Recent Achievements in Macroscale Hydrological Modelling

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In the early 1990s, during the planning stage of the GEWEX Asian Monsoon Experiment (GAME), the topic of "how to develop macroscale hydrological models" was seriously discussed among Japanese scientists related to land-atmosphere interaction studies. Two approaches for this were identified by this group. The first approach was to expand a conventional microscale rainfall-runoff hydrological model into a macroscale model that could run on the continental scale with a detailed energy balance and vegetation representation. The alternative approach was to enhance hydrological processes in land surface models (LSMs) and couple them with horizontal water flow processes, particularly with river flow.

The river routing scheme, "Total Runoff Integrating Pathways (TRIP)" (Oki and Sud, 1998; Oki et al., 1999), was developed with a global flow direction map. This scheme can be coupled with any LSM, and also used as a post-processor by integrating the runoff estimated by LSMs into river discharge. The first version of TRIP adopted a primitive fixed velocity scheme (Miller et al., 1994). A variable velocity version was later developed (Ngo-Duc et al., 2007). TRIP was coupled with some of the Global Circulation Model (GCM) projections used in the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) to identify the impact of climate change on hydrological cycles (Faloon and Betts, 2006), and there have been some studies of future assessment on the world water resources and global flood disasters utilizing the TRIP model as well (Oki and Kanae, 2006; Hirabayashi and Kanae, 2009). Further, Kim et al. (2009) underscored the importance of river components in terrestrial water storage (TWS) variation over global river basins. To reduce simulation uncertainty, ensemble simulations were performed with multiple precipitation data, and a localized Bayesian model averaging technique was applied to the TRIP simulation.

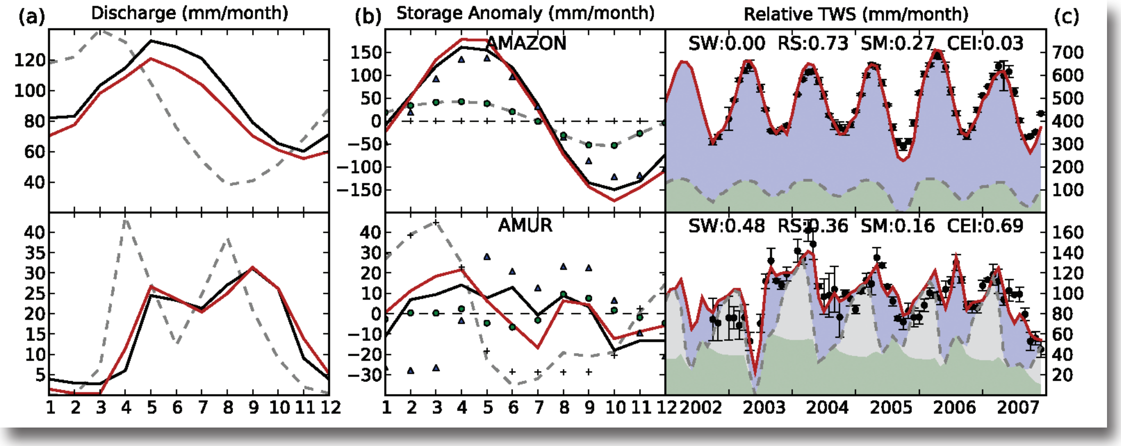
The figure at the top of the next page shows that river storage not only explains different portions of total TWS variations, but also plays different roles in different climatic regions. It is the most dominant water storage component in wet basins (e.g., Amazon, Brazil) in terms of amplitude, and it acts as a "buffer" which smoothes the seasonal variation of total TWS especially in snow-dominated basins (e.g., Amur, Russian and China). It signifies that the model simulation of TWS may not be able to properly reproduce the amplitude and seasonal pattern of observed TWS variation by GRACE (the Gravity Recovery And Climate Experiment, see Tapley et al., 2004) without an appropriate representation of river storage component. The dominant role of river storage had already been indicated in a pilot study which compared total TWS changes estimated by the atmospheric water balance method and a GCM simulation coupled with TRIP in the Amazon River Basin (Oki et al., 1996). However, the message was not fully convincing until recent years when satellite-observed GRACE data became available. Using a geodesy approach, Han et al. (2009) employed a fixed velocity version of TRIP in the Amazon River Basin and its vicinity, and compared the model simulations to the residual of GRACE raw measurements derived from removing all the gravity-influencing factors except for the horizontally moving water. They demonstrated that the optimal flow velocity of TRIP in the Amazon varies between rising and falling water levels.

