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THE DEVELOPMENT AND APPLICATION OF THE ECO-HYDRODYNAMIC AND ENVIRONMENTAL MODELING SYSTEM FOR THE ESTUARINE AND COASTAL AREAS OF VIETNAM

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Abstract

The development and application of the multi-dimensional and its coupled models give the possibility to investigate the variability of the hydro-meteorological (wind, current, temperature), ecological and environmental (contaminants, nutrients, primary productions, fish) characteristics and its structure in the complex estuarine and coastal region.

In the multi-dimensional (1D, 2D and 3D) and its coupled (air-sea and hydro-ecological) modeling system, the principal element is three-dimensional (3D) model. A complete 3D eco-hydrodynamic coastal sea model had build up, using the system of the thermo-hydrodynamic primitive equations with GHER turbulent closure scheme and ecological advection-diffusion model. The complex boundary software and double σ-coordinate transformation technique were developed and applied in the numerical model.

The ecosystem and environmental models are imbedded on-line in to 3D thermo-hydrodynamic model with superimposed cycle for the light intensity. The main findings of the thermohydrodinamic model are summarized stressing those aspects of circulation and thermohaline fields that affect the ecosystem.

The results of the applications of the 3D model to investigate the circulation, temperature and salinity and ecosystem variations in the coastal regions of the South China Sea show the possibility to develop multi-dimensional and coupled modeling system using advanced coupling and nesting techniques. The cooperation with Japanese scientists in this direction is very useful to create the system of the models for marine and coastal environmental modeling and monitoring in Vietnam.

Keywords: Eco-hydrodynamic and environmental modelling system, coastal and estuarine areas

Introduction

The coupled multi-dimensional models give the possibility to investigate the variability of the hydro-meteorological (wind, current, temperature), ecological and environmental (contaminants, nutrients, primary productions, fish) characteristics and its structure in the coastal regions with the complex topography and boundaries. In the multi-dimensional (1D, 2D and 3D) and its coupled (air-sea and hydro-ecological) modeling system, principal element is three-dimensional (3D) model. A three-dimensional primitive equation turbulent closure ecohydrodynamic mathematical model developed at the GeoHydrodynamics and Environment Research Laboratory (GHER) of the University of Liege is the principal element of this system. The model consists in two sub-models:

– The hydrodynamic model, the state variables of which are the three components of the velocity vector, the pressure, temperature, buoyancy (or salinity), the turbulent kinetic energy and the turbulent dissipation rate (or mixing length);

– The plankton ecosystem model, the state variables of which are defined, according to the recommendations of the GLOBEC Numerical Modeling Group (Globec, 1995), as those which are necessary and sufficient to assess the effects of the physical processes on primary and secondary productions (the so-called "minimum critical set")

This model has applied with success to the Black Sea, the Northern Bering Sea (Nihoul et al, 1994, Gregoire et al, 1997, Walsh et al, 1989), the state variables are NO3-, NH4+, the phytoplankton and zooplankton biomasses and dissolved organic matter.

The ecosystem model is embedded on-line into the 3D hydrodynamic model with a superimposed light intensity cycle.

In this paper, the main findings of the hydrodynamic model are summarized stressing those aspects of the water circulation and hydrological fields that affect the ecosystem. The ecosystem model is briefly described emphasizing the modifications made in the original formulation to adapt the equations to the conditions of the Gulf of Tonkin.

Three-dimensional hydrodynamic model

The equations

The hydrodynamic model, the state variables of which are the three components of the velocity vector, the pressure, temperature, buoyancy (or salinity), the turbulent kinetic energy and the k-ε turbulent closure scheme (Nihoul et Beckers, 1992).

The sea is assumed to be hydrostatic and incompressible (Boussinesq approximation). The thermohydrodynamics equations for velocity (v), temperature (T), salinity (S) and turbulent kinetic energy (k) are written in the Cartesian co-ordinates with x eastward, y northward, and z upward:

$$\nabla . v = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + v.\nabla u + f e_3 \Lambda u = -\nabla_h q + \frac{\partial}{\partial x_3}\left(\tilde{v} \frac{\partial u}{\partial x_3} \right) \tag{2}$$

$$\frac{\partial T}{\partial t} + v.\nabla T = \frac{\partial}{\partial x_3}\left(\tilde{\lambda}^T \frac{\partial T}{\partial x_3} \right) \tag{3}$$

$$\frac{\partial S}{\partial t} + v.\nabla S = \frac{\partial}{\partial x_3}\left(\tilde{\lambda}^S \frac{\partial S}{\partial x_3} \right) \tag{4}$$

