International Conference on Hydroinformatics

2014

The Benthic Geoecology Model Within The Modular System For Shelves And Coasts (MOSSCO)

Mohammad Hassan Nasermoaddeli

Carsten Lemmen

Richard Hofmeister

Frank Koesters

Knut Klingbeil

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

THE BENTHIC GEOECOLOGY MODEL WITHIN THE MODULAR SYSTEM FOR SHELVES AND COASTS (MOSSCO)

NASERMOADDELI, M.H. (1), LEMMEN, C.(2), HOFMEISTER, R. (2), KOESTERS, F. (1), KLINGBEIL, K. (3)

(1): Department of Hydraulic Engineering in Coastal Areas, Federal Waterways Engineering and Research Institute, Hamburg, 22559, Germany

(2): Helmholtz Centrum Geesthacht, Centre for Materials and Coastal Research, Institute for Coastal Research, Geesthacht, 21502, Germnay

(3): Leibniz Institute for Baltic Sea Research Warnemuende, Dept. for Physical Oceanography and Instrumentation, Rostock-Warnemuende, 18119, Germany

The Modular System for Shelves and Coasts (MOSSCO) integrates physical, biological, chemical and geological models of shelves and coasts for the North Sea and Baltic Sea in an exchangeable way. The MOSSCO software forms a coupling framework for exchanging data and models, which distinguishes between physical domains (Earth System compartments such as the benthic and pelagic zone) and processes (such as benthic geochemistry, physical erosion and biological stabilization). Information exchange across physical domains with different grids and time steps are managed using the ESMF (Earth System Modelling Framework), whereas coupling of processes within individual modules is achieved using FABM (Framework for Aquatic Biogeochemical Models). This paper reports coupling of a newly developed benthic geoecology model to the MOSSCO framework. This new model incorporates the biological effects of macrofauna (the bivalve Tellina fabula is taken as an example) and microphytobenthos on erodibility and critical bed shear stress. The model is implemented in an object-oriented generic modular way so that it can be extended to any number of biological effects on the sediment transport for an arbitrary number of species. Finally, the application of the coupled model is demonstrated in simulation of a1D setup.

INTRODUCTION

Challenging questions within and at the boundaries of different Earth System compartments such as the flux of carbon between the pelagic and benthic zone (e.g. de Haas et al. 2002[3]) make the integration of different physical domains (compartments) and processes in Earth system modelling inevitable. Besides the traditionally coupled domain models, such as atmosphere and ocean, models of coastal systems must integrate more chemical and biological process models, which are typically not coupled within the larger Earth System Model (ESM) context. If represented at all, biological and biogeochemical processes are incorporated in ocean models. Such monolithic approaches, however, are dominated by the physical ocean modeling communities. Progress in understanding of biological and chemical processes can only partially and slowly be integrated in monolithic ocean models due to the model complexity. The ability to exchange process descriptions in such monolithic models is limited, or even impossible, which makes model intercomparisons, and extensions by different international scientific communities difficult.

Conversely to this strongly-coupled monolithic approach, a flexible modular approach, which aims at making models as modular and exchangeable as possible, offers the opportunity to exchange, maintain and develop each sub-model independently by different communities. Furthermore, it promotes communication and collaboration among scientists from different disciplines. One of the most successful strategies for modular domain coupling is employed in Earth System Models, where individual physical domains of the Earth System(compartments), e.g. ocean, ice, atmosphere, or biosphere are concurrently simulated and the exchange of information is mediated by a domain coupler. If the individual stand-alone domain representations exhibit a coupler specific interface they can be coupled to one another with coarse granularity. The role of this coupler typically is to negotiate different physical grid representations, or coordinate systems between the domain models, to ensure the correct transport of fluxes across the domains, and to distribute the computing loads of the different domain models in a high performance computing (HPC) parallel execution environment.

Among the current coupling technologies are, the Model Coupling Toolkit (MCT), the Earth System Modeling Framework (ESMF), the Flexible Modeling System (FMS), the Community Climate System Model (CCSM), the OASIS coupler or the Bespoke Framework Generator (BFG). These and other techniques have recently been reviewed and compared quantitatively by Jagers (2010[4]) or qualitatively by Valcke et al. (2012[12].) The coupling technologies differ in several aspects, such as code invasiveness, code-level generator versus executable-level coupling, performance, flexibility, research community heritage, implementation languages and addressee. Jagers (2010[4]) concludes that most coupling technologies are converging towards common concepts and recommends reusability of components and co-operation of developers. Valcke et al. (2012[12]) conclude that “in the end, science needs both flexible and high performance coupling capabilities“.

