Comparison of Grid-2-Grid and TRIP runoff routing schemes

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1 Introduction

The purpose of this report is to compare two river flow routing schemes, TRIP and G2G, for use in global and regional climate models. TRIP is the Total Runoff Integrating Pathways scheme developed by [*Oki et al.*, 1999]; G2G is the Grid-to-Grid routing scheme designed by [*Bell et al.*, 2007]. In this report, the two routing schemes are tested offline using surface and sub-surface runoff data from JULES forced with GSWP-2 data. The performance of each routing model is evaluated against observed data, where available, for ten of the largest river catchments globally. The model outputs are also compared when forced with data produced by HadGEM3.

In the remaining sections of this report, the river routing models are described briefly; the driving data is documented, and the domain and catchments of interest for which observed data are available are described. Results of the comparison are then presented, and the implications for future work are discussed.

2 Methods

2.1 TRIP

The Total Runoff Integrating Pathways (TRIP) river routing model [*Oki and Sud*, 1998] has been implemented in the Met Office Unified Model and in JULES [*Falloon and Betts*, 2006; *Falloon et al.*, 2007] (see also: http://hydro.iis.u-tokyo.ac.jp/~taikan/TRIPDATA/TRIPDATA.html). The aim of TRIP is to provide a method for routing runoff from the land surface to river basin outlets to enable the validation of the runoff part of land-surface parametrizations in global climate models (GCMs), and to permit estimates of the effects of climate change on runoff. The TRIP scheme consists of two main components: (i) a gridded dataset of river flow pathways; and (ii) a relation expressing the time-varying integral of runoff over all grid-boxes that comprise a river basin.

Flow pathways for use with TRIP are available at 1° or 0.5° horizontal resolution, depending on the version used. A refined flow direction dataset is also available at 0.5° horizontal resolution [*Döll and Lehner*, 2002]. This dataset, known as DDM30, has been adjusted with reference to mapped river outlines and GRDC river gauge locations. In the present evaluation, we use the standard 1° TRIP ancillaries (see Figure 1 for an example)

The river flow routing scheme used in TRIP [*Oki et al.*, 1999] assumes a single linear river routing store, *S*, the contents of which are updated at each time-step, *t*, according to the following rule:

$$\frac{dS}{dt} = D_{in} - D_{out}, \quad [1]$$

where D_{in} is the input from upstream and

$$D_{out} = cS, \quad [2]$$

where *c* is a wave-speed (adjusted to account for the extra path length of rivers that meander). The wave-speed is constant in time and uniform in space, and is usually set to 0.5 m s^{-1} [*Oki et al.*, 1999].

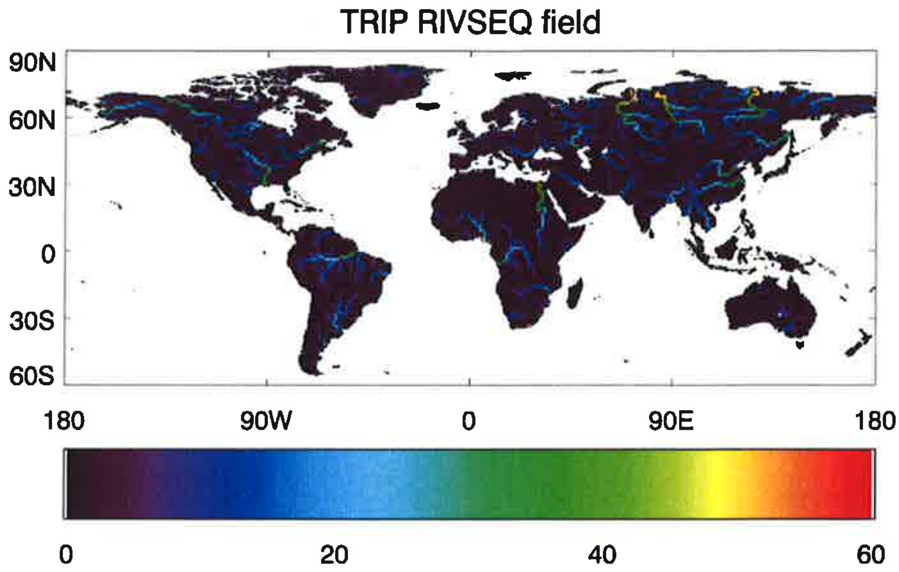

Figure 1: TRIP river network.

