New Global River Routing Scheme in the Unified Model

Hadley Centre technical note 72

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Summary
A new global river-routing scheme has been implemented in HadCM3 and HadGEM. In HadCM3, the new scheme produced improved agreement in river flow seasonality with observations for most major rivers. The new scheme is available in the current version of HadGEM.

Introduction

The proper representation of river flows in GCMs is important for a number of reasons:

(i) Changes in river flow may be a major effect of climate change on society.

(ii) The flow of freshwater from the land to the oceans exerts a significant influence on the thermohaline circulation, so a good representation of river flow is important for a realistic reproduction of the thermohaline circulation in a coupled atmosphere-ocean GCM.

(iii) River flow is also a potentially useful quantity for validating hydrological aspects of large-scale models, as rivers can indicate the state of the surface water budget across very wide areas.

The old global river routing scheme in HadCM3 represented runoff from river basins by simply aggregating the runoff in all gridboxes within the basin and instantaneously inputting this to the ocean at the gridbox containing the river mouth. While this provided a good representation of annual mean transport of freshwater to the oceans at river outflow points, it does not facilitate the simulation of river flows at points within the basin. It is therefore not useful for validating the model against river flow measurements at points other than at the coastal outflow point, so the wealth of data available from river gauging stations cannot be exploited. Neither can the current scheme be used to predict future changes in river flows upstream from the coast, limiting the applicability of the model to studying the hydrological effects of climate change.

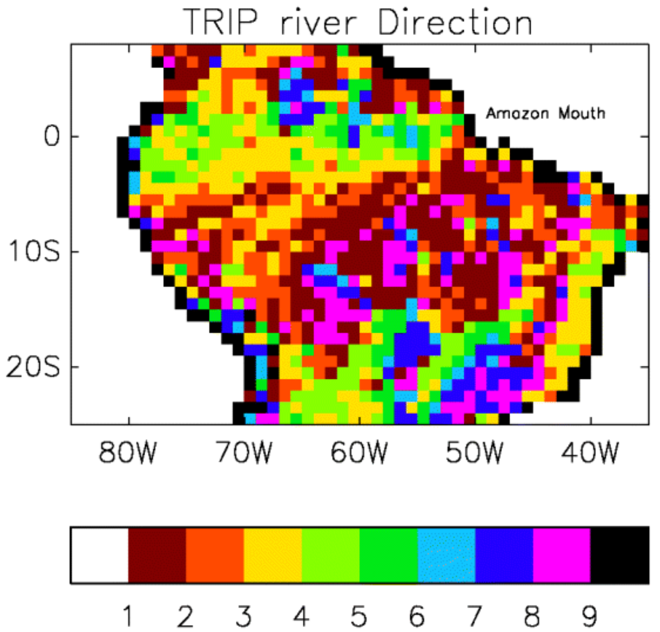
Moreover, the instantaneous transport of water means that the model neglects the lag between the production of runoff by rainfall and its flow through river channels and into the ocean. For major rivers such as the Amazon, this lag can be of the order of months. In rivers with significant seasonal variation in flow, for example due to highly seasonal rainfall or snowmelt, neglecting this lag can result in major discrepancies between modelled and observed runoff. This again reduces the usefulness of validating against river station data, and also affects the timing of maximum and minimum freshwater flows into the oceans. The new scheme addresses these issues by routing runoff through a river network and introducing a finite rate of flow.

The TRIP River Routing Scheme

The new scheme uses the model Total Runoff Integrating Pathways (TRIP), developed by Oki & Sud (1998). Detailed information on TRIP may be found from the TRIP homepage at http://hydro.iis.u-tokyo.ac.jp/~taikan/TRIPDATA/TRIPDATA.html. TRIP uses a simple advection method to route total (surface and subsurface) runoff along prescribed river channels. The river channels are represented by two datasets giving the direction (Figure 1) and sequence (Figure 2) of the flow of water. In the version of TRIP currently implemented in the UM, Oki & Sud (1998) produced these at $1^{o} \times 1^{o}$ resolution from the Digital Elevation Map ETOPO5 using a combination of automation and manual alteration.

In the river sequence dataset, each box in the channel is numbered starting at 1 (at the head of a channel) until it meets a more major channel or reaches the sea. Calculations are first performed for all gridboxes labelled 1, then all gridboxes labelled 2, and so on. Many small tributaries will have only a sequence of 1 until they meet a more major channel. In Figure 2, the dark brown boxes represent short tributaries with a 1,2,3 or 4 sequence of flow until they meet a more major channel or the main Amazon channel itself.

Figure 1: Prescribed direction of river flow from gridboxes in Amazonia.
1: N, 2: NE, 3: E, 4: SE, 5: S, 6: SW, 7: W, 8: NW and 9: river mouth.

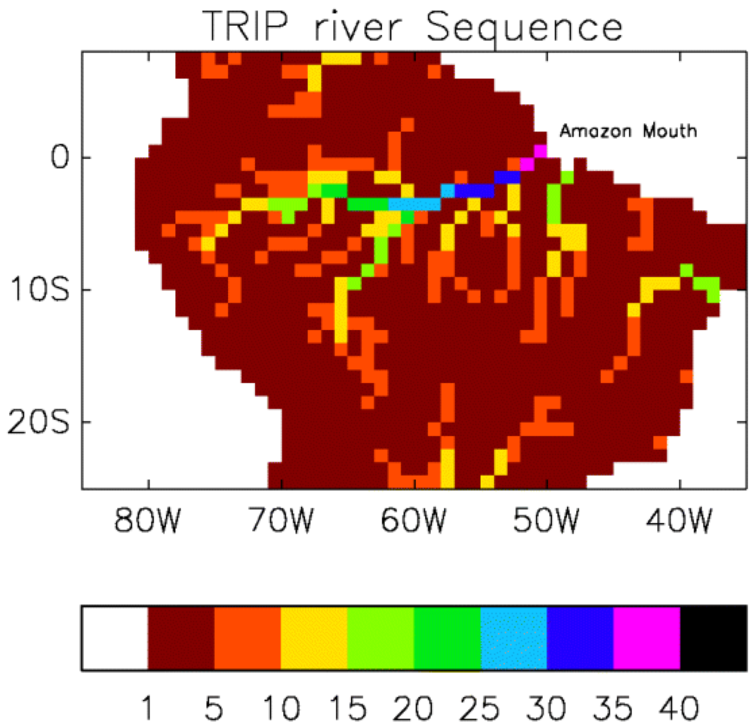


The linear routing algorithm of TRIP is given below. For conservation of river storage:

$$dS_{rc}/dt = D_{IN} - D_{OUT} \qquad (1)$$

where S_{rc} is the river water storage (kg) in a gridbox, D_{IN} the sum of inflow (kg s^{-1}) from neighbouring gridboxes and runoff (kg s^{-1}) produced within the gridbox. The flow direction file is used to calculate D_{IN} and gives the direction D_{IN}.

Figure 2: River sequence labelling for gridboxes in Amazonia.



$D_{OUT} = cS_{rc}$

is the outflow from a gridbox (one direction only per gridbox) and c = u/d, where u is the effective velocity (m s^{-1}) and d the distance (m) across the gridbox multiplied by a meandering ratio to better represent the real length of the river. Oki & Sud (1998) chose a universal meandering coefficient of 1.4 by comparing the actual length of the longest rivers with those in his river network (the range of the ratio was between 1.0 and 1.6).

