Figure 3-7. To compute tidal flows without the effect

of waves, inside the first tab menu “Tidal”, one can select “Tidal Flow Only” from the window of the right side of “Select a Flow Type”.

To specify time series of water elevations at the offshore, you may use (1) the data of tidal components (constituents), or (2) observed water elevations. By means of the combination of tidal components, one can select “Progressive Wave Only” from the window of “Open Bnd Type”. The tidal elevations then can be calculated by using the following formulation:

$$\eta(t) = \sum_{i=1}^N a_i \sin\left(\frac{2\pi}{T_i}t + \varphi_i\right) \quad (40)$$

where  $\eta(t)$  = tidal elevation above the datum (e.g. NAVD88) (m),  $a_i$ =amplitude (m),  $T_i$ =period of a tidal component (s) (e.g. M2, S2, K2, etc),  $\varphi_i$ =phase delay (rad). To input these parameters of tidal components, use the window below “Incident Waves”. Inside the menu, “Total Num” is to give the total number of tidal components; “ Period (s)” is to specify the period of a tidal component (in second); “Amplitude (m)” to input the amplitude of the tidal constituent, and “Phase Delay (rad)” for providing the phase of the constituent in radian. To input the parameters of the first tidal constituent, type “1” into the window above the button “Set”. And after having input all the values of the parameters, push this “Set” button to save these values of the first tidal component. Repeat this procedure to input and save all other sets of parameters of the rest of tidal constituents.

If the tidal elevations at the offshore boundary are given by times series observed at the offshore, one can select “Times Series” from the “Coast Offshore B.C.” menu as shown in Figure 3-5. Then, a data file will be needed for inputting the time series of the water elevations. For this purpose, use may create a data file to store the tidal elevations, of which the format is shown in Figure 3-6. The first line of this data file is the total number of the data records. Starting from the second line, time in second and elevation in meter are located. After clicking this data file from the folder, a “Stage Hydrograph” menu will pop up. User can use this pop-up menu (e.g. Figure 2-21) to create times series of the observed tidal elevations, and plot the variation of the elevations.

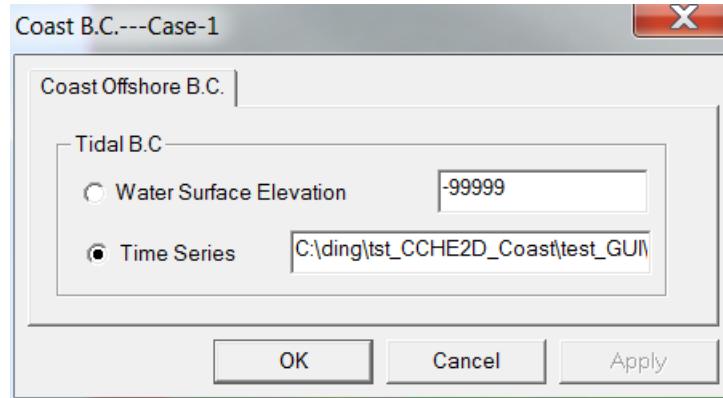


Figure 3-5 Water elevation boundary condition at offshore

Time (s)	Water Level (m)
6481	
0.00	-0.018
360.00	-0.017
720.00	-0.016
1080.00	-0.015
1440.00	-0.013
1800.00	-0.011
2160.00	-0.010
2520.00	-0.007
2880.00	-0.005
3240.00	-0.003
3600.00	0.000
3960.00	0.003
4320.00	0.006
4680.00	0.009
5040.00	0.012
5400.00	0.016
5760.00	0.019
6120.00	0.023
6480.00	0.026
6840.00	0.030
7200.00	0.034
7560.00	0.038
7920.00	0.042
8280.00	0.046
8640.00	0.050
9000.00	0.054
9360.00	0.058
9720.00	0.062
10080.00	0.066
10440.00	0.070

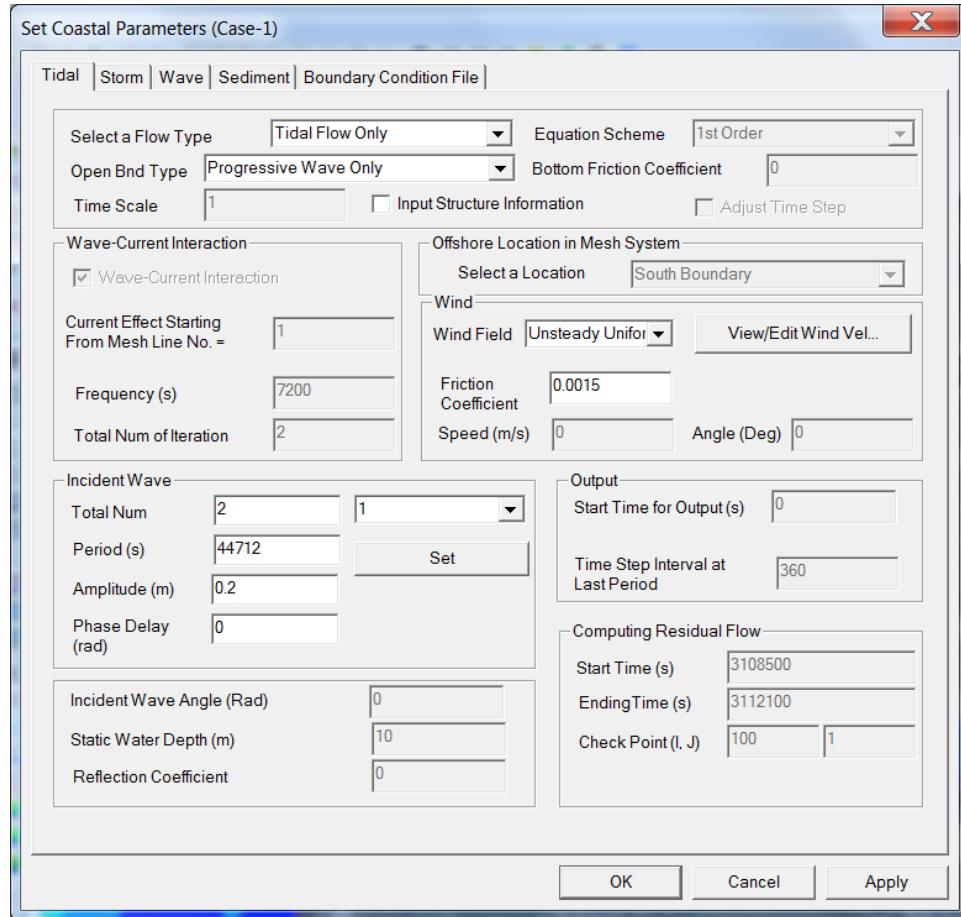
Figure 3-6 A data file for storing the time series of the tidal elevations

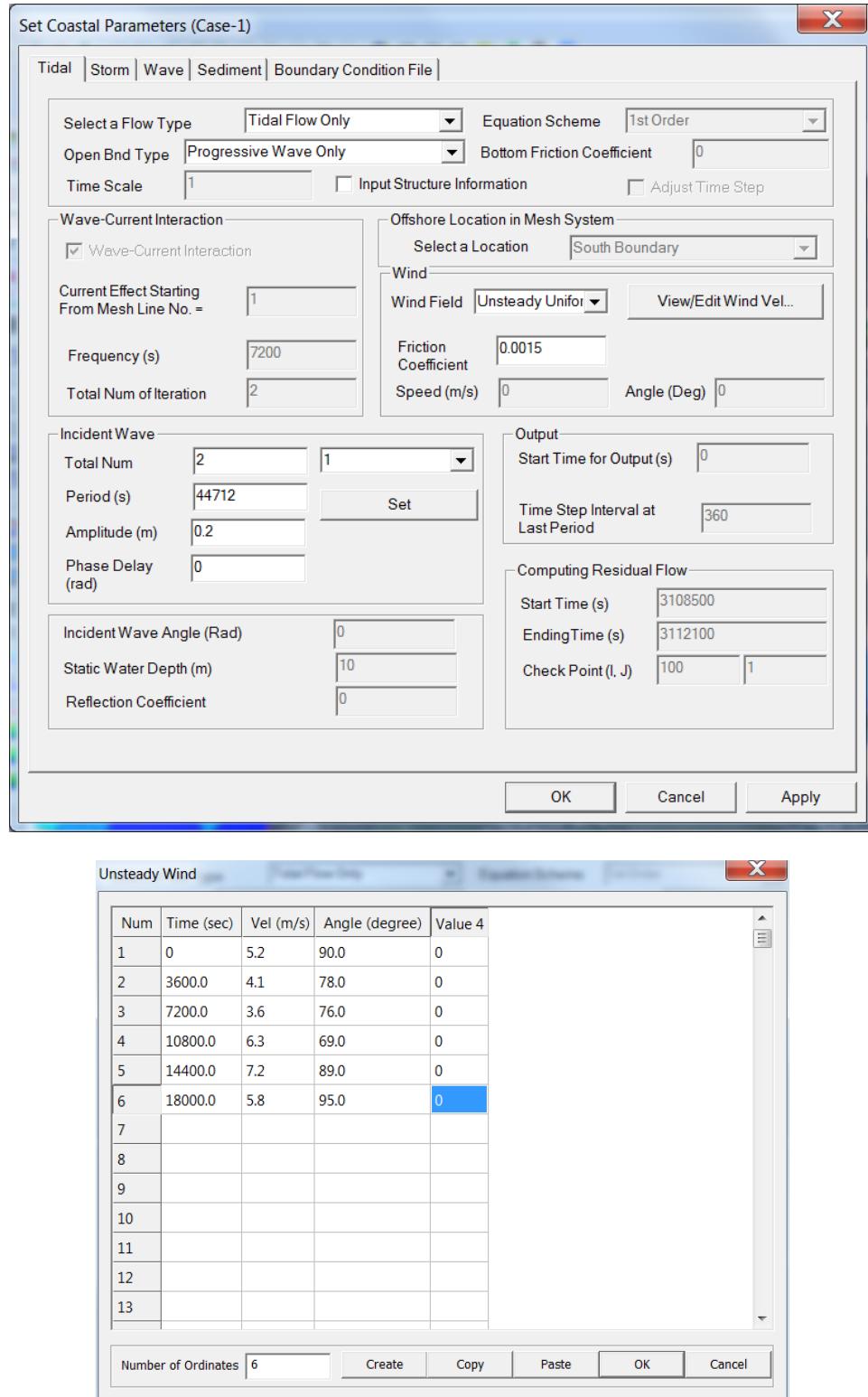
Using the windows in the menu of “Wind”, user can specify the surface wind fields (i.e. the wind at 10-m above the sea surface). By selecting “Steady Uniform”, one can input a constant wave field over the entire computational period. In the “Tidal” menu presented in Figure 3-7, the velocity amplitude is given by the value in the window of “Speed (m/s)”; the direction of wind by that below “Angle (Deg)”. Please notice that the value of angle is the angle between the wind direction and the x-axis direction and counterclockwise from the x-axis direction (usually from the horizontal direction, or the west-north direction). The value of the surface wind drag/friction coefficient (i.e.  $C_d$  in Eq. (32)) can be directly specified through the window of “Friction Coefficient”.

