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A variable streamflow velocity method for global river routing model: model description and preliminary results

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Abstract

This paper presents an attempt of simulating daily fluctuations of river discharge at global scale. Total Runoff Integrating Pathways (TRIP) is a global river routing model which can help to isolate the river basins, inter-basin transport of water through river channels, as well as collect and route runoff to the river mouths for all the major rivers. In the previous version of TRIP (TRIP 1.0), a simple approach of constant river flow velocity is used. In general, that approach is sufficient to model mean long-term discharges. However, to model short-term fluctuations, more sophisticated approach is required. In this study, we implement a variable streamflow velocity method to TRIP (TRIP 2.0) and validate the new approach over the world's 20 major rivers. Two numerical experiments, one with the TRIP 1.0 and another with TRIP 2.0 are performed. Input runoff is taken from the multi-model product provided by the second Global Soil Wetness Project. For the rivers which have clear daily fluctuations of river discharge, TRIP 2.0 shows advantages over TRIP 1.0, suggesting that TRIP 2.0 can be used to model flood events.

1 Introduction

Understanding the movement of water over the earth's surface has long been a fascinating research target. Many hydrologic studies have been done to determine the quantity of flow along rivers at various points in time and space. Most of these studies have focused on small watersheds. Recently with the technology development and the concerns about global climate change, the climate modeling community has focused attention on the need for routing models to track the flow of water from continents to oceans at global scale.

Several advantages of routing models can be listed here. First, routing runoff provides a basis for comparing and validating estimates of streamflow with observed hydrograph data. As most variables describing the state of the surface are not directly observable, river discharge is an appropriate measure to assess model qualities. Second, the simulated fresh water flux into the oceans alters their salinity and may affect the thermohaline circulation (e.g. Wang et al., 1999; Wijffels et al., 1992). Third, estimates of river discharge from climate change simulations can also be used to assess the impact of climate change on water resources and the hydrology of the major river basins (e.g. Arora and Boer, 2001; Milly et al., 2005; Oki and Kanae, 2006). Approaches for routing water through large-scale systems are thus evolving in response to the modeling needs.

In state-of-the-art global routing models, most of the approaches either assume a constant velocity (e.g. Miller et al., 1994; Coe, 1998; Oki et al., 1998) or use simple formulae that use time-independent flow velocities parameterized as a function of the topographic gradient (Miller et al., 1994; Hagemann and Dümennil, 1996; Ducharne et al., 2003). In general, these approaches are sufficient to model discharges in monthly or longer time scales. However, to model in shorter temporal scales, more sophisticated approach is required. Arora and Boer (1999) and more recently, Schulze et al. (2005) use the Manning's equation to determine time-evolving flow velocities as a function of discharge, river cross-section and channel slope:

$$v=n^{-1}\times R^{2/3}\times s^{1/2} \tag{1}$$

where v is the flow velocity [m/s], n is the Manning roughness coefficient [–], R is the hydraulic radius [m], and s is the channel slope [m/m]. In their studies, the Manning roughness coefficient n is supposed to be constant globally (Arora and Boer, 1999) or determined by tuning (Schulze et al., 2005). Since values of n vary between 0.015 and 0.07 in natural streams for flows less than bankfull discharge and reach up to 0.25 for overbank flow (Fread, 1993), the assumption of a global constant roughness coefficient or the tuning method would contain limitations.

Dingman and Sharma (1997) developed the following relation from objective statistical analysis of over 500 in-bank flows:

$$Q=1.564\times A^{1.173}\times R^{0.400}\times s^{-0.0543\times\log_{10}s} \tag{2}$$

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where Q [m^3/s] and A [m^2] are river discharge and cross-sectional area respectively.

Note that:

$$Q = A \times v \tag{3}$$

We can induce that Eq. (2) is another representation of the Manning equation (Eq. 1) with the roughness coefficient calculated by:

$$n = \frac{1}{1.564} \times A^{-0.173} \times R^{0.267} \times s^{0.5+0.0543\times \log_{10} s} \tag{4}$$

Thus, Eq. (2) proposed by Dingman and Sharma has potential to overcome the limitations of constant roughness coefficient assumption or a tuning procedure for global routing models.

Total Runoff Integrating Pathways (TRIP) is a global river routing model which can help to isolate the river basins, inter-basin tranport of water through river channels, as well as collect and route runoff to the river mouths for all the major rivers (Oki and Sud, 1998). In the previous version of TRIP (hereafter TRIP 1.0), the simple approach of constant river flow velocity was used. In this paper, we implement the Dingman and Sharma equation to TRIP (hereafter TRIP 2.0) and perform the validation of the new approach over the Mekong and some other world's largest rivers.

2 Methodology

In TRIP 2.0, we define two water reservoirs: groundwater reservoir and surface water reservoir. Groundwater is represented by a simple linear reservoir (e.g. Maidment, 1993):

$$\frac{dS_g}{dt} = D_{\mathrm{LSMg}} - D_{\mathrm{OUTg}} \tag{5}$$

where S_g [m^3], D_{LSMg} [m^3/s], and D_{OUTg} [m^3/s] are groundwater storage, input subsurface runoff (obtained from the output of Land Surface Model (LSM)), and the outflow from the groundwater reservoir, respectively. The outflow is parameterized as:

$$D_{\mathrm{OUTg}}=\frac{1}{T_g}\times S_g \tag{6}$$

where T_g is a groundwater delay parameter expressed in days.