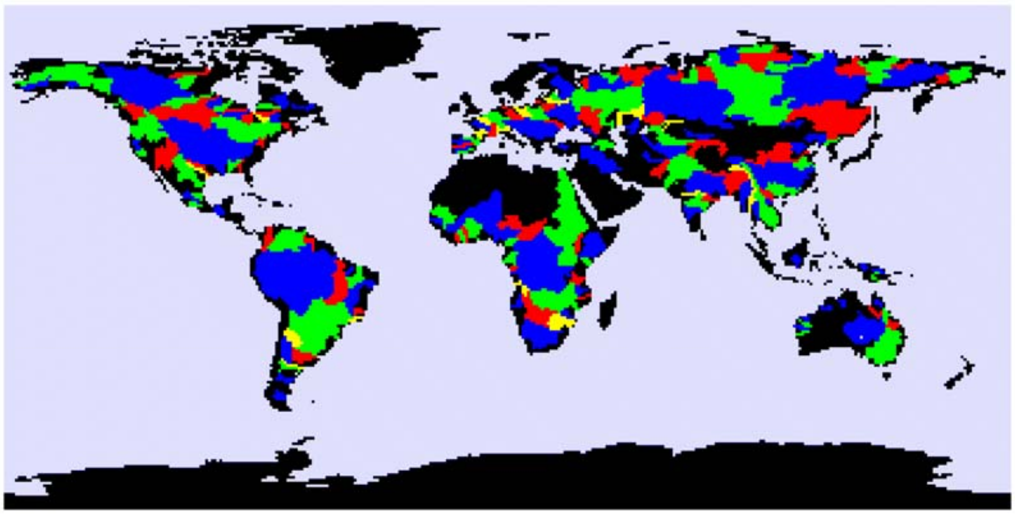
Then, if $C_t = \exp(-c\ dt)$, water storage S_{rc} at time $t_0 + dt$ is given by

$$S_{rc}(t_0 + dt) = C_t S_{rc}(t_0) + (1-C_t)D_{IN}/c \qquad (1)$$

The value of u was chosen to satisfy u.dt < d. In Polar Regions, d < 20,000m for 1° distance East-West . The major river basins in TRIP are shown in Figure 3.

Testing TRIP prior to coupling
The TRIP scheme was first tested offline of the climate model using monthly means of runoff from a HadAM3 simulation performed with AMIP II sea-surface temperatures. The runoff data were regridded from the HadAM3 resolution 2.5° × 3.75° grid to the 1° × 1° TRIP grid. In comparison with the old scheme, TRIP was found to improve the seasonality of freshwater flow into the oceans for most of the major rivers.

Figure 3: Major river basins in TRIP



The original TRIP scheme uses 10 day mean values of runoff and initial water storage which is spun-up using the first year of runoff data until the water storage reaches equilibrium. It has a 12 hour timestep and an effective velocity of 0.5 m s^{-1}. It was found that satisfactory results were obtained using monthly means of runoff instead of 10 day means, which are more readily available from GCM experiments. The scheme was also tested with a 24 hour timestep and an effective velocity of 0.4 m s^{-1} (Taikan Oki, personal communication) which produced similar results to those from the original 12 hour timestep.

Coupling to the GCM
TRIP was coupled to HadCM3/HadGEM by taking daily mean (total surface and subsurface) runoff from the HadCM3/HadGEM land hydrology scheme as input and providing daily mean outflow at river mouths to the HadCM3/HadGEM ocean as output. Diagnostic output from TRIP consists of total inflow, total

outflow and water storage for each grid-box on every river routing timestep. As the river sequence and direction file could not be interpolated to the GCM Atmosphere grid, the 1º resolution of TRIP was maintained when coupled, so the inputs and outputs are regridded between the HadCM3 and TRIP grids. River flow calculations use a timestep of 1 day and a flow velocity of 0.4 m s^{-1} (Taikan Oki, personal communication). Although the TRIP timestep can theoretically be any multiple of the atmosphere model timestep, a daily timestep gives the best balance between realistic timescales and computational efficiency. Initial water storage files were provided by Taikan Oki (University of Japan) so these were spun-up off-line, using HADAM3 long-term monthly means of runoff and a daily timestep to produce monthly initial ancillary files. It would be best to spinup water storage off-line using the first year of daily runoff values from the model run. However, for most of the major rivers, 5 years appears to be enough to spin-up water storage. The water storage field can be kept in a model dump to initialise a new simulation. TRIP can be used in an atmosphere-only simulation (without the ocean component of the full model) in order to provide river flow diagnostics for model validation. Due to non-congruence of the TRIP 1º × 1º degree grid and the GCM Atmosphere grid there was some manual alteration of the river direction and sequence files to ensure that river grid river mouths mapped onto Atmosphere grid seapoints. Also, due to this non-congruence, some runoff needed to regridded from the Atmosphere to a TRIP seapoint so the resulting TRIP grid runoff was added directly to the output for this point for conservation.

TRIP was implemented in HadCM3 experiments as a modset and has been available in the UM since version 5.5 code. The old routing scheme and the new scheme in the HadCM3 experiment were originally part of the Coupling routines but the Atmosphere Model was considered more appropriate so in HadGEM1 (and the UM code) the new scheme has been inserted into the Atmosphere model. This has the added advantage that it can be run in an Atmosphere-only mode if being used for validation purposes.

Observations

Long-term observations of river flow at many gauging stations are available from the Global Runoff Data Centre (GRDC). These cover varying periods of time and the stations are rarely at river mouths which made it difficult to compare them with basin outflow from the old scheme. However, the new TRIP scheme outputs the outflow from each gridbox so the observations can be compared with the outflow from the 1º × 1º degree gridbox containing the gauging station. Observations are often used from stations as close to the river mouth as possible, although stations upstream and particularly those above dams and wetlands (which interfere with flow) may be useful for further validation.

Results from HadCM3

A 42-year run was been completed in HadCM3 including TRIP, although the first 22 years were ignored as there were found to be small errors in the code. This was also considered as a spin-up period for the river water storage. The results of the 20 year continuation run and the old river routing scheme were compared with observations taken from GRDC gauging stations as close to the river mouth as possible in order to best represent the outflow from the whole. For the new scheme, simulated river flow was taken from the gridbox corresponding to the location of the gauging station used for observations, but the old scheme only provided flow at the river mouth. This may therefore account for some of the disagreement between the flow simulated by the old scheme and the observations, and illustrates why it is useful for TRIP to diagnose flow in all gridboxes. Furthermore, since the old scheme used the same resolution as the atmosphere model (2.5º × 3.75º) the coarseness of the grid led to larger approximations in the model's representation of river basins. Table 1 gives an approximation of distances from the river mouth of observations. For both schemes, validation for some rivers was inappropriate because of significant human intervention (such as dams) which is not yet accounted for in the model.

Figure 4 illustrates the positions of the major rivers and shows the 10-year mean annual flow from the HADCM3 run. As this is the outflow from each gridbox on the river grid the flow along rivers can be seen. A table of a comparison of the annual discharge and basin areas in the old and new scheme with observations is shown in Table 2. There was an improvement in the annual discharge in the new scheme, even when the difference in area between the old and new schemes was taken into account. The exceptions to this were the Huanghe, La Plata (the outlet for the rivers Parana and Uruguay) and Murray basins. Table 1 also gives the position upriver of the lowest gauging station which illustrates a problem in validating river outflow at the sea. Figures 5, 6 and 7 show the validation for the world's major rivers. There was improved seasonality of flow using the TRIP river routing scheme (green solid line) compared to the old river routing scheme (red solid line). In the Northern hemisphere rivers (Mackenzie, Ob, Amur, Yukon) the new scheme gives extremely good agreement in amount and phase of flow with long-term GRDC mean values. The exception is the Lena, which appears better in the old scheme in both amount and phase. The old scheme shows the peak of snowmelt better than the new but the lag in its flow is missing.