If unsteady wind fields (but uniformly distributed in space) are given as the surface wind condition, user can select “Unsteady Uniform” from the drop-down menu of “Wind Field”. As shown in Figure 3-8, by clicking “View/Edit Wind Vel...”, an “Unsteady Wind” table will pop up. User can use this table to create time series of wind velocity in meter per second and angle of wind direction in degree.

For simulation of storm surges, “Storm or Hurricane (Holland’s Model)” has to be selected, and the parameters of a storm track need to be input in the menu of “Storm”. But the details on specifying parameters of storm will be discussed in Chapter 5 for simulation of storm surges.

Other parameters such as “Computing Residual Flow” in the menu of “Tidal” do not affect the simulation. User may use the default values for these parameters. If neither waves nor sediment transport are computed, no input of parameters is needed in the menus “Wave” and “Sediment”.

**Figure 3-7 Set Coastal Model Parameters**



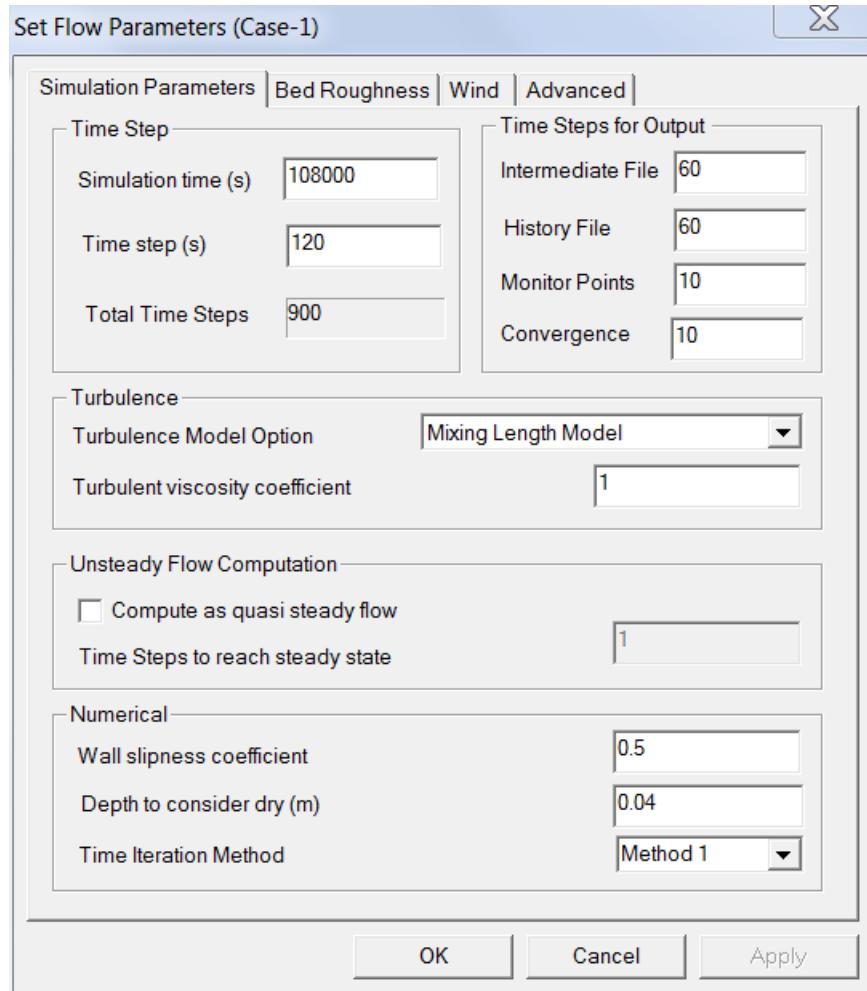
**Figure 3-8 Create time series of wind speed and direction for inputting unsteady wind field**

### 3.3. Step 3: Specify parameters for numerical simulation

The flow parameters consist of the parameters for controlling simulations of flows, bed roughness coefficients, wind data for CCHE2D (not for CCHE2D-Coast), and other numerical constants.

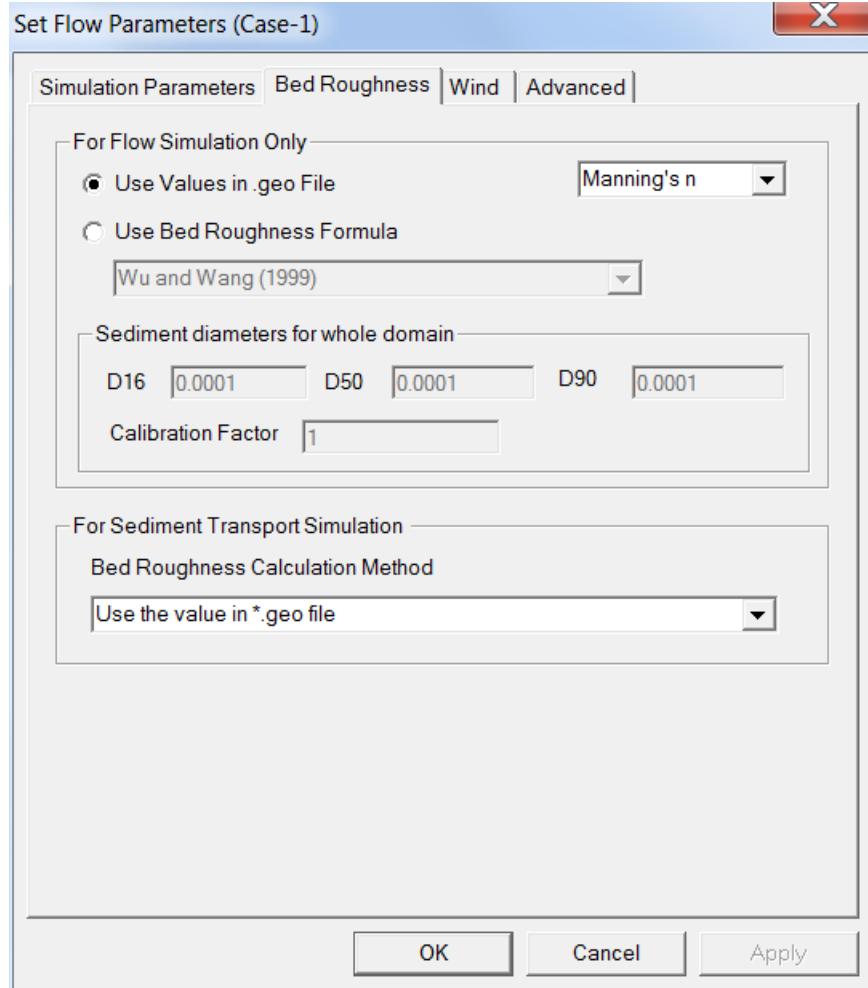
By selecting the toolbar “Set Flow Parameters” from the menu “Simulation”, one can find four menus called “Simulation parameters”, “Bed Roughness”, “Wind”, and “Advanced parameters”, as shown in Figure 3-9. In the menu for “Simulation Parameters”, user can specify the total simulation time and the time step size, select a turbulence model, give parameters for slip wall boundary condition, determine the critical depth for the wetting and drying process, and control output frequencies for monitoring intermediate simulation results and convergence of simulation, and storing flow fields into history files and time series at monitoring stations.

For the further details for specifying flow parameter, user may refer to the User’s Manual of CCHE2D ([Zhang 2013](#)).



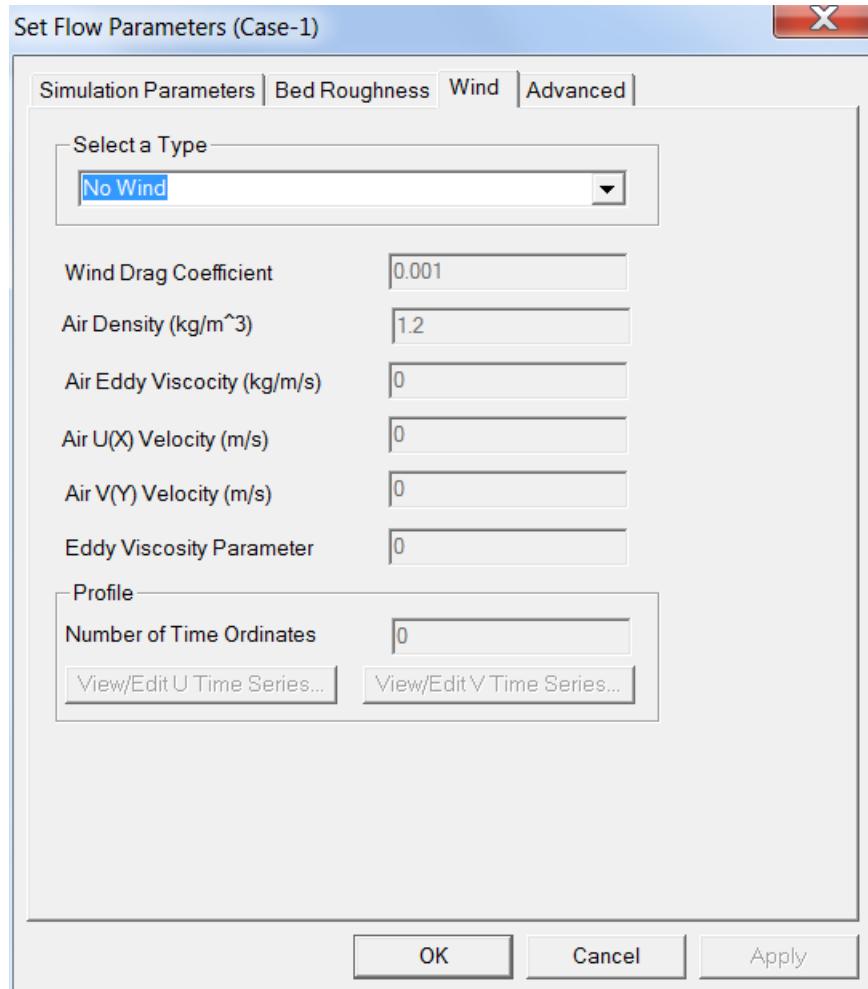
**Figure 3-9 Menu for setting flow parameters for simulation**

Similar to simulation by using CCHE2D, Manning's  $n$  values in the mesh file (a .geo file) can be used as bed roughness coefficients, as shown in Figure 3-10. For simulations of coastal processes by CCHE2D-Coast, user is not allowed to use bed roughness formula for calculating the  $n$  values during the simulation.