From Eq. (5) and Eq. (6), we obtain the solution for S_g:

$$S_g(t+dt)=e^{-dt/T_g}\times S_g(t)+(1-e^{-dt/T_g})\times T_g\times D_{\mathrm{LSMg}}(t+dt) \tag{7}$$

If T_g=0, we define S_g=0, $D_{\mathrm{OUTg}}=D_{\mathrm{LSMg}}$, i.e. TRIP 2.0 will route the total runoff and not separate anymore surface runoff and subsurface runoff.

The water balance within a grid cell for the surface water reservoir storage, S_s [m^3], is given by:

$$\frac{dS_s}{dt}=D_{\mathrm{up}}+D_{\mathrm{OUTg}}+D_{\mathrm{LSMs}}-Q \tag{8}$$

where D_{up} [m^3/s] and D_{LSMs} [m^3/s] are total inflow from upstream grid boxes and surface runoff calculated by LSM, respectively.

The volume of water in the river channel is:

$$S_s=A\times l\times r_M \tag{9}$$

where l is the straight length of the river channel within the grid box calculated geometrically and r_M is the meandering ratio (Oki and Sud, 1998) adjusting the river length to be realistic. In this study, we set r_M=1.4 globally.

Substituting Eq. (3), Eq. (9) into the continuity equation Eq. (8) yields:

$$\frac{dS_s}{dt}=D_{\mathrm{up}}+D_{\mathrm{OUTg}}+D_{\mathrm{LSMs}}-\frac{v}{l\times r_M}\times S_s \tag{10}$$

One should note that v depends itself on S_s. To solve Eq. (10), we assume that v is constant during each time step.

We obtain thus the solution of Eq. (10)

$$S_s(t+dt)=e^{-dt\times\frac{v(t)}{l\times r_M}}\times S_s(t)+\left(1-e^{-dt\times\frac{v(t)}{l\times r_M}}\right)\times\frac{l\times r_M}{v(t)} \times\left(D_{\mathrm{up}}(t+dt)+D_{\mathrm{OUTg}}(t+dt)+D_{\mathrm{LSMs}}(t+dt)\right) \tag{11}$$

where $v(t)$ is calculated in the time step t as followings:

From Eq. (2), Eq. (3), v can be described as:

$$v=1.564\times A^{0.173}\times R^{0.400}\times s^{-0.0543\times\log_{10}s} \tag{12}$$

Assuming the river channel is shaped as a rectangle of width W [m] and depth h [m], thus we have:

$$R=\frac{h\times W}{2\times h+W} \tag{13}$$

W is obtained using a geomorphological relationship with annual mean discharge Q_m [m^3 s^{-1}] proposed by Arora and Boer (1999):

$$W=\max(10,(6.0+10^{-4}\times Q_{\mathrm{m.mouth}})\times Q_m^{0.5}) \tag{14}$$

where $Q_{\mathrm{m.mouth}}$ [m^3 s^{-1}] is the annual mean discharge at the river mouth. Sensitivity of flow velocity to river width has shown that an error of 100% in the prescribed river width results in a corresponding error of about 25% in flow velocity (Arora and Boer, 1999). Q_m is initially calculated from TRIP 1.0, the constant velocity version of TRIP.

Eq. (12) thus becomes:

$$v=1.564\times s^{-0.0543\times\log_{10}s}\times\frac{S_s^{0.573}}{(l\times r_M)^{0.573}\times\left(\frac{2\times S_s}{l\times r_M\times W}+W\right)^{0.400}} \tag{15}$$

3 Experiments design

3.1 Input runoff forcing

The second Global Soil Wetness Project (GSWP2) (International GEWEX Project Office, 2002; Dirmeyer et al., 2006) is an ongoing environmental modeling research activity aiming at producing global estimates of soil moisture, temperature, snow water equivalent, and surface fluxes by integrating one-way uncoupled LSMs using externally specified surface forcing and standardized soil vegetation distributions. In May 2005, 15 institutes from five nations have submitted their baseline run, and model ensemble mean (or simple arithmetic average of outputs among models) of surface fluxes and state variable have been produced using 13 models (Dirmeyer et al., 2006). Gao and Dirmeyer (2006) compared the products (GSWP2-Multi Model Analysis, hereafter GSWP2-MMA) with in-situ soil moisture observation from the Global Soil Moisture Data Bank (Robock et al., 2002) and found that GSWP2-MMA is better than the best individual model at any location in the representation of both soil wetness and its anomaly.

The GSWP2-MMA data, as well as the data submitted by the participating modeling groups conform to the Assistance for Land-surface Modelling Activities convention (ALMA) (Polcher et al., 2000). The data has 1 degree by 1 degree (longitude-latitude) spatial resolution, and daily temporal resolution spanning the years 1986–1995.

All models (and GSWP2-MMA) provide two runoff variables: surface runoff and subsurface runoff. However, the partition of runoff into surface and subsurface varies significantly between models. Thus in this study, TRIP 2.0 is used to route total runoff from GSWP2-MMA on a digital river network map with a spatial resolution of 1 degree longitude by 1 degree latitude.