The southern hemisphere rivers (Amazon and Orinoco) showed much improved seasonality over the old scheme but the annual mean flow was much too low. This may be partly due to HadCM3 simulating too little precipitation in some areas, which can be seen in Figures 8 and 9 which show the difference between HadCM3 precipitation and Legates and Willmot observations. It is also a consequence of shortcomings in the HadCM3 land hydrology scheme which is known to produce too little runoff. These shortcomings have been addressed in the new large-scale hydrology (LSH) scheme developed for HadGEM (Gedney & Cox 2002).

In the mid-latitudes, the Brahmaputra also lacks the peak in the autumn months in the new scheme which may also be due to low precipitation in the model in the spring and summer months. In the old scheme the peak appears well represented but this may be because the basin combines the Brahmaputra and Ganges due to the coarse resolution of HadCM3.

It is difficult to validate some rivers due to the interference of human intervention in river flow by the use of dams, irrigation and also the presence of areas of wetlands e.g. River Niger. Some validation can be done where there are gauging stations above the 'interference'. This can be seen in Figure 10 for the river Niger at Koulikoro (approximately 1200 miles from the river mouth) upriver of vast wetlands (approximately 300 miles along the river) and at Niamey which is below them. There is good agreement from the new routing scheme for Koulikoro but poor agreement for Niamey. Unfortunately the gauging stations on the Nile and Huanghe are both below dams. However in both the Mississippi and Mekong, the outflow from gridboxes containing stations (Figure 11) which are further up river (1200 miles and 600 miles upriver of stations (Figure 11) respectively) show a closer match to observations.

Another factor which could affect the results is the meander factor which is set constant in all gridboxes. Oki & Sud (1998) chose this as a first order approximation for all rivers although in different meander ratios could be used for different river basins depending on the basin area.

Figures 12-15 show the resulting outflow in the ocean from the old and new schemes which show a definite seasonal difference reflecting the lag in freshwater reaching the sea.

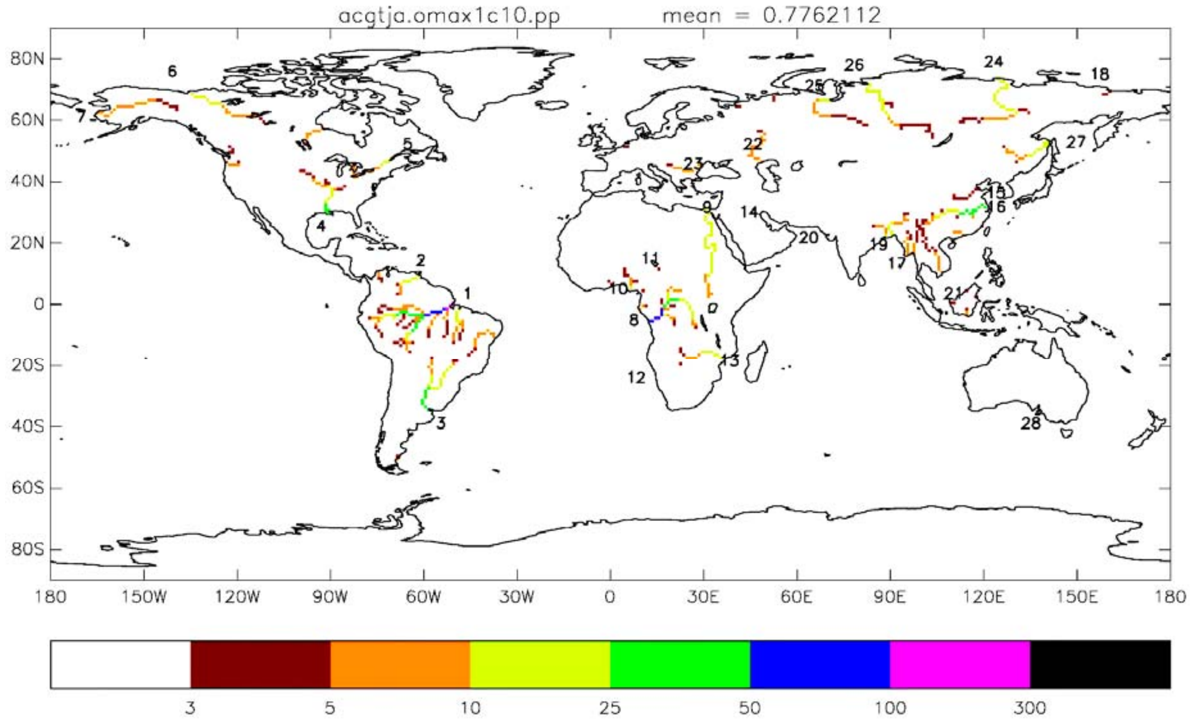
Table 1: Approximate distances from the river mouth of the GRDC observational gauging station nearest to the river mouth

The Chari runs into Lake Chad

* No guaging station values.

RIVER	STATION NAME	DISTANCE from mouth (approximate miles)
AMAZON	Obidos	450
ORINOCO	Puente Angostura	200
LA PLATA-PARANA:	Corrientes	550
LA PLATA-URUGUAY	Concordia	250
MISSISSIPPI	Vicksburg	280
St LAWRENCE	Cornwall (Ontario)	250
MACKENZIE	Arctic Red River/Fort Simpson	200
YUKON	Pilot Station	150
ZAIRE	Kinshasa	200
NILE	El Ekhsase	120
NIGER	Gaya	700
CHARI	Ndjamena (Fort Lamy)	#
ORANGE	Vioolsdrif	100
ZAMBEZI	Matundo-Cais	230
TIGRIS/		*
EUPHRATES	Keban (Turkey)	1000
HUANG HE	Huayuankou	450
CHANGJIANG	Datong	180
IRRAWADY	Sagaing	500
KOLYMA	Kolymskaya	100
GANGES/	Farakka	250
BRAHMAPUTRA	Bahadurabad	370
INDUS	Kotri	200
MEKONG	Pakse	480
VOLGA	Volgograd Power Station	300
DANUBE	Ceatal Izmail	30
LENA	Kusur	150
OB	Salekhard	100
YENISEY	Igarka	200
AMUR	Komsomolsk	300
MURRAY	Lock 9 Upper	150

Figure 4: HadCM3 10 year mean annual river flow (1000 kg s^{-1}) showing major rivers.



