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Application of isotope tracers in continental scale hydrological modeling

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Summary Isotope tracers are widely used to study hydrological processes in small catchments, but their use in continental-scale hydrological modeling has been limited. This paper describes the development of an isotope-enabled global water balance and transport model (iWBM/WTM) capable of simulating key hydrological processes and associated isotopic responses at the large scale. Simulations and comparisons of isotopic signals in precipitation and river discharge from available datasets, particularly the IAEA GNIP global precipitation climatology and the USGS river isotope dataset spanning the contiguous United States, as well as selected predictions of isotopic response in yet unmonitored areas illustrate the potential for isotopes to be applied as a diagnostic tool in water cycle model development. Various realistic and synthetic forcings of the global hydrologic and isotopic signals are discussed. The test runs demonstrate that the primary control on isotope composition of river discharge is the isotope composition of precipitation, with land surface characteristics and precipitation-amount having less impact. Despite limited availability of river isotope data at present, the application of realistic climatic and isotopic inputs in the model also provides a better understanding of the global distribution of isotopic variations in evapotranspiration and runoff, and reveals a plausible approach for constraining the partitioning of surface and subsurface runoff and the size and variability of the effective groundwater pool at the macro-scale.

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Introduction

Fractionation of the stable isotopes of water (^{18}O, ^{2}H) during phase changes and water cycle mixing produces a natural labelling effect that has been widely applied to local and regional-scale hydrological studies. In contrast to the case for small watershed studies, interpretation of isotopic signals arising from a complex overlay of hydrological processes at the large scale requires new model platforms for simulating isotopic fractionation, transport, and the mixing process. Water isotopes have previously been incorporated into global or regional climate models for simulating broad-scale features of isotope climatology, mainly for analysis of air mass/precipitation origin and paleoclimate archives of precipitation (Hoffman et al., 1998; Joussaume et al., 1984; Jouzel et al., 1987, 2000). Quantitative application of these heavy-isotope tracers and transferability of the approach is strengthened by the fact that the water isotopes are mass-conservative, incorporated within the water molecule ($H_2\,^{18}O$, $^{1}H^{2}H^{16}O$), and are transported predictably but slightly differently than common water ($^{1}H_2\,^{16}O$) among water phases, a property which can provide additional information on magnitude and the importance of water fluxes and pathways (Gibson et al., 2005).

Application of stable isotopes in large- (continental-) scale hydrological studies has lagged behind the small scale applications primarily due to the lack of a systematic collection of global-scale data. Long-standing efforts of the International Atomic Energy Agency (IAEA) – to coordinate a global monitoring network for deuterium (^{2}H) and oxygen-18 (^{18}O) in precipitation and more recently in large river discharge – will continue to provide new opportunities to utilize isotope information at the continental scale. To date, IAEA collects monthly precipitation data at over 550 stations worldwide, beginning as early as the 1960s as part of IAEA/WMOs Global Network for Isotopes in Precipitation (GNIP). This has permitted compilation of a global monthly climatology of ^{2}H and ^{18}O in precipitation (Birks et al., 2002). A similar effort to coordinate collection and analysis of monthly river discharge samples from large river basins is likewise under development (Gibson et al., 2002). Recent studies have also demonstrated integration of stable water isotopes into meso-scale hydrological models for specific basins or regions (Stadnyk et al., 2005; Henderson-Sellers et al., 2005).

The present paper demonstrates a global-scale application of an isotope-enabled hydrological model. We describe an approach used to modify a well-tested water balance model developed by researchers at the University of New Hampshire (Vörösmarty et al., 1998, 1996) to include a basic representation of isotope fractionation in evapotranspiration processes and isotopic mixing through all components of the terrestrial hydrological cycle. Primary forcing of the model is accomplished with the global monthly precipitation climatology for ^{2}H and ^{18}O developed from the IAEA precipitation observations (Birks et al., 2002), and validated for the contiguous United States using river data compiled by the US Geological Survey (Kendall and Coplen, 2001). Long-term average monthly climate data are also used to estimate interception/evaporation and transpiration, soil moisture change and runoff and to predict the isotopic composition of these elements of the hydrological cycle. The aim is to map and interpret some of the major spatial patterns associated with isotope fractionation during evaporation and runoff generation. The model is also tested with synthetic forcings, which help to better understand the sensitivity of the model to the parameterization of fractionation and mixing processes. Overall, through these baseline comparisons, we establish the potential value of an isotope-enabled global hydrology model as a tool for improving understanding of the relative significance of hydrological processes and to create a more realistic representation of these processes in the model.

Methods

We focus here on stable isotopes of hydrogen (^{2}H) and oxygen (^{18}O) that are naturally present in water molecules. Stable isotope compositions are expressed conventionally as delta values (δ), representing deviation in per mille (‰) from the isotopic composition of a specified standard (R_{ref}), such that

$$\delta = \frac{R}{R_{\text{ref}}} - 1 \qquad (1)$$

where R values refer to $^{2}H/^{1}H$ or $^{18}O/^{16}O$ in sample and standard, respectively. The universal standard in water cycle applications is Vienna Standard Mean Ocean Water (V-SMOW) distributed by IAEA, which is the approximate isotopic composition of the present-day oceans, and has $\delta\,^{2}H$ and $\delta\,^{18}O$ values of 0 ‰ (Craig, 1961; Edwards et al., 2004). We treat the deviation (δ) values like conservative constituent concentrations.

The isotopic composition in precipitation shows clear seasonal cycles and spatial variations (Birks et al., 2002). This spatially and temporally varying signal of isotopic composition is altered through hydrological cycle via enrichment or depletion during water phase changes and mixing in various storage pools in vertical and horizontal water transport processes. A description of how each of these component processes is represented in the model and how the isotope response is simulated is described below. For a more general discussion of stable isotopes in the hydrological cycle the reader is referred to Gat (1996).

Isotopic transformations in hydrological processes

The water balance/transport model (WBM/WTM) (Vörösmarty et al., 1998, 1996, 1991) is designed to simulate the key hydrological processes at large scales operating at a monthly time step. The water balance model quantifies the vertical exchange of water between the soil/vegetation and the atmosphere. Water in excess of evaporations while passing through various storage pools follows two runoff pathways. Surface runoff immediately enters the river network, while recharge passes through the groundwater pool, which controls the subsurface flow to the organized river channels. The water transport model simulates the horizontal transport via a predefined channel network and a corresponding riverbed geometry that determines the residency time. Changes of the isotopic characteristics through the hydrological processes are the