A different approach is taken by the Highly Structured Modular Earth Submodel System (MESSy, Jöckel et al. 2005[5]) to describe the coupling of processes within a domain at very high process modularity; this allows for a fine-grained coupling and efficient data flow between processes. In MESSy, which is currently operational in the atmospheric domain, diverse processes such as the quasi-biannual oscillation, water physics, radiocarbon generation or aerosol scavenging are independently described in submodels. All these submodels, however, had to be written or rewritten, to meet the specific infrastructure enforced by MESSy.

Similar to MESSy, but emerging from the pelagic ecosystem community is the Framework for Aquatic Biogeochemistry (FABM, Trolle et al. 2012[10]). This is a community based model framework that facilitates the integration of local process models within a larger spatial context and coupling to other local process models by providing interfaces for information sharing. Also within FABM, existing models have to be partially rewritten to meet these interface standards. Currently, the FABM library of process models includes a diversity of exchangeable descriptions of food web, nutrient, and suspended sediment interactions.

Challenges in coastal and shelf areas, for example, human pressure on resources and ecosystem, call for the integration of physical, chemical and biological processes both between and within domains, and thus for a coupling strategy that goes beyond pure domain and process coupling. This is the goal of the MOSSCO infrastructure, which takes a hybrid approach of domain and process coupling relying on ESMF and FABM as major (but not exclusive) coupling technologies.

The Modular System for Shelf and Coasts (MOSSCO) is a software architecture enabling exchangeability of process descriptions in various model levels through standard interfaces. This software architecture utilizes the Earth System Modeling Framework (ESMF) to couple processes between Earth compartments, such as benthic and pelagic compartments. Additionally, it applies the Framework for Aquatic Biogeochemical Models (FABM) to set up communication among different processes within each compartment, such as biogeochemical processes within the pelagic domain. Thus MOSSCO couples different physical, chemical and biological processes across and within physical domains.

The present work demonstrates coupling of a newly developed generic modular geoecology model with MOSSCO. In the current 1D setup, the General Ocean Turbulence Model (GOTM) has been applied to model 1D-vertical hydrodynamics (pelagic domain) representing conditions at the shallow North Sea shelf. We make use of the FABM framework to describe the local pelagic dynamics of suspended particulate matter (SPM) as used in Burchard et al. (2004). FABM provides a library that holds models, each containing state variables with its local zero-dimensional rate of change. The SPM process model used here defines mass concentration of SPM as state variable and considers light attenuation due to shading and sinking of particles only. Non-local processes of pelagic dynamics on a numerical grid, such as mixing, advection and boundary fluxes of FABM's state variables, are handled by the gridded 1d pelagic ecosystem component. Each FABM model can run in multiple instances. The SPM state variables in FABM comprise basic properties such as density and equivalent spherical diameter. These properties are communicated together with the data, a standard name and unit description as ESMF fields.

The sediment flux between pelagic and benthic domain is computed using an abridged version of the Delft3D bed model. The bed model, in the following called erosed, was at the present stage simplified not taking into account sediment mixing in the bed. The exchange layer between the two mentioned domains is assumed to be an earth component, which is coupled to the MOSSCO framework by means of ESMF.

Since benthic life is not simulated dynamically yet, the demand for coupling of biogeochemical processes is limited. The description of biological effects on the entrainment of bed sediments (benthic geoecology model) was introduced as a new generic modular component, called "benthos effect", to the MOSSCO system via ESMF. The MOSSCO system provides an integrated infrastructure to communicate data arrays and metadata across domains and processes (refer to Figure 1).

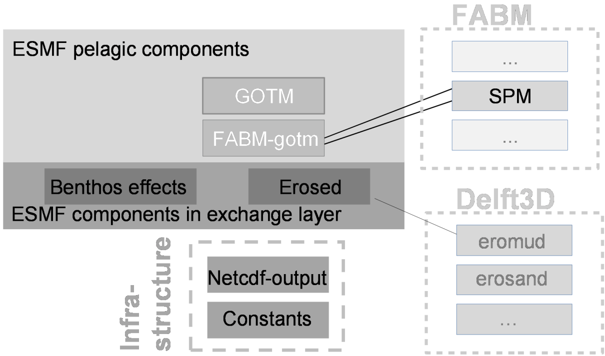

Figure 1. The coupled system consisting of water physics (GOTM), pelagic ecosystem (FABM-gotm), bed sediment flux (erosed) and benthic geoecology (benthos effects).

