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Modeling a coastal ecosystem to estimate climate change mitigation and a model demonstration in Tokyo Bay

Akio Sohma[a,*], Hisashi Shibuki[b], Fumiyuki Nakajima[c], Atsushi Kubo[d], Tomohiro Kuwae[e]

[a] *Graduate School of Engineering, Osaka City University, 3-3-138 Sugimoto, Sumiyoshi-ku, Osaka, 558-8585, Japan*
[b] *Science Solutions Division, Mizuho Information & Research Institute, Inc., 2-3 Kanda-Nishikicho, Chiyoda-ku, Tokyo, 101-8443, Japan*
[c] *Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan*
[d] *Department of Geosciences, Shizuoka University, 836 Ohya, Suruga-ku, Shizuoka 422-8529, Japan*
[e] *Coastal and Estuarine Environment Research Group, Port and Airport Research Institute, 3-1-1 Nagase, Yokosuka, 239-0826, Japan*

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ABSTRACT

An ecosystem model called the “EMAGIN-B.C. ver 1.0 (Ecosystem Model for Aquatic Geologic Integrated Network for Blue Carbon)”, describing the Carbon-Nitrogen-Phosphorus-Oxygen-Calcium cycle was developed to estimate/predict carbon capture and storage in estuaries. EMAGIN-B.C. analyzes (1) carbon burial, wherein carbon is captured biologically in the pelagic and benthic ecosystems and stored in deeper sediments, (2) CO_2 uptake at the ocean surface while considering the carbonate chemistry with total alkalinity and Dissolved Inorganic Carbon (DIC) production/consumption due to biochemical processes, (3) DIC capture associated with grazing at the trophic level among phytoplankton, zooplankton, and benthic fauna, (4) the effects of hypoxia on benthic fauna and bacteria by precise modeling of the biochemical oxygen production/consumption and the resultant hypoxia, and (5) the carbon transport by integration with the hydrodynamic model. EMAGIN-B.C. was applied to Tokyo Bay, a eutrophic, shallow coastal area, and reproduced the observations well. From the model outputs, it can be observed that Tokyo Bay shows functions of climate change mitigation. In the one-year carbon budget, Tokyo Bay captured 16.6% of the DIC from the atmosphere and river as organic matter by biological processes, and 3.9% of the total carbon flowing from the atmosphere and river was stored in the deeper sediment layer.

1. Introduction

Fossil fuel combustion and changes in land use after the industrial revolution have been known to destabilize the carbon equilibrium state between the atmosphere and ocean on a global scale, and it is estimated that it will take several millennia to regain equilibrium (Hoffert et al., 1979). The global ocean contains approximately 50 times more carbon than does the atmosphere (Archer and Brovkin, 2008), and it is an important sink of atmospheric CO_2 (Houghton and Intergovernmental Panel on Climate Change. Houghton, 2001). Major global carbon reservoirs are comprised of the atmosphere, oceans, terrestrial biosphere, fossil fuels, and lithosphere (kerogens and sedimentary rocks), among which the oceans are the second largest reservoir (Falkowski et al., 2000; Solomon, 2007; McLeod et al., 2011). However, it is unclear whether the carbon reserved/sequestered by the shallow coastal waters comprised of estuaries, shallows, salt marshes, seagrass, mangroves, and intertidal flats have been included in these past estimations (McLeod et al., 2011). Recently, despite their relatively small areal coverage of 0.5% of the global earth (UNEP), several studies have focused on exploring the potential of shallow coastal waters as carbon reservoirs (stocks) and sinks (flows) due to their dense biological activities. (Alongi et al., 2016; Chen et al., 2013; Chmura et al., 2003; Donato et al., 2011; Fourqurean et al., 2012; Frankignoulle et al., 1998; Kubo et al., 2017; Kuwae et al., 2016; Murdiyarso et al., 2015)