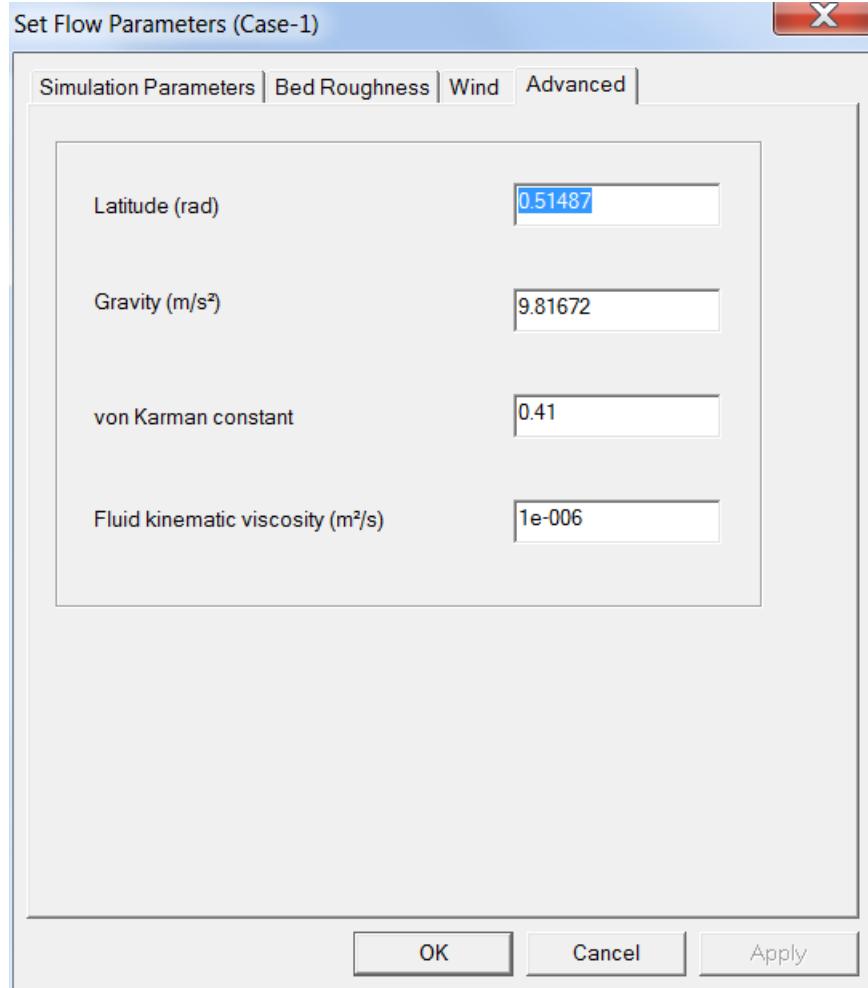
**Figure 3-10 Menu for specifying bed roughness coefficient**

Since the wind parameters are determined through the “Set Coast Parameters” menu, which is presented in Figure 3-8, there is no need to specify wind data thought the “Wind” menu in this section. As demonstrated in Figure 3-11, the type of wind in this menu is “No Wind”.



**Figure 3-11 Menu for inputting wind for CCHE2D**

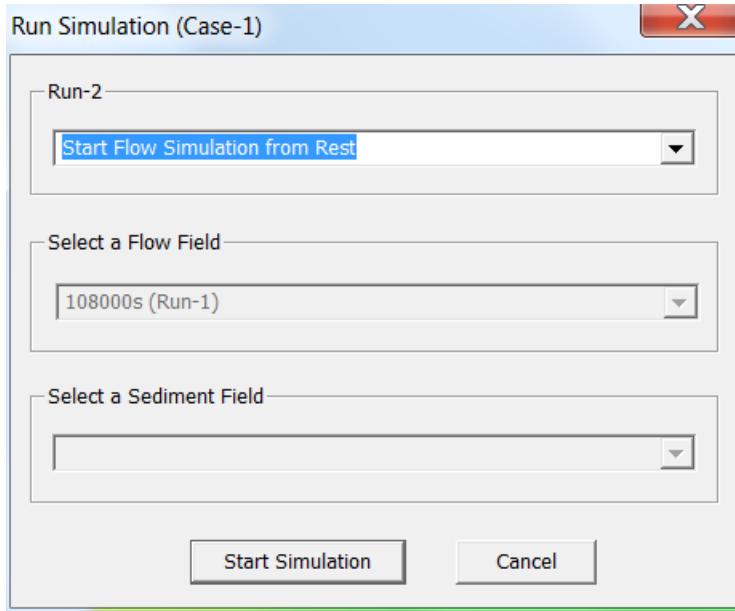
For other parameters for the simulations, one can use the “Advanced” menu to specify the latitude in radian at the center of the computational area, the gravitational acceleration, von Karman constant (usually equal to 0.41), and the kinematic viscosity of water. Figure 3-12 presents those parameter values for the simulation of the tidal flows in the northern Gulf coast.



**Figure 3-12 Menu for specifying model constants**

### 3.4. Step 4: Run the simulation

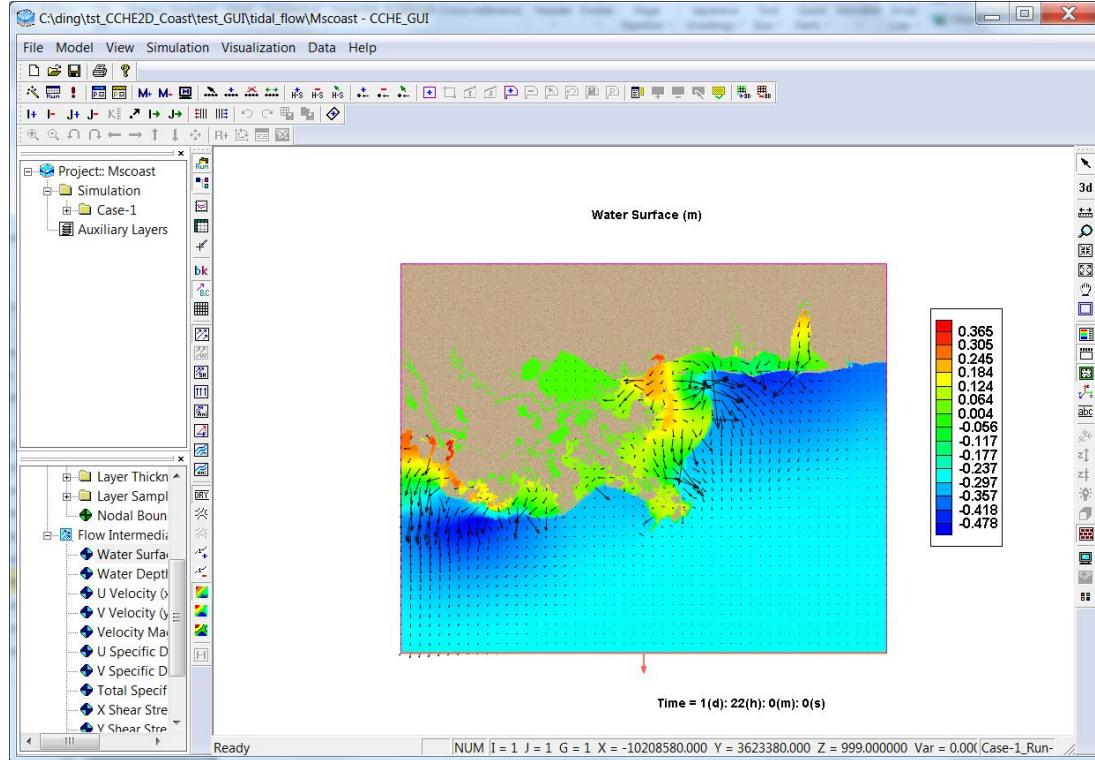
From the “Simulation” menu, click “Run Simulation” to execute the coastal model CCHE2D-Coast. As presented in Figure 3-13, user may start the simulation from a “cold start” initial state, or a “hot start” state to continue the simulation from a previous computed flow field.



**Figure 3-13 Execute the coastal model**

### 3.5. Step 5: Visualize the computed results

User may visualize flow fields during a computation, and create animations of computed tidal flows by using the “Visualization” menu. Figure 3-14 presents a snapshot of a computed ebb tide flow displayed during the computation. For the instructions of visualization by the GUI, please refer to Chapter 5 in the user’s manual of CCHE-GUI ([Zhang 2013](#)). After a successful computation, the “Command Prompt” window will report the CPU time. As shown in Figure 3-15, for computing a tidal flow over a 60-hour period, it took approximately 11 minutes by using an Intel-Core i7 CPU on a laptop.