In the following, technical issues regarding the coupling of an existing model (here: erosed) and a new model (here: benthos-effect) to MOSSCO are demonstrated. Finally, the application of the newly developed benthic geoecology model within MOSSCO for modelling the effect of benthic fauna on sediment transport in a 1D-set up is presented.

METHODS

The purpose of this section is first to describe how an existing model can be prepared to be coupled with MOSSCO and second to explain the structure of the benthic geoecology model.

In order to study SPM dynamics a representation of erosion and deposition is needed. For this reason the open source code of Delft3D was taken, which was made available in an abridged form by Deltares. This simplified version computes sediment fluxes of non-cohesive soil and mud at the bed surface for different sediment fractions, thus different classes of sediments with different grain sizes. The bed stratification methods are currently left out and have been disintegrated to be later coupled as a separate earth compartment using ESMF. The coupling strategy was to leave the Delft3D routines unchanged by integrating them through wrappers. For this purpose the already exiting main routine “erosed” was modified to a wrapper (interface) invoking Delft3D routines, which are encapsulated in Fortran 2003 object classes as shown in Figure 2.

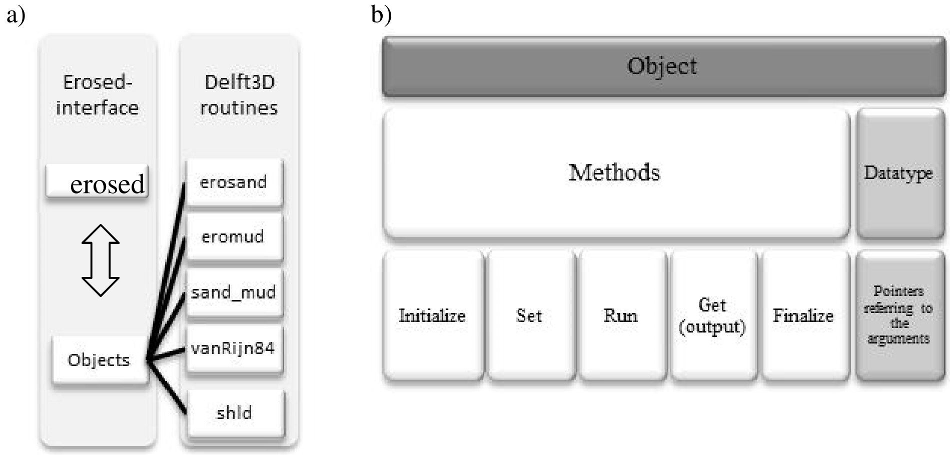

Figure 2. Embedding erosed in an interface to the objects (a) and encapsulation of Delft3D routines within the object structure (b)

Encapsulation of subroutines and their arguments in objects allows to make them inaccessible outside the interface (private to the interface), for example, from ESMF routines. The arguments of each subroutine were embedded in a data structure using pointers that are initialized and finalized in separate methods. Passing arguments through pointer assignment, running the subroutine and pointer assignment of the output arguments are done separately, as well (Figure 2).This approach enables independent development of original routines by other scientific communities without the need to change the interfaces to the MOSSCO system. Even later modification of the argument list can be easily implemented using this approach. Additionally, it is straightforward to generate such interfaces for almost any existing well-structured process-oriented routines. To maintain compatibility with ESMF, any interface should be implemented in a way to be invoked in three general steps: initialize, run and finalize (see Figure 3).

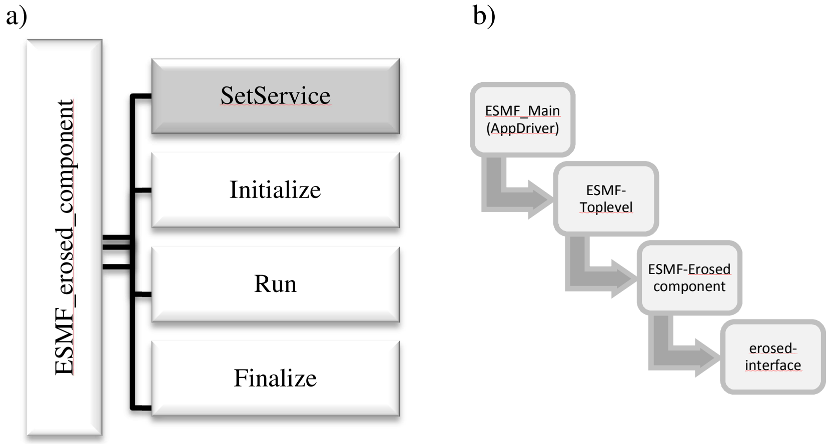

Figure 3. ESMF-component and its routines (a), and coupling procedure to ESMF (b)

