Evaluation of a physically-based base flow time constant in ORCHIDEE Land-Surface Model at global scale

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Introduction

Base flow is an important source of water to rivers representing the part of the stream flow that is sustained by groundwater discharge. Although an important component on water management, and a key variable in Land Surface Models (LSMs), base flow quantification depends on estimation, since there are no available techniques to directly measure it. Large scale LSMs use two main approaches to estimate base flow: by solving the diffusion equation numerically, or by using a linear reservoir that relies on a base flow time constant (τ). The estimation of base flow from the diffusion equation depends on numerical methods that are computational demanding, and becomes difficult at large scales. LSMs with a linear reservoir depend on observation data to calibrate τ, which are scarce with increasing scale. To overcome the lack of observed data, a common practice is to extrapolate calibrated values over a region to the entire globe, as in [1] with ORCHIDEE (using a τ of 67 days in average that varies with topography, calibrated over the Senegal basin) or locally with CLSM in [2] (using a τ of 700 days, calibrated over the Somme basin). The calibrated values are in agreement with τ obtained from studies of river discharge recession analysis at the basin scale. However, the extrapolation over large regions neglects natural hydrogeological heterogeneities, a problem that is not observed with the diffusion equation. To combine the simplicity of a linear reservoir with the hydrogeological properties of the diffusion equation, another approach is to use an analytical solution of the diffusion equation to estimate τ. [3] proposed a linear solution of the Boussinesq equation for sloping, unconfined, isotropic and homogeneous aquifers that depends on the effective porosity, transmissivity, slope, and drainage density. In this framework, the spatial variations of τ results in a physical way from hydrogeological heterogeneities, but τ can be overestimated up to five orders of magnitude depending on the data used on its estimation when compared to literature values. This raises a major question: can such a physically-based τ improve the base flow dynamics in large-scale LSMs? In this work we use the LSM of the Institute Pierre Simon Laplace called ORCHIDEE to evaluate the effect of a physically-based τ on river discharge simulations.

Evaluation of τ

τ was estimated with the formulation proposed by [3] multiplied by a factor $8/\pi^2$ to have the horizontal case proposed by [4] as the limit when the slope tends to zero. τ is sensitive both to drainage density and transmissivity, since τ depends on the square of the drainage density, and transmissivities can vary from several orders of magnitude. Different values were tested for transmissivity (based on the work of [5] and [6]), effective porosity (from [6]–[8]), drainage density (from [9] and [10]), and slope (from [5] and [9]). The use of a sloping formulation, combined with drainage density from [10] that accounts for heterogeneities found in natural river networks resulted in values more coherent to the 117 evaluated τ from recession analysis in the United States, Australia, Brazil, Germany, China, and Great Britain at the basin scale. The highest correlation coefficients (0.60 and 0.49) and lowest biases (0.4 and 116 days) were found for transmissivities and effective porosity from [8] (here called τ_V), and combining a transmissivity obtained from the average hydraulic conductivities from soil and rock (based on the work of [5] and [6]) with effective porosity of [7] (called τ_{UG}). Although τ_{UG} is in agreement with references for the spatial correlation, it is still overestimated. When τ_{UG} was divided by a factor 10 ($\tau_{UG/10}$), it resulted in better estimations, with a bias of 12 days. This behavior was described by [11] showing an overestimation by a factor 10 of effective porosity from [7] when compared to average values at the basin scale. As expected, the τ currently implemented in ORCHIDEE (here called τ_{ORC}) showed a weak performance over the 117 evaluated basins for the spatial correlation coefficient of -0.09, since τ_{ORC} was obtained by extrapolation of calibrated values over the Senegal basin over the entire globe [1], accounting for small variations based on topography. However, τ_{ORC} have the same order of magnitude of the recession analysis results from the 117 references at the basin scale, explaining the mean bias of 2 days.

Impact of τ in ORCHIDEE

Global simulations using ORCHIDEE model were used to evaluate the impact of a physically-based τ in a LSM with linear reservoir. In a first step, river discharge results of the 276 major basins of the world were evaluated in a reference simulation that uses τ_{ORC}, showing that ORCHIDEE has currently biased results for river discharge (positively and negatively), with a correlation coefficient for river discharge per evaluated station over 0.75 for only 23% of the stations. The introduction of a physically-based τ improved Nash-Sutcliffe coefficients in only 18% of the evaluated basins, with degradation of the results for the remaining 82%. As expected, since τ_{UG} and $\tau_{UG/10}$ are usually higher than τ_{ORC}, it induced an increased buffering of river discharge variability, with smoother hydrographs. However, this buffering effect is also shown to depend on the recharge of the groundwater reservoir. A reservoir with small recharge will have little impact on the river discharge. τ_{UG} and $\tau_{UG/10}$ are not suitable to be implemented in ORCHIDEE groundwater reservoir, since τ is still overestimated when compared to references at the basin scale, not representative of the dominant local flow. However, τ_V showed better spatial correlation when compared to τ references at the basin scale from recession analysis, which could indicate a better performance than τ_{ORC} when evaluating river discharge simulations. We will also perform an additional simulation using τ_V in the groundwater reservoir, and we expect an improvement of river discharge simulations when compared to τ_{ORC}. However, the bias of mean river discharge is not influenced by τ, since the current ORCHIDEE routing scheme does not change the routed volumes. This bias is mostly caused by two factors: failures in the water budget computation by ORCHIDEE; and human disturbances. The human disturbances can lead to reduced observations compared to natural flows, if there are a lot of withdrawals; and/or altered hydrographs shapes, in case of damming in particular.

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