2.2 G2G

The Grid-to-Grid (G2G) model [*Bell et al.*, 2007] is based on a 1D kinematic wave routing model which relates channel flow, *q*, and lateral inflow per unit length of river, *u*, by:

$$\frac{\partial q}{\partial t} + c\frac{\partial q}{\partial x} = cu, \qquad [3]$$

where *c* is the kinematic wave speed and *x* and *t* are distance along the reach and time, respectively. In practice, the formulation in Equation 2 is employed in discretized form for discharge, *q*, in the *n*th reach at time *k*:

$$q_k^n = (1-\vartheta)q_{k-1}^n + \vartheta\left(q_{k-1}^{n-1} + u_k^n + R_k^n\right), \qquad [4]$$

where n $\vartheta = c\,\Delta t/\Delta x$ is the dimensionless wave-speed, and R_k^n is a term to represent return flow between the surface and sub-surface flow pathways.

The version of G2G used for testing here is an offline equivalent of the version being implemented for use in regional climate model configurations of the UM with a modification to account for variable grid box sizes encountered on the global model grid. The latitudinal variation of grid-box area with latitude can be written approximately as

$$A_i = 1/2\,(R_e \sin\alpha)^2(\cos\vartheta_i + \cos\vartheta_{i+1}), \qquad [5]$$

where A_i is grid box area, R_e is the radius of the Earth, α is the angular resolution of the model grid, and ϑ_i is the latitude of the grid box. In practice, a UM routine, arealat1.f90, is available to perform this calculation; this routine was used in the present tests. It was also necessary to modify the code so that the dimensions of the prognostic store were those of discharge rather than runoff (i.e., $m^3\ s^{-1}$ rather than $kg\ m^{-2}\ s^{-1}$), so that water volumes were correctly accounted for when adding accumulated runoffs from grid-boxes of differing areas.

In order to ensure consistency in the comparison, the same TRIP 1° flow directions were used in the evaluation of G2G model (see Figure 1). We note that in contrast to TRIP, G2G does not account for the effects of river meanders on flow path lengths.

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2.3 Driving data

Two types of runoff data were used to drive the offline G2G model: (i) reanalysis data from the Global Soil Wetness Project 2 (GSWP-2) project; and (ii) HadGEM3 model output. These forcing datasets are described in more detail below. TRIP outputs from simulations using identical forcing datasets were supplied by N. Gedney and A. Wiltshire (Met Office) for the purposes of the present evaluation.

2.3.1 GSWP-2

Driving data for offline comparisons were taken from the GSWP-2 project [*Dirmeyer et al.*, 2007]. GSWP-2 provides a global 1° gridded multi-model land surface analysis forced with a 'hybridized' combination of reanalysis data and observations. Reanalysis outputs from NCEP/NCAR and ERA-40 were used as the basis for a dataset at high temporal resolution (which resolves the diurnal cycle), but systematic biases in the reanalysis data were corrected with reference to a monthly global observed dataset compiled as part of the ISLSCP Initiative II [*Dirmeyer et al.*, 2007]. The resulting meteorological data were used to drive JULES (Gedney, pers. comm.), to produce surface and subsurface runoff fields.

JULES, the Joint UK Land Environment Simulator, resolves four soil layers in the vertical direction, each with a temperature and soil moisture content associated [*Cox et al.*, 1999; *Essery et al.*, 2003]. In common with most land-surface models, water and heat are assumed to move in the vertical direction only. Flow of water between the layers is determined using the Richards equation. Estimates of surface and subsurface runoff are calculated as the amount of liquid water leaving a grid square on the land and below ground, respectively. The runoff-production scheme employed to create the driving data used here is JULES-PDM [*Blyth*, 2002]. In this model, soil water capacity is assumed to follow a Pareto distribution in a manner based on the PDM of [*Moore*, 1985]. This formulation allows spatial and temporal variation in the proportion of the grid square which is saturated and producing runoff. The surface and sub-surface runoff produced then formed the driving data for the present study.

2.3.2 HadGEM3

In addition to the GSWP-2 driving data described above, climate model data from the AR5 HadGEM2-ES pre-industrial control experiment was used. In these simulations, the land-surface scheme used was identical to that employed in the GSWP-2 example above, but the fraction of each grid box that is saturated and producing runoff was determined using the TOPMODEL-based formulation of [*Gedney and Cox*, 2003], in which the height of the water table is explicitly modeled and related to local topography.

2.4 Observed river flow data

In order to compare modelled and observed river flows for a number of major world river basins, daily flow data were obtained from the Global Runoff Data Centre (GRDC). Ten river basins (the top two from each of the five major continents) were chose for analysis; of these eight had a suitable observed record for additional comparisons with measured flow data. The catchments range in area from 0.81×10^6 km^2 to 4.64×10^6 km^2 (Table 1).

