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Analyzing coastal turbidity under complex terrestrial loads characterized by a 'stress connectivity matrix' with an atmosphere-watershed-coastal ocean coupled model

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ABSTRACT

Atmospheric, watershed and coastal ocean models were integrated to provide a holistic analysis approach for coastal ocean simulation. The coupled model was applied to coastal ocean in the Philippines where terrestrial sediment loads provided from several adjacent watersheds play a major role in influencing coastal turbidity and are partly responsible for the coastal ecosystem degradation. The coupled model was validated using weather and hydrologic measurement to examine its potential applicability. The results revealed that the coastal water quality may be governed by the loads not only from the adjacent watershed but also from the distant watershed via coastal currents. This important feature of the multiple linkages can be quantitatively characterized by a "stress connectivity matrix", which indicates the complex underlying structure of environmental stresses in coastal ocean. The multiple stress connectivity concept shows the potential advantage of the integrated modelling approach for coastal ocean assessment, which may also serve for compensating the lack of measured data especially in tropical basins.

1. Introduction

Coastal and estuary ecosystems such as coral reef, seagrass bed, salt marsh and mangrove sustain high biodiversity and vigorous production, providing a wide variety of goods and ecosystem services (Barbier et al., 2011). At least 60% of the world's population live within 60 km from coastline and enjoy the benefits from the coastal ecosystem resources for their livelihood (Ramsar Convention Secretariat, 2010). However, due to its geographical feature as an interface between the sea and the land, they are susceptible to various environmental stresses caused by human activities. Intensified inland human activities such as agriculture, deforestation and urbanization increase terrestrial loads such as sediments (Syvitski et al., 2005), nutrients (Cloern, 2001; Lotze et al., 2006) and other pollutants (Doney, 2010) to the coastal ecosystems. In addition to the terrestrial stresses, human activities also have impacts on coastal ecosystems through climate change, for example, rises in temperature, precipitation augmentation and increases in the frequency and magnitude of meteorological disturbances (Hoegh-Guldberg et al., 2007; Hoegh-Guldberg and Bruno, 2010; Knutson et al., 2010). Therefore coastal ecosystems are facing various threats, which have close relationships with atmospheric and terrestrial phenomena.

Coastal simulation models are recognized as promising tools to address human impacts on coastal ocean. One of key requirements of applying simulation model to the coastal issues is accurate quantitative assessment of atmospheric and terrestrial influences, which are some of the most important drivers normally given as initial and boundary conditions in coastal simulation. Obtaining accurate atmospheric and terrestrial input data is one of the common challenges for coastal ocean modelers. Conventionally observation data are utilized, if available, to drive the models. However, obtaining atmospheric and hydrologic data is not always easy and often laborious and expensive. In particular, this is the case for developing countries. In these countries, monitoring data are

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seldom complete if they exist at all. Moreover, atmospheric and associated hydrologic phenomena in tropical and subtropical regions, where most of the developing countries are located, have significant spatiotemporal variability that widens the gap between the data requirements and availability.

Given this situation, coastal simulation modelling coupled with terrestrial hydrologic and atmospheric climate models is a remedy for filling the gap. Some researchers have utilized hydrologic models to provide terrestrial inputs in coastal ocean modelling (Krysanova et al., 1989; Yuan et al., 2007; Inoue et al., 2008; Bedri et al., 2014). Weather input data are the most critical factor in modelling watershed hydrology (Obled et al., 1994). Several hydrologic modelling studies have been conducted using atmospheric simulation products as weather input data for hydrologic modelling (Hay and Clark, 2003; Chen et al., 2011; Fuka et al., 2013; Kleinn et al., 2005, Huang et al., 2013; Dile and Srinivasan, 2014; Praskievicz and Bartlein, 2014), as direct coupling of hydrologic models with atmospheric models (Danner et al., 2012; Goodall et al., 2013). Coupling of ocean models with atmospheric models is a common practice for driving hydrodynamic simulation (e.g. Bender, and Ginis, 2000; Chen et al., 2007; Seo et al., 2007; Bonthu et al., 2013; Sanna et al., 2013; Xue and Eltahir, 2015; Katsafados et al., 2016). Warner et al. (2010) incorporated wave and sediment transport simulation components into an ocean-atmosphere coupled model.

