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Scaled-dependence and seasonal variations of carbon cycle through development of an advanced eco-hydrologic and biogeochemical coupling model

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ABSTRACT

Recent research has shown that inland water may play some role in carbon cycling, although the extent of its contribution has remained uncertain due to the limited amount of reliable data available. In this study, the author developed a new model coupling original eco-hydrology model and five biogeochemical cycle models (NICE-BGC), which incorporates complex coupling of hydrologic-carbon cycle in terrestrial-aquatic linkages and interplay between inorganic and organic carbon during the whole process of carbon cycling. This improved model was applied to Eurasian wetland by using three types of river network data to evaluate scaled-dependence of carbon cycle there. The model improved accuracy of low pH and alkalinity and DOC flux increase in the wetland in the northern part of study area with the finer river network data. The model showed that the difference in the carbon flux between different river network data becomes larger in downstream region, and that this difference is more predominant in the stream channel than in the hillslope, implying the importance of dry watercourses and intermittent rivers. The model was then extended to the global scale to evaluate seasonal variations of carbon cycle both in hillslope and river. The result extended from the previous studies to clarify that; (i) soil temperature has some effect on the carbon transport by biologic process responsible for carbon production in addition to clear relationship between runoff and carbon export, (ii) the high runoff during April to June and the large DOC and POC flux (about 458.38 ± 474.41 TgC/season and 239.25 ± 289.90 TgC/season) during January to March in hillslope, (iii) CO_2 evasion becomes maximum about 294.66 ± 93.80 TgC/season during January to June primarily affected by Amazon River, and (iv) sediment storage is larger and takes about 76.80 ± 13.19 TgC/season during July to September particularly in Asian and North American rivers. This scaled-dependence and seasonal variations of carbon cycle helps to bridge the gap between carbon transport to the longitudinal direction and gas emission to the atmosphere in previous researches. This simulation system would also help for the further field observations, remotely-sensed imagery, and satellite datasets, and play important role in improvement in biogeochemical activity in spatio-temporal hot spots.

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1. Introduction

Previous researches have suggested that variations and uncertainties of biogeochemical cycle in terrestrial ecosystem are relatively larger than those in atmosphere and ocean, and that the terrestrial biosphere sequesters most available carbon. Recently, some research has started to reconsider the importance of inland waters including rivers, lakes, and groundwater (Cole et al., 2007; Battin et al., 2009). In particular, inland waters play a role in transport, mineralization, and sequestration of carbon, which also might be complicated by surface–groundwater interactions around wetland and riparian areas; water movement there drives carbon storage and flux.

The author has so far developed the process-based National Integrated Catchment-based Eco-hydrology (NICE) model (Nakayama, 2014; Nakayama, 2015), which includes complex interactions between the forest canopy, surface water, the unsaturated zone, aquifers, lakes, and rivers. The model can simulate iteratively nonlinear interactions between hydrologic, geomorphic, and ecological processes, and include new feedback and down-scaling process from regional simulation to local simulation with finer resolution. The author previously attempted to extract the impacts of groundwater-level change, sediment deposition, and nutrient

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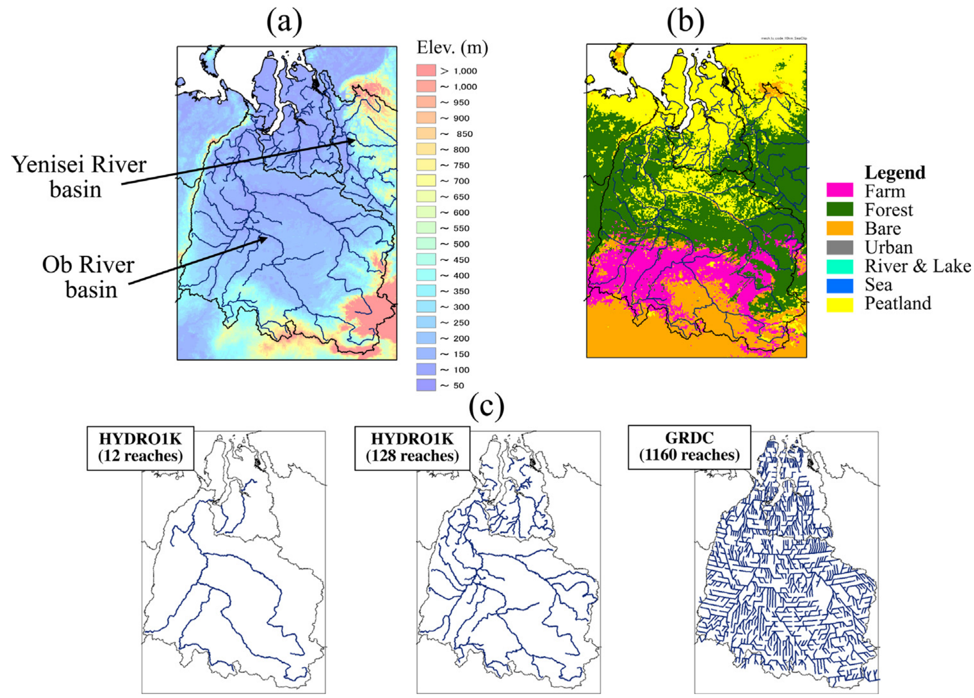