Table 1: Properties and locations of test catchments

Basin	Area	Lat	Lon
	10^6 km^2	°	°
Amazon	4.64	-0.5	-51.5
Parana*	2.35	-34.5	-58.5
Congo	3.48	-5.5	-13.5
Nile*	3.25	30.5	30.5
Mississippi	2.96	30.5	-90.5
Mackenzie	1.66	67.5	-133.5
Danube	0.81	45.5	28.5
Volga	1.36	47.5	46.5
Ob	2.95	67.5	71.5
Yenisey	2.44	70.5	82.5

2.5 Model calibration

The G2G model has never been applied at this resolution before. In order to investigate the sensitivity of model performance to choice of parameters a latin hypercube experimental design was used, in which the G2G surface and subsurface wave speeds and return flow proportions parameters were perturbed from their standard values. The G2G parameters *criver* and *cbriver* correspond to the *c* terms in Equation 3 and the *retr* parameter corresponds to the *R* term in Equation 4. Standard values of *criver* = 0.5; *cbriver* = 0.05, and *retr* = 0.005 were examined across the ranges *criver* = [0.1, 1.0]; *cbriver* = [0.01, 0.1], and *retr* = [0.001, 0.01] using the root-mean-squared error (RMSE) and Nash-Sutcliffe model efficiency score as objective functions, averaged over the catchments in

Table 1 for which observed data were available. The greatest influence on model performance was from *criver*, the surface river wave speed. As indicated in Figure 2 the optimal value for *criver* was adjusted upwards to 0.62 for the present application.

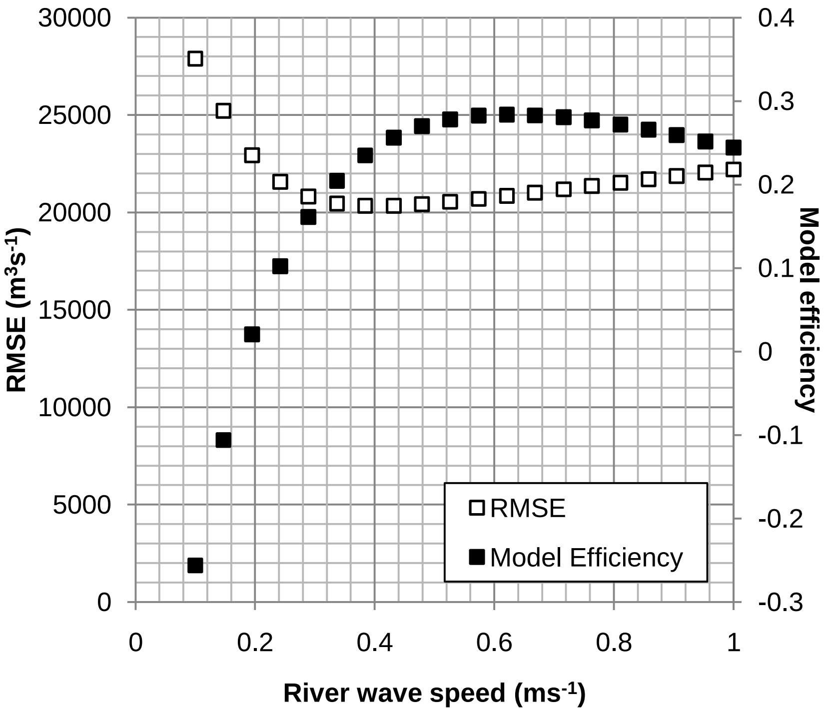

Figure 2: Calibration of model parameters

3 Results and analysis

3.1 Model performance

An indicative map of G2G flow output is given in Figure 3. The white grid boxes on land represent locations where the TRIP flow direction dataset indicated no outflow grid-box (i.e., the grid box was internally drained). These locations were excluded from the analysis because G2G does not currently account for endorheic basins.

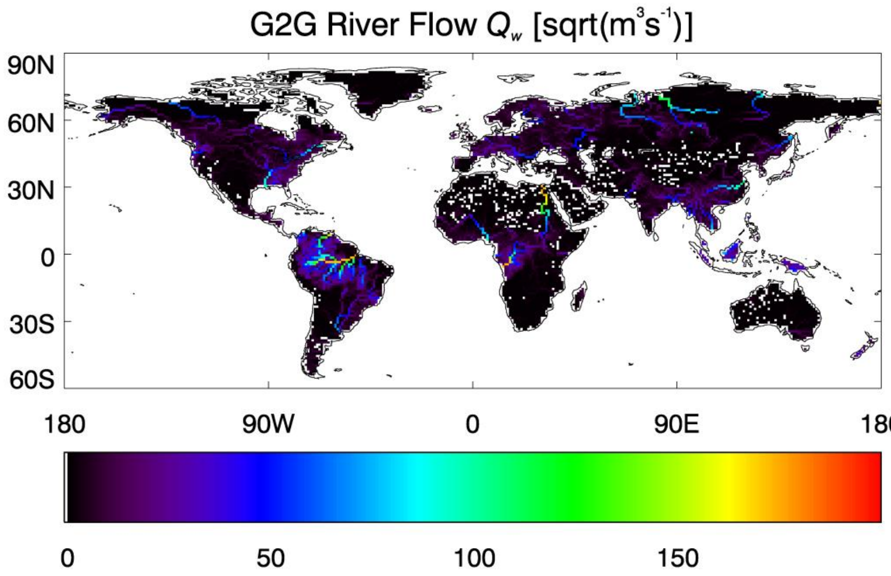

Figure 3: Example of G2G river flow output.