1 AMAZON	15 HUANGHE
2 ORINOCO	16 CHANGJIANG
3 LA PLATA	17 IRRAWADY
4 MISSISSIPPI	18 KOLYMA
5 ST.LAWRENCE	19 GANGES/BRAHMAPUTRA
6 MACKENZIE	20 INDUS
7 YUKON	21 MEKONG
8 ZAIRE	22 VOLGA
9 NILE	23 DANUBE
10 NIGER	24 LENA
11 CHARI	25 OB
12 ORANGE	26 YENISEY
13 ZAMBEZI	27 AMUR
14 TIGRIS/EUPHRATES	28 MURRAY

Table 2: Comparison of Annual River Discharge and Basin Areas for some Major Rivers from HADCM3 Long Term means

RIVER	OLD SCHEME $		NEW SCHEME *		OBSERVATIONS *	
	Outflow (m^3s^{-1})	Area (km^{-2})	Outflow (m^3s^{-1})	Area (km^{-2})	Outflow (m^3s^{-1})	Area (km^{-2})
AMAZON	115957.	6754460	87159.5	4757830	176620	4640300
ORINOCO	12593.1	1264380	13796.5	820240	31080	836000
LA PLATA- PARANA	7122.91	334850.	31709.6	2097620	16358	1950000
URUGUAY	-	-	1549.4	226970	5218	249312
MISSISSIPPI	30762.4	3428570	25444.4	3052510	16945	295389
St LAWRENCE	18837.1	1195370	9909.92	835680	7098	773892
MACKENZIE	12007.2	1802230	11364.1	1736950	8966	1660000
YUKON	9345.08	912950.	8333.2	826480	6355	831390
ZAIRE	80900.3	3574190	78603.7	3649110	40250	3475000
NILE	12888.9	4300650	13819.0	2886160	1251	290000
NIGER	29038.0	5055950	2798.23	883460	1093	1000000
CHARI	-	-	4159.9	558320.	1045	600000
ORANGE	1724.85	822148.	1672.1	884460	262	850530
ZAMBEZI	17736.3	2330900	12906.6	1070130	3337#	940000
TIGRIS	1987.57	1568680	-	159900	-	-
EUPHRATES	-	-	289.6	47880.	662	63835
HUANG HE	8484.64	1907300	4510.95	734580	1448	730036
CHANGJIANG	42456.6	1805210	41203.3	1751120	28710	1705383
IRRAWADY	5746.23	428160.	3478.	146150	8137	117900
KOLYMA	2855.80	657604.	3312.73	536660	3217	526000
GANGES	34651.1	2564780	8014.6	926280	12037	835000
BRAHMAPUTRA	-	-	11892.9	519950	22103	636130
INDUS	5339.96	2090580	2617.5	956360	2626	832418
MEKONG	12557.4	1001530	6251.4	535540	9751	545000
VOLGA	4557.49	2126010	5573.6	1326740	8104	1360000
DANUBE	8181.53	883182.	8719.6	797650	6412	807000
LENA	12031.7	2503230	12121.8	2310400	16697	2430000
OB	15396.1	6767170	9862.4	2902190	12617	2949998
YENISEY	19272.9	3232110	16235.8	2505170	18600	2440000
AMUR	574.020	70564.3	12051.8	1772050	10057	1730000
MURRAY	627.025	1079130	783.4	953660	257	991000

$ Area of basin to river mouth and outflow values at nearest sea-point to river mouth.
* Values at nearest gauging station to river mouth (often well upstream).
# Not included in the main GRDC data as observation period is only 1973-1979
NOTE that some gauging stations on edge of a gridbox may not be in the correct one.

Figure 5: Comparison of long term mean observations against long term mean river discharge from the old and new river routing schemes in HadCM3

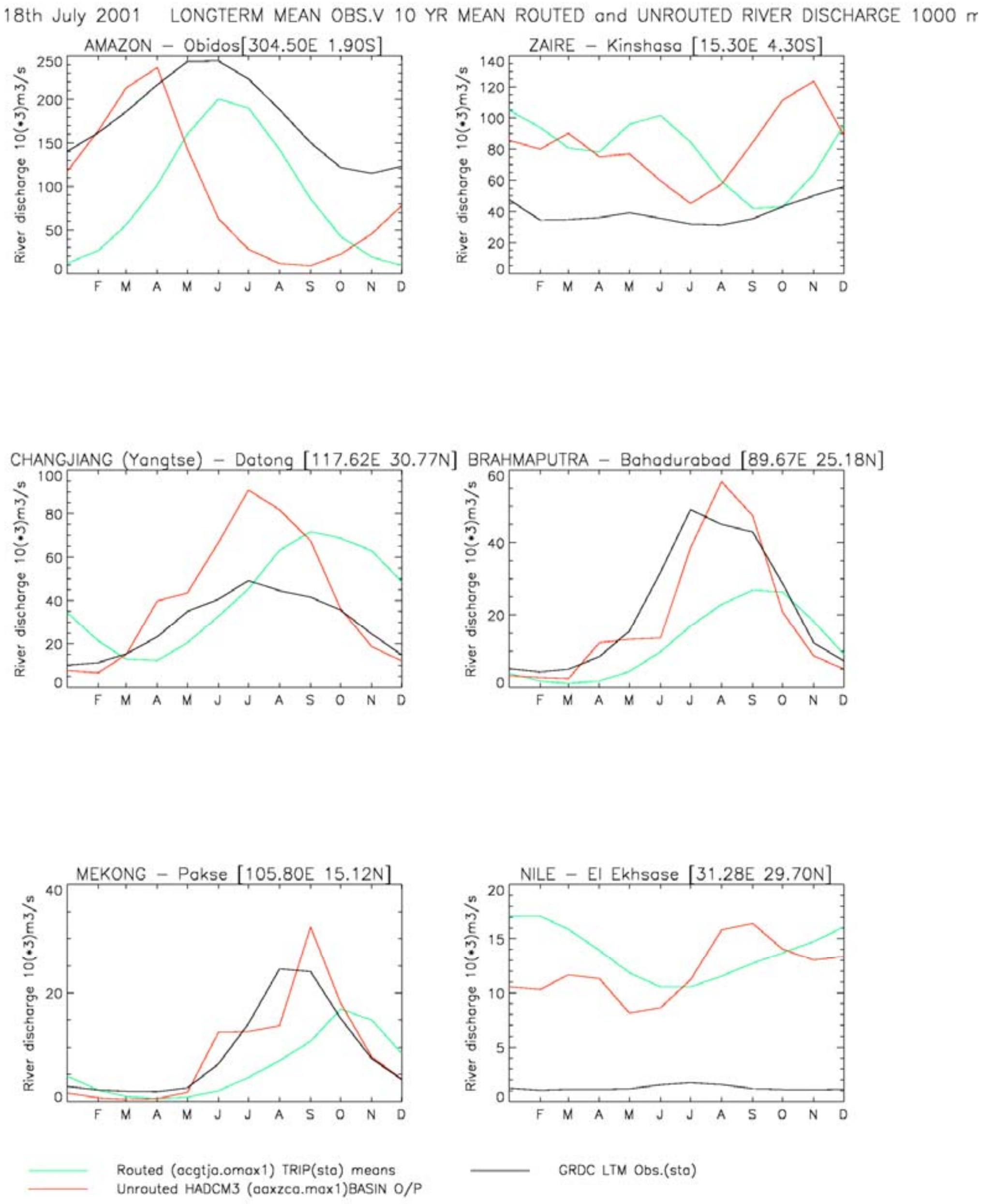


Figure 6: Comparison of long term mean observations against long term mean river discharge from the old and new river routing schemes in HadCM3

