Effects of calibrated current speeds and groundwater scheme in a global river-flow model on river discharge and terrestrial water storage

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Abstract:
This study modifies a Global River-flow model (GRiveT) to more realistically represent groundwater and river-flow processes and examines the effects of these modifications on the reproducibility of the hydrological processes. These modifications include assigning calibrated spatially distributed current speeds and implementing a groundwater scheme. A current speed calibration method is proposed to eliminate river discharge phase differences (RPDs) between the observation and the simulation. We performed nine-year integrations of the modified version of GRiveT. The experimental results were then compared with the observed data for 70 of the world’s major rivers. The proposed calibration method provides reasonable calibrated speeds that eliminate RPD for most of the 70 rivers considered. The calibration significantly improves the river discharge correlation coefficient and phase difference and improves the terrestrial water storage (TWS) correlation coefficient and phase difference to a lesser extent. However, there was little improvement to river discharge and TWS amplitudes. The implementation of the groundwater scheme improves river discharge and TWS correlation coefficients and phase differences for experiments without calibration. The calibration can compensate for the disadvantages of not implementing the groundwater scheme.

KEYWORDS global river-flow model; river discharge; terrestrial water storage

INTRODUCTION
River discharge prediction is important in the management of water resources and floods. This has lead to the addition of river-routing models in global hydrological models (e.g., Doll et al., 2003) and global climate models (GCMs; e.g., Yukimoto et al., 2002). A groundwater scheme is implemented in some river-flow-routing models to improve the accuracy of river discharge estimates (e.g., Coe, 2000) since land-surface schemes of GCMs have only shallow soil layers.

Either a globally uniform current speed (e.g., Miller et al., 1994; Doll et al., 2003) or a spatially distributed current speed computed from the Manning equation (e.g., Arora and Boer, 1999; Coe, 2000) is used in current river-routing models. However, these do not guarantee accurate output of river discharge. A comparison between a pair of these results demonstrated that a uniform current speed and a topography-dependent current speed did not rate qualitatively differ in reproducibility (Nakaegawa et al., 2007), suggesting that the current speed should be calibrated (Nijssen et al., 2001).

In this study, we modify a Global River-flow model using Total River routing Pathway (TRIP; Oki and Sud, 1998) (GRiveT; Nohara et al., 2006) to more realistically represent groundwater and river-flow processes and examine the effects of these modifications on the reproducibility of river discharge and terrestrial water storage (TWS). The modifications consist of assigning spatially distributed current speeds and implementing a groundwater scheme. A current speed calibration method to eliminate river discharge phase differences (RPDs) between the observed and simulated data is proposed. We also perform a set of long-term integrations of the modified version of GRiveT forced with Re-analysis data, and examine the effects.

MODEL AND MODIFICATIONS

GRiveT
GRiveT is a widely used linear river-flow-routing model (e.g., Nohara et al., 2006; Kitoh et al., 2008). GRiveT predicts river-water storage (S) and computes river-water flux (F) diagnostically. The lateral water transport of GRiveT is a simple flux form written as dSt/dt = R + \sum F_{down} - F_{up}, where R is the total runoff, which is usually composed of surface and subsurface runoffs; F_{down} is the river-water flux from the upstream grid with the summation indicating the confluence at a grid; and F_{up} is the river-water flux to the downstream grid. The river discharge is linearly parameterized as F = c/dS, where c is the effective current speed and d is the river length between two adjacent grid boxes. This expression indicates that the river discharge is a linear function of river storage. The global flow network of TRIP is used as a constant boundary condition, and the river length was computed from TRIP. The current speed is set at a globally uniform default value of 0.4 m/s. The current speed can be considered as the effective speed since the speed implicitly considers processes such as lakes, groundwater, and topography-dependent variable speed, since these processes are not explicitly represented in the scheme.

Modifications
We modified GRiveT to enable a distributed current speed to be assigned at each grid point and to incorporate a groundwater scheme. A locally uniform speed is commonly used and is set from 0.15 to 2.1 m/s (Arora and Boer, 1999) so that the simulated river discharge phases agree well with the observed ones for some major rivers. As a result, the uniform speed produces RPDs in other rivers, and the speed must be calibrated to reduce RPDs (Nijssen et al., 2001). We therefore modified GRiveT to assign the globally distributed current speed after the calibration proposed below.