$$\frac{\partial k}{\partial t} + v.\nabla k = \tilde{v}\left\| \frac{\partial u}{\partial x_3} \right\|^2 - \tilde{\lambda}^b \frac{\partial b}{\partial x_3} + \pi^0 - \varepsilon + \frac{\partial}{\partial x_3}\left(\tilde{\lambda}^k \frac{\partial k}{\partial x_3} \right) \tag{5}$$

$$\frac{\partial \varepsilon}{\partial t} + v.\nabla \varepsilon = \frac{\varepsilon}{k}\left(\gamma_1 \tilde{v}\left\| \frac{\partial u}{\partial x_3} \right\|^2 - \gamma_2 \tilde{\lambda}^b \frac{\partial b}{\partial x_3} + \gamma_1 \pi^0 - \gamma_3 \varepsilon \right) + \frac{\partial}{\partial x_3}\left(\tilde{\lambda}^\varepsilon \frac{\partial \varepsilon}{\partial x_3} \right) \tag{6}$$

where:

$$\nabla \equiv e_1 \frac{\partial}{\partial X_1} + e_2 \frac{\partial}{\partial X_2} + e_3 \frac{\partial}{\partial X_3} ; \nabla_h \equiv e_1 \frac{\partial}{\partial X_1} + e_2 \frac{\partial}{\partial X_2}$$

$$v \equiv u + u_3 e_3 \ ; q \equiv \frac{p}{\rho_0} + g x_3 + \xi; \frac{\partial q}{\partial x_3} = b \ ;$$

$$b = -\frac{\rho - \rho_0}{\rho_0} g = b(T,S); \quad \tilde{\nu} = \frac{\alpha_k k^2}{16\varepsilon}; \quad \alpha_k \approx 1$$

$f = 2\Omega\cos\lambda$ - Coriolis parameter, $\tilde{\lambda}$ - turbulent diffusion coefficients, ν - turbulent viscosity, γ_i - dimensionless coefficients: O(1), ξ - tidal potential, ρ - sea water density (ρ_0 - reference value), π^0 - mesoscale turbulent energy component . The turbulent scheme is characterized by equation for turbulent kinetic energy, k, and for the energy dissipation, ε. J.C.J.Nihoul proposed turbulent closure scheme using the turbulent mixing length would be determined for each concrete case:

$$\varepsilon = \frac{\alpha_k k^2}{16\tilde{\nu}} \tag{7}$$

$$\tilde{\nu} = \frac{1}{2}\alpha_k^{1/4}\sqrt{k}l_m; \qquad l_m = (1 - R_f)l_n(x_3) \tag{8) - (9}$$

$$Rf \equiv \frac{\tilde{\lambda}^b N^2}{\tilde{\nu}M^2 + \pi^0}; N^2 \equiv \frac{\partial b}{\partial X_3}; M^2 \equiv \nabla\nu;\nabla\nu \approx \left\|\frac{\partial u}{\partial X_3}\right\|^2 \tag{10)-(12}$$

$$\pi^0 = \left[\langle -w_1 w_1\rangle : \nabla u_1\right]_0 \sim \beta\left[\tau^{3/2}\right]_0 D^{-1} \tag{13}$$

$$\tilde{\lambda}^b = \Psi^b \tilde{\nu}; \Psi^b \sim \gamma\sqrt{1 - R_f}; \gamma \sim 1.1 - 1.4 \tag{14}$$

$$1 - R_f = \left(\tilde{R}_i + \sqrt{\tilde{R}_i^2 + 1}\right)^{-2}$$

$$\tilde{M}^2 \equiv M^2 + \frac{\pi^0}{\tilde{\nu}}$$

$$\tilde{R}_i \equiv \frac{\gamma N^2}{2\tilde{M}^2}$$
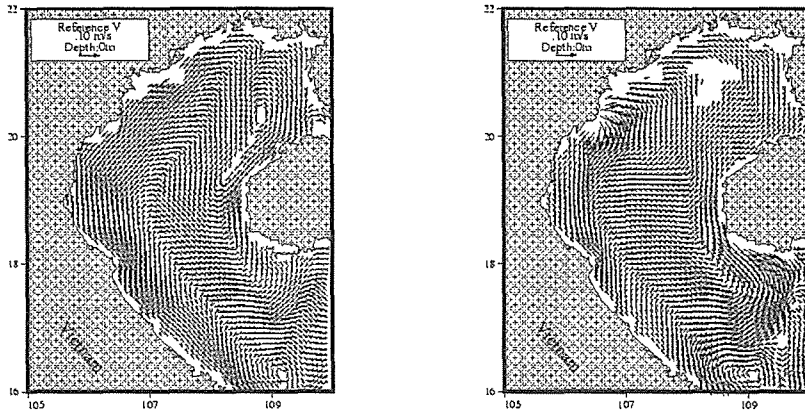
The simulations

The bottom bathymetry database and analyzed temperature and salinity fields were interpolated into the model grids to obtain the initial and nudging fields. The implementation of the vertical co-ordinate change is cut into two regions superposed vertically. One region covers the deeper part of the deep sea region and a second one covers the shallow water region and the upper layer. In each of these regions a classical σ-co-ordinate change is introduced. The model uses non-uniformly distributed vertical levels in the first σ-region and in the 2nd region.