3.2 Numerical experiments

Two numerical experiments are performed. The first one, called T1 is obtained with the TRIP 1.0 version which used the constant velocity approach. In T1, the stream flow velocity is assumed constant and uniform at 0.5 m s^{-1} (e.g. Decharme and Douville, 2007; Oki and Sud., 1998). The second one, called T2 is obtained with TRIP 2.0 which used the new variable velocity approach. Both simulations use the GSWP2-MMA runoff of 1986 for spin-up (Fig. 1). Water storage in the river channels is initialized with zero value. The spin-up procedure is finished when the difference of water storage between the 1st January 1987 and the 1st January 1986 is less than 5% for more than 95% of the whole grid cells. For T2, we use the TRIP 1.0 version in the beginning to initialize the value of annual mean discharge required by Eq. (14).

River slope s, which is not required in T1, plays an important role in T2 (see Eq. 15). s is calculated from the 1 degree digital elevation and the drainage flow direction maps created by Oki and Sud (1998). However as consequence of the corrections which were applied to create a more realistic flow direction map, there are many grid points having negative slope values due to the fact that the downstream points have higher elevation. We thus generally set a minimum river slope value of 10^{-6} m m^{-1} (i.e. 0.1 m per 100 km) to avoid those irregular points.

In both T1 and T2, we set the meandering value, r_M to 1.4 globally. For simplicity reason, and for avoiding the inconsistency among the GSWP2 models in the partition of total runoff into surface and subsurface components, the groundwater mode is switched off (i.e. T_g=0). Time step of the simulation is set to 6-hourly.

The sensitivity of river discharge simulated by TRIP to all the above parameters/model settings will be discussed in our further paper.

4 Results

4.1 Over the mekong

The Mekong River is the 12th longest river in the world, runs 4800 km from its headwaters on the Tibetan Plateau through Yunnan Province of China, Burma, Thailand, Cambodia, Lao and Vietnam. Lancang is the name for the river's 2160-km upper and middle reaches running through China, while the lower reaches outside China are known as the Mekong. From 1986 onwards, China began to build eight hydroelectric dams and two reservoirs on the waterway in Yunnan, where the Lancang traverses more than 1000 km, to lift the backward western region out of poverty. The first dam at Manwan, was finished in June 1995. While the GSWP2-period is for 1986–1995, our result would not be affected by the dam's operations.

In this section, we will access the quality of T1 and T2 over the Mekong by comparing the simulated and observed river discharges.

The river discharge observations used in this study are the daily data obtained from the Global Runoff Data Center (GRDC). In the GRDC data, there are 12 stations over the Mekong. However, only 6 of them overlap the GSWP2 simulation period (1986–1995). The 3 stations Nong Khai, Near Vieanntiane and Chiang Khan are closely located (or coincide) on the 1 degree flow direction map created by Oki et al. (1998). We use thus the most downstream station, NongKhai, among those 3 stations. Then, the stations over the Mekong which are used to validate our simulation results are: Luang Prabang, NongKhai, Mukdahan, Pakse (see Table 1 and Fig. 2).

Figure 3 represents a time-series comparison of river discharge for T1, T2 and the observations over the year 1990. The average upstream velocity variations simulated by T2 are also displayed in Fig. 3. In the high flow season, T2 shows that flow velocity can reach to 3 m s^{-1} while this value is only about 1 m s^{-1} in the low flow season. Variable streamflow velocity allows a quick response of river discharge to a high precipitation event in the upstream region. T2 is thus able to capture the short term fluctuations (in this study is daily fluctuations) of river discharge over the Mekong.

Figure 4 displays a Taylor diagram which shows errors of simulated river discharges for T1 (black filled circles) and T2 (white filled circles). A Taylor diagram (Taylor, 2001) provides the ratio of standard deviation as a radial distance and the correlation with observations as an angle in the polar plot. Each circle corresponds to the quality of simulated discharge at a predefined station. The observed discharge is represented by a point on the horizontal axis (zero correlation error) at unit distance from the origin (no error in standard deviation). In this representation the linear distance between each simulation result and observed discharge is proportional to the root mean square error (RMSE). Only the overlap period between simulations and observations is used to compute statistics.

For the 4 stations Luang Prabang, Nong Khai, Mukdahan, Pakse, a clear improvement of T2 compared to T1 is shown. T2 has smaller RMSE comparing to T1. Particularly the correlations with the observations are well improved, from an average value of 0.78 for T1 to an average value of more than 0.93 for T2.

4.2 Over the world's largest rivers

The objective of this section is to compare T2 with T1 for other rivers of the world. From the GRDC daily discharge data, 20 stations in 20 major rivers (see Table 2 and Fig. 5) were selected and compared with the simulated discharges. The stations were chosen according to the following criteria:

- Stations which have upstream drainage area greater than 300 000 km^2.
- Stations with a minimum observed period of 4 y which overlaps the GRDC 1986–1995 period.
- The most downstream station (i.e. maximum upstream drainage area) among the available ones on a river which fit the 2 above conditions.