Received 7 November 2007
Accepted 26 February 2008
Most land-surface models of GCMs have only shallow soil layers (maximum depth of 10 meters) and do not have a groundwater layer. This is because the soil moisture anomaly in shallow layers has a persistency exceeding three months in mid- and high-latitude zones (e.g., Nakaegawa et al., 2003), and the shallow layers are sufficient for reproducing the seasonal-scale interactions between the atmosphere and the land surface. However, a groundwater scheme is essential for river-discharge reproducibility (e.g., Coe, 2000; Döll et al., 2003).

We incorporate the groundwater scheme into GRiveT to realistically reproduce the phase of the river discharge (e.g., Miller et al., 1994; Döll et al., 2003). The groundwater layer receives the subsurface runoff ($R_g$), retains water for a constant decay time ($\tau_r$), and releases the groundwater discharge ($Y_g$). This is expressed as

$$Y_g = S_g / \tau_r,$$

(1)

where $S_g$ is the groundwater storage. The water balance equation for the layer is expressed as

$$ds_g / dt = R_s - Y_g.$$  

(2)

We use the surface runoff ratio ($\phi$) to separate the surface (subsurface) runoff from the total runoff, when only total runoff data are available. The subsurface runoff is obtained by $R_s = (1 - \phi)R$. The total runoff in the lateral water transport mentioned above is $R = R_s + R_g$, but $R = R_s + Y_s$ in the modified version. Equation (2) indicates that $R_s = Y_s$ as long as the climatological mean of the groundwater storage does not change significantly. That is, the climatological means of the original and the modified versions have almost the same total runoff. $\tau_r$ and $\phi$ are model parameters, and their default values are assumed to be globally uniform values of 60 days and 0.5 respectively.

**CALIBRATION**

We propose a calibration method to eliminate the RPD between the observed and simulated data. GRiveT uses a linear relationship between river channel storage and river discharge. In this study, the total runoff is the summation of the surface runoff and the groundwater runoff to the channel, and river discharge is the flow in the channel. We assume that uniform runoff occurs in an entire basin. The river discharge can then be expressed as the linear coupling of the instantaneous unit hydrograph (IUH). Only a brief summary of the calibration method is presented here (refer to Supplement for a detailed explanation).

Let the optimized speed be $C$ and the speed after the $n$-th iteration step be $C_n$. There are three phase differences here: the phase difference between the simulated runoff and the observed discharge ($\Delta T_r$); the phase difference between the simulated runoff and the simulated discharge ($\Delta T_r(C_r)$); and the phase difference between the observed and simulated discharges ($\Delta T_o(C_o)$). The relationship among the three phase differences can be expressed as $\Delta T_r = \Delta T_o(C_o) - \Delta T_r(C_r)$. A mean travel time to the river mouth or gauging station for a basin for the initial speed of $C_0$ can be obtained from the IUH. The relationship between the speed and the phase difference is finally expressed as $C \Delta T_r = L$, where $L$ is the characteristic length of the river channel network of the basin. Substitution of $\Delta T_r = \Delta T_r(C_r)$ for $C \Delta T_r = L$ and manipulation yields the following equation.

$$C_{n+1} = \frac{-L + \sqrt{L^2 + 4 \Delta T_r(C_r)L}}{2 \Delta T_r}$$

(3)

RPD can be defined as the peak discharge difference

```plaintext
EFFECTS OF CALIBRATED CURRENT SPEEDS AND GROUNDWATER SCHEME

| Experiment | Groundwater scheme | Current speed calibration |
|------------|--------------------|--------------------------|
| a.1        |                    | X                        |
| b.1        | X                  |                          |
| b.2        | X                  | X                        |
| b.3        | X                  | X                        |
```

(Coe, 2000), the lowest discharge difference, or the difference at which the lag correlation reaches a maximum value (Nakaegawa et al., 2007).

**EXPERIMENTS AND DATA**

**Experiments**

GRiveT used in this study is the modified version mentioned above with a spatial resolution of 1 degree. The inputs to GRiveT are obtained from the land data analysis (LDA) of Japan Re-analysis 25 years (JRA-25; Onogi et al., 2007). Only the total runoff is available in JRA-25; the surface and subsurface runoffs are separated with the surface runoff ratio set at a default value. JRA-25 has a horizontal resolution of 1.125 degrees and a time resolution of 6 hours. The data are interpolated into a 1 degree grid. The integration period is nine years (April 1996 to March 2005).

We performed the five experiments listed in Table I to examine the effects of the use of calibrated speeds and the implementation of the groundwater scheme on the simulated results. Experiment b.3 was obtained by combining Experiments a.2 and b.2 so as to achieve the best reproducibility. Nine-year integrations were performed for each revision of the speed, after which the calibration, which is terminated after less than 10 iterations for each experiment, was performed.