The model is initialised with the Helleman and Rosenstein (1983) wind climatology and air-sea heat and masse fluxes with local modification (Uu D.V., 1995). There are two type of the open boundaries: open sea boundary and open boundary with the rivers and coastal discharge sources.

Analysis of the simulated fields

The model is run for several years from January to December using 9 x 10 km grids for Gulf of Tonkin and 1x1 km for Quang Ninh- Halong region. We use our three-dimensional analyzed results for temperature and salinity in January as the initial conditions. The initial water circulation and elevation are computed from this thermohaline field by mode-splitting method.

After several period of simulation we can get the key features of the currents in the simulated region. For the seasonal variation, the water circulation is dominated by the monsoon winds. There is the main surface current according to general wind direction for each season (fig.1).

Figures 1. The simulated surface circulation in the winter (left) and summer (right) seasons
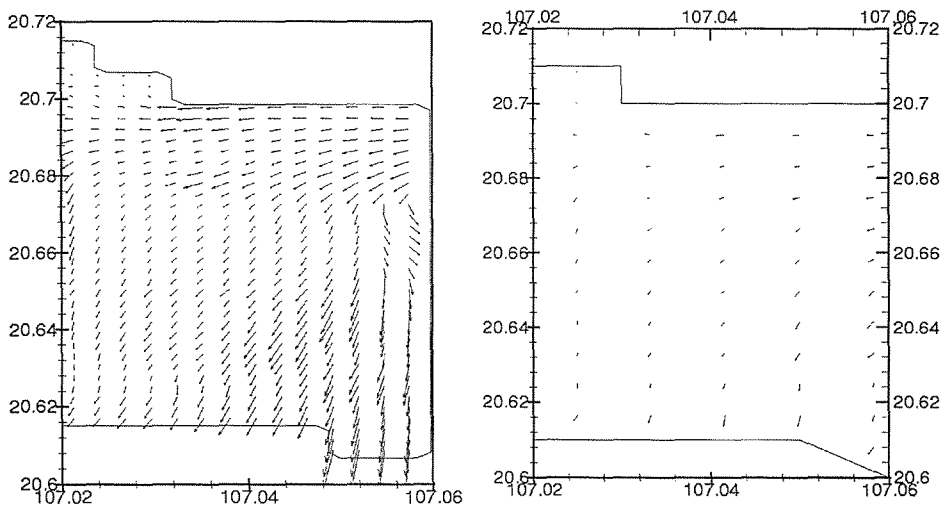
Figure 2. The simulated surface water circulation in Halong Bay for fine (left) and coarse (right) nesting grid.

In order to investigate the system of the specific meso-scale eddies in the region, the nesting technique was applied for north-west of Gulf of Tonkin: Quang Ninh- Halong region. The simulated 3D hydrodynamic (fig.2) and water elevation fields for the coarse and fine grids agree well with observed and analysis data.

This model could be coupled with the regional atmospheric model (RAMS- Regional Atmospheric Modeling System, CSU, OASIS-Osaka University Atmospheric Simulation model, Yamaguchi et al, 1992) to investigate the land and sea breeze over the coastal region and its influence on the variability of the marine environmental conditions.

The Japanese experiences of the coupling 3-D and 2-D modelling (Nakatsuji, 1999) may be used with our 3D model to adjacent estuarine region where the river – sea interaction is very important.

The ecosystem model

The model used in this preliminary investigation of the Gulf of Tonkin ecohydrodynamics is very simple and must be regarded rather as a tool for testing the coupling of hydrodynamic and ecosystem submodels, while acquiring some preparatory assessment of the effect of physical processes on ecodynamics. The advection-diffusion equation for the ecological variables y_j written in the form general

$$\frac{\partial y_j}{\partial t} + \nabla.(v+m) y_j = Q_{yj} + \frac{\partial}{\partial x_i}\left(\tilde{\lambda}^{yj}\frac{\partial y_j}{\partial x_i}\right) \qquad (15)$$

$$Q_{yj} = q_j + \sum q_{j\alpha\beta} - \sum f_{j\alpha\beta}, \qquad j,\alpha,\beta = 1,N$$

m- migration velocity for variable y_j.