Despite a number of studies that combined atmospheric, terrestrial and coastal ocean models, to the best of our knowledge, few studies have directly integrated all three models. As mentioned earlier, weather and terrestrial observation data required for coastal ocean simulation are often difficult to obtain and are even unavailable for some areas. Integration of atmospheric, watershed and coastal ocean models is a possible approach for driving coastal ocean simulation in such areas. In addition, one of the important advantages of coupling the models instead of using the available observation data is the capability of quantitatively predicting and assessing relative effects of employing different policies in, e.g., land use/cover plan on coastal oceans as a scenario analysis.

In this study, we provide a holistic approach based on coupling three independent models, in which coastal, watershed and atmospheric dynamics are simulated. Development of the coupling system aims to model coastal physical and chemical dynamics in relation to terrestrial and atmospheric processes. Emphasis is especially on examination of coupling models in atmosphere, watershed and coastal ocean as a system to compensate the forcing input data for coastal modelling rather than investigation of an increase in the precision of each individual model. We examined, however, some possible factors that affect the model accuracy in the coupling system for improvement in the precision of coupling systems in the future. We applied the coupled model system to a study site in the Philippines where excess terrestrial sediment loads from adjacent watersheds are partly responsible for the coastal ecosystem degradation and both weather and terrestrial observation data for coastal ocean modelling are limited to demonstrate its applicability. As a result of applying the coupled model to the study site in which coastal waters are facing various sources of environmental stresses, we elucidated characteristic features of coastal hydrodynamics and turbidity by highlighting the multiple stress connectivity, which is quantitatively expressed with "stress connectivity matrix".

This paper is organized in the following manner. Section 2 explains the study site and simulation set up. Section 3 describes the result of each model and some validation works. Section 4 explains coastal environmental stress conditions that can be analyzed based on the coupled model system. Conclusions are presented in section 5.

2. Materials and methods

2.1. Study site

The target area for coastal ocean modelling encompasses the Guimaras Strait, the Iloilo Strait and the Panay Gulf located between Panay and Negros Islands in central Philippines (Fig. 1). The Guimaras Strait is a main channel that connects the Panay Gulf to the southwest and the Visayan Sea to the northeast. It has an average depth of approximately 15 m, with depths of as much as approximately 40 m. Panay Gulf which is connected to the Sulu Sea to the southwest has a depth of 2000 m. The Iloilo Strait is located between Panay and Guimaras Islands and connects the Panay Gulf and the Guimaras Strait.

Highly turbid water is a typical environmental stressor which could trigger the ecosystem degradation observed in the seagrass, benthos, and fish communities in this area. Terrestrial sediment load, one of the major sources of suspended sediment, has increased due to human activities such as intensified agriculture and forestry, which make the land surface more prone to soil erosion. Several tens of river basins are located on Panay and Negros Island in which agricultural activities such as rice, maize and sugarcane cultivation are commonly operated. The river network provides freshwater inflow to the adjacent coastal waters with sediments, nutrients and organic matter loads, which are considered as potential stressors to the coastal ecosystems. Hydrologic analysis was conducted in a total of thirty-five river basins in Panay and Negros Islands to quantify the terrestrial loads. The watersheds analyzed include the major ones such as the Jalaur and Jaro River Basins in Panay Island and the Bago and Ilog River Basins in Negros Island.

2.2. Numerical simulation setup

Three types of numerical models were applied in this study, namely, coastal, watershed and atmospheric simulation models. The outputs of each simulation were utilized as inputs for the other simulation (Fig. 2). Each model simulation was conducted offline and thus input data transferred from one model to the other were considered only to the downstream simulations (Fig. 2); therefore the simulations did not incorporate feedback from the coastal simulation to the hydrologic and the atmospheric simulation such as effects of backwater and sea surface temperature, respectively, and that from the hydrological simulation to the atmospheric simulation like effects of vegetation dynamics, soil moisture, etc. Online coupled model exchanges values and fluxes between each coupled model and the feedbacks are considered to benefit more realistic representation of non-linear interactions between different components (Warner et al., 2010; Zeng et al., 2015). On the other hand, online coupled model is generally more time-consuming compared to offline coupled model due to additional overheads mainly posed by the exchange and temporal synchronization between each model. Moreover, online coupled model which runs more than one model simultaneously may require a high-end computing platform (e.g. supercomputer) for its operation. In this study we aimed to develop a resource effective model which does not require such a high-end computing platform from a viewpoint of implementation of the model to local communities in which usually only small-scale computing platforms are available. Hence we developed an offline coupled model instead of an online one at the cost of accuracy to some extent in the aspect of implementation of the system.

Data format converter (DFC) was run between different model simulations to convert data into a readable form (Fig. 2). DFC 1 and 2 extract ground surface atmospheric parameters which include