**Data**

We evaluated the climatological seasonal cycle of the river discharge and TWS of each of the 70 major river basins of the world (see Figure 1 of Nakaegawa (2006)) by comparison with observed data. The observed climatological river discharge and TWS were prepared by Masuda et al. (2001). The original river discharge was obtained from the Global Runoff Data Center, and TWS was computed using the combined water balance method. The period from 1973 to 1995 with a time resolution of 1 month was used. The station used in each basin is selected based on the larger basin area and data availability. The simulated TWS is the summation of four components, soil moisture and snow water equivalence in LDA of JRA-25, and river water and groundwater storages in GRiveT. Because the observations and simulations do not coincide in time, the comparisons are made in climatological seasonal cycles.

**RESULTS AND DISCUSSION**

**Holistic comparison**

In the following comparison, we use two metrics: the amplitude ratio and RPD. The amplitude ratio is the standard deviation ratio computed from the monthly deviation from the annual mean (the standard deviation for the LDA for that for the observed data). RPD in month defined here is the difference at which the lag correlation reaches a maximum value.
The calibration eliminates RPDs for most of the rivers with only five RPDs in Experiment a.2 (without the groundwater scheme) failing to reach zero months after the calibration. These RPDs were for the Murray, Kolyma, Indigirka, Fraser, and Brazos Rivers. RPDs in Experiment b.2 (with the groundwater scheme) are zero months for two of these five rivers: the Indigirka and Fraser Rivers. However, RPDs are not zero months for the Congo and Yana Rivers. The degraded RPDs for these two rivers stem from the retarding effect of the groundwater layer. We then allowed the decay time for the Congo and Yana Rivers to vary and recalibrated the speed (Experiment b.3). Only three RPDs remained – the Murray, Kolyma, and Brazos Rivers. The calibrated decay times for the Congo and Yana Rivers are 0.1 and 10 days, respectively.

The 70-river mean current speed for Experiment a.2 without the groundwater scheme is 0.23 m/s. The 70-river mean current speed for Experiment b.3 with the groundwater scheme is 0.70 m/s. These values are within the ranges of both model studies (e.g., Arora and Boer, 1999; Coe, 2000) and measured values (Schulze et al., 2005). No RPDs are found in the Nelson and Olenek Rivers, but the speeds were too low. No RPDs are found in either experiment, so other processes are responsible for them. The speed calibration thus works well for the phase tuning.

Table II compares the reproducibility among the experiments. The number of basins for amplitude improvement (deterioration) is counted when the ratio of the amplitude ratios is in (outside) the range from 0.9 and 1.1. The number of basins for correlation improvement (deterioration) is counted when correlation difference exceeds 0.10 (falls below –0.10).

The difference between Experiments a.1 and a.2 in Table IIa suggests that the river discharge correlation coefficient and phase difference are significantly improved with calibration. Approximately twice as many rivers have better TWS correlation and phase differences with the calibration than without. River channel storage, a component of TWS, is linearly related to the river discharge with the same phase, so improvements in the river channel storage reproducibility directly relate to those in TWS correlation and phase shift. However, the river discharge and TWS amplitudes are improved in some rivers and degraded in others, indicating that the speed calibration does not systematically improve the amplitude in both river discharge and TWS.

The difference between Experiments b.1 and b.3 in Table IIb indicates similar results for the river discharge as in Table IIa. According to TWS, only the amplitudes are improved; the correlation coefficients and phase differences are not. From a comparison between Tables IIa and IIb, fewer calibration improvements in the correlation coefficients and phase differences of the river discharge indicates that GRiveT with the groundwater scheme eliminates RPDs in more rivers than without the scheme.

Table IIc presents the difference between experiments using the uniform speed with and without the groundwater scheme (Experiments a.1 and b.1). The correlation coefficients and phase differences of river discharge and TWS are improved, suggesting that the groundwater scheme effectively improves the correlation coefficients and reduces phase differences.

The differences in the reproducibility between experiments using the calibrated current speed with and without the groundwater scheme in Table II.d are not obvious. This suggests that calibration can compensate for the lack of a groundwater scheme in the model. This confirms that the effective current speed can include the groundwater functions and that previous river-routing models without it can simulate the river discharge reasonably well.