Results from the optimised simulations are given in Table 2. Mean flows in the majority of catchments are approximately equal (to within one percent) for G2G and TRIP. However, in the Ob, Yenisey, and Mackenzie, the average flow calculated by TRIP was up to six percent lower than was calculated by G2G. Possible reasons for this discrepancy include the differential treatment of surface and subsurface flow in each of the models (although usually this would lead to a lower surface water volume in G2G compared to TRIP, because in G2G some water is passed out to the ocean as subsurface flow). Whilst this feature may explain the one percent discrepancy between the two models for the Amazon, it does not explain why the three northern catchments have distictly lower flow averages in TRIP compared to G2G. It is possible that a problem related to water conservation in TRIP is responsible, and is worthy of further investigation.

Table 2: Evaluation of model performance

	Mean flow			RMSE		NS	
	10^3 m^{3}s^{-1}			%(obs)		[-]	
	G2G	TRIP	OBS	G2G	TRIP	G2G	TRIP
Amazon	159.7	162.0	172.8	24	17	0.37	0.68
Congo	51.5	52.0	40.3	73	66	-0.17	0.02
Mississippi	17.6	17.8	18.5	42	44	0.29	0.25
Mackenzie	12.4	11.7	9.0	91	90	-0.55	-0.52
Danube	4.8	4.8	5.7	42	41	-0.05	-0.04
Volga	9.9	9.9	7.7	133	131	-2.28	-2.22
Ob	12.1	11.5	12.6	44	49	0.72	0.65
Yenisey	17.3	16.3	19.3	100	103	0.28	0.24

Table 2 also gives the RMS error between model and observed data, evaluated on a daily basis. Values are comparable: in some catchments TRIP is better (e.g., Amazon, Congo, Mackenzie, Danube, Volga), but in others G2G is better (e.g, Mississippi, Ob, Yenisey). The overall average RMSE was identically 68 percent for each of the routing methods. Some error may be attributed to catchment area errors arising from the use of TRIP 1° flow directions, which may be up to 20 percent [*Oki and Sud*, 1998].

Similar results were obtained for the Nash-Sutcliffe model efficiency: TRIP performs best in the Amazon, the Congo, and the Volga (although in the Volga neither model gave an improvement over using the observed mean flow as a predictor); whereas G2G outperformed TRIP in the Mississippi, the Ob, and the Yenisey. In the Mackenzie and the Danube the results lay within three percentage points of each other and so are probably, in practice, indistinguishable.

3.2 Detailed flow time-series

Investigation of individual flow time-series for particular catchments gives some insight into the reasons for model performance (Figure 4). In the Amazon, for example, the higher surface wave speed used for the G2G makes it too responsive to runoff peaks: a slower wave speed would be an obvious solution in an application focused specifically on this river basin. The effect is similar in the Parana and Congo. The effect of floodplain attenuation of flood peaks may be significant: the kinematic wave approach, in which the momentum term from the full shallow water equations is ignored, does not account for the effects of floodplain attenuation. An alternative explanation is that anthropogenic modification to the river system has not been accounted for in the model.

In contrast, for the Missisippi, where both TRIP and G2G exhibit responses that are too slow compared with the observed record, anthropogenic effects may result in flow conveyance being higher than the globally-calibrated model would predict (through channelization and dredging, for example). The same problem of the model being too slow affects the Mackenzie and the Volga, although the effects of anthropogenic modifications in the latter two rivers are less well known. For the Danube, both models capture the broad seasonal patterns of flow although day-to-day flow variations are not always adequately resolved. Again, the possibility of anthropogenic modification to observed flow record may be significant here (and is highly likely given the pattern of consistently higher low flows in the observed record than in the modelled results).

The record of observed flow in the Yenisey shows a consistent sharp peak each spring, which is not represented in the modelled output. This river drains much of central Siberia and is dominated by meltwater from previously frozen ground. The deviation between modelled and observed flow in this basin suggests that improvements to JULES runoff in freezing conditions may be required. It is noteworthy that both models perform better in the Ob, which drains western Siberia, although there are some years when the magnitude of the meltwater pulse is poorly estimated. It might be speculated that this result indicates that JULES includes the correct physics to represent meltwater peaks, but that meltwater is poorly simulated in the Yenisey owing to deficiencies in the GSWP-2 data. Further speculation on these matters is beyond the scope of the present report, but we suggest that further investigation of JULES' ability to model melting permafrost is warranted.