Table 2 represents the stations used for comparing T1 and T2. The correlation (r^2) and normal standard deviation (std) between simulated and observed discharges are also displayed in Table 2. Over the period used for comparing, T2 is not statistically better than T1 for most of studying rivers. For some rivers (e.g. the Amazon, Ob, Kolyma), both r^2 and std of T2 are worse than those of T1. For some others (e.g. the Mississippi, Amur, Indigirka), std of T2 is better but r^2 is worse or vice-versa. For the Brahmaputra and the Mekong, T2 discharge is statistically better than T1.

Figure 6 shows daily time-series discharges of T1 and T2 compared to the observations at the 20 studying stations, over the two year 1987–1988. Over the stations where sub-monthly fluctuations are observed (e.g. the Mississippi, Danube, Brahmaputra, Mekong), T2 shows advantages over T1. Changing river velocity in T2 allows river discharge to vary quickly, which in consequence make T2 be able to represent the sub-monthly observed discharge fluctuations. Over some stations where there are no clear short term fluctuations of river discharge, T2 seems to over-estimate those fluctuations (e.g. over the Amazon, the Orinoco). For the Niger and the Chari in Africa and some other rivers such as the Columbia, the simulated discharges are practically un-correlated with the observations. The reason can be attributed to the GSWP2 precipitation quality over those basins and the fact that TRIP does not represent the natural dissipation of water from river channels to surrounding land, water used by the cities, irrigation and dam construction (Ngo-Duc et al., 2005; Hanasaki et al., 2006).

5 Discussion

One can notice that the simulated discharge however is still significantly different from the observations. Understanding the reasons for which such differences occur is important for further study and further development of the routing model. We divide the sources of errors into two main categories, errors originate from the input runoff forcing data and errors originate from the river routing models itself.

The first one is the error due to the input runoff forcing data. In this study, we use the multi-model runoff product from GSWP2. Each LSM participated to GSWP2 has its own approach for calculating runoff. Therefore the runoff can be quite different from one model to another. Gao and Dirmeyer (2006) has compared the GSWP2-MMA products with in-situ soil moisture observation from the Global Soil Moisture Data Bank (Robock et al., 2002) and found that GSWP2-MMA is better than the best individual model at any location in the representation of both soil wetness and its anomaly. For runoff, no such study has been done yet.

Runoff quality depends also on the input precipitation of the LSMs (Oki et al., 1999; Ngo-Duc et al., 2005). Nevertheless, the accuracy and reliability of the 10-y GSWP2 atmospheric forcing remain questionable. Decharme and Douville (2006) showed that the baseline GSWP2 precipitation forcing is generally overestimated over the mid and high latitudes, which implies systematic errors in the simulated discharges.

The second source of errors origins from the global river routing model. TRIP contains several parameterizations and several assumptions as well as it neglects certain river processes. In the numerical experiments used in this study, TRIP doesn't take into account the groundwater reservoirs. The current version of TRIP also does not represent the natural dissipation of water from river channels to surrounding land, water used by the cities, irrigation and dam construction.

In T2, drainage flow direction map is used together with the elevation map. Oki and Sud (1998) have created the 1 degree flow direction map from the 1 degree digital elevation map and have applied several corrections (including manual correction in comparison with river pathways available in the atlases). They therefore obtained a more realistic map of flow direction. However as consequence of the corrections, there are many grids points on the 1 degree map having negative slope value due to the fact that the downstream points have higher elevation (see Fig. 7). This suggests a further study of adjusting the digital elevation map to fit the new flow direction map or further simulations using some new global hydrological datasets recently available (e.g. HydroSHEDS by Lehner et al., 2006). In T2, at those irregular points, we use a minimum slope of $10^{-6}\,\mathrm{m\,m^{-1}}$ instead of the negative values.

Other reasons of errors which come from TRIP can also be listed here: (a) Eq. (2) and Eq. (14) using in this study are empirical equations obtained for certain rivers and may not be appropriate for everywhere; (b) the meandering value of river is set to 1.4 globally, although it is 1.3 for rivers with areas larger than $500\,000\,\mathrm{km}^2$ (Oki and Sud, 1998); (c) the assumption of constant velocity during each time step in order to solve Eq. (10) may also be too rude.

The sensitivity of river discharge to different above factors (minimum slope value, empirical equation, meandering coefficient, etc.) would deserve another careful study in the near future.

6 Conclusions

This study was aimed at constructing a new version of the global river routing model TRIP, based on a variable streamflow velocity approach, in order to simulate shorter time scale fluctuations of river discharge globally. We have used the Dingman and Sharma (1997) equation to represent the relation between river discharge and river geomorphology. Two numerical experiments, T1 obtained with the previous model version TRIP 1.0 and T2 obtained with TRIP 2.0 have been performed. The river discharges simulated T1 and T2 were used to compare with the daily observations from GRDC for the world's 20 large rivers.

It was shown that, T2 has clear advantages over T1 in representing the short-term fluctuations of river discharges over certain rivers such as the Mekong, the Brahmaputra, the Mississippi, and the Danube. For the rivers where short-term fluctuations of discharge are not clear, T2 is not better than T1. The differences between simulations by TRIP and GRDC observations have been attributed to several sources of errors: errors from the input forcing data and errors from the models itself. A sensitivity study which helps to quantify how much river discharge depends on those factors would be done in the near future.