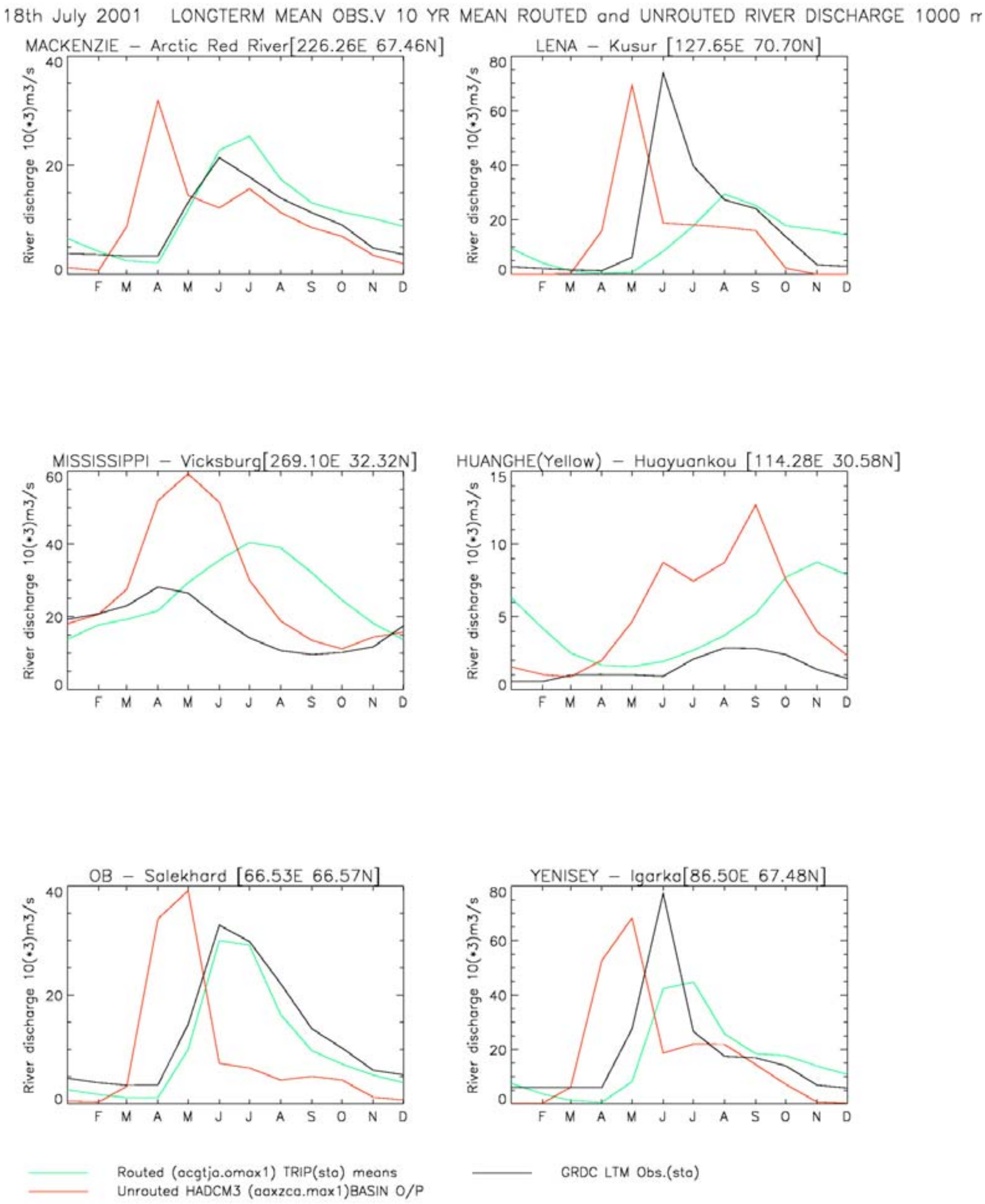


Figure 7: Comparison of long term mean observations against long term mean river discharge from the old and new river routing schemes in HadCM3

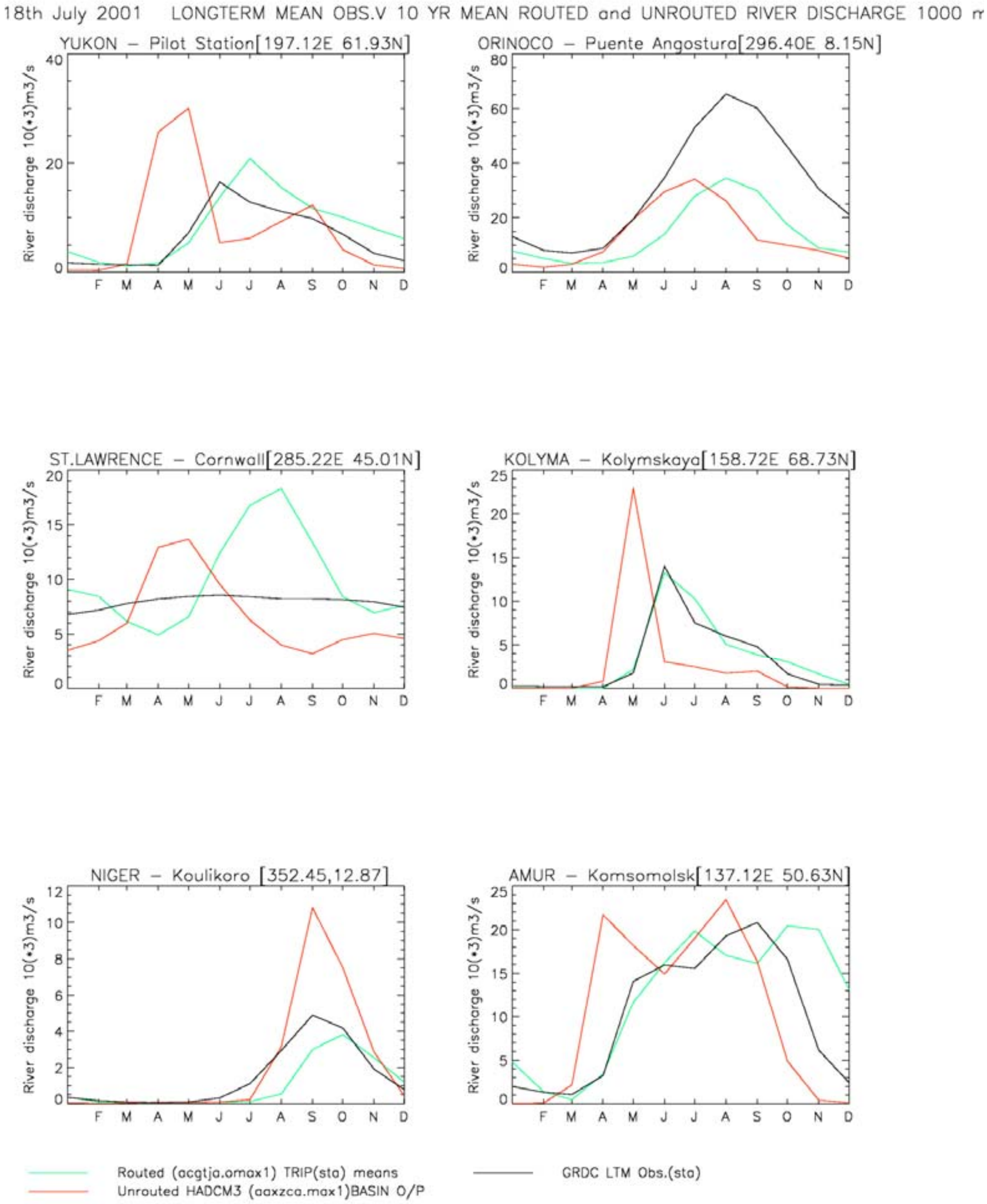
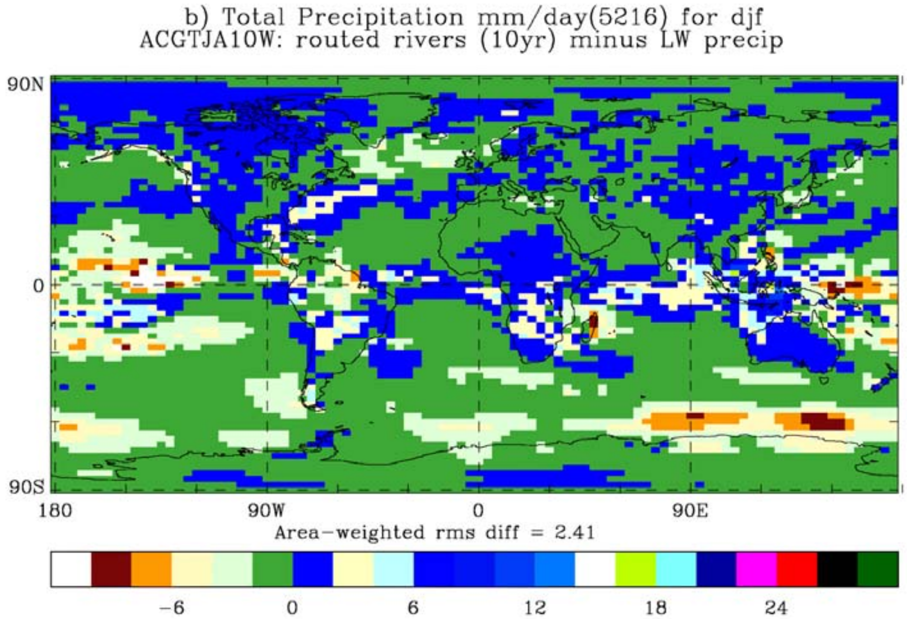