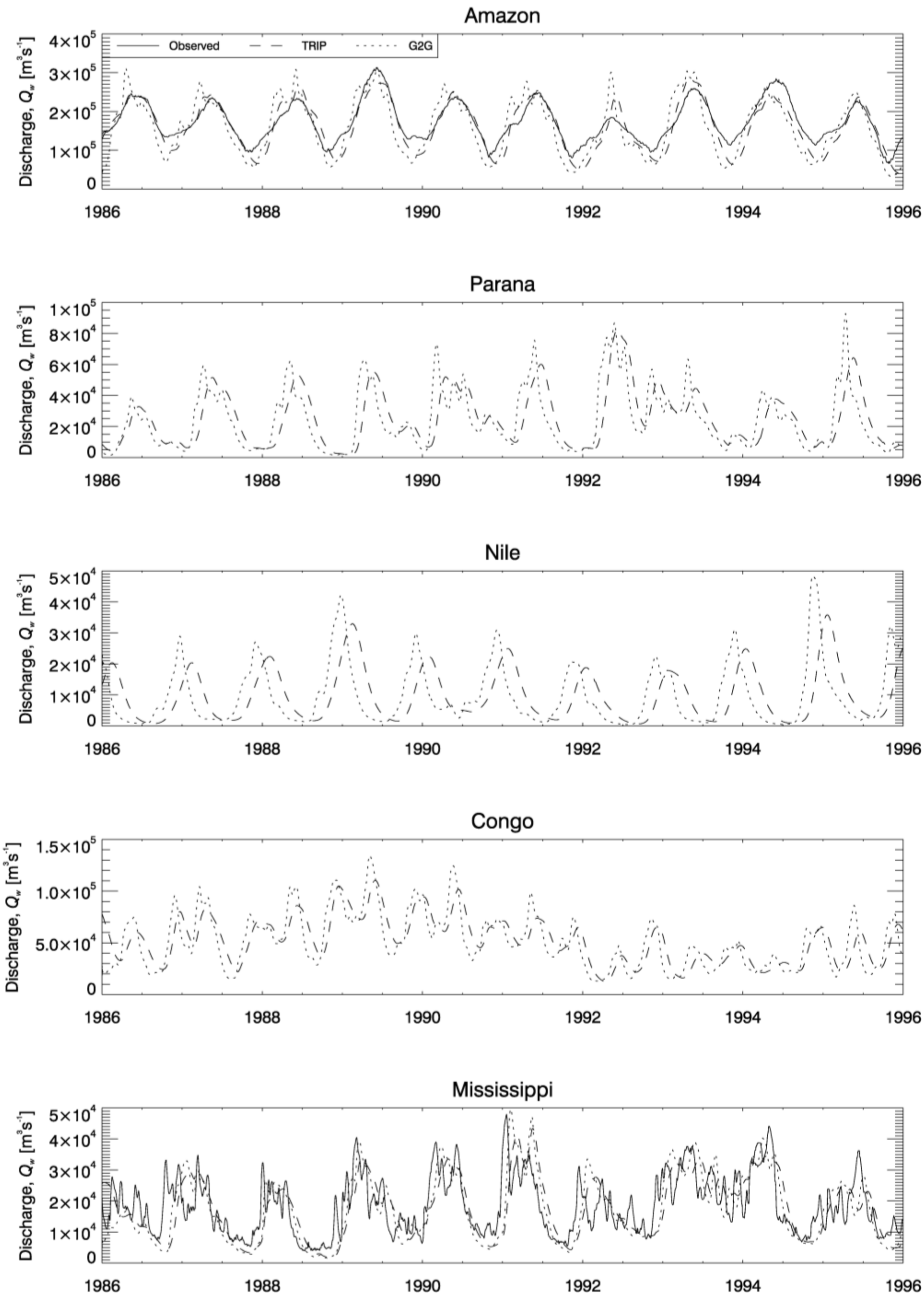

Figure 4: Flow time-series (GSWP-2)