**Figure 3-14 Snapshot of a computed ebb flow**

```
C:\windows\system32\cmd.exe
      860    95.55556    % of the total timesteps
IT=    860 TIM=    211200.000
NUERUEL= 37949 UERUEL=  0.23085199 NUERSUR= 37949 UERSUR=  0.20470682
      870    96.66666    % of the total timesteps
IT=    870 TIM=    212400.000
NUERUEL= 30722 UERUEL=  0.23860903 NUERSUR= 30722 UERSUR=  0.21931115
      880    97.77778    % of the total timesteps
IT=    880 TIM=    213600.000
NUERUEL= 101299 UERUEL=  0.09581575 NUERSUR= 101299 UERSUR= -0.09075551
      890    98.88889    % of the total timesteps
IT=    890 TIM=    214800.000
NUERUEL= 110937 UERUEL=  0.16091967 NUERSUR= 147661 UERSUR=  0.25783348
IT=    900 TIM=    216000.000
NUERUEL= 154095 UERUEL=  0.03477055 NUERSUR= 110402 UERSUR=  0.01969061
ZONE T="t= 216000.0 ", I=        401 , J=        501 , F=BLOCK,
SOLUTIONTIME= 216000.0
      900    100.0000    % of the total timesteps
IT=    900 TIM=    216000.000
NUERUEL= 154095 UERUEL=  0.03477055 NUERSUR= 110402 UERSUR=  0.01969061
      15 SOLUTIONS ARE SAVED IN ".his" FILE
PRINT OUT Maximum Water Elevations
CPU-TIME= 0h10m57s
SUCCESS:
Press <RETURN> to continue...
```

**Figure 3-15 A “Command Prompt” window for monitoring computation process.**

## 4 EXAMPLE CASE NO. 2: SIMULATION OF WAVE AND CURRENT

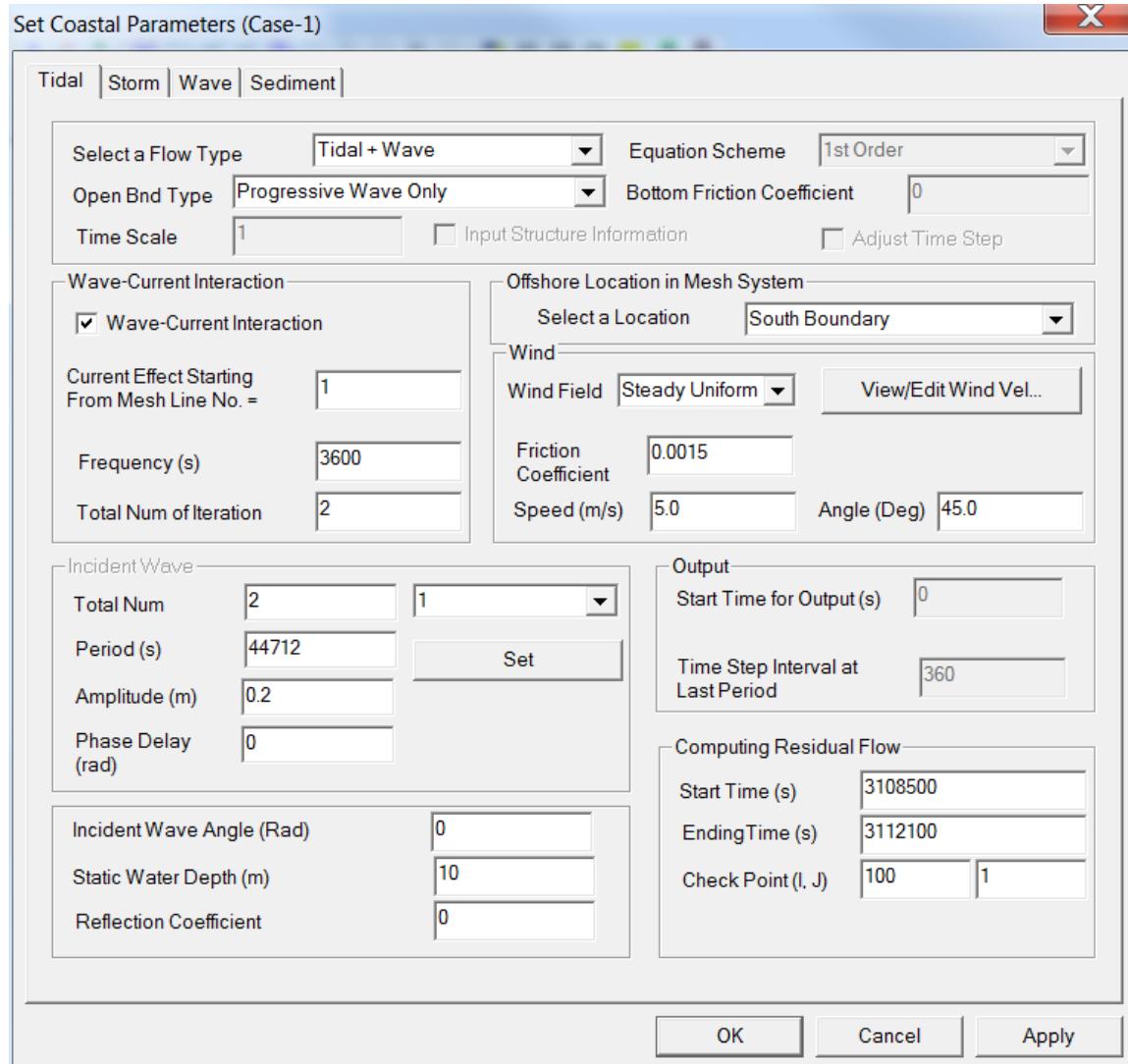
This example case is to demonstrate the coastal model to simulate the combined wave and current by using the first example case. Data files for this case can be found in a folder called “examples\wave\_tide”.

### 4.1. Step 1: Select flow type and define parameters for wave-current interaction

First, select the “Tidal+Wave” option from the “Select a Flow Type” menu, as shown in Figure 4-1. Check “wave-Current Interaction” if the computation of wave considers the effect of wave-current interaction. If this effect is taken into account only in some part of the computational domain, user may input the number of the grid line where the model will include the wave-current interaction. If one needs to include this effect, the default value, “1”, will appear in the window at the left side of “Current Effect Starting from Mesh Line No.=”. If no the effect of wave-current interaction is considered, without the check of the effect, it will save the CPU for computing wave fields.

The window at the left of “Frequency” is to ask for input of the duration of time in second, by which the wave field will be updated (computed) once every this duration. A typical duration for updating the wave field is 3600.0 (s) or 7200.0 (s).

To locate the offshore boundary for incident waves, user has to determine which edge of the computational domain is the offshore. Select “South Boundary” as the offshore from the window for “Offshore Location in Mesh System” if the incident wave or a cyclonic storm comes from the south of the domain (Figure 4-1). Choose “West Boundary” as the offshore if it comes from the west side.



**Figure 4-1 Set parameters for simulation of wave and current**

## 4.2. Step 2: Set wave boundary conditions

Boundary conditions for simulating wave deformation over a computational domain covering ocean, coast and estuary are comprised of offshore wave spectra determined by wave heights, periods, and directions. The present wave spectral model supports two kinds of offshore (deepwater) wave spectrum inputs, i.e., the TMA spectrum (Bouws et al. 1985) and the Bretschneider-Mitsuyasu (B-M) spectrum (Mitsuyasu 1970).

To compute multidirectional and irregular waves, in Figure 4-2, user needs to specify a range of wave direction and a band width of wave frequency in the windows under “Angles (deg)” and “Frequency (Hz)”, respectively. If simulation is for swelling waves, the range of wave direction could be the one from  $-90^\circ$  to  $+90^\circ$ . For simulations of waves by cyclonic winds, the range of wave direction should cover all the four quadrants, i.e. from  $-180^\circ$  to  $+180^\circ$ . User can select a type of wave spectrum in the window for “Wave Spectrum”. One also can determine if the computation of wave fields includes the unsteady term (i.e. “Unsteady”) or not (i.e. “Quasi-steady”). For simulation of waves with a steady offshore wave, one may select the latter option to compute the wave fields as a quasi-steady state.

For this example case, we suggest using the “Half-Plane” as the wave simulation model.

Under the window of “Num of Bins”, user can determine the total number of bins of wave direction and frequency for splitting the multidirectional spectrum at offshore. If the computational domain is extended to inland, user may find a mesh line close to the shoreline, or a mesh line at upstream of a river, beyond which the wave effect can be ignored. The number of the mesh line is given in the window of “Mesh Line No. For”. Above this line, the waves won’t be computed.