TRIP 2.0 is a very first step which allows river routing model to represent short-term fluctuations of river discharge at global scale. On the technical side, input and output of TRIP 2.0 are in netCDF format. TRIP 2.0 can be configured to run with different resolutions and can also be extracted to run for only one region of interest in order to economize computer time consuming. More technical information about TRIP 2.0 can be found at: http://hydro.iis.u-tokyo.ac.jp/TRIP2.

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Table 1. GRDC stations over the Mekong, which have observations overlapping the period of GSWP2 simulations. The station ID defined by GRDC, the name, the localizations (country, longitude, Lon, and latitude, Lat), the drainage area (given by GRDC) and the discharge observation period at each station are given.

GRDC-No	Station	Country	Lat (° N)	Lon (° E)	Area (km^2)	Period
2469050	Luang Prabang	Laos	19.5	101.5	268 000	86–93
2969090	Nong Khai	Thailand	17.5	102.5	302 000	86–93
2969100	Mukdahan	Thailand	16.5	104.5	391 000	86–93
2469260	Pakse	Laos	15.5	105.5	545 000	86–93

Table 2. The world's 20 rivers which have daily discharge observations during the GSWP2-period (1986–1995). The approximate river length, the name, the station ID defined by GRDC, the drainage area (given by GRDC and by the TRIP river network), the localizations (longitude, Lon, and latitude, Lat) and the discharge observation period at each basin downstream station are given. Correlation (r^2) and normal standard deviation (std) between the simulations and the observations are also displayed on the Table.

	River	Station	GRDC-ID	Lon (° N)	Lat (° E)	Drainage area (km^2)	Period	r^2−T1	r^2−T2	std−T1	std−T2
1	Amazon	Obidos	3629000	−55.5	−2.5	4 640 300	86–95	0.91	0.63	1.20	1.33
2	Mississippi	Vicksburg	4127800	−91.5	32.5	2 964 255	86–95	0.81	0.88	1.69	2.08
3	Ob	Salekhard	2912600	66.5	66.5	2 949 998	86–95	0.85	0.11	2.38	3.13
4	Yenisei	Igarka	2909150	86.5	67.5	2 440 000	86–95	0.78	0.49	0.84	0.87
5	Lena	Kusur	2903420	127.5	70.5	2 430 000	86–94	0.74	0.56	0.57	0.69
6	Amur	Komsomolsk	2906900	137.5	50.5	1 730 000	86–90	0.73	0.54	0.77	0.92
7	Mackenzie	Arctic red river	4208025	−133.5	67.5	1 660 000	86–95	0.87	0.57	0.79	0.87
8	Volga	Volgograd Power Plant	6977100	44.5	48.5	1 360 000	86–95	0.66	0.60	3.11	3.91
9	Orinoco	Puente Angostura	3206720	−63.5	8. 5	836 000	86–89	0.92	0.79	0.94	1.00
10	Yukon	Pilot station	4103200	−162.5	61.5	831 390	86–95	0.85	0.60	2.28	2.90
11	Danube	Ceatal Izmail	6742900	28.5	45.5	807 000	86–89	0.73	0.68	2.34	2.64
12	Niger	Niamey	1234150	2.5	13.5	700 000	86–95	0.75	0.46	8.41	10.38
13	Brahmaputra	Bahadurabad	2651100	89.5	25.5	636 130	86–91	0.82	0.88	0.69	0.78
14	Columbia	The Dalles, OR	4115200	−121.5	45.5	613 830	86–95	0.68	1.76	7.15	8.25
15	Chari	Ndjamena	1537100	15.5	12.5	600 000	86–90	0.93	0.67	0.19	0.22
16	Mekong	Pakse	2469260	105.8	15.12	545 000	86–93	0.75	1.18	0.91	1.32
17	Kolyma	Kolymskaya	2998510	158.5	68.5	526 000	86–95	0.80	1.33	0.71	1.62
18	Severnaya Dvina	UST-Pinega	6970250	41.5	64.5	348 000	86–95	0.88	0.54	1.85	2.12
19	Pechora	Oksino	6970700	52.5	67.5	312 000	86–95	0.86	0.54	1.23	1.41
20	Indigirka	Vorontsovo	2998400	147.5	69.5	305 000	86–94	0.79	0.53	0.77	0.93

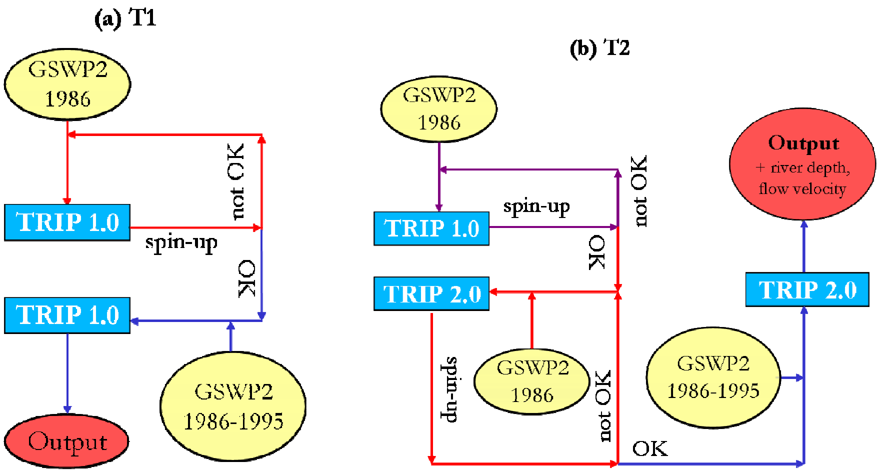

Fig. 1. Schema for **(a)** Constant Velocity Run (T1), **(b)** Variable Velocity Run (T2).