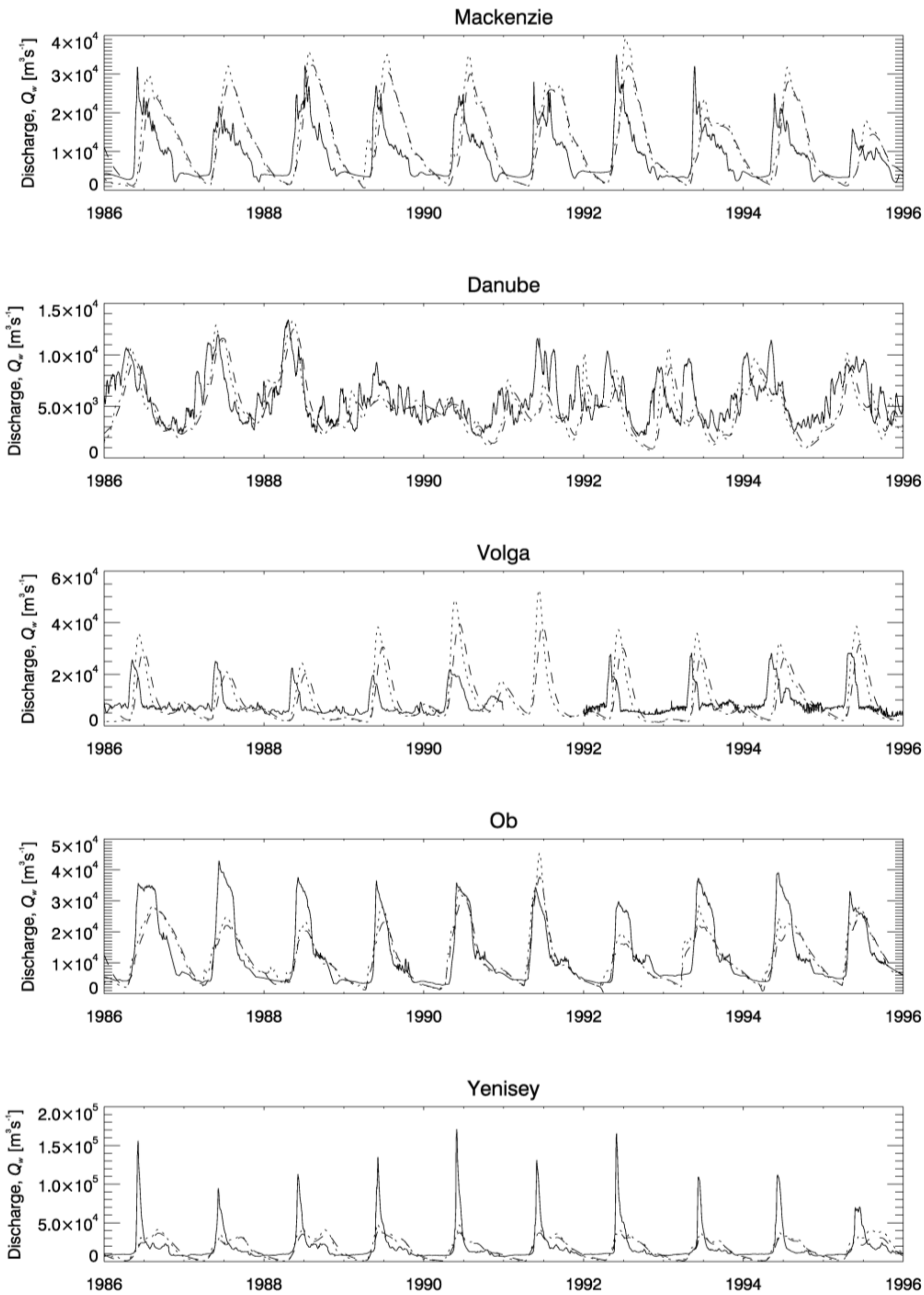

Figure 4 (ctd): Flow time-series

3.3 HadGEM3 Comparison

Outputs from a simulation driven with HadGEM3 data are given in Figure 5. We present these to give an indication of the likely differences between the two routing schemes when employed in a global modelling application. These experiments were performed using the same model parameters as with the GSWP-2 data. Naturally the two time-series are very similar (it should be noted that TRIP flows were available from the model only as monthly means). In most basins (e.g., Amazon, Mississippi, Mackenzie), G2G shows a less flashy response than TRIP, with lower peaks and higher low flows. This is not surprising given the slower sub-surface flow pathway used by the G2G but absent from TRIP.