Macroscale hydrological models have also been developed in response to societal expectations for solving current and future world water issues. There is an increasing demand for information on water resources and the future prediction of these. Conventionally, available freshwater resources are commonly defined as annual runoff estimated by historical river discharge data or water balance calculation (Baumgartner and Reichel, 1975; Korzun, 1978). Such an approach has been used to provide valuable information on the annual freshwater resources in many countries. Atmospheric water balance using the water vapor flux convergence data could alternatively be used to estimate global distribution of runoff owing to the advent of atmospheric reanalysis and data assimilation system (Oki et al., 1995).

Simple analytical water balance models have been widely used to estimate global-scale available freshwater resources in the world since the beginning of this century (Alcamo et al., 2000; Vörösmarty et al., 2000). Later, LSMs were used to simulate global water cycles (Oki et al., 2001; Dirmeyer et al., 2006), and to assess global water resources by estimating the water demand under future climate change scenarios (Shen et al., 2008). Some of those estimations were calibrated by multiplying an empirical factor for the river basins where observed discharge data are available. However, recent model simulations with advanced climate forcing data can estimate global runoff distribution with adequate accuracy without the need for calibration (Hanasaki et al., 2008a).

Several recently developed macroscale hydrological models for water resources assessment also include a reservoir operation scheme (Haddeland et al., 2006; Hanasaki et al., 2006) to simulate the "real" hydrological cycles that are significantly influenced by anthropogenic activities and modified from "natural" hydrological cycles on the global scale in "Anthropocene" (Crutzen, 2002). An integrated water resources model is further coupled with a crop growth submodel, which can simulate the timing and quantity of irrigation requirement, and a submodel, which can estimate environmental flow requirement (Hanasaki et al., 2008a). Such an approach is able to assess the balances of water demand and supply on a daily time scale. A gap in the subannual distribution of water availability and water use can be detected in the Sahel, the Asian monsoon region and southern Africa, where conventional water scarcity indices such as the ratio of annual water withdrawal to water availability and available annual water resources per capita (Falkenmark and Rockström, 2004) can not properly detect the stringent balance between demand and supply (Hanasaki et al., 2008b).

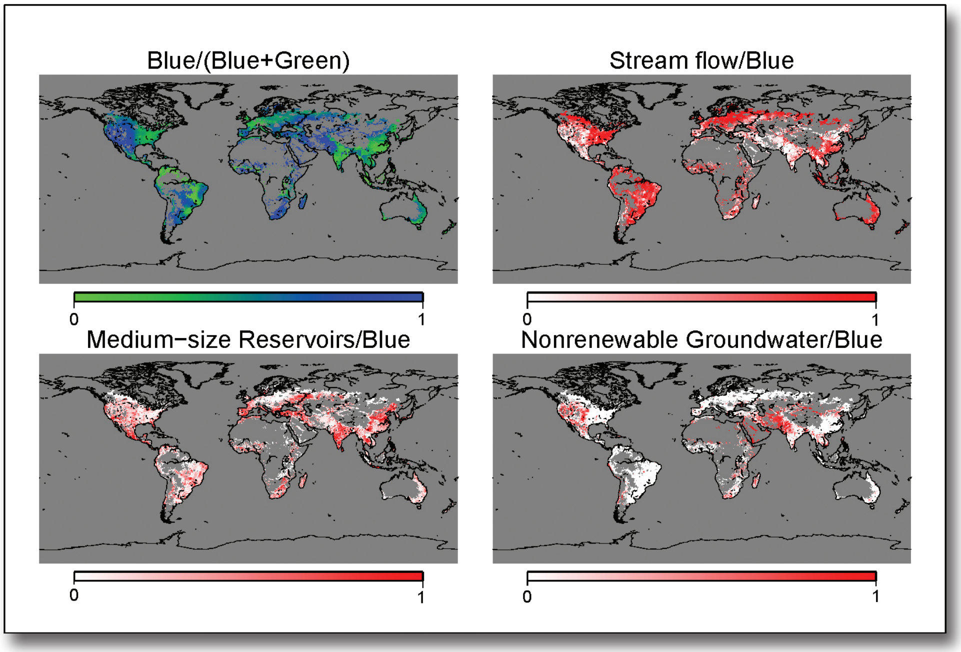
Numerical models can be associated with a scheme tracing the origin and flow path as if tracing the isotopic ratio of



