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GLOBAL OFF-LINE EVALUATION OF THE ISBA-TRIP GROUNDWATER SCHEME

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1 INTRODUCTION

Continental Hydrological Systems (CHSs), composed of Land Surface Models (LSMs) and River Routing Models (RRMs), provide the lower boundary conditions of temperature and moisture to atmospheric processes in Atmospheric General Circulation Models (AGCMs) and then affect the simulated weather and climate. LSMs simulate the energy and water budgets at the interface between land surface and atmosphere, while RRMs convert the total runoff provided by LSMs into river discharges in order to evaluate the simulated water budget and/or transfer the continental fresh water to oceans, thereby closing the global hydrological cycle.

Despite its relative slow response time, groundwater plays an important role in the hydrological cycle due to the large amount of water involved and its interaction with rivers and lakes. Moreover, its interaction with surface water is likely to influence soil moisture in unsaturated zones, as well as water and energy exchanges with the lower atmosphere. Recently, some studies suggest that the absence of groundwater in CHSs could lead to underestimate continental evaporation and overestimate the seasonality of simulated discharges, which could in turn have an impact on climate models[2].

Despite their importance, most LSMs used in climate modelling do not take into account groundwater processes , and works are underway to incorporate them. Some studies proposed to add a simple pseudo-groundwater reservoir into RRMs using a time delay factor only to delay the flow to river, but without explicit groundwater dynamics[2]. A number of researchers used more realistic approaches by introducing a groundwater component in one-dimensional LSMs for global climate applications[8,9]. Two-dimensional groundwater models have also been employed, but at smaller scale and mostly for regional climate applications[5,6]. Such methods rely on calibrated parameters using in-situ measurements or fine resolution grids, and therefore are not yet applicable for large scale studies.

At the Centre National de Recherches Météorologiques (CNRM), the Interactions between Soil, Biosphere, and Atmosphere-Total Runoff Integrating Pathways (ISBA-TRIP) CHS is used in the CNRM-CM earth system model. Recently, a simple representation of groundwater has been developed in the TRIP RRM and tested with success over France in off-line mode[12]. This study underlines the impact of groundwater processes on the simulated river discharges, and demonstrates the feasibility of including groundwater in a global climate model even using a coarse resolution.

As an extension of this work, the purpose of this paper is to present the preliminary results of the global application of this TRIP version with groundwater using a similar methodology as for the French case study.

2 METHODS

2.1 Model

The TRIP RRM was originally developed at Tokyo University[10]. It is used at Météo-France to convert surface runoff and deep drainage simulated by the ISBA LSM into river discharges using a river network at 0.5 ° grid cell resolution in global simulations[3]. TRIP is based on a mass balance equation for the stream water mass S (kg) solved at a 60-min time step on each cell of the river network.

The groundwater scheme added to TRIP is based on the two-dimensional groundwater flow equation for the piezometric head H rewritten in spherical coordinates[12]. This equation is solved through an implicit finite-difference numerical method based on the MODCOU hydrogeological model[7] with a time step of 1 day, and only for the uppermost unconfined aquifer:

$$\omega \frac{\partial H}{\partial t} = \frac{1}{r^2 \cos(\varphi)} \left[\frac{\partial}{\partial \theta} \left(\frac{T_\theta}{\cos(\varphi)} \frac{\partial H}{\partial \theta} \right) + \frac{\partial}{\partial \varphi} \left(T_\varphi \cos(\varphi) \frac{\partial H}{\partial \varphi} \right) \right] + q_{sb} - q_{riv} \tag{1}$$

ω (m^3 m^{-3}) is the effective porosity, θ and φ are the longitude and latitude coordinates respectively, r (m) is the mean radius of the Earth, T_θ and $T\varphi$ (m^2 s^{-1}) are the transmissivities along the longitude and latitude axes respectively, q_{sb} (m s^{-1}) the deep drainage from ISBA per unit area of aquifer and q_{riv} (m s^{-1}) the groundwater-river flux. This equation is then solved in m^3 s^{-1} in TRIP.

