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Representing Natural and Manmade Drainage Systems in an Earth System Modeling Framework

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Drainage systems can be categorized into natural or geomorphological drainage systems, agricultural drainage systems and urban drainage systems. They interact closely among themselves and with climate and human society, particularly under extreme climate and hydrological events such as floods. This editorial articulates the need to holistically understand and model drainage systems in the context of climate change and human influence, and discusses the requirements and examples of feasible approaches to representing natural and manmade drainage systems in an earth system modeling framework.

Drainage systems, defined as hierarchical flow network structures for effective transport of water, can be grouped into three categories: 1) natural or geomorphological drainage systems which collect water from landscape and transport to basin outlets or oceans; 2) agricultural drainage systems which improve soil moisture conditions for crop growth; 3) urban drainage systems which dispose domestic and industrial sewage or waste water.

Natural and artificial drainage systems do not behave independently. They interact closely among themselves and with climate and human society, particularly under extreme climate and hydrological events such as floods. For a recent example, a heavy convective rainfall event poured on average 170 mm of rainfall on the Beijing urban area and 281 mm on the suburban Fangshan County in 16 hours (afternoon of July 21, 2012 - morning of July 22, 2012). This caused extensive disastrous floods in the areas. The floods led to 77 deaths and millions affected. Figure 1 shows the floods detected in the area (Hai River basin) by the Global Flood Monitoring System (GFMS) [1], a NASA-funded experimental system using real-time TRMM Multi-satellite Precipitation Analysis (TMPA) precipitation information as input. Figure 1 shows the calculated depth (mm) above the local pre-defined flood threshold at a 1/8th degree resolution. The local threshold is calculated from a 13-year retrospective global run of the flood model with the TMPA rainfall over that period by Wu et al. [1].

Besides heavy rainfall, there are several more reasons making the flood more intensive and destructive. First, the storm system moved from west to east consistent with the orientation of the river systems of the Hai River Basin. Second, the flood control/relief capacity of the natural river system has been significantly reduced because: 1) many rivers have been converted from perennial to ephemeral rivers or even completely dried out during the last decades due to climate change and over-exploitation of ground water; 2) in many of the flood-buffering zones there have been numerous tourism activities, domestic constructions as well as vegetation changes [2,3]. In addition, the existing urban drainage system cannot efficiently divert the excess water into the natural system. Even worse, the elevated water levels in the natural system caused significant backflow to the urban drainage system.

Therefore, it is of great value to understand the impacts of climate change and human influences on the behavior of drainage systems and how their responses, in the context of climate mitigation and adaption, will in turn affect human society and climate at local, regional or global scales. By integrating earth system processes over a wide range of spatial and temporal scales, an earth system modeling framework such as the Community Earth System Model (CESM) [http://www.cesm.ucar.edu/] can provide a powerful platform to conduct research in a systematic and coherent way. To address the above question, improving representations of drainage systems in earth system models becomes crucial. Since earth system models must represent the complex interactions among many systems over large domains, a balance between computational efficiency and process description is necessary. To this end, drainage system representations in earth system models should be: 1) physically based and parameter parsimonious for simulating the transport of water and other scalars (e.g., sediment, carbon, and nitrogen) to provide freshwater, sediment, and nutrient inputs to the ocean, as well as for coupling with the land components; 2) applicable at multiple spatial (and temporal) scales for short-term and long-term (e.g., decadal) simulations; 3) able to adequately respond to extreme climate events to capture their effects on subsequent hydrological and biogeochemical processes. In what follows, we discuss examples of feasible approaches that meet the above requirements for representing drainage systems in an earth system model framework.

