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Isotope processes in continental scale water balance and transport simulations

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1 Introduction

Isotope tracers are useful tools for better understanding hydrological processes. The use of stable oxygen and hydrogen isotopes as tracers in hydrologic studies has expanded over the past five decades following the initial description of systematic variations in world precipitation [1], development of theory describing isotopic fractionation during evaporation, and testing and validation under a range of field conditions and scales [2,3,4,5].

The processes that impact the isotopic composition of precipitating water are phase changes and mixing in the various storage pools. The most conventional application of stable isotopes in smaller catchments is the identification of "old-water" and "new-water", in other words distinguishing surface runoff (that rapidly reached the river stream) from base-flow (that was in contact with the groundwater for extended periods). Recent studies have shown that isotopes are also useful tools to better understand snow-melt and evaporation processes [6,7,8].

Continental and global scale applications of stable isotopes lagged due to the lack of comprehensive stable isotope data. Recent effort by the International Atomic Energy Agency [9] is aiming to establish a Global Network for Isotopes in Rivers (GNIR) complementing the already established Global Network for Isotopes in Precipitation (GNIP) [10].

As an application of the existing GNIP and evolving GNIR databases, the Water Systems Analysis Group at University of New Hampshire teamed up with experts from the Isotope Hydrology Section of IAEA to implement the isotope processes in the context of a global water balance/transport model [11]. The primary motivation of this work was a better understanding of the key hydrological processes at coarse scales via the use of isotopic information as an additional constraint for model validation.

2 Isotope enabled WBM/WTM

The water balance/transport model (WBM/WTM) developed at UNH [11] was designed to simulate the key hydrological processes at coarse scales operating at a monthly time step. The water balance model represents the vertical water exchange between the soil/vegetation and the atmosphere. The surplus water from the water balance calculations forms runoff (and enters the river network immediately) or recharges the groundwater pool that alters the timing of the runoff release to the organized river channels. The water transport model simulates the horizontal transport along a gridded representation of the channel network.

The key components of the water balance model include the snow pack, canopy interception, soil moisture and groundwater. The dominant isotopic process in each component is the mixing of the new input water and the already present storage water. Fractionation occurs in interception and evaporation from soil (which are calculated in the soil moisture module). The horizontal water transport introduces further mixing of the runoff originating from different source areas with varying isotopic characteristics.

2.1 Snow Pack

The WBM/WTM by Vörösmarty et al. [11] implemented a simple mechanism to simulate the snow accumulation and melting. The forms of precipitation as snow and rain are distinguished by mean monthly temperature. Precipitation falling in months when the mean temperature was below a threshold of -1 ºC is assumed to be snow and rain otherwise. Snow accumulates in each month when the mean monthly air temperature is below this threshold. The entire accumulated snowpack melts when the mean monthly temperature is above the 1 ºC treshold and the local elevation is $<$ 500 m above sea level. In mountainous regions (elevation $>$ 500 m) half of the snow pack melts in the first non-freezing month and the rest is released in the following month.

Since this treatment of the snow accumulation and melting processes is rather simplistic, the simulation of the processes affecting the isotopic characteristics are limited to simple mixing without any fractionation of the heavy isotopes. The snow pack (S_{sp}) acts as a mixing pool that collects snow precipitation (P_{sn}) during the freezing season. The accumulated snow pack (S_{sp}) with its isotopic composition (δ_{sp}) gets released during snow melt as snow recharge.

2.2 Soil Moisture

From an isotopic perspective, soil moisture acts as a storage pool that mixes rainfall (P_{rn}), snow recharge (S_{sr}), and soil moisture (S_{sm}). Fractionation occurs directly from the rainfall and from the mix of inputs (rainfall+snow) and storage (recharge+soil moisture) as soil evaporation (since transpiration does not fractionate). The fractionating evaporation goes through a Raleigh process:$\delta = \left(1 + \delta_0\right) f^{\varepsilon} - 1$ where δ_0 is the initial isotopic composition of the evaporating water, f is the ratio of the evaporating water volume and the total fractionating water, ε is the isotope fractionation and δ is the isotopic composition of the remaining water. The isotope fractionation $(\varepsilon = \varepsilon_{V/L} + \varepsilon_{diff})$ is a sum of the equilibrium fractionation $(\varepsilon_{V/L})$ and the kinetic or diffusion fractionation (ε_{diff}). The equilibrium fractionation is given by Majoube [12]. The kinetic fractionation can be derived from the Craig and Gordon model.

2.3 Groundwater

The WBM maintains a simple runoff detention pool to represent the runoff delay due to groundwater storage. The water surplus from the soil moisture calculation is partitioned as surface runoff (that enters to a nearby stream immediately) and groundwater recharge by a simple coefficient. The dynamics of the detention pool is governed by decay coefficients that dictate how much storage is released during a given time step. From the isotopic aspect, the groundwater acts as a mixing pool.

2.4 Horizantal Water Transport

The runoff released from the groundwater pool is propagated along a predefined 30' minute simulated network [13] using a simple routing scheme. The routing model considers temporally uniform but spatially varying flow velocity to calculate the residence time in each grid cell. The velocity field was computed by using empirical relationships relating mean annual discharge to riverbed and flow characteristics [14] where the mean annual discharge was estimated for each grid cell by summing up the mean annual runoff upstream for each cell. The residence time calculated from the flow velocity was used to delay the transport of the runoff generated in individual grid cells along the predefined gridded network. This simple routing scheme is sufficient for monthly flow simulation and can be applied easily to constituent transport as well

The primary isotopic impact of the transport model is the spatial and temporal mixing of the runoff that comes from different source areas with varying isotopic characteristics.

3 Results

The isotope enabled WBM/WTM was applied at point scale (for selected test sites in different climate zones) and globally. The point scale test were performed to better understand the isotopic processes and verify that the model represents the fractionation and the mixing processes realistically. The global simulations were carried out using isotopically uniform and spatially and temporally varying (GNIP) precipitation input. A scenario assuming isotopically uniform precipitation isotopes was performed to assess the climate impact on the fractionation processes, while the spatially and temporally varying (GNIP) simulations were used for validation and to map the isotopic composition of the runoff.

Our first results show that the isotope enabled WBM/WTM represents the isotopic processes (both fractionation and mixing) realistically. Validation against isotope records at selected sites across the U.S. [15] shows that the model applies the right enrichment in the river runoff where the GNIP and the river isotope records are consistent. Numerous river runoff isotopes are inconsistent with the GNIP precipitation (either much more enriched than the fractionation would allow, or heavily depleted relative to the precipitation).

The isotope enabled WBM/WTM shows greater sensitivity to groundwater storage than fractionation differences due to land cover and climate variability. This finding is consistent with the current practice of using isotopes primarily to differentiate water sources (“old-water” “new-water”) and only secondarily to infer information on the land surface characteristics and evaporation processes. The model needs further improvement to better represent the deviation from the meteoric water line due to differences in fractionation of the ^{2}H and ^{18}O species.

Our presentation will describe the model structure and its applications to global scale analysis. We will show the spatial and temporal patterns of isotopic composition of river runoff and demonstrate the model sensitivity to climate and landcover properties. We will discuss the apparent inconsistencies between GNIP and observed isotope composition of runoff and the possible causes of the inconsistencies.

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