The groundwater-river flow is parameterized using the concept of a river conductance coefficient RC widely used in a majority of regional groundwater models[5,7]. Most of the time, this coefficient need to be calibrated. In order to estimate RC, we introduce a coefficient, τ (s), representing the time transfer between river and groundwater:

$$Q_{riv} = \left| \begin{array}{ll} RC\,(H - H_{riv}) & \text{where } H > Z_{bed} \quad (a) \\ RC\,(Z_{bed} - H_{riv}) & \text{where } H < Z_{bed} \quad (b) \end{array} \right. \text{ with } \quad RC = \frac{LW}{\tau} \qquad (3)$$
$$Z_{bed} = Z - h_c \text{ and } H_{riv} = Z_{bed} + h_s$$

Q_{riv} is the groundwater-river flow now expressed in m^3 s^{-1}, Z_{bed} (m) is the river bed elevation calculated as the river elevation Z in the grid cell minus the river bankfull height h_c[3], H_{riv} (m) the river stage elevation[12] and W (m) and L (m) are the river width and river length within the grid cell respectively[3]. Equation 5a corresponds to the case where the water table is connected to the river, and Equation 5b to the case where they are disconnected. When the flow is from river to groundwater and h_s falls under 10 cm, Q_{riv} is set to zero to avoid a completely empty river and/or negative discharges.

2.2 Parameters

The river elevation (Z in Equation 3) is derived from the GTOPO30 Digital Elevation Model provided at 30 arc-seconds resolution. A first step consists in constructing this elevation at the intermediate resolution of 1/12th °: each grid cell is computed as the averaged value of the first decile of the actual 30 arc-seconds resolution topographic values within the grid cell ranked in ascending order. Then, the global river elevation at 0.5 ° is calculated by taking the average of the whole 1/12th ° topographic values within each 0.5 ° grid cell. Previous results over France show that using an intermediate resolution allow to construct low-resolution river elevation giving more realistic river network and simulated river discharges[12].

Since the groundwater scheme is developed for global climate applications, only major regional groundwater basins concerned by diffusive groundwater movements are simulated. The World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP; http://www.whymap.org) is used as the primary information to delineate such regions. In this database, the aquifers are subdivided in 3 main hydrogeological units. The “major groundwater basins” concern the sedimentary basins constituted by permeable porous and fractured rocks, and also the alluvial plains with high permeability materials such as gravel or sand, and are therefore intended to be simulated. The “local and shallow aquifers” correspond to the old geological platforms or shields characterized by crystalline rocks with scattered and superficial aquifers, and are not considered. At last, the “complex hydrogeological structures” regroup complex aquifer systems. Karstic areas or orogens belong to this category, but are mostly not concerned by regional groundwater flow and are not intended to be simulated. To deal with this category, two supplementary digital maps are used: a global map of the lithology helping us to keep, or remove, some of these complex formations[4], and a slope criterion allowing us to squeeze out the mountainous cells[12].

The coefficient τ varies arbitrary from 30 days in major river streams to 5 days in the upstream grid cells through a linear relationship with the river stream order, SO, given by the TRIP network in each grid cell of a given basin[12]. Finally, transmissivity and effective porosity are estimated by taking mean values from the literature for each unit of lithology encountered on the lithological map. These values are summarized in Table 1.

Rock type		Porosity	Transmissibility
Consolidated sedimentary rocks	Siliciclastic rocks (Ss)	0.07	0.02
	Mixed siliciclastic-carbonate rocks (Sm)	0.02	0.001
	Carbonate rocks (Sc)	0.03	0.005
Unconsolidated sedimentary rocks	Unconsolidated to semi-consolidated rocks (Su)	0.05	0.01
	Alluvial deposits (Ad)	0.1	0.05
	Loess (Lo)	0.2	0.1
	Dunes sands (Ds)		
Other rocks (Igneous or metamorphic rocks, Precambrian basement)		0.01	0.001

Table 1: Transmissivity ($m^2 s^{-1}$) and effective porosity values by type of lithology.