Representation of natural drainage systems, i.e., river routing, is generally absent or oversimplified in earth system models. For example, the River Transport Model (RTM) [4], currently implemented in the land component of CESM, omits the spatiotemporal variability of river

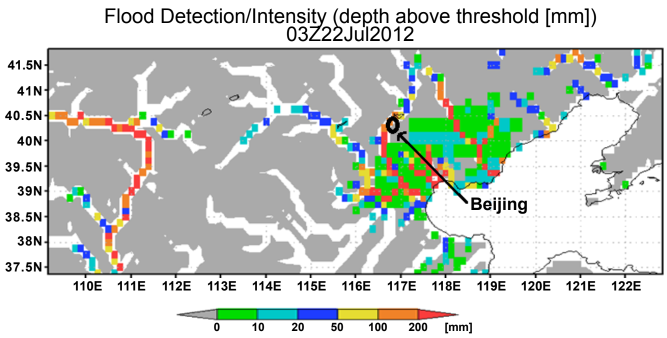

Figure 1: Flood detection and intensity by GFMS for the Beijing flood at 3:00 am, July 22, 2012.

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network dynamics therefore even monthly stream flow simulations at the regional scale are inadequate [5]. To address this limitation, Li et al. [5] developed a simple yet physically based river routing scheme, Model for Scale Adaptive River Transport (MOSART). MOSART explicitly represents three runoff routing processes within a spatial unit: overland flow routing, tributary routing and main channel routing. Tributary routing is mediated via a hypothetical channel (sub-network channel) whose transport capacity is equal to all the tributaries combined within a modeling unit. MOSART has been evaluated using stream flow and channel velocity observations across multiple scales over the Columbia River Basin in the U.S. Pacific Northwest. It has been shown that introducing sub-network channel structure helps reduce the impacts of spatial resolutions, which facilitates the applicability of MOSART over a wide range of scales. As a physically based model, MOSART can couple seamlessly with biogeochemical transport and water resources management modules.

Manmade drainage systems (agricultural and urban) are currently missing from earth system models to our knowledge. Hydraulic models are very often parameterized with great details that inhibit their use in earth system models because of huge data and computational demand. For instance, tile drains are important to reduce soil water content to improve crop yield in agricultural lands with flat topography and humid climate. Instead of using the classical hydraulic equations that require the exact locations of the tile drains [6-8], Li et al. [9] proposed a simple equation to conceptualize the drainage effects of all tile drains within a spatial unit (i.e., watershed or sub-basin):

$$q_{tile} = \begin{cases} 0 & y_s \le Z - z_{tile} \\ \alpha k_s\left[(y_s - (Z - z_{tile}))/z_{tile}\right]^{\beta} & y_s > Z - z_{tile} \end{cases} \quad (1)$$

Where q_{tile} is the average discharge rate through the tile drains [m/s]; k_s is the saturated hydraulic conductivity, [m/s]; Z is the total depth from ground surface to an impervious layer [m]; y_s is the depth from the water table to the impervious layer [m]; Z_{tile} is the depth of drainage tiles [m]; α is a dimensionless constant controlled by the hydraulic properties of the tile drain network and β is an exponent parameter reflecting the spatial layout of tile drain system.

As discussed above, modeling and understanding the behavior of urban drainage systems are increasingly more important, particularly for predicting disastrous floods over highly urbanized regions. Cantone and Schmidt [10] suggested that detailed hydraulic/hydrologic input data may not be critical for simulating the hydrologic response of urban drainage systems to climate events. Adapting the geomorphologic instantaneous unit hydrograph concept originally developed for natural drainage systems, they developed a probabilistically based method to simulate the hydrological response of urban drainage systems. This method explicitly solves the overland flow from sewer sheds (similar concept as watersheds, but for urban area), discharge into inlets, and pressurized flow within a conduit network. It has been successfully validated against observed data at Chicago, IL, USA and is potentially extensible to large regions where detailed data are not available. The simple parameterizations discussed here can be easily implemented in earth system models to capture the first order effects of agricultural and urban drainage systems so that the dynamic interactions between human systems and water cycle processes can be investigated.

To summarize, this editorial articulates the need to holistically understand and model drainage systems in the context of climate change and human influence, and discusses the requirements as well as the examples of feasible approaches to representing natural and manmade drainage systems in an earth system modeling framework. These approaches should be more extensively evaluated and fully explored and improved with adequate calibration for successful applications. This calls for community efforts to accelerate the development, implementation, testing, and evaluation of drainage system modules in an earth system modeling framework towards fully integrated human-earth system models useful for climate and hydrologic predictions over a wide range of spatial and temporal scales.

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