Comparison

Figure 1, a Taylor diagram (Taylor, 2001) with time lag (Nakaegawa and Tokuhiro, 2005), presents the amplitude ratios and correlation coefficients of the climatological seasonal cycles of the river discharge and TWS for three river basins in Experiments a.1 and b.3. The ratio becomes better as it approaches unity, and the correlation coefficient, represented by arc cosine, becomes better as it approaches the horizontal axis. Point (1, 0) represents the complete reproducibility or the observation. In addition, the distance between a plotted point and a point (1, 0) is the normalized root-mean-square error.

The Ob River has no RPD in Experiment b.3, and the correlation coefficient is dramatically improved. However, the amplitude is underestimated. The basin has a better TWS phase difference and very good reproducibility of the TWS amplitude. The modifications improve the reproducibility of the river discharge phase, as well as TWS amplitude and phase for the Ob River basin.

The Nile River also exhibits no RPD for Experiment b.3, but the amplitude is far more underestimated due to the excessively low current speed obtained from the calibration. The TWS correlation coefficient is reduced but the TWS amplitude improves slightly. The modifications improve the RPD and TWS amplitude but not the others, probably because Aswan High Dam, which accounts for most of the opposite phase of river discharge, is not explicitly treated.

Experiment a.1 reproduces the river discharge in the Mekong River very well, and the modifications in Experiment b.3 reproduce it even better. However, the improvement in TWS is very restrictive. This may be due to the storage in Lake Tonle Sab significantly changing the area and the water depth with seasonal march. These three rivers are not systematically improved by the modifications, which is generally consist.

Table II. Number of rivers exhibiting improved (I) or deteriorated (D) reproducibility between two experiments. a. Difference in experiments without groundwater scheme with and without calibration. b. Same as in a. except with groundwater scheme. c. Difference in experiments without calibration with and without groundwater scheme. d. Same as in c. except with calibration. RD represents river discharge; TWS, terrestrial water storage. The first experiment of each pair is the reference for reproducibility.

| Experiment | (a) a.1 and a.2 | (b) b.1 and b.3 | (c) a.1 and b.1 | (d) a.2 and b.3 |
|------------|----------------|----------------|----------------|----------------|
| Variable   | RD  | TWS | RD  | TWS | RD  | TWS | RD  | TWS |
|            | I   | D   | I   | D   | I   | D   | I   | D   |
| Amplitude  | 22  | 16  | 22  | 20  | 14  | 14  | 34  | 14  |
| Correlation| 1   | 16  | 8   | 6   | 27  | 5   | 43  | 24  |
| Phase      | 58  | 10  | 8   | 9   | 32  | 6   | 55  | 18  |
This study modifies GRiveT by assigning spatially distributed current speeds and implementing the groundwater scheme. It also proposes a method for tuning the simulated river discharge phases by calibrating the current speed. We performed nine-year integrations with the forcing data obtained from JRA-25 to examine the reproducibility of the modified version of GRiveT, and compared experiment results with the observations. The proposed calibration method eliminates RPD for most of the major 70 rivers, and the calibrated speeds are within the previous model parameter values and measured values.

We conducted five experiments to separate the effects of the assignment of the calibrated current speeds for each river from the implementation of the groundwater scheme, and identified the following holistic features. The calibration significantly improves the river discharge correlation coefficient and phase difference, but only slightly improves the TWS correlation coefficient and reduces phase differences. The calibration has negligible effect on river discharges and TWS amplitudes. Implementing the groundwater scheme improves river discharges and TWS correlation coefficients and reduces phase differences for experiments without calibration. The calibration can compensate for the lack of a groundwater scheme within the model. This result reinforces the idea that the speed used in these kinds of models is not an actual speed but an effective speed which takes different hydrological processes into account.

This study refines GRiveT, improving the timing of freshwater supply to oceans in GCMs. In addition, TWS will soon be measurable using satellite gravity missions (e.g., Nakaegawa, 2006), and its reproducibility is being closely evaluated (e.g., Yamamoto et al., 2007). The refinement of this model will be extremely useful for this reason. Further refinement will be required to widely apply the model outputs to hydrological and water resource studies.

CONCLUDING SUMMARY

This study modifies GRiveT by assigning spatially distributed current speeds and implementing the groundwater scheme. It also proposes a method for tuning the simulated river discharge phases by calibrating the current speed. We performed nine-year integrations with the forcing data obtained from JRA-25 to examine the reproducibility of the modified version of GRiveT, and compared experiment results with the observations. The proposed calibration method eliminates RPD for most of the major 70 rivers, and the calibrated speeds are within the previous model parameter values and measured values.

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