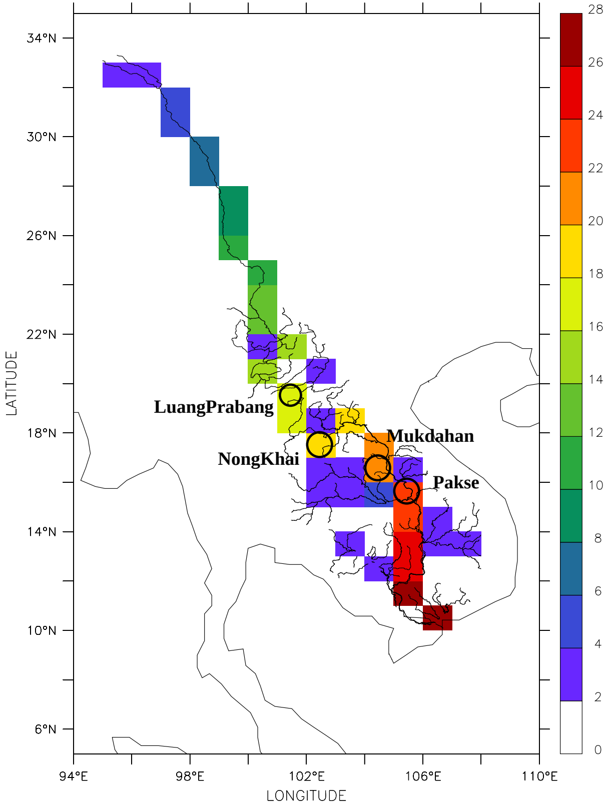

Fig. 2. 1 degree Mekong river sequence map designed by Oki et al. (1998). River information from the World Data Bank II (WDBII) developed by the U.S. Central Intelligence Agency is superimposed. The discharge stations using in this study are located by the circulars on the 1 degree resolution map.

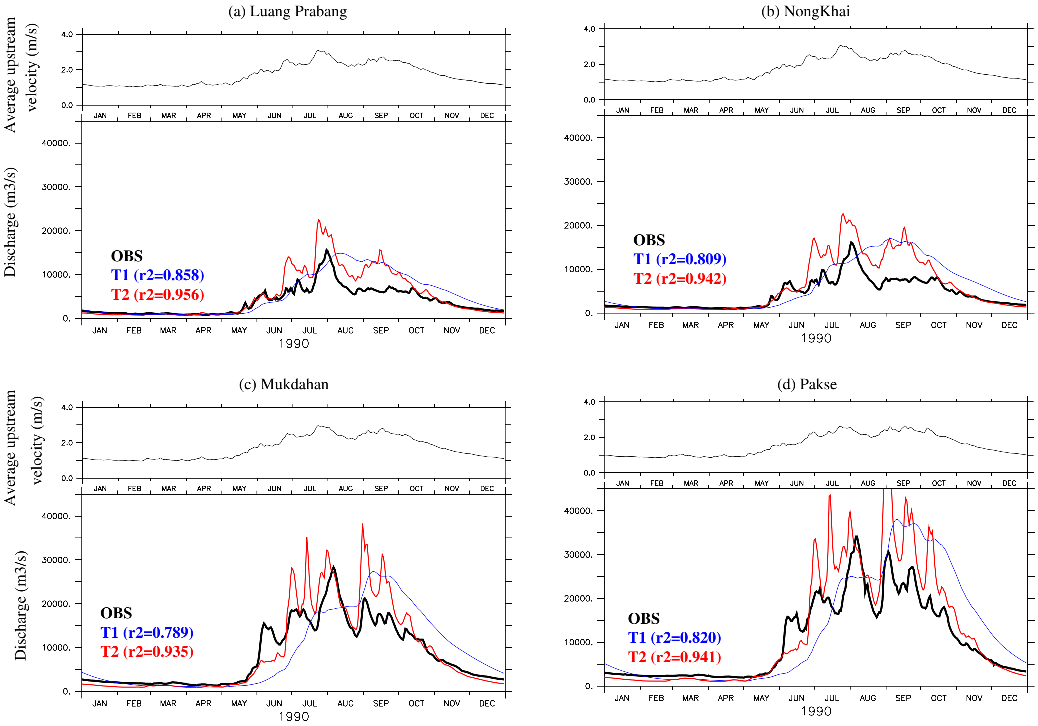

Fig. 3. River discharges simulated by T1 (blue curve), T2 (red curve) compared to the observations (black curve) at **(a)** Luang Prabang, **(b)** NongKhai, **(c)** Mukadahan and **(d)** Pakse.