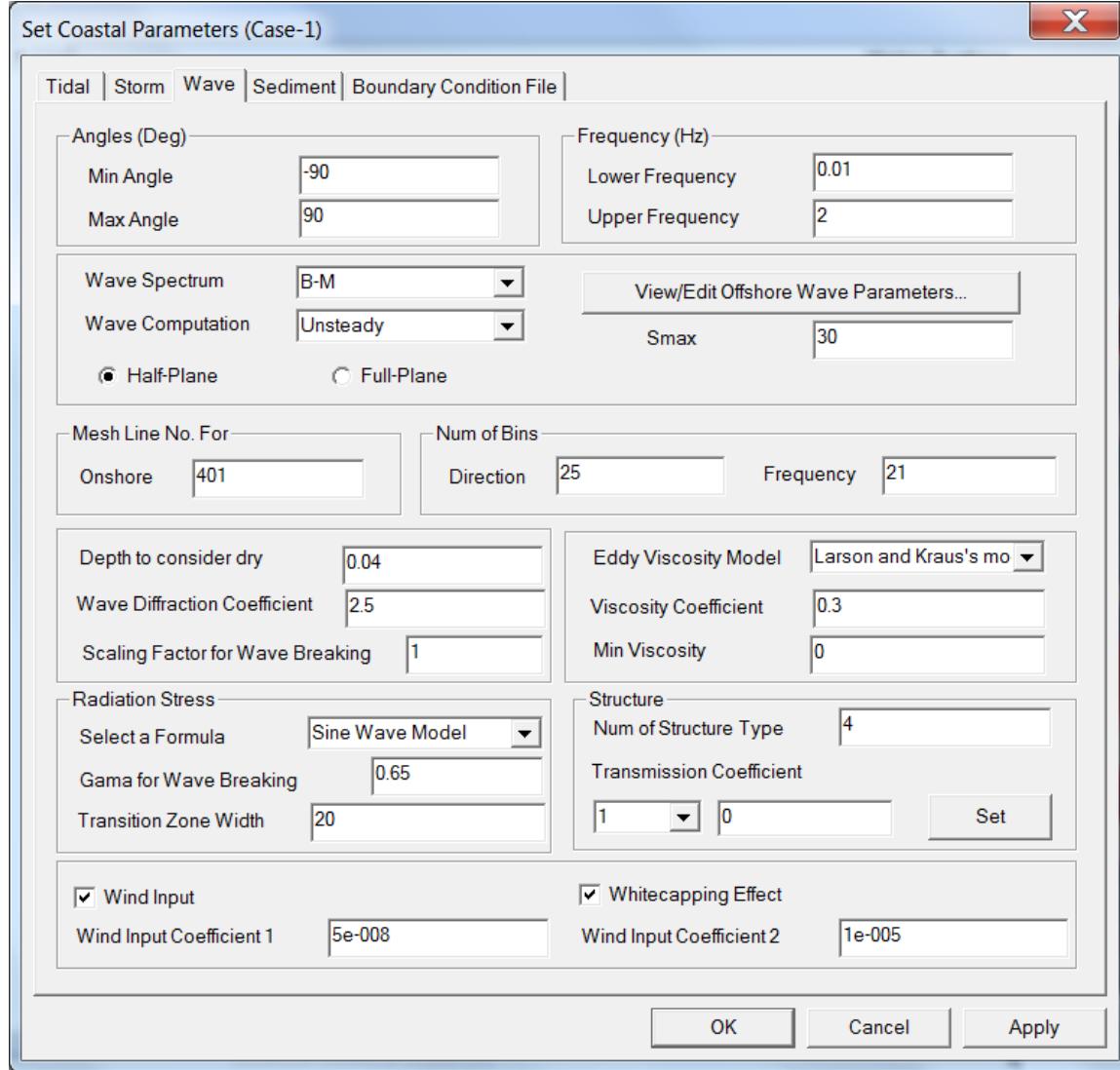
The criterion for wetting and drying is given in the window for “Depth to consider dry (m)”, which may be the same as the critical depth for computing flow or be different from it. To including the wave diffraction into wave computation, one has to give the value of the wave diffraction coefficient. Usually, 2.5 is a typical value for the diffraction term.

The wave breaking process has been taken into account in the simulation. However, the breaking effect can be scaled by multiplying a factor, of which the value is between zero and unit. If the scaling factor for wave breaking is set up to 1, the attenuation of wave energy due to breaking will be included completely into the calculation of wave energy balance.

The eddy viscosity model, which considers the wave effect in the turbulence mixing in the momentum equations, can be selected in the window of “Eddy Viscosity Model” as either the Larson and Kraus’ model or “Longuet-Higgins Model”. The viscosity coefficient can be changed by user. The type of radiation stresses can be chosen from the two options in the window of “Radiation Stress”.

The types of coastal structures can be also specified under the windows for “Structure”. But the capability is temporally disabled in the current version.

If the wind energy input is considered in wave computation, one has to check two buttons for “Wind Input” and “Whitecapping Effect”, and specify the values of “Wind Input Coefficient”, i.e.  $a_1$  and  $a_2$  in Eq. (10).



**Figure 4-2 Specify wave parameters**

To define the wave spectra at every wave computation, one has to specify the time series of offshore wave parameters such as significant wave height ( $H_s$  (m)), Significant wave period ( $T_s$  (s)), mean wave direction (Alfa (deg)), spectral enhancement factor (Gama), and Smax. By clicking the button for “View/Edit Offshore Wave Parameters” in the “Wave” menu (Figure 4-2), a menu called “Offshore Wave” will pop up (Figure 4-3). Using this window, user can edit the offshore wave parameters at every time for wave computation. For example, if the computational duration is one day (i.e. 24 hours), and the frequency to update the wave field is two hours, a

total 12 sets of wave parameters have to be inputted into this table. One has to input a few more wave parameter sets. Meanwhile, as shown in Figure 4-4, the direction of the offshore mean wave is defined as the angle between the wave direction and the on-offshore axis direction (pointed to the onshore). If the direction is in the upper plane of the domain, the angle is positive; otherwise it will be negative if located in the lower plane.

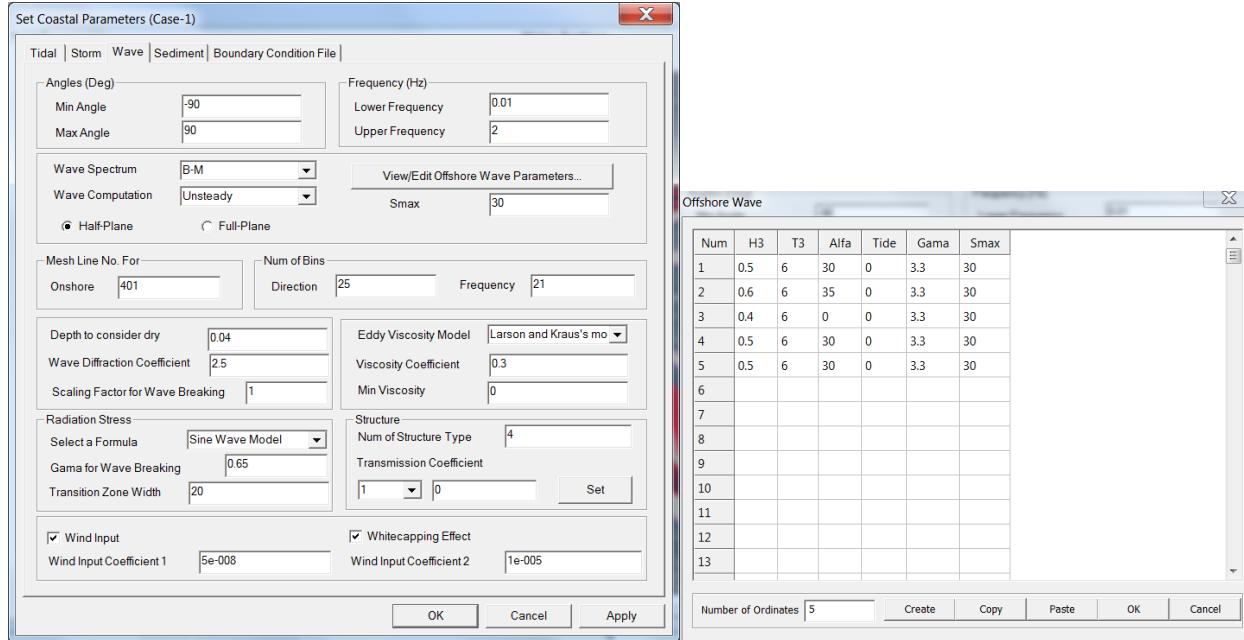


Figure 4-3 Menu for inputting the offshore wave parameters

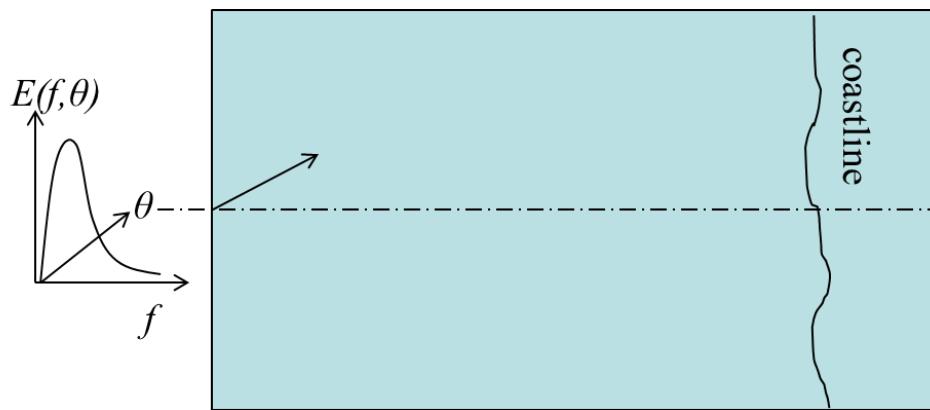


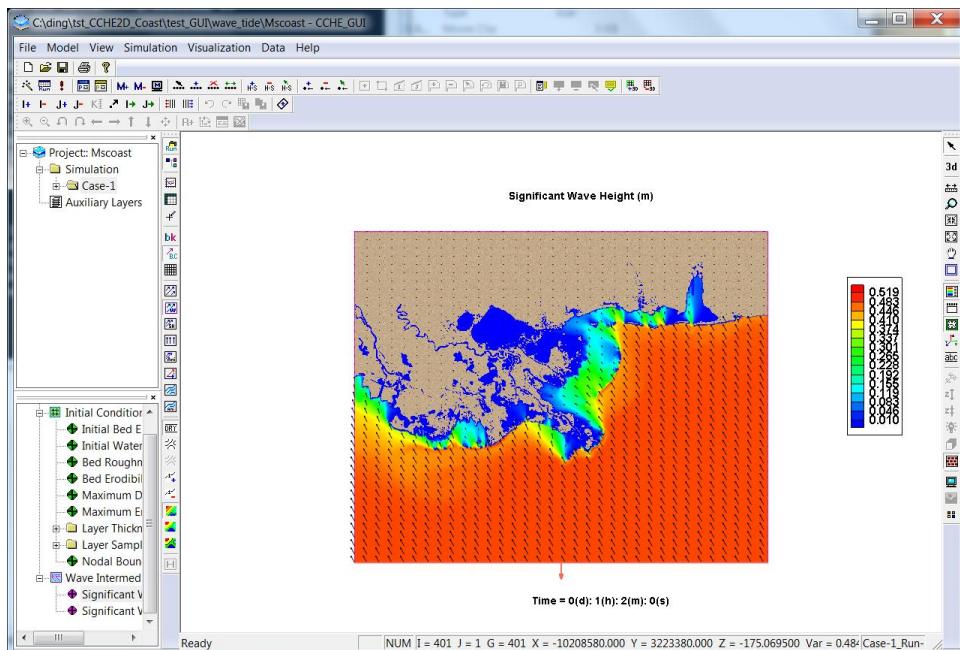
Figure 4-4 Definition of wave spectrum at offshore and wave direction

### 4.3. Step 3: Run wave and current simulation

Similar to the previous description, the simulation of wave and current has to be performed by click the button of “Run Simulation” from the “Simulation” menu. Please notice that the wave simulation won’t be able to start from a “hot start”.