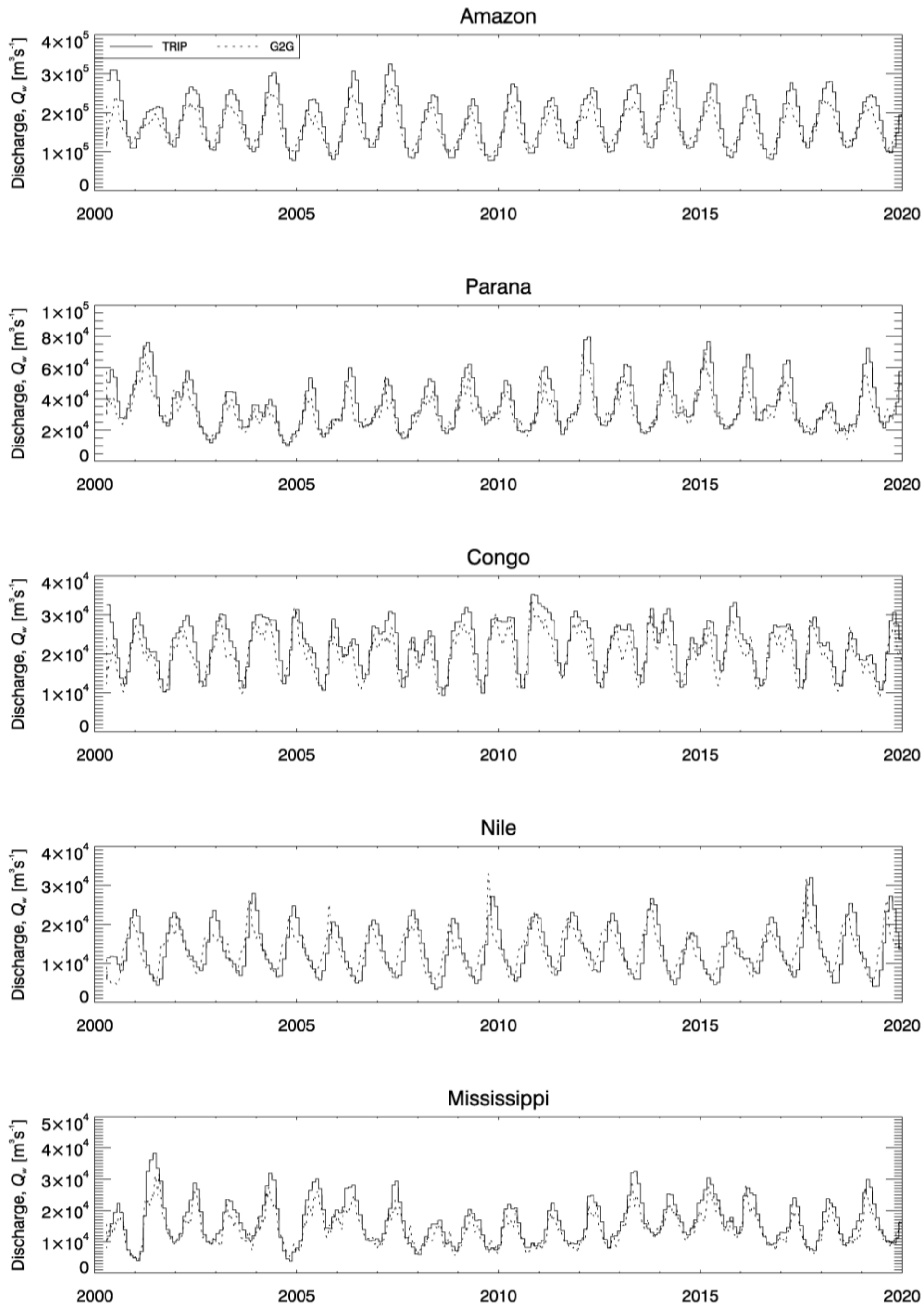

Figure 5: HadGEM3 flow time-series

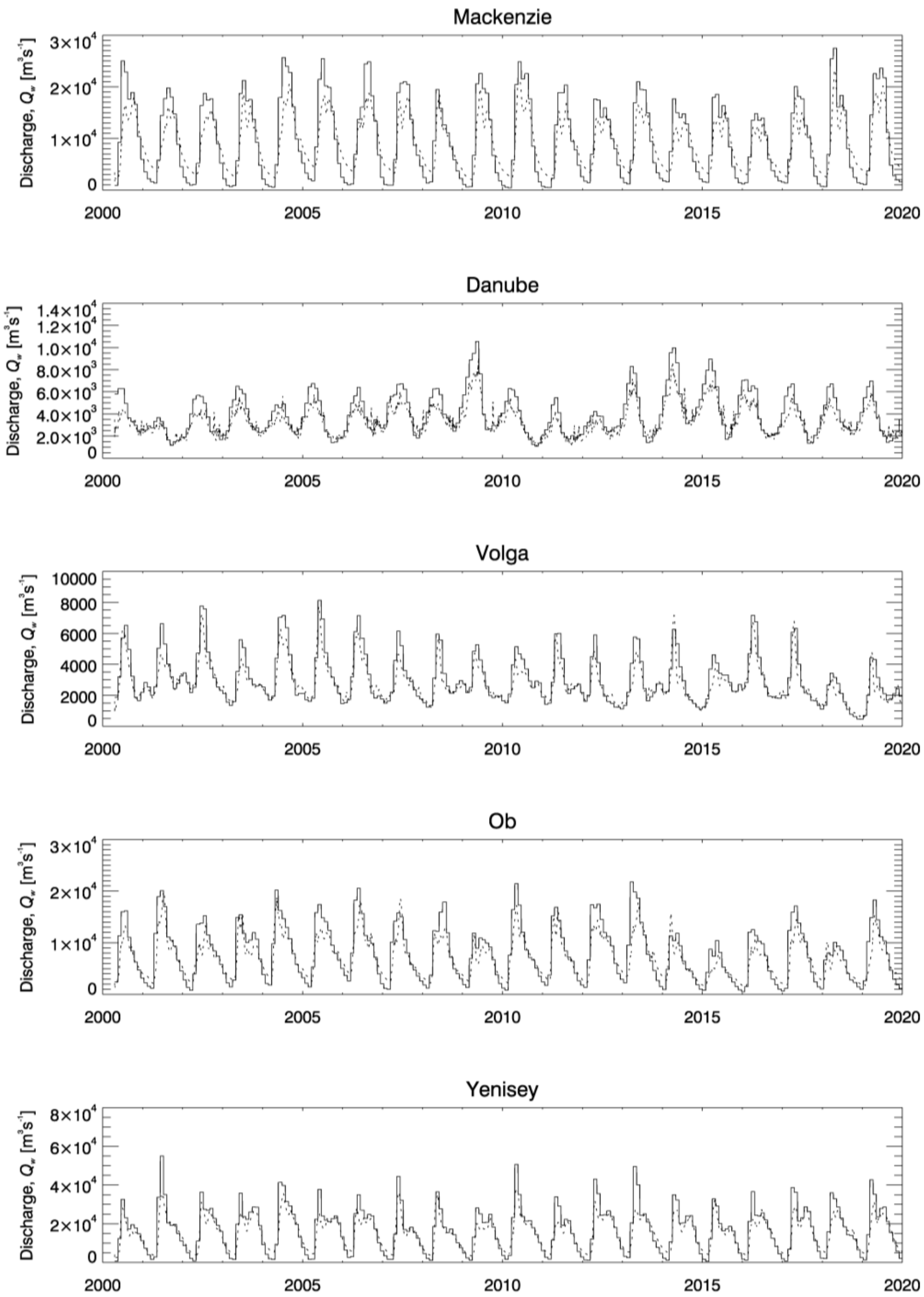

Figure 5 (ctd): HadGEM3 flow time-series (note that vertical scales differ from those used in Figure 4)

Discussion and conclusion

In this report, we have shown that G2G and TRIP offer comparable performance in simulating river flows for selected major river basins. Neither model was universally better than the other, when compared with observed data from the GRDC. Model performance in individual basins points to a number of potential improvements to the models. G2G could be improved through: (i) the incorporation of extra information on sub-grid meandering, (ii) introduction of an explicit treatment of internally-draining basins, and (iii) consideration of the fate of sub-surface flow at the coast. Issues relating to the conservation of water in TRIP may explain some of the differences in model performance. Note that for the finer-scale resolution for which the G2G model was developed, a correction for sub-grid-scale river meandering was not required.

Overall, aside from possible water losses in TRIP, the main difference between the two schemes is likely to be due to the use by G2G of two parallel routing pathways, with G2G surface and sub-surface routing wave speeds being faster and slower, respectively, than the single routing component of TRIP. In areas where a greater proportion of runoff is partitioned to the surface, the G2G will tend to have higher flow peaks, while in areas with a greater proportion of sub-surface runoff, the G2G will tend to produce a steady baseflow and lower flow peaks than TRIP. It is likely that the type of runoff-production scheme used (e.g., PDM or Topmodel) will influence the relative proportions of surface and sub-surface runoff, and the chosen routing scheme may require separate parameters for use with each runoff-production scheme.

Although the G2G model was developed for regional applications, these results indicate that it can also be applied globally to good effect, although some of the functionality (e.g., parallel surface and sub-surface routing and the distinction between land and river pathways) may be less relevant at the global scale.

More generally, we note that future work to extend this comparison to other catchments may be of use. In any case, better knowledge of anthropogenic changes to flow is needed Additional calibration or validation datasets available from EO data would complement the methods used here, and may be particularly appropriate in remote locations such as the Siberian rivers where data on the extent of frozen ground would be useful in diagnosing the reasons for poor model performance.

5 Acknowledgements

Nic Gedney provided data from JULES simulations forced with GSWP-2 meteorological data and associated TRIP flow outputs; Andy Wiltshire provided HadGEM3 runoffs and associated TRIP outputs. We thank Douglas Clark for additional information on the TRIP runoff routing scheme.

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