Figure 8: Differences in long term mean precipitation produced by HadCM3 compared to Legates and Willmot Observations



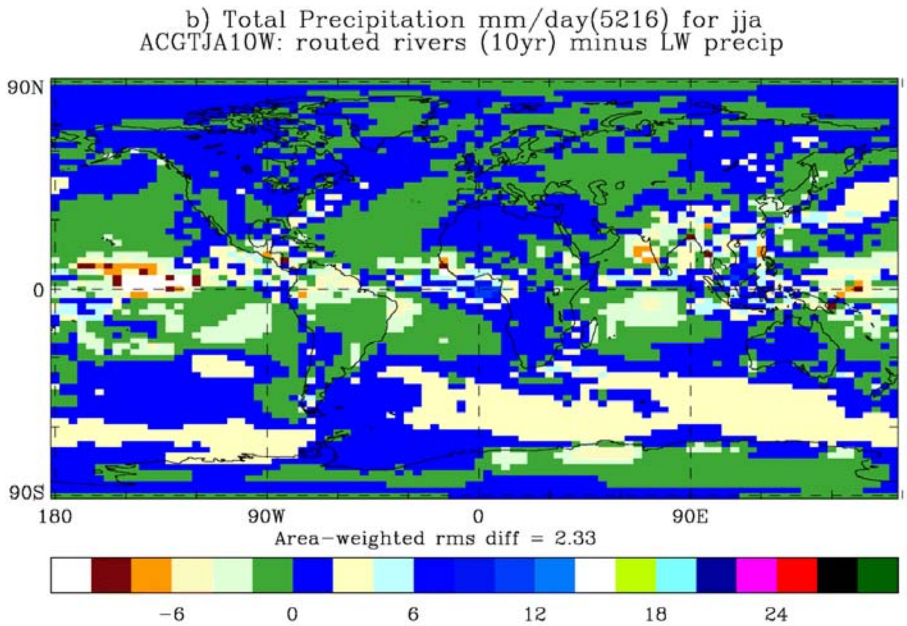
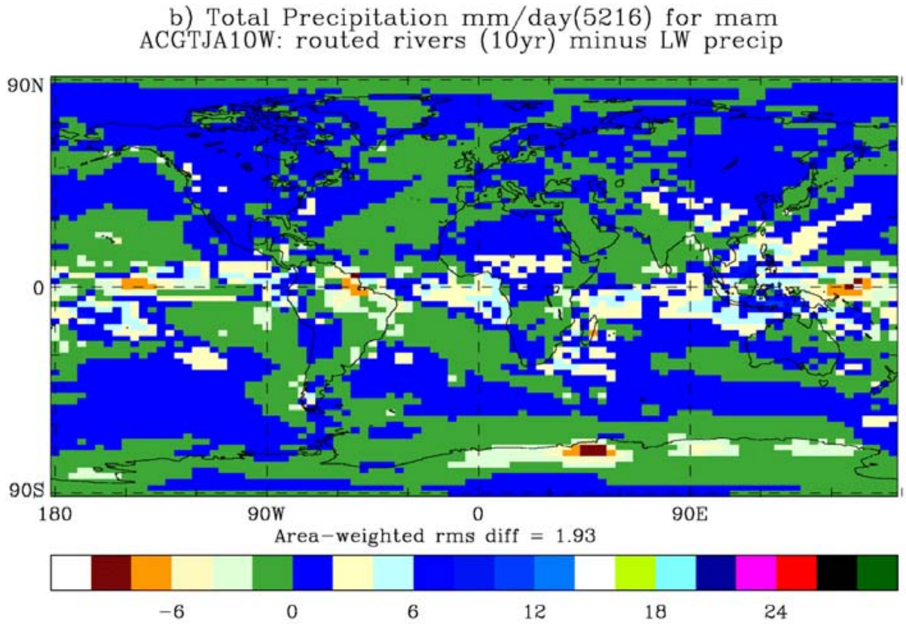


Figure 9: Differences in long term mean precipitation produced by HadCM3 compared to Legates and Willmot Observations



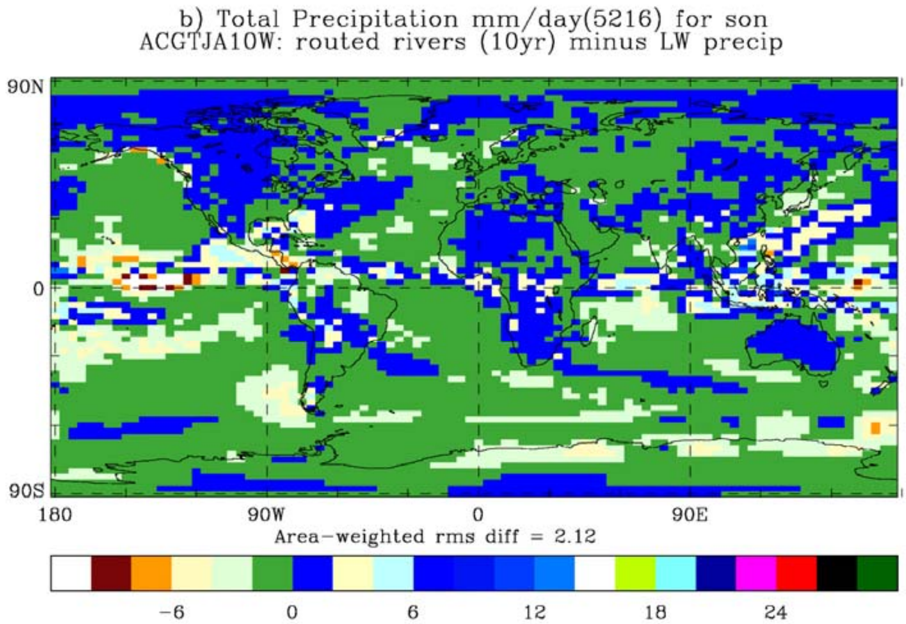


Figure 10: A comparison of the HadCM3 long-term mean routed flow (green line) with observations (black line) for several rivers with two or more gauging stations.