### 4.4. Step 4: Monitor and visualize the wave and current results

The GUI provides user with several options to monitor the intermediate wave and flow results (e.g. Figure 2-29) and to create animations of wave and flow as well after the simulation has been done (e.g. Figure 2-30). Figure 4-5 presents a snapshot of a computed wave field displayed by significant wave heights and mean directions in a domain of the Gulf coast.



**Figure 4-5** A snapshot of a computed wave field shown by significant wave heights and mean directions

## 5 EXAMPLE CASE NO. 3: SIMULATION OF STORM SURGES WITHOUT WAVE SETUP<sup>1</sup>

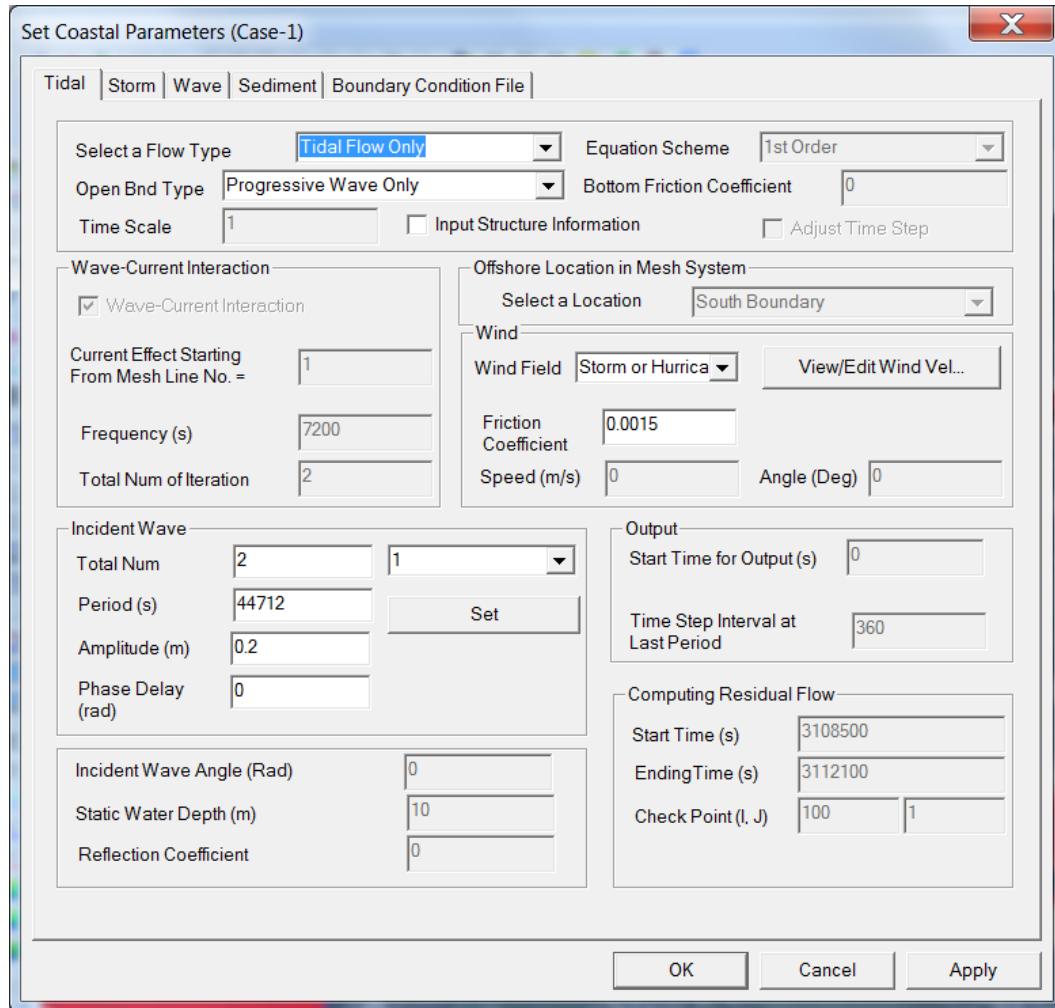
A set of data files for simulating storm surges induced by tropical cyclones in the northern Gulf coast can be found inside the folder of examples, named “\examples\storm\_surge”, in the package of this model.

To simulate storm surges induced by cyclonic wind fields due to hurricanes or typhoons, user has to define a parametric wind model to simulate the storm wind speed and directions based on the parameters of storm track.

With exclusion of wave effect (wave setup), user can select the “Tidal Flow Only” option from the menu of “Select a Flow Type”, as indicated in Figure 5-1. To select “Storm or Hurricane (Holland Model)” from the “Wind Field” menu, the wind parameters for cyclonic wind fields such as atmospheric pressure, wind speed, and direction will be calculated by using a parametric wind model (herein the Holland’s wind model). Please note that the drag/friction coefficient of the surface wind shear stresses (i.e.  $C_d$  in Eq. (32)) will be calculated by using an internal formulation in the model (i.e. Eq. (36) of the Large and Pond’s model). So, the value in the window of “Friction Coefficient” has nothing to do with the simulation of storm surges.

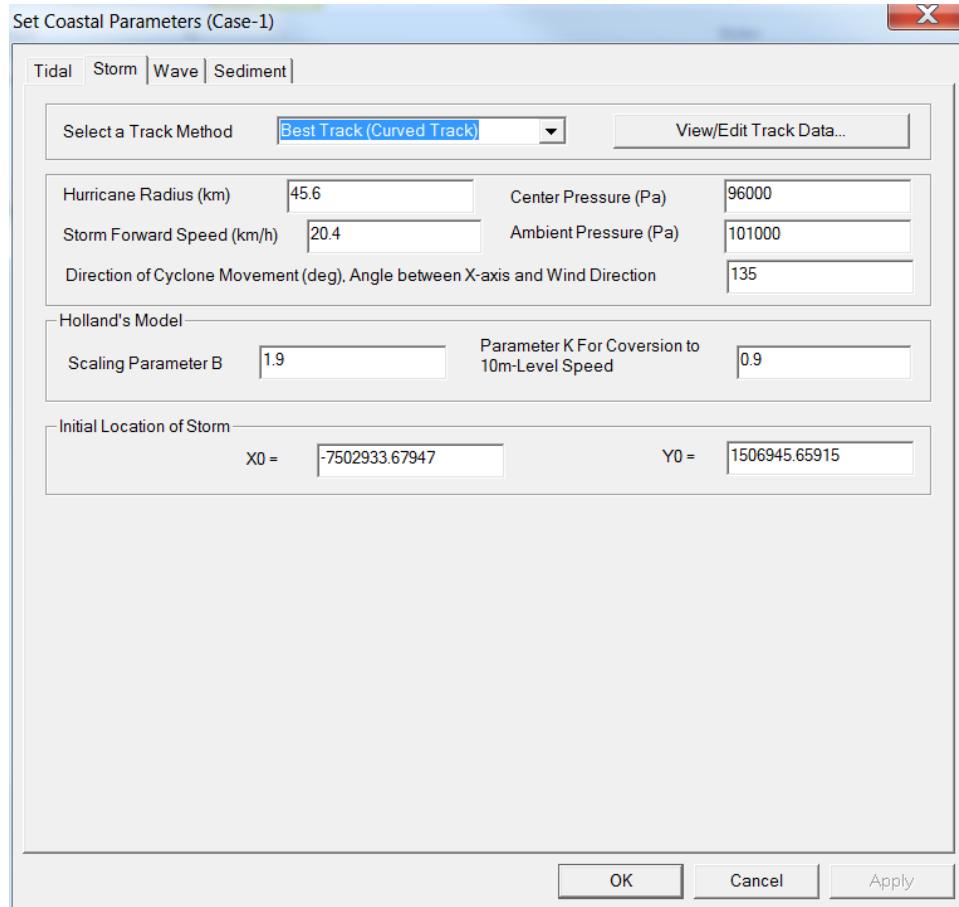
---

<sup>1</sup> CCHE2D-Coast is capable of computing wind setup in hydrodynamic processes. But for computing storm surges driven by cyclonic wind and air pressure of a hurricane or typhoon, CCHE2D-Coast-Storm is required.



**Figure 5-1 Specify the wind model**

The parameters of storm track are inputted through the “Storm” menu (Figure 5-2). If one select “Linear Storm Track” from the “Select a Track Method” window, the storm parameters for defining cyclonic radius, central pressure, storm forward speed, and forward direction will be constant through the whole duration of storm. The initial position of the storm is always needed. The parameters for the wind model such the scaling parameter B and the parameter K can be given by users.