(a) Seasonal variations of gauged discharge (black solid line), discharge routed by TRIP (red solid line) and runoff without routing (gray dashed line). (b) Seasonal variations of GRACE observed Terrestrial Water Storage Anomalies (TWSA) (black solid line), simulated TWSA with river storage (red solid line), simulated TWSA without river storage (gray dashed line), and the major water storage components in TWS. Gray crosses (+), green circles, and blue triangles represent the individual storage component of snow water, soil moisture, and river storage, respectively. (c) Interannual variations of relative TWS: the GRACE observation (black dots), simulation with river storage (red solid line), and simulation without river storage (gray dashed line). Each area shaded by blue, gray, and green indicates the portion of river storage, snow water, and soil moisture in the simulated relative TWS, respectively.

water (Yoshimura et al., 2004). Such a flow tracing function of water in the integrated water resources model (Hanasaki et al., 2008a) with the consideration on the sources of water withdrawal from stream flow, medium-size reservoirs and nonrenewable groundwater in addition to precipitation to croplands enabled the assessment of the origin of water producing major crops (Hanasaki et al., 2009). See figure below. Areas highly dependent on nonrenewable groundwater are detected in the Pakistan, Bangladesh, western part of India, north and western parts of China, some regions in the Arabian Peninsula and the western part of the United States through Mexico. Cumulative nonrenewable groundwater withdrawals estimated by the model are corresponding fairly well with the country statistics of total groundwater withdrawals, and such an integrated model has the ability to quantify the global virtual water flow (Allan, 1998; Oki and Kanae, 2004) or "water footprint" (Hoekstra and Chapagain, 2007) through major crop consumption (Hanasaki et al., 2009).

It seems that these achievements illustrate how the framework of global offline simulation of land surface models coupled with lateral river flow model and/or anthropogenic activities, driven by best estimates of meteorological "forcing" data, such as precipitation and downward radiation, is relevant for estimating global energy and water cycles, validating the estimates and sometimes the quality of "forcing" data with independent observations, and improving the models. There are attempts to utilize this framework for assessing the impacts of climate change on future hydrological cycles, which would demand



The top left panel illustrates the ratio of blue water to total evapotranspiration during a cropping period in irrigated croplands. The "blue" water is defined as that part of evapotranspiration originating from irrigation, whereas the "green" water is from precipitation (see Falkenmark and Rockström, 2004). This panel also shows a distinctive geographical distribution in the dependence on blue water. The ratios of the source of blue water for stream flow include the influence of large reservoirs (top right panel), medium-size reservoirs (bottom left panel) and nonrenewable groundwater (bottom right panel).

adaptation measures in water resources management, flood management and food production. For such purposes, it is necessary to develop reliable "forcing" data for the future based on GCM projections probably with bias corrections and spatial and temporal downscaling, as well as developing best estimates for the future boundary conditions for hydrological simulations such as vegetation type and land use/land cover. It should be also examined how much the framework can be applied to finer spatial and temporal scales, such as 1-km grid spacing and hourly simulations. For such researches, observational data from regional studies provide significant information, and efforts to integrate data sets from various regional studies should be promoted. It is for sure that cooperation among Global Environmental Change Programs under ICSU, including WCRP, is and will be accelerating the macro-scale hydrological studies effectively.

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