These three routines are only accessible through an ESMF-SetService routine within the ESMF component, which is the last stage of coupling an existing routine to ESMF. The rest of the necessary coupling steps with ESMF are generic routines (ESMF Main and ESMF Toplevel components in Figure 3) which are generated automatically within MOSSCO. Couplers take the role of integration of such ESMF-components into MOSSCO. The role of such couplers is the management of the data flow among components.

As second aspect of this section, the newly developed benthos effect component is explained briefly in the following and technical issues are discussed. Species living on or within the sea floor range from plants to animals and are collectively referred to as benthos (Lalli und Parsons 1997[6]). Benthic animals larger than 1 mm are called macrofauna (such as the bivalve Tellina fabula). Marine plants attached to the seabed and micro algae (benthic microphytes) are other examples of benthic organisms.

Flow and sediment transport can be affected by the presence of benthic organisms in different ways. Protrusion of benthic animals and macrophytes in the boundary layer change the bed roughness and thus the bed shear stress and consequently the sediment transport. The erodibility of sediment can be modified by the mucus produced by benthic organisms, for example, extracellular polymeric substances secreted by microphytobenthos (Paterson 1997[8]). The erodibility of the upper bed sediment can be altered by bioturbation generated by macrofauna (Deckere et al., 2001 [2]). In the present work, the biological effects of microphytobenthos and of benthic macrofauna on sediment erodibility and critical bed shear stress are taken into account. Benthic macrofauna consists of a broad range of different species, e.g. worms, starfishes, bivalves and snails. In the following the bivalve Tellina fabula is taken as an example, which has been studied before (e.g. Borsje et al., 2009[1]).

It was seen as a requirement to implement the biologic effects in a generic way so that the number of biological effects and species can be arbitrarily extended. Hence the benthos effect was implemented object-oriented manner. An abstract generic object (super class) has been defined from which other species can be generated with all features of the super class, having polymorphism capability. This allows the modification and addition of biological effects of each new species while keeping the same generic methods and classes used by the super class for invoking necessary subroutines. The two main classes generated from the benthos-effect class are microphytobenthos and macrofauna; later macrophytes will be added too. Special measures were required for the implementation of macrofauna, since several species having different effects on sediment transport belong to this group of benthic organisms. In fact the effect of a community of different marine species on the sediment transport is non-linear. As yet there exists no theoretical approach to parameterize the effect of macrofauna communities on sediment transport; their stabilizing and destabilizing effects are simply treated as a multiplication of individual effects on each abiotic parameter such as roughness or erodibility. This is carried out as a public interface over which all macrofauna classes (including methods) are initialized, set, run and finalized (refer to Figure 4). This approach facilitated coupling the benthic geoecology into the MOSSCO framework with ESMF-components as previously shown.

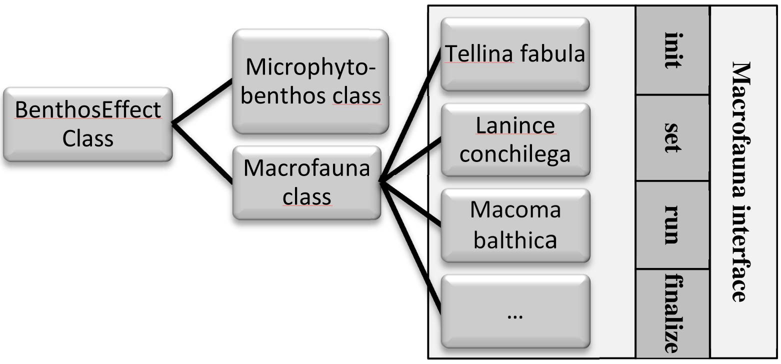

Figure 4. Structure of the generic modular benthic geoecology model in MOSSCO framework

RESULTS AND DISCUSSIONS

The coupled system is applied to simulate benthos effects on SPM dynamics at a station on the shallow shelf in the North Sea far enough offshore in order to assume lateral coastal SPM transport as a secondary effect only. The SPM dynamics are expected to be controlled mainly by vertical exchange processes, such as turbulent mixing, erosion, settlement of SPM and sedimentation. The mean water depth was set at an effective depth of 25 m. Tidal currents in this region are dominated by the M2 and S2 tide, such that a spring-neap cycle is a characteristic feature. Current velocities generally do not exceed 100 cm/s. The water column is resolved by 12 vertical layers, which position varies in height with the tidal surface elevation. Wind stress, radiation and heat fluxes at the sea surface are calculated based on meteorological data for the station Helgoland.