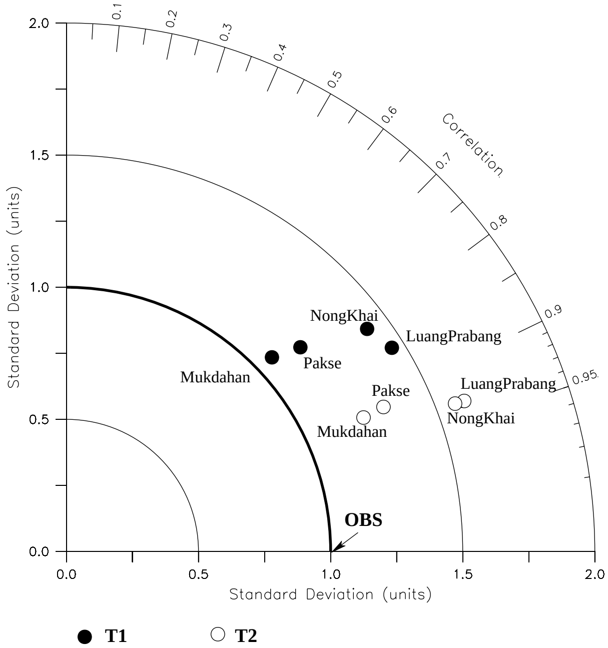

Fig. 4. Taylor diagram illustrating the statistics of simulated river discharge compared with daily observations at (a) Luang Prabang station, (b) Nong Khai station, (c) Mukdahan satation, (d) Pakse station.

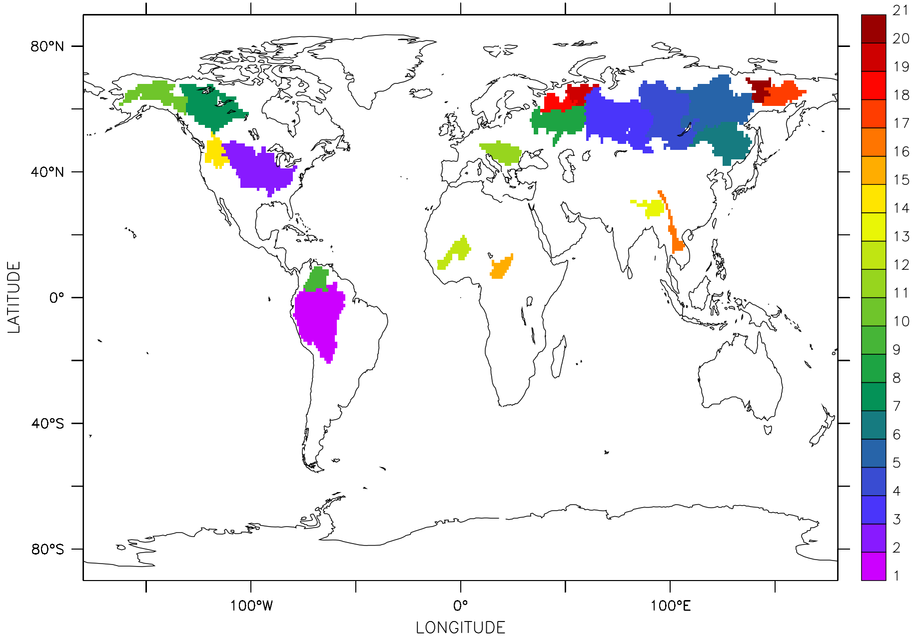

Fig. 5. Upstream of the 20 stations used in this study. Number corresponds to the number of river in Table 2.

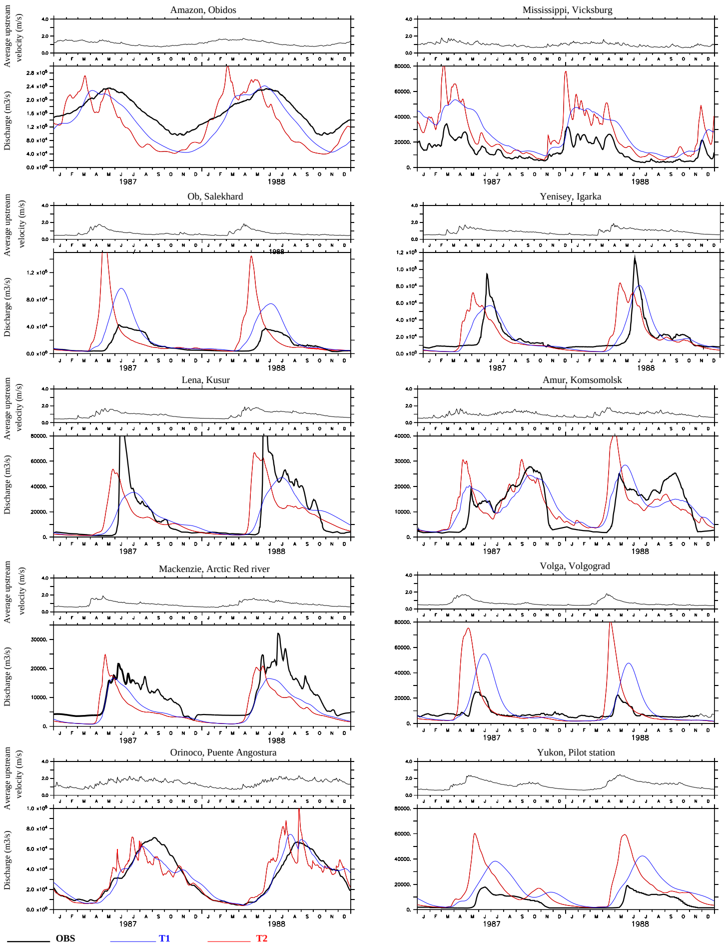

Fig. 6a. Daily discharges of T1 and T2 compared to the observations at the 20 studying stations, over the two year 1987–1988. Observations: red; T1: black; T2: blue. Unit in $m^3 s^{-1}$.