Our definition of ocean functions for carbon capture and storage, the so-called “climate mitigation functions of the ocean” are those classified into (1) a CO_2 uptake function, (2) a Dissolved Inorganic Carbon (DIC) capture function, and (3) a carbon storage function (Fig. 1). The CO_2 uptake function is absorption of atmospheric CO_2 into the ocean by an air-sea CO_2 gas exchange (physical CO_2 uptake), while the DIC capture function is temporally fixing DIC as organisms or as $CaCO_3$ by biological production (biological DIC capture), and the carbon storage function is long-term (on a geological time scale) carbon sequestration deep into the sediment. When considering the shallow coastal water as composed of benthic and pelagic systems and focused on captured and stored carbon stocks within the ecosystem, the amount

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[*] Corresponding author at: #C321, Graduate School of Engineering, Osaka City University, 3-3-138, Sugimoto, Sumiyoshi-ku, Osaka, 558-8585, Japan.
E-mail address: sohma@eng.osaka-cu.ac.jp (A. Sohma).

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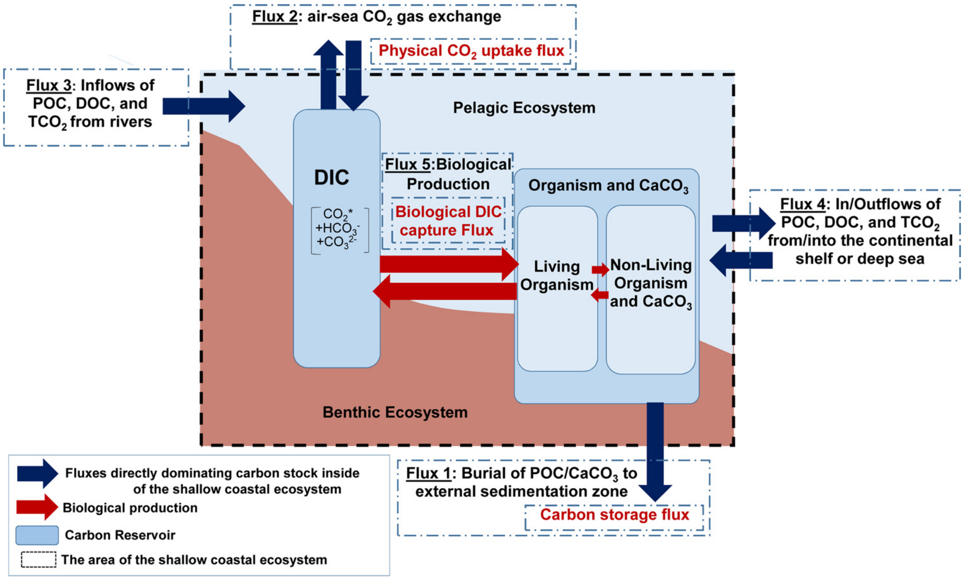

Fig. 1. The five fluxes dominating the dynamics of carbon stock in the shallow coastal area. The area inside the dotted line is the shallow coastal ecosystem, which is the target of estimation.

of carbon remaining in the system results in the following fluxes: Flux 1 is the burial of the particulate organic carbon (POC, comprised of detritus) and calcium carbonate ($CaCO_3$) into a sedimentation zone on a geological time scale; Flux 2 is the air-sea CO_2 gas exchange; Flux 3 is inflows of POC, dissolved organic carbon (DOC), and DIC (which is comprised of $CO_{2,aq}$, H_2CO_3, HCO_3^-, and CO_3^{2-}) from the river; and Flux 4 is the inflow/outflow of POC, DOC, $CaCO_3$, and DIC into the continental shelf or deep sea (Fig. 1). Here, the effects of the input of DIC and DOC through groundwater flow and volcanic activity, the subtraction of DIC, and the DOC associated with non-resident fish are omitted in Fig. 1 and are also currently excluded from our research objectives. If the value of Flux 1, burial, is higher, the geological time scale carbon stock that exists as fossil fuels and $CaCO_3$ in the shallow coastal system increases. If the sum of Fluxes 2, 3, and 4 is positive, the temporal carbon stock in the shallow coastal area increases, and, conversely, it decreases if the sum of the fluxes is negative. The flux directly affecting atmospheric CO_2 is Flux 2, and its effect is relatively in the short-term. In contrast, Flux 1 affects atmospheric CO_2 indirectly but long-term. Fluxes 3 and 4 affect Fluxes 1 and 2 through the biochemical and physical processes in the shallow coastal ecosystem.