2.3 Experiments and evaluation datasets

An off-line hydrological simulation with groundwater scheme (GW) is compared to a control experiment without groundwater (NOGW). TRIP is forced by surface runoff and deep drainage coming from an ISBA simulation covering the 1950-2008 period[1]. Every day, TRIP computes piezometric heads and river discharges. In order to start the model at the equilibrium, a simplified version of the groundwater scheme resolving Equation 2 at steady state was used to compute an equilibrium state of the water table. This equilibrium state was reached using the annual average over the 1950-1959 period of the deep drainage from ISBA, and of the river water height h_s (Equation 3) from NOGW. The model evaluation is then carried out over the 1960-2008 period.

A list of about 3500 gauging stations was elaborated to evaluate monthly simulated river discharges, with 1900 of them potentially impacted by the groundwater scheme. These in-situ measurements have been in majority provided by the Global Runoff Data Center (GRDC)[14] and completed with other sources of data: the USGS stream flow data for the United States (http://waterdata.usgs.gov/nwis/sw), the R-ArcticNet database (http://www.r-arcticnet.sr.unh.edu/v4.0/index.html), the HYBAM observations over Amazon (http://www.ore-hybam.org/index.php/eng) and the French Hydro database (http://www.eaufrance.fr).

Finally, the simulated Terrestrial Water Storage (TWS) variations are compared to the TWS derived from the Gravity Recovery and Climate Experiment (GRACE) satellite mission. GRACE provides monthly TWS variations based on highly accurate maps of the earth's gravity fields[11]. Here, we use three different data products over 77 months from August 2002 to December 2008: the Release 4 data from the Center for Space Research (CSR at The University of Texas at Austin), the Release 4.1 data produced by the Jet Propulsion Laboratory (JPL), and the Release 4 from the GeoForschungsZentrum (GFZ).

The simulated TWS is calculated as the sum of total soil moisture WG, snow water equivalent SWE, vegetation interception WR , stream water content S, and groundwater H when necessary.

While filtering is necessary to reduce noise in the GRACE data, several studies have shown that it may modify the signal by reducing the seasonal amplitude of the TWS signal [11]. Therefore, the ISBA-TRIP results have been smoothed using a 300-km width Gaussian filter consistent with those used for the GRACE data products.

3 RESULTS

The simulated river discharges are first compared to gauging measurements. The efficiency (*Eff*) criterion is taken as the primary skill score for evaluating the model ability to capture the monthly discharge dynamics. It is expressed as follows:

$$Eff = 1{,}0 - \frac{\sum\left(Q_{sim}(t) - Q_{obs}(t)\right)^2}{\sum\left(Q_{obs}(t) - \overline{Q_{obs}}\right)^2} \qquad (4)$$

where $\overline{Q_{obs}}$ represents the observed temporal mean. *Eff* can be negative if the simulated discharge is very poor, and is above 0.5 for a reasonable simulation.

Figure 1a shows the spatial distribution of the NOGW monthly discharge efficiencies. It reveals some weaknesses in the original version of TRIP with about 58 % of negative efficiencies. Most of these problems occur in the western part of the United States, in Africa, in the Amazon watershed and in the West Siberian Plain. 20 % of the skill scores of NOGW are above 0.5 and concern the eastern part of the North America, the Paraná river basin in South America, and some other places in Europe such as the Danube river basin or the East European Plain.

Figure 1b compares the scores of GW and NOGW in order to evaluate the impact of the groundwater scheme on the simulated monthly discharges. 70 % of the 1900 gauging stations potentially influenced by groundwater are improved, particularly in Africa, in the West Siberian Plain, in the Amazon watershed, and also in Europe. Conversely, 15 % of the efficiency scores are deteriorated. For example, the efficiencies are deteriorated with the groundwater model in the eastern part of the Paraná basin in South America, even if this region is known to be underlaid by the well-known Guarani Aquifer. Similar problems appears in Europe or in the eastern part of North America. These biases reveal some weaknesses of our approach that will be discussed later.