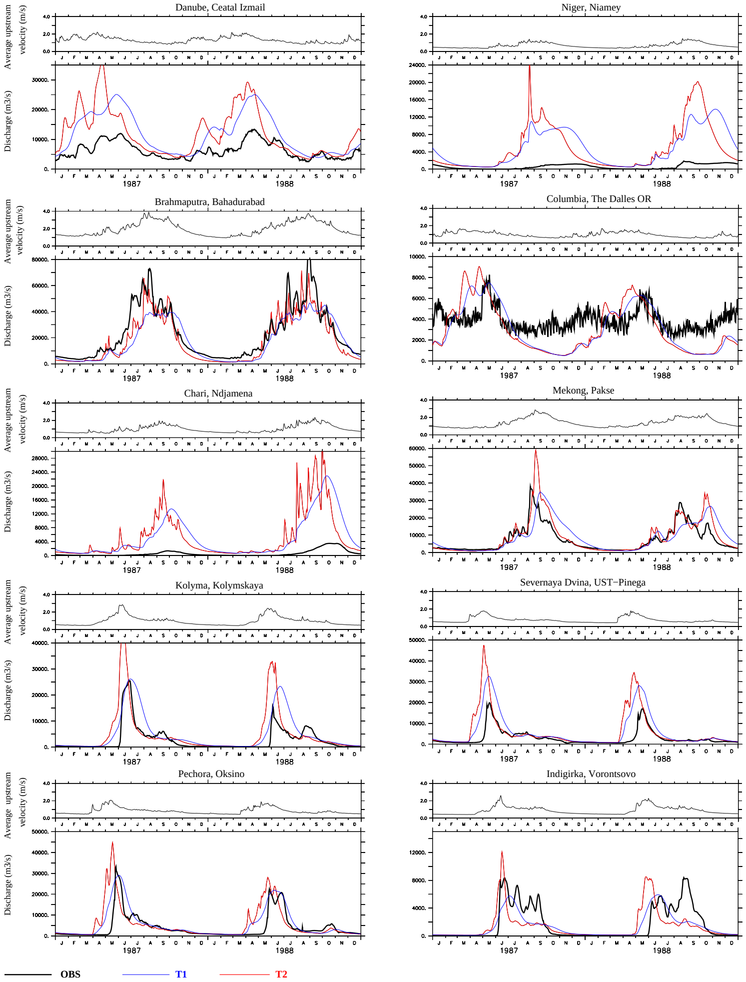

Fig. 6b. Continued.

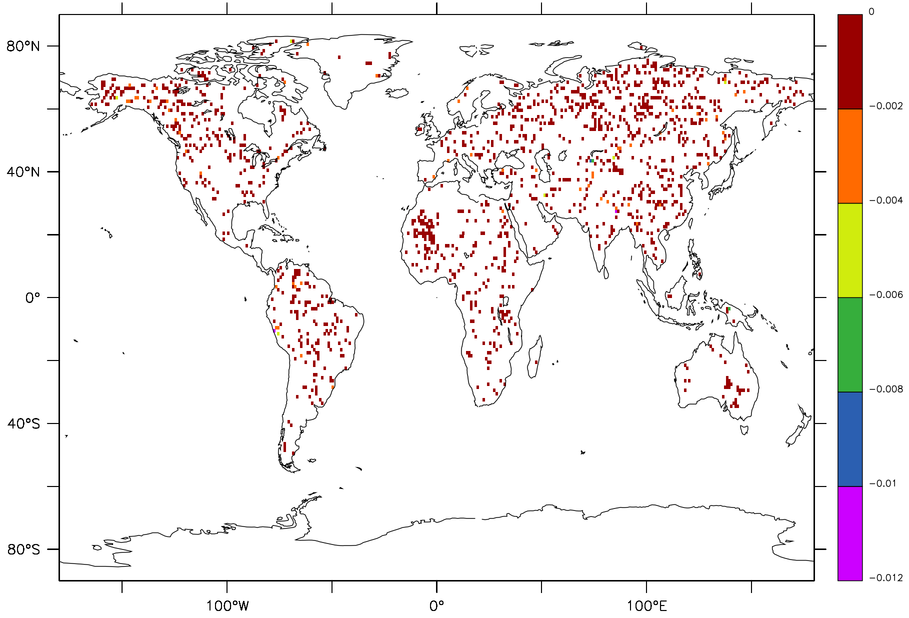

Fig. 7. Grid points on the 1 degree global map where the river slope is less than zero (i.e. the downstream point has higher elevation). In T2, the river slope of those points will be set to the minimum river slope value (which is positive).