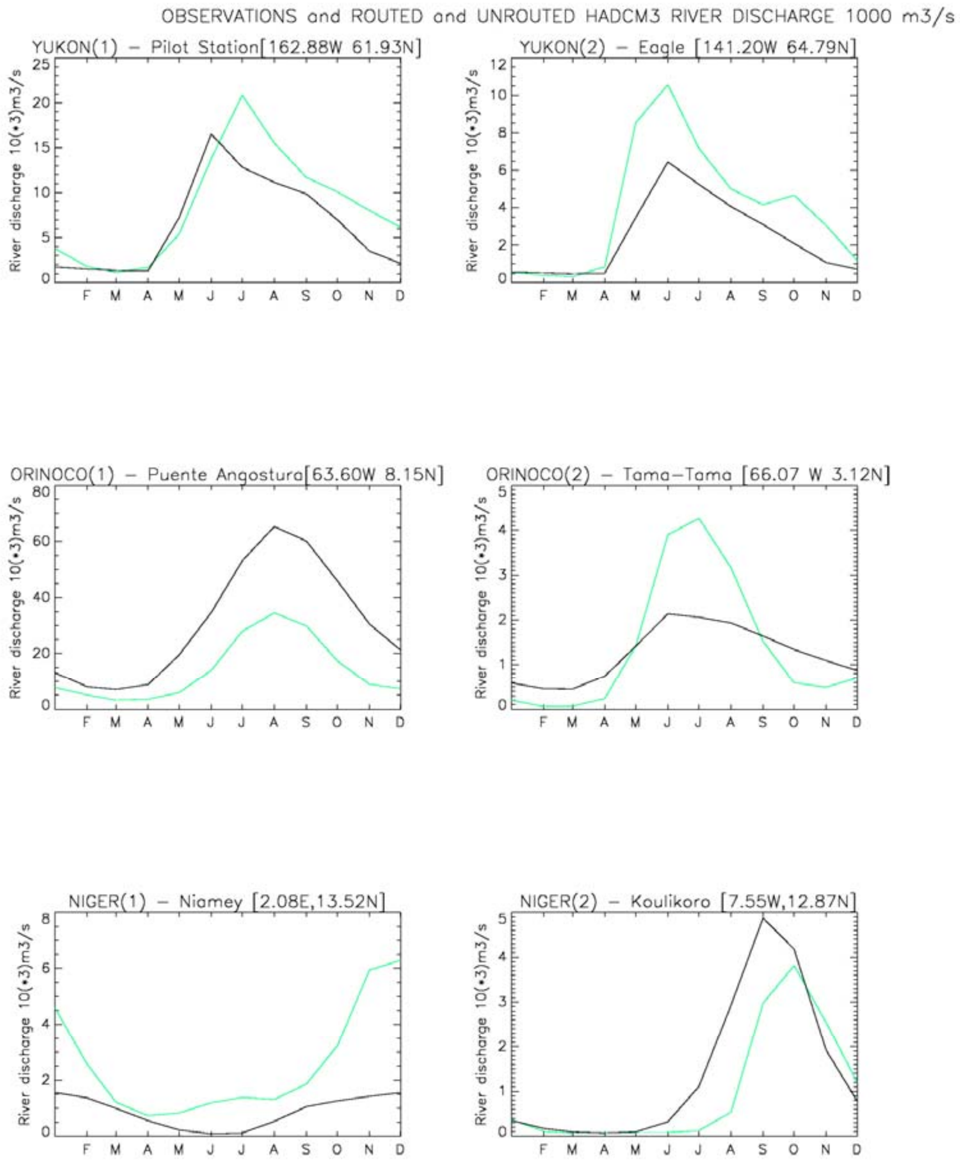


Figure 11: A comparison of the HadCM3 long-term mean routed flow (green line) with observations (black line) for several rivers with two or more gauging stations.