Figure 2 shows the comparison between the TWS simulated by ISBA-TRIP and estimated by GRACE. The time series shown here are spatially averaged over the globe after removing Greenland and Antarctic. The left panel compares the monthly anomalies of the smoothed ISBA-TRIP TWS with (red) and without (blue) groundwater, and the mean GRACE products with the associated errors. The TWS anomalies are correctly reproduced by the simulations, and the comparison between the GW and NOGW curves shows that groundwater have minor impacts on the TWS anomalies, at least for the GRACE period shown here.

The mean annual cycles are presented in the right panel of Figure 2. The annual cycles for each component are also shown. Note that RMSE and correlation given on the annual cycle concern the whole GRACE period. Both simulations reproduce appreciably the TWS. Nevertheless, GW appears better correlated ($r = 0.91$) than NOGW ($r = 0.84$). Indeed, groundwater seems to introduce a slight temporal shift of 1 month with respect to the NOGW annual cycle. For GW, the snow mass variation represents about 46 % of the signal, soil moisture 22 %, surface storage and groundwater 16 % respectively, while vegetation interception is negligible.

4 DISCUSSION

These first results show that the groundwater scheme is applicable at the global scale with a coarse resolution adapted to climate models. The groundwater scheme seems to have globally a positive impact on the simulated discharges. The comparison between the simulated ISBA-TRIP and the GRACE TWS shows that groundwater contributes to delay the simulated TWS signal and to improve the skill scores. Indeed, the groundwater component appears as important as the surface storage component in the total TWS signal. These results confirm the relevance of groundwater modeling for global hydrological and climate applications[1,5,9].

Nevertheless, groundwater can deteriorate the simulated discharges over a few regions where aquifers are normally defined, and even if the NOGW scores were initially acceptable. This suggests some limitations in our simple methodology to delineate the aquifer basins. Indeed, even if WHYMAP is useful to determine the major aquifers, its low accuracy does not allow to take into account the complex structures encountered locally: kartistified areas, confined aquifers, etc. Moreover, one layer is modeled in TRIP, while in reality multi-layer aquifers can be present. Combined with the hypothesis of TRIP to consider each grid cell as a river cell, this could explain some deteriorations of the simulated discharge scores.

For example, the simulated groundwater over the Paraná basin corresponds to the younger sandstones and basalts formations which form a sedimentary free aquifer, but in reality this formation is underlain by a complex multi-layer system comprising confined and unconfined aquifers (Guarani aquifer)[13]. Such complex system establish a stronger complexity of the flow system that does not necessarily correspond to the simple parameterization of TRIP and can explain the errors observed for this watershed.

Other sources of errors can be listed: uncertainties in the forcing fields, possible anthropogenic influences, no flooding taken into account[3], no coupling with the overlying soil column, or uncertainties in the groundwater parameters. However, this first global application of the TRIP groundwater scheme shows that the methodology proposed here is sufficient to have consistent results on the simulated discharges and TWS. Next steps of this work will be first to confirm this suitability with more diagnostics on the results and test sensitivities to the parameters, and secondly to introduce the coupling between the water table simulated in TRIP with the unsaturated zone of the soil column represented in the ISBA LSM. The aim of such coupling will be to represent the impact of the water capillary rise on the land surface energy and water budgets, and ultimately on the simulated climate.

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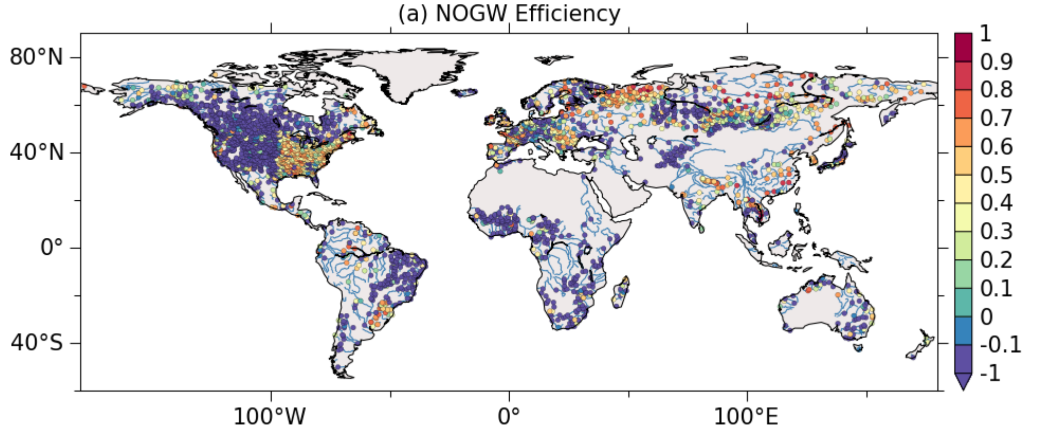
(a) NOGW Efficiency