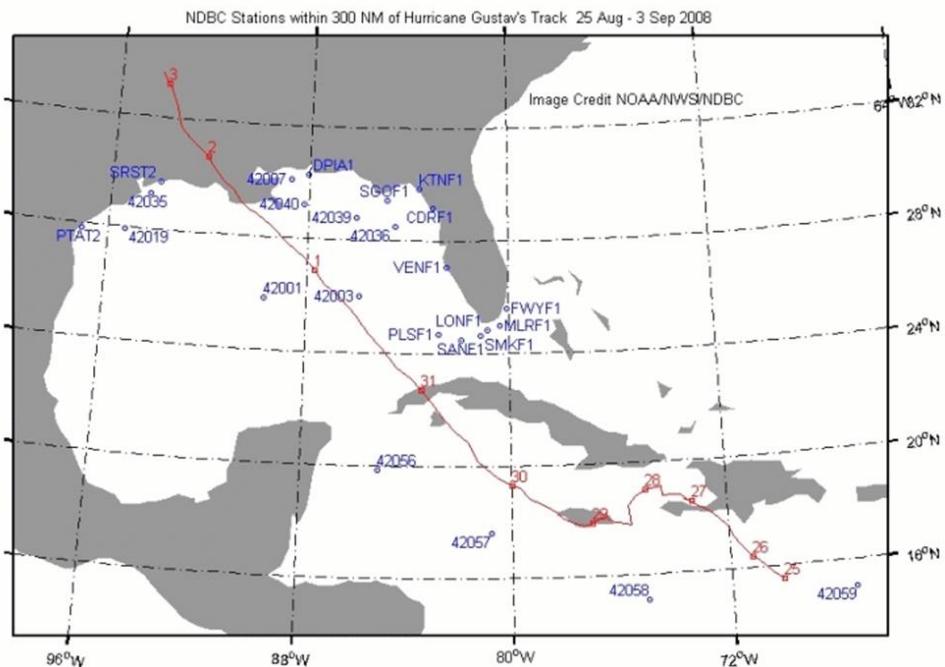
**Figure 5-2 Set storm parameters**

If “Best Track (Curved Track)” is selected, the track information has to be inputted through a table, which can be activated by clicking “View/Edit Track Data”. As shown in Figure 5-3, the parameters of the best track of Hurricane Gustav (2008) such as the coordinates, central pressure (Pcen in pa), cyclonic radius (Rmax in meter), and time can be given through this table. The best track is plotted in Figure 5-4. A data file for the best track of Gustav can be found in a file, MsCoast\_besttrack.dat, inside the folder, examples\storm\_surge.

Track Data					
Num	Time (sec)	X	Y	Pcen (Pa)	Rmax (m)
1	0	-7.50293e+006	1.50695e+006	100800	166680
2	21600	-7.62539e+006	1.60953e+006	100500	37040
3	43200	-7.74784e+006	1.6896e+006	100200	37040
4	64800	-7.84802e+006	1.76995e+006	99600	37040
5	86400	-7.92595e+006	1.83903e+006	99100	27780
6	108000	-7.98161e+006	1.89677e+006	98600	18520
7	129600	-8.02614e+006	1.96626e+006	98100	18520
8	151200	-8.10406e+006	2.03599e+006	99200	18520
9	172800	-8.13745e+006	2.07094e+006	99500	18520
10	194400	-8.17085e+006	2.09428e+006	99900	37040
11	216000	-8.20425e+006	2.10595e+006	99800	18520
12	237600	-8.23764e+006	2.12933e+006	99900	18520
13	259200	-8.36009e+006	2.11764e+006	99900	18520

Number of Ordinates  Create Copy Paste OK Cancel

**Figure 5-3 Specify storm track parameters of Hurricane Gustav (2008)**



**Figure 5-4 Best track of Hurricane Gustav (2008)**

With the input of all the other parameters related to flow simulation as shown in Figure 3-9, the simulation of storm surges can be performed by clicking the “Run Simulation” from the “Simulation” menu. Please notice that simulations of storm surges have to start with a “cold start” run, as the current version of this coastal model does not support a “hot start” simulation option.

After simulations are finished, user can find time series of physical variables including atmospheric pressure and two wind velocity components in the data files for the monitoring stations. An example of the time series file is shown in Figure 5-5, in which the last three columns are the variables for storm wind.

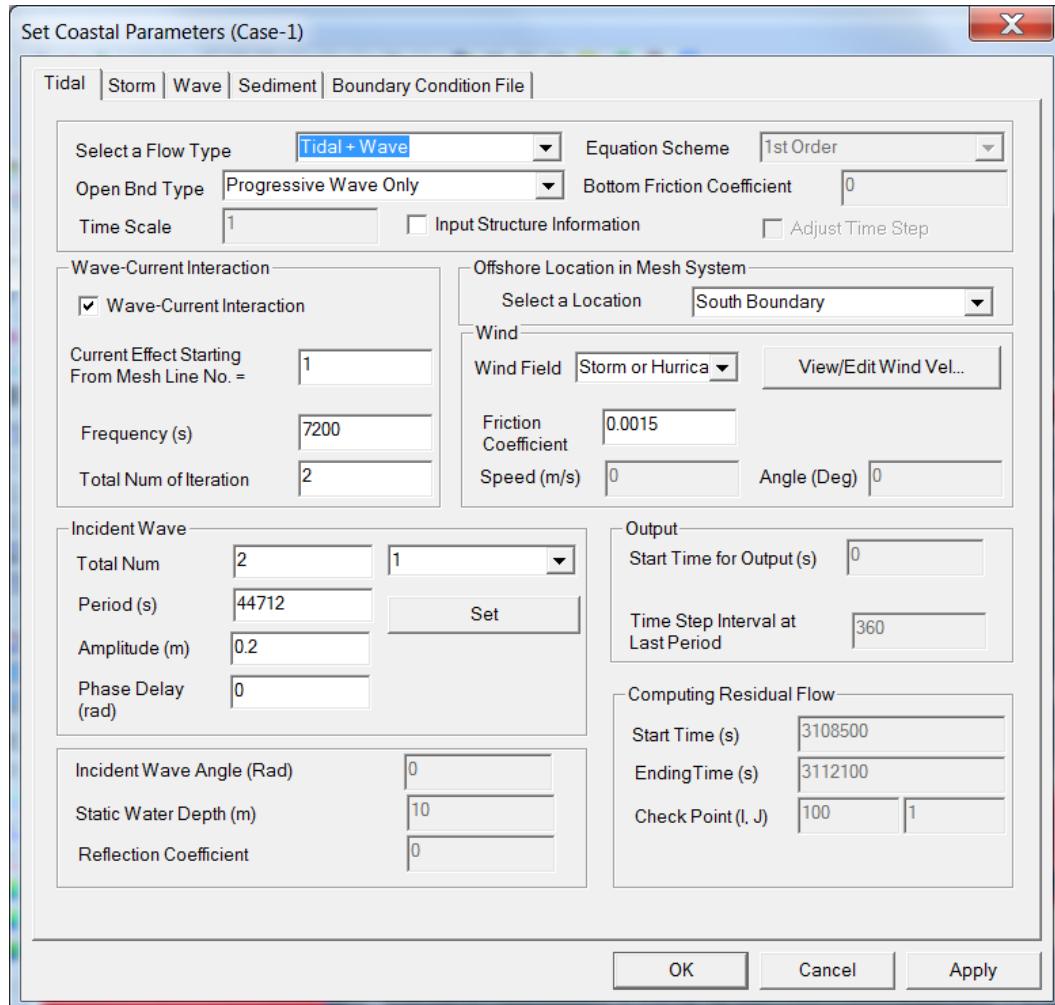
The screenshot shows a Microsoft Notepad window with the title 'Mscoast.mnt\_03 - Notepad'. The window contains a table of data with 13200 rows. The columns are labeled at the top: TIME, Point No., I, J, K, SUF, BED, UEL, VEL, ED, RXA, RYA, Pre, UWx, UWy. The data consists of numerical values representing atmospheric pressure and wind components over time for a specific monitoring station. The 'Point No.' column shows values ranging from 3 to 13200. The 'TIME' column shows values from 600,000 to 13200,000. The 'SUF', 'BED', 'UEL', 'VEL', 'ED', 'RXA', 'RYA', 'Pre', 'UWx', and 'UWy' columns contain scientific notation values representing physical variables like surface elevation, bed elevation, and wind components.

**Figure 5-5 a data file for storing time series of physical variables at a monitoring station (e.g. the number 3 station as the file name is Mscoast.mnt\_03. The last two digit number is the station number)**

## 6 EXAMPLE CASE NO. 4: SIMULATION OF STORM SURGES AND WAVES

A set of data files for simulating storm surges and waves induced by tropical cyclones in the northern Gulf coast can be found inside the folder of examples, named “\examples\storm\_surge\_wave”, in the package of this model.

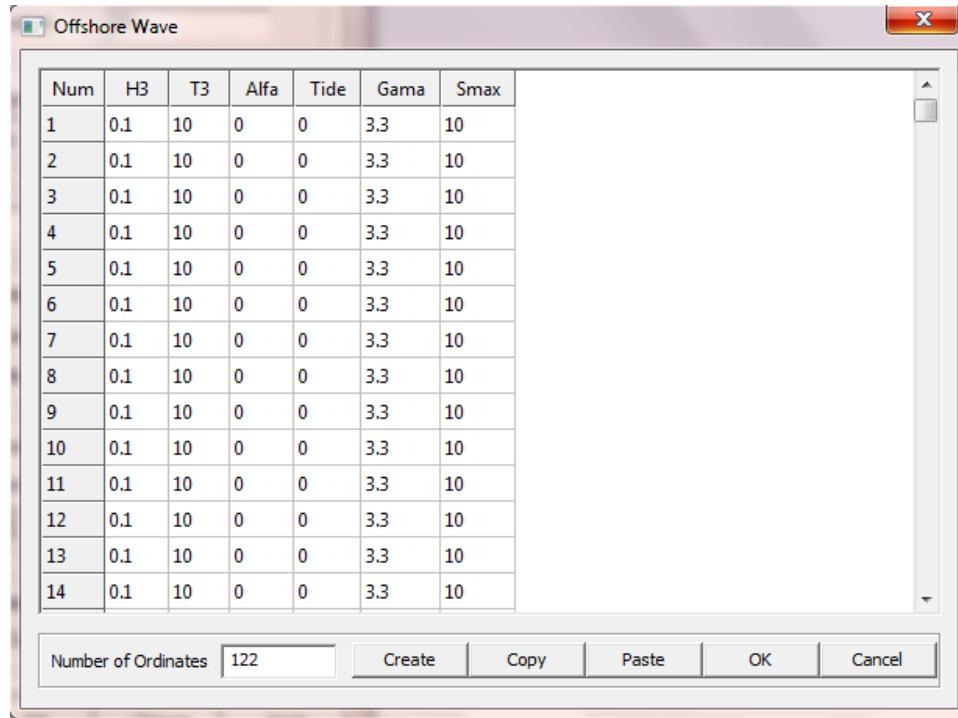
With the knowledge gained from the previous three cases, it will be relatively simple to perform simulations of storm surges and waves. Therefore, the computed storm surges will include the effect of wave setup. As shown in Figure 6-1, user needs to select “Tidal+Wave” from the menu of “Select a Flow Type” in order to carry out the simulations by coupling waves and storm surge flows. Meanwhile, a “Storm or Hurricane (Holland) Model” has to be used for calculate the wind fields along a storm track.