GOTM (Umlauf and Burchard, 2005[11]) is applied for the 1 DV hydrodynamic modelling having a k-epsilon turbulence model. Temperature stratification and current profiles are taken into account internally by the turbulence model. The water density varies with temperature due to meteorological forcing. Current velocities are forced by analytical tidal pressure gradients. Salinity is taken as constant in the present setup.

The pelagic ecosystem component uses two instances of the SPM model in FABM to represent two fractions of different size of SPM, which are consistent with those in the erosed component. The parameter configuration is given in table 1. The vertical movement of sediments in the water column is calculated based on a constant settling velocity and turbulent mixing obtained from the GOTM routines.

Table 1. Parameter configuration of SPM model classes.

parameter	fraction	value	Unit
Sinking velocity	1	0.0005	m/s
	2	0.001	m/s
density	1	2650	kg/m³
	2	2650	kg/m³
Mean diameter	1	20	µm
	2	100	µm

A single bed layer of non-cohesive soil without a mud fraction was assumed for the present simulation. A Chezy factor of 50 and a reference height of 10 cm above the bed were chosen. Critical bed shear stress is calculated within erosed and the biological effects on erodibility and critical bed shear stress are computed within the benthic geoecology model based on the assumed intensity of Tellina fabula and biomass of Chlorophyll a at the bed surface.

In the following the simulation results of the first sediment fraction are presented. As it can be seen from Figure 5 the SPM concentration in the water column follows the tidal water level fluctuations (and thus mainly the tidal current, not shown here). As expected, raising the intensity of T. fabula (0, 150 and 350 ind. m^{-2}) results in an increase of SPM in the water column compared to the case without biological effects (Abundance = 0, Chlorophyll = 0 µgg^{-1} in Figure 5). In contrast, an increase of the biomass of microphytobenthos, Chlorophyll a, (5, 10 µgg^{-1}) yields in a decrease of SPM in the water column.

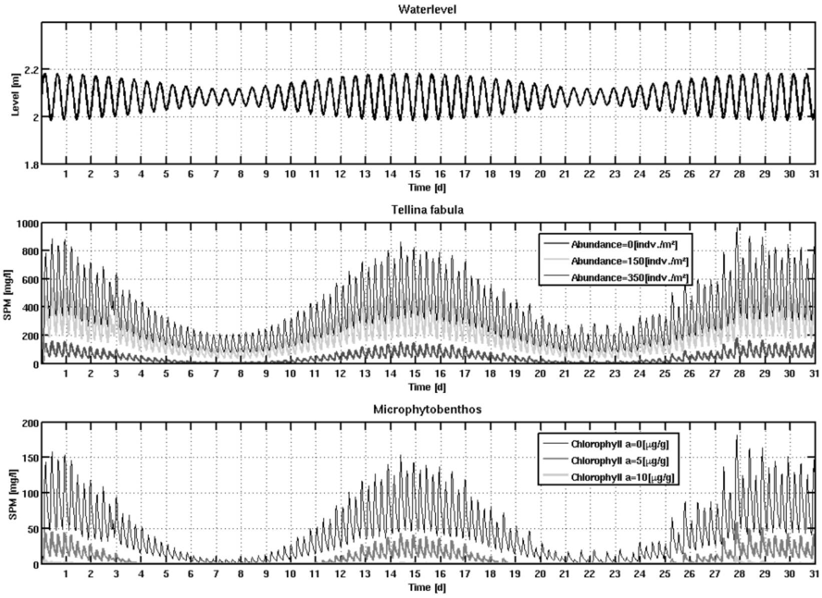

Figure 5. Simulation results of 1D-set-up showing the biological effects on the sediment concentration in the water column. T. fabula abundance has been made dimensionless.