Fig. 1. Geographical characteristics in the study area of West Siberian Lowland and Ob River basin; (a) elevation, (b) land use, and (c) three types of river network data for the simulation (12, 128, and 1160 stream channels, respectively).

availability on the complex alder invasion pattern, and vice versa by using NICE. About scale similarity and discontinuity of eco-hydrological process, it is heuristically important to identify spatial coupling of local ecosystems including energy, materials, and organisms across ecosystem boundaries. Recent research suggests serious concerns against extrapolation of experimental results at a small scale to entire landscapes and therefore inevitably the necessity to bridge the gap between ecosystems at various scales (Deegan et al., 2012). It is powerful to re-evaluate the ecosystem as an extension of the "metabolic theory of ecology" (Brown et al., 2004) from the perspective of a meta-ecosystem analysis by considering multi-scaled aspects between global-regional-micro levels in the same way as the "river continuum concept" (Vannote et al., 1980). From this point of view, the author's previous improvement in feedback and down-scaling processes in the model becomes further powerful to evaluate this complex ecosystem metabolism by coupling with its opposite up-scaling process.

About the carbon cycle in inland waters, previous researches evaluate biogeochemical cycle in inland water to indicate that carbon budgets are diverse at various basins/catchments and that there is a close and complex relationship between pCO_2 (partial pressure of CO_2 in water), DOC (Dissolved Organic Carbon), DIC (Dissolved Inorganic Carbon), and POC (Particulate Organic Carbon) in inland water (Cole et al., 2007; Tranvik et al., 2009; Aufdenkampe et al., 2011; Raymond et al., 2013). While pCO_2 and pCH_4 are necessary to evaluate CO_2 and CH_4 flux to the atmosphere (evasion), DOC, DIC, and POC are also important to evaluate CO_2 flux to the ocean and sediment storage. From this viewpoint, it is necessary to develop a process-oriented model to obtain a better grasp of the biogeochemical cycle in the biosphere (terrestrial and aquatic ecosystems) as 'unifying currency' through a holistic approach (Prairie and Cole, 2009). This would help to clarify the mechanism of the carbon cycle in more detail, particularly the interplay between inorganic and organic carbon and its relationship to nitrogen and phosphorus, etc. in the context of the hydrologic cycle.

In this paper, the author developed the NICE further to couple it with various biogeochemical cycle models, including those for terrestrial ecosystems, those for water quality in aquatic ecosystems, and those for carbon weathering. This revised NICE model (NICE-BGC) incorporates the connectivity of the biogeochemical cycle accompanied by the hydrologic cycle between surface water and groundwater, hillslopes and river networks, and other intermediate regions (Nakayama, 2016). This model was applied to the entire Ob River in the higher latitude where West Siberian Lowland (WSL) is located at the downstream region for the verification of simulated eco-hydrological process and biogeochemical cycles (Fig. 1). The simulated hydrologic and biogeochemical cycle was then compared with previous data compiled from as many sources as possible, and the resulting model showed great variability of the carbon cycle in regional scale. In particular, the wetlands located in such as WSL contribute to carbon cycle through the respiration from flooded roots of vegetation and by providing labile organic carbon to sustain bacterial degradation in addition to non-flooded vegetation (Borges et al., 2015). After that, the model was extended to the global scale to evaluate eco-hydrological cycle and the role of inland water in the seasonal biogeochemical cycle change. The model was able to clarify quantitatively and in detail the mechanism of rock weathering, degassing above water bodies, sediment storage, and transport to the ocean. In particular, the new model could show that there is a great variability of DOC, POC, and DIC transport to the ocean reflecting biologic and hydrologic processes, and CO_2 degassing affected by both terrestrially derived CO_2 and CO_2 production through aquatic metabolism, which were usually evaluated separately in the previous researches and so there is a great improvement from them. Because the recent research showed that increasing of carbon retention in ecosystems was a major determinant for enhancement bioproductivity and biodiversity (Zalewski, 2015), the new model developed in this study, so-called, integration of current understanding of environmental processes, might also become a background for strategy of adap-

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