The sources function Q_{yj} is parameterized by the production q_j and destruction part $f_{j\alpha\beta}$.

For the conservative components these parameters are zero.
The advection term is:

$$\left(\frac{\partial y_j}{\partial t}\right)_{adv} = -\nabla.(v+m) y_j$$

and the diffusion term:

$$\left(\frac{\partial y_j}{\partial t}\right)_{diff} = \frac{\partial}{\partial x_i}\left(\tilde{\lambda}^{j}\frac{\partial y_j}{\partial x_i}\right)$$

The model has five state variables: NO_3^-, NH_4^+, phytoplankton, zooplankton, and dissolved organic matter. Bacterioplankton has been eliminated assuming quasi-equilibrium prey-predator relationship within the microbial loop (Walsh et al 1989, Nihoul et al 1994), and no independent state variable is introduced to account for the particulate organic matter; particles are included in the sedimenting fractions of both the phytoplankton (dead cells) and zooplankton (dead animals, faecal pellets) biomasses (with appropriate sedimentation velocities determined by inspection of the data base).
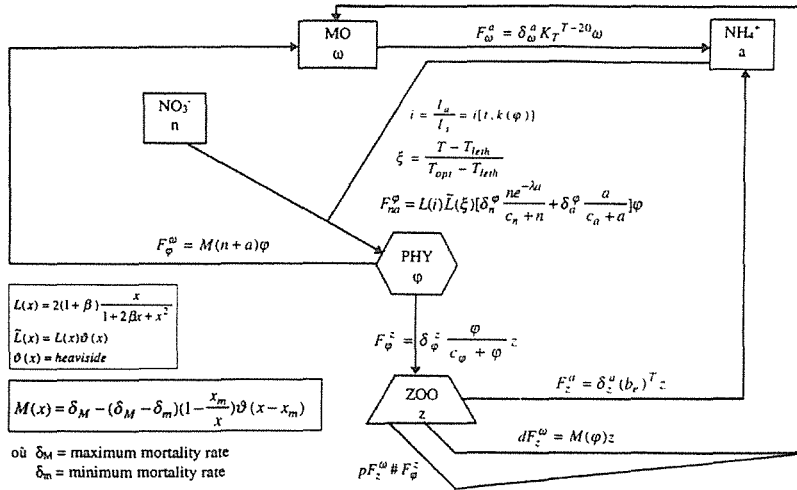
Figure 3. Schematic representation of the ecosystem model. The interaction rate is written on the arrows. The parameters dependent on the temperature are circled

The nitrification (ammonium oxidation in nitrate) and denitrification (under low DO conditions) processes are included in a special relationship. Matter exchanges between compartments are described in the form of a nitrogen cycle and the state variables are measured in nitrogen content units. The interaction rates used in the Gulf of Tonkin calibrated model are written on the box-arrow representation of the model shown in figure 3.
The box version of the model has been used to determine the most sensitive parameters of the ecosystem model. One these parameters are known, the calibration of the 3D model can be realized by adjusting them.

Discussion

The simulation is performed by solving the ecosystem model conjointly with physical model. In the region of the river plume and in the relative warm waters the phytoplankton mass is maximum. Zooplankton development is important in the phytoplanton maximum region. The mixing layer extends to the bottom leading to the light limitation of phytoplankton.

During summer period, the phytoplankton growth in the region of river plume, and the bloom occurs here. These simulated results also show the important zooplankton development in the regions of the river plume.
The simplicity of the model and the lack of sufficient data available at the time of this preliminary simulation did not allow a thorough validation of the model. The observed values of phytoplankton and zooplankton masses in the coastal region give us some comparison that shows a good agreement.

The simulated turbidity (or tracer) fields show the river plume is maximum in the rain season and extends to north and south direction along west coast of the Gulf of Tonkin.

Conclusion

In this paper, one showed how a hydrodynamic model was implemented and extended to include an ecosystem and environmental model. The simulated circulation and thermohaline fields are probably accurate enough for the simulation of a phytoplankton bloom at regional scale.

On the shallow region, the information provided by the model are primarily related to the physical constraints imposed on the system; a fine resolution interdisciplinary model will be implemented to simulate eutrophication processes. But this regional mesoscale model depends on the information flowing in the large scale water circulation.

The developed model could be developed the diagnostic and predictive models for different phenomenon in the estuarine and coastal area as erosion and coastal line change; tide and storm surge propagation; water quality monitoring and conservation.

The Japanese experiences of the coupling and nesting technique may be used to develop multi-dimensional and coupled modeling system for marine and coastal environmental modeling and monitoring in Vietnam.

Acknowledgements

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