**Figure 6-1 Model parameters for computing storm surges and waves**

For considering the offshore waves which propagate into the computational domain together with the wind-induced waves, user can have two options: one is to input a set of offshore wave parameters in which the wave heights are relatively small, if no swelling waves come from the offshore. However, to have fixed bins in wave frequency, the significant wave period should be kept the same, because each period at the offshore will be used for discretizing the frequency domain of wave spectra. One example for a set of offshore wave parameters for a case without swelling waves is given in Figure 6-2. If swelling waves need to be considered in the simulations of waves, actual values of the offshore wave parameters can be inputted from this table for “Offshore Waves”.

For simulating waves generated by cyclonic storm winds, the range of wave direction bins should cover all the four quadrants of the horizontal plane, i.e. from  $-180^{\circ}$  to  $+180^{\circ}$ . The range of the direction bin can be reset from the “Wave” menu as shown in Figure 4-2.



The screenshot shows a Windows-style dialog box titled "Offshore Wave". The main area contains a table with 14 rows and 7 columns. The columns are labeled "Num", "H3", "T3", "Alfa", "Tide", "Gama", and "Smax". The data in the table is as follows:

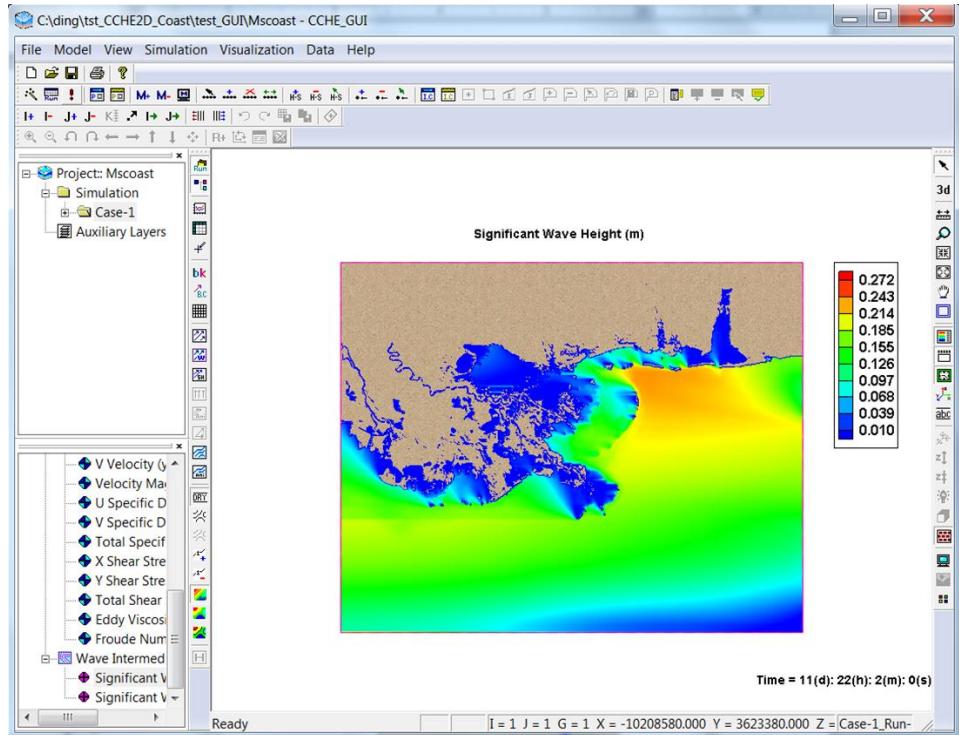
Num	H3	T3	Alfa	Tide	Gama	Smax
1	0.1	10	0	0	3.3	10
2	0.1	10	0	0	3.3	10
3	0.1	10	0	0	3.3	10
4	0.1	10	0	0	3.3	10
5	0.1	10	0	0	3.3	10
6	0.1	10	0	0	3.3	10
7	0.1	10	0	0	3.3	10
8	0.1	10	0	0	3.3	10
9	0.1	10	0	0	3.3	10
10	0.1	10	0	0	3.3	10
11	0.1	10	0	0	3.3	10
12	0.1	10	0	0	3.3	10
13	0.1	10	0	0	3.3	10
14	0.1	10	0	0	3.3	10

At the bottom of the dialog box, there is a "Number of Ordinates" input field containing "122", and buttons for "Create", "Copy", "Paste", "OK", and "Cancel".

**Figure 6-2 Offshore wave parameters for computing waves in a storm**

Similarly, by clicking “Run Simulation” from the drop-down menu of “Simulation”, the waves and storm surges (or flow fields) will be computed in sequence. Figure 6-3 presents a spatial distribution of an intermediate wave result in the simulation of a cyclonic storm. A

cyclone usually last a week from its early stage of storm development to its landfall at coasts. It, therefore, will take more CPU hours to compute the coupled wave-current processes. However, with the advanced numerical efficiency of CCHE2D-Coast, this kind of heavy-duty computations can be done within reasonable CPU hours on a standard PC. Finally, the computed storm surges and waves can be visualized by the GUI.



**Figure 6-3 A snapshot of significant wave height computed by CCHE2D-Coast**

The time series of wave parameters (significant wave heights, periods, and mean directions) at monitoring stations are stored into a data file called “\*\_HsHis.lst”. Here, “\*” means a project name (e.g. Mscoast in the tutorial examples). An example of this history record of wave parameters is presented in Figure 6-4. The time series of wave parameters are stored in the order of the monitoring stations. Namely, the first line of data is for the first stations, the second line for the second stations, and so on.

Mscoast_HsHis.lst - Notepad				
File	Edit	Format	View	Help
<b>TITLE = "Time History of wave parameters"</b>				
VARIABLES=t, Hs, ang1, ts, tmean				
120.00000000000000	9.999998E-03	0.000000	6.000000	
4.539873				
120.00000000000000	9.999998E-03	0.000000	6.000000	
4.539873				
120.00000000000000	0.1601646	-11.01991	5.794887	
4.384676				
120.00000000000000	0.4606727	3.918265	6.055299	
4.581715				
120.00000000000000	0.4317167	14.65740	5.917689	
4.477593				
120.00000000000000	0.5064909	9.822144	5.947836	
4.500404				
120.00000000000000	0.5008851	10.02924	5.992632	
4.534298				
3720.000000000000	9.999998E-03	0.000000	6.000000	
4.539874				
3720.000000000000	9.999998E-03	0.000000	6.000000	
4.539874				
3720.000000000000	0.1596416	-11.01060	5.831412	
4.412313				
3720.000000000000	0.4588715	3.938616	6.113648	
4.625865				
3720.000000000000	0.4298030	14.64070	5.977244	
4.522655				
3720.000000000000	0.5048415	9.806460	6.002532	
4.541790				
3720.000000000000	0.5094872	9.929836	6.081017	
4.601175				
7320.000000000000	9.999998E-03	0.000000	6.000000	

**Figure 6-4 Data file for storing wave parameters at monitoring stations**

Apparently, this format is not convenient for drawing a chart for time variations of any wave parameters. Consequently, user can use a small application called “readHsHis\_Tp.exe”, which can be found in the folder of the CCHE2D Program, under \CCHE2D\_GUI. By executing this code and inputting a project name (e.g. Mscoast), time series of wave parameters will be rearranged and outputted into a data file called “\*\_HsHisTp.plt” . As shown in Figure 6-5, the format of the times series of wave parameters at monitoring stations is given as follows:

First Column = time in hour

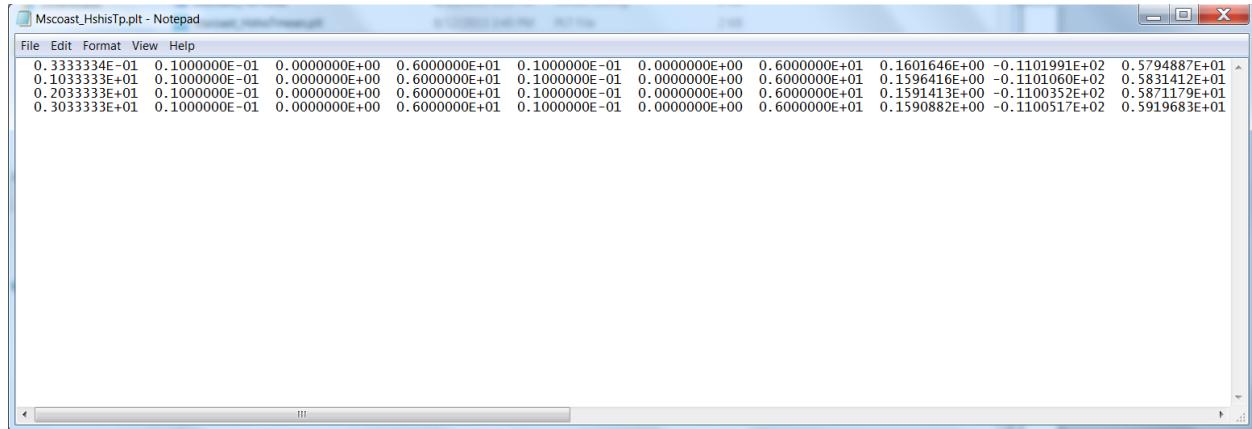
Second Column = significant wave height of the first station

Third column = Mean eave direction in degree of the first station, as defined in Figure 4-4.

Fourth column = Peak period in second of the first station

Fifth column = significant wave height of the second station

...



**Figure 6-5 Data file for storing wave parameters converted by using readHsHis\_Tp.exe**

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