(b) GW-NOGW Efficiency Difference

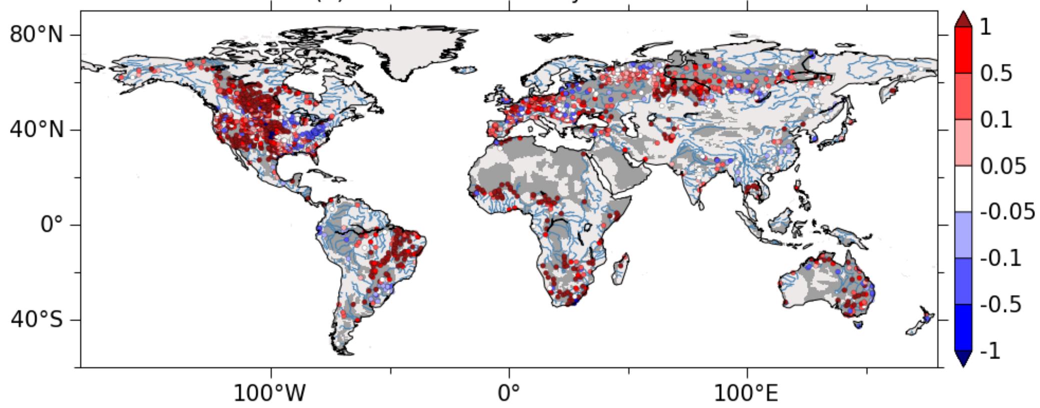


Figure 1: (a) spatial distribution of the NOGW efficiency at 3500 gauging stations; (b) differences between GW and NOGW at 1900 gauging stations potentially influenced by groundwater. Gray-colored zones on (b) correspond to the simulated aquifers.

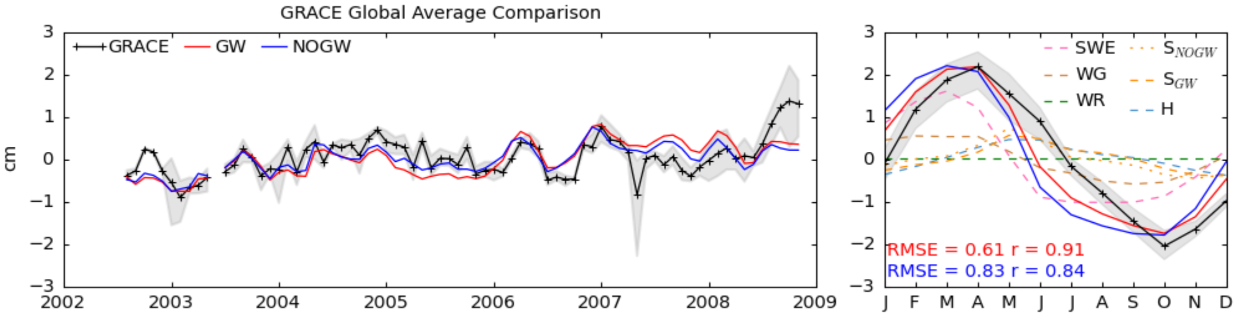


Figure 2: Global comparison between the (right) mean annual cycle and (left) monthly anomalies of smoothed ISBA-TRIP TWS and the mean GRACE product. Annual cycles of each TWS component are also shown. Note that the skill scores are computed over the entire period and not over the annual cycle.