As for the value of Flux 1, burial rates of organic carbon in vegetated shallow coastal waters are exceptionally high, exceeding those in the soils of terrestrial forests by 30- to 50-fold (Duarte et al., 2013). Globally, coastal vegetated habitats and terrestrial forests bury comparable amounts of organic carbon annually, despite the extent of coastal marine vegetation being less than 3% of forests, although this estimated value has great uncertainty (Duarte, 2017; Duarte and Cebrian, 1996; Duarte et al., 2005). As for the value of Flux 2, some shallow coastal waters are recognized to be net emitters of CO_2 to the atmosphere through air-sea CO_2 gas exchange (Borges and Abril, 2011; Cai, 2011; Chen et al., 2013; Laruelle et al., 2013); however, some studies have indicated CO_2 uptake (Kone et al., 2009; Kubo et al., 2017; Kuwae et al., 2016). In terms of Flux 3, Chen et al. (2012) estimated the air-sea CO_2 gas exchange from the head to the mouth of large river estuaries and concluded that the head of the estuary is a strong CO_2 source while the mouth of the estuary functions as a large CO_2 sink. Kuwae et al. (2016) also argued that the nutrient load from rivers affects the air-sea CO_2 gas exchange. In terms of Flux 4, several sources estimate the inflow/outflow of DOC, DIC, and POC in terms of the carbon stock of shallow coastal areas based on observations or budget models (Algesten et al., 2006; Eyre and McKee, 2002; Kubo et al., 2015; Mahmud et al., 2017).

In general, estimations of Fluxes 1, 2, 3, 4, and shallow coastal carbon stock are derived from the limited observations and statistical analyses on each flux. In addition, available observational data from particular systems are insufficient to cover the large spatial and temporal variability of carbon cycles. Furthermore, Fluxes 1, 2, 3, 4, and the carbon stock of shallow coastal areas are influenced by biological DIC capture flux, Flux 5 in Fig. 1, and all these factors are the result of interactions between physical and biochemical processes in the shallow coastal ecosystem. Therefore, the ecosystem model describing the physical and biochemical processes, i.e., the ecological connectivity, is a powerful tool (1) to understand the spatiotemporal patterns and variability, (2) to pursue the key mechanisms and interactions, and (3) to predict the ecosystem response to environmental measures. In addition, the model's representation of the results from the ecological connectivity enables us to reveal the unknown partial processes from the dynamics of the whole ecosystem. In fact, while taking into account the above advantages of the ecosystem model, a number of ecosystem models describing the ocean biogeochemistry and the lower trophic levels of the food web have emerged over the last two decades, in a variety of contexts ranging from simulations of batch cultures or mesocosms over the shallow coastal waters to the global ocean (Aumont et al., 2003; Butenschoen et al., 2016; Fasham et al., 1990; Flynn, 2010; Geider et al., 1997; Stock et al., 2014; Wild-Allen et al., 2010; Yool et al., 2013; Zavatarelli and Pinardi, 2003).

When the ecosystem model is applied to shallow coastal waters with high biological productivity and is used to reveal the spatiotemporal dynamics of Fluxes 1–5 (Fig. 1) as results of ecological connectivity, it is significant for it to satisfy the following requirements simultaneously:

I Coupling the benthic and pelagic ecosystems to demonstrate the series of processes in which carbon is captured in water or sediment surfaces and is stored in deeper sediments.

II Describing the food web of detritus, phytoplankton, zooplankton, and benthic fauna to estimate the carbon capture function associated with grazing at the trophic level.

III Incorporating the carbonic chemistry theory among DIC, total alkalinity, pH, and partial pressure of CO_2 (pCO_2) while describing detailed alkalinity production/consumption through biochemical processes to estimate the air-sea CO_2 gas exchange.

IV Treating Carbon-Nitrogen-Phosphorus-Oxygen-Calcium coupled