The coexistence of both benthos organisms counteracts their effects on the sediment transport, so that for example at a T. Fabula abundance of 500 ind. m^{-2} and Chlorophyll a biomass of 12 µg g $^{-1}$ the net biological effect diminishes according to Paarlberg et al. (2005)[8]. This case could be reproduced in the current coupling effort (not shown here).

CONCLUSIONS

We have presented a newly developed generic modular benthic geoecology model and its coupling to the MOSSCO framework to investigate the biological effects on sediment transport. MOSSCO utilizes the ESMF, but not exclusively, to manage information flow between Earth system compartments and FABM to handle the data exchange within compartment level. Its modular approach enables exchangeable coupling of different physical, chemical and biological processes descriptions within and between earth compartments. It was shown how a generic modular structure of a newly developed benthos geoecology model allows for a straightforward coupling procedure. Additionally it was shown how an already existing model can be coupled to the MOSSCO framework. Finally, the simulation of a 1D coupled setup has shown plausible results of the coupled benthic geoecology model. It should be noted here that the biological input data was chosen within the range of observations but is not based on observations on a specific site. The intensity of biological effects on the SPM concentration is closely related to sediment properties such as the mean grain diameter, which will be further investigated in future process studies.

Acknowledgements

The MOSSCO project was funded by the German BMBF as part of the Coastal Research Agenda for the North Sea and Baltic Sea. This work results from joint efforts of the MOSSCO partners (grants 03F0668A, 03F0667A, 03F0667B); contributions of Deltares are thankfully acknowledged.

REFERENCES

[1] Borsje, Bastiaan Wijnand; Hulscher, Suzanne Jacqueline Marie Hélène; Herman, Peter Maria Jozef; Vries, Mindert Bareld, “On the parameterization of biological influences on offshore sand wave dynamics”, *Ocean Dynamics*, Vol. 59, No.5 (2009), pp 659–670

[2] Deckere, E.M.G.T de; Tolhurst, T.J; Brouwer, J.F.C de, “Destabilization of Cohesive Intertidal Sediments by Infauna”, *Estuarine, Coastal and Shelf Science*, Vol. 53, No.5 (2001), pp 665–669.

[3] De Haas, H., T.C.E.van Weering and H.C.de Stigter,” Organic Carbon in shelf seas; sinks or sources, processes and products”. *Continental Shelf Research*, Vol. 22(2002),pp 691-717.

[4] Jagers, H. R. A., "Linking Data, Models and Tools: An Overview", *International Congress on Environmental Modelling and Software Modelling for Environment's Sake*, Ottawa, Canada, 2010.

[5] Jöckel, P., Sander, R., Kerkweg, A., Tost, H., & Lelieveld, J., “Technical Note: The Modular Earth Submodel System (MESSy) - a new approach towards Earth System Modeling*”, Atmospheric Chemistry and Physics*, Vol. 5 (2005), pp 433–444.

[6] Lalli, C., Parsons, T.R., “*Timothy Richard Biological oceanography. An introduction*”, 2nd Edition, Oxford (1997).

[7] Lemmen, C., Hofmeister, R., Wirtz, K.W., Nasermoaddeli, M.H., Klingbeil, K., “Modular Coupling in Coastal and Shelf Science”, To be submitted to *Geoscientific Model Development*, 2014

[8] Paterson, D. M. and Black, K. S., ”Water flow, sediment dynamics and benthic biology”, *Advances in Ecological Research,* Vol. 29 (1999), pp. 155–193.

[9] Paarlberg, A. J., Knaapen, M.A.F., Vries, M. B. de, Hulscher, S.J.M.H., Wang, Z. B., “Biological influences on morphology and bed composition of an intertidal flat*”, Estuarine, Coastal and Shelf Science*, Vol. 64,No. 4,(2005), pp 577–590.

[10] Trolle, D., Hamilton, D.P., Hipsey, M.R., Bolding, K., Bruggeman, J., “A community-based framework for aquatic ecosystem models”, *Hydrobiologia*,Vol. 683(2012), pp 25- 34.

[11] Umlauf, L., and Burchard, H., “Second-order turbulence closure models for geophysical boundary layers. a review of recent work”, *Cont. Shelf. Res.*, Vol. 25(2005), pp 795-827.

[12] Valcke, S., Balaji, V. , Craig, A. , Deluca, C., Dunlap, R., Ford, R., Jacob, R., Larson, J., O'Kuinghttons, R., Riley, G., Vertenstein, M., “Coupling technologies for Earth System Modelling”, *GeoscMD.*, Vol. 5 (2012), pp 1589-1596.