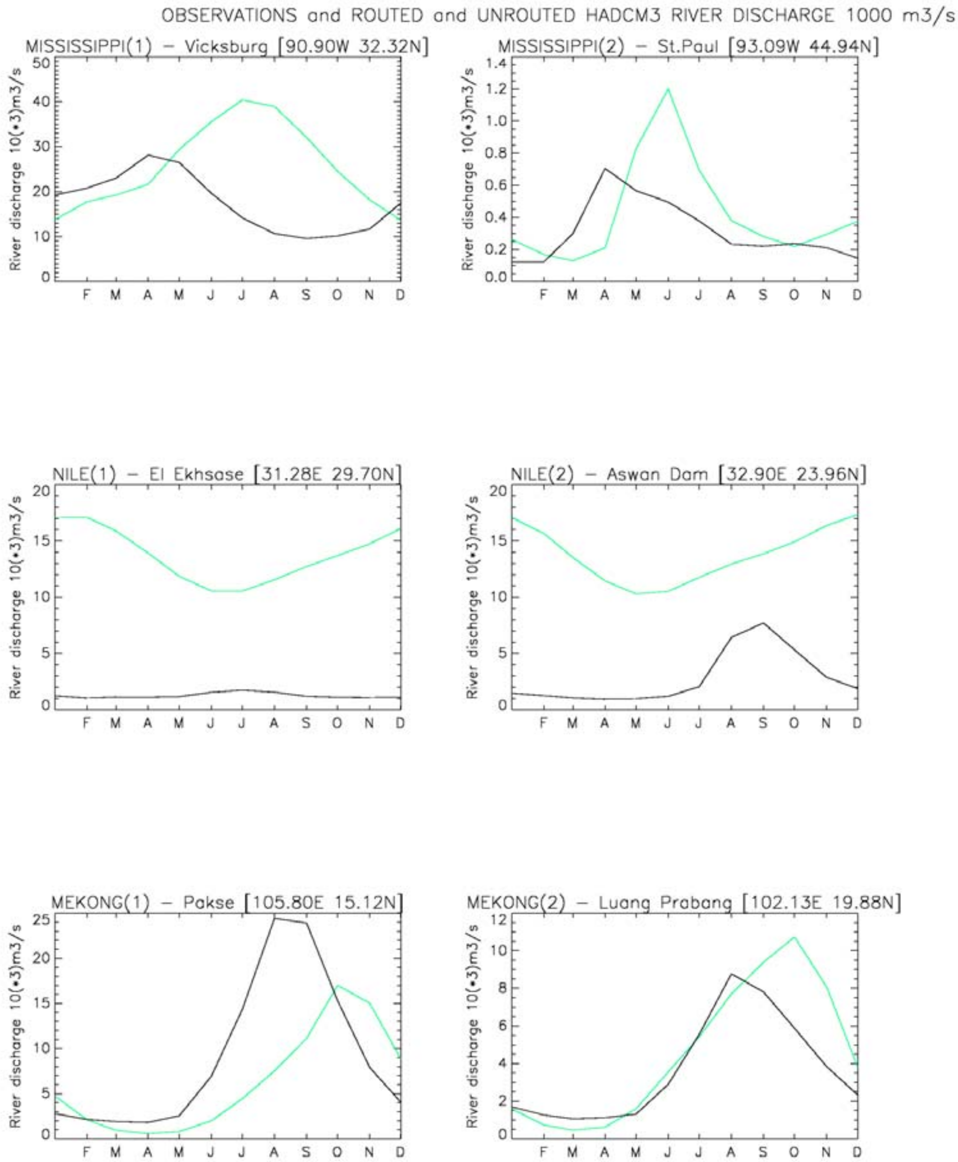


Figure 12: Comparison of the long-term mean seasonal outflow to the ocean

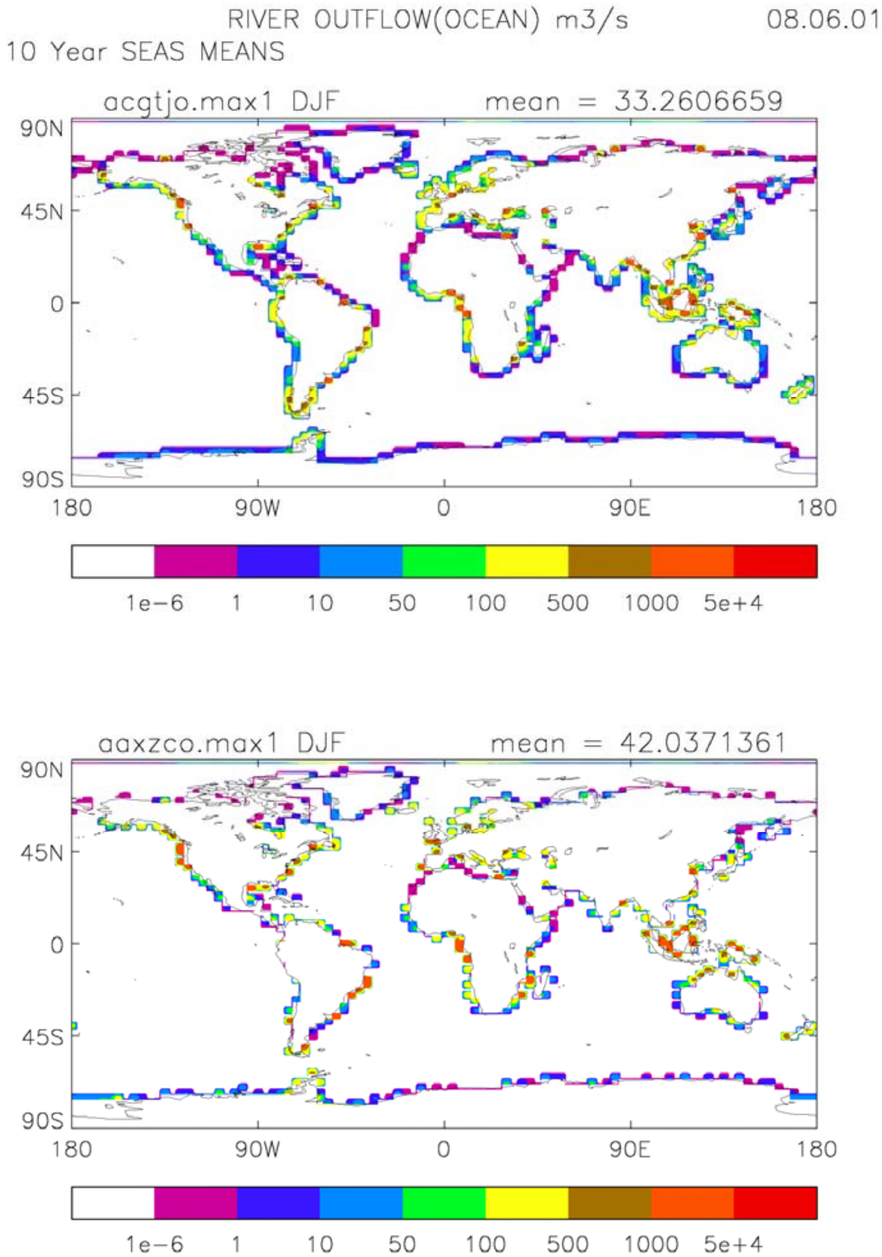


Figure 13: Comparison of the long-term mean seasonal outflow to the ocean

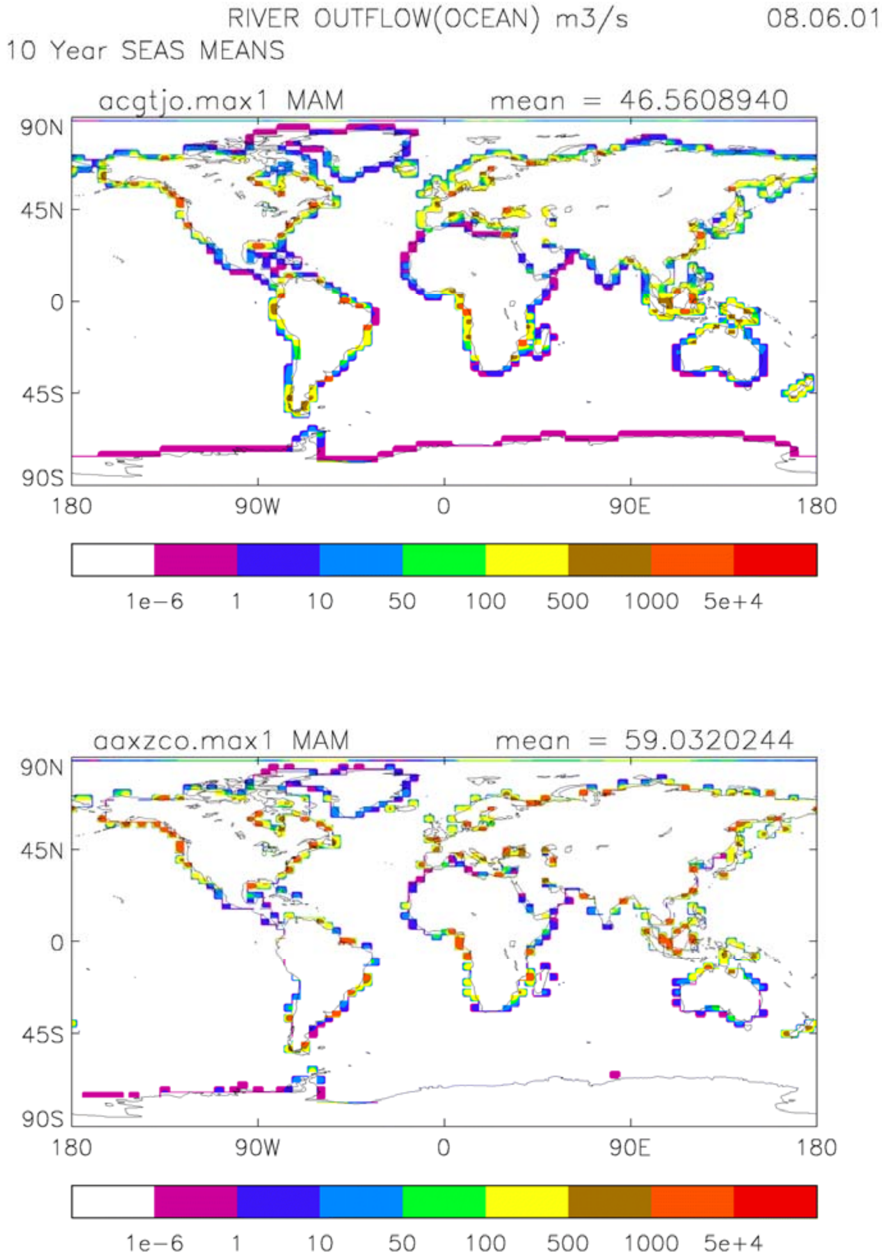


Figure 14: Comparison of the long-term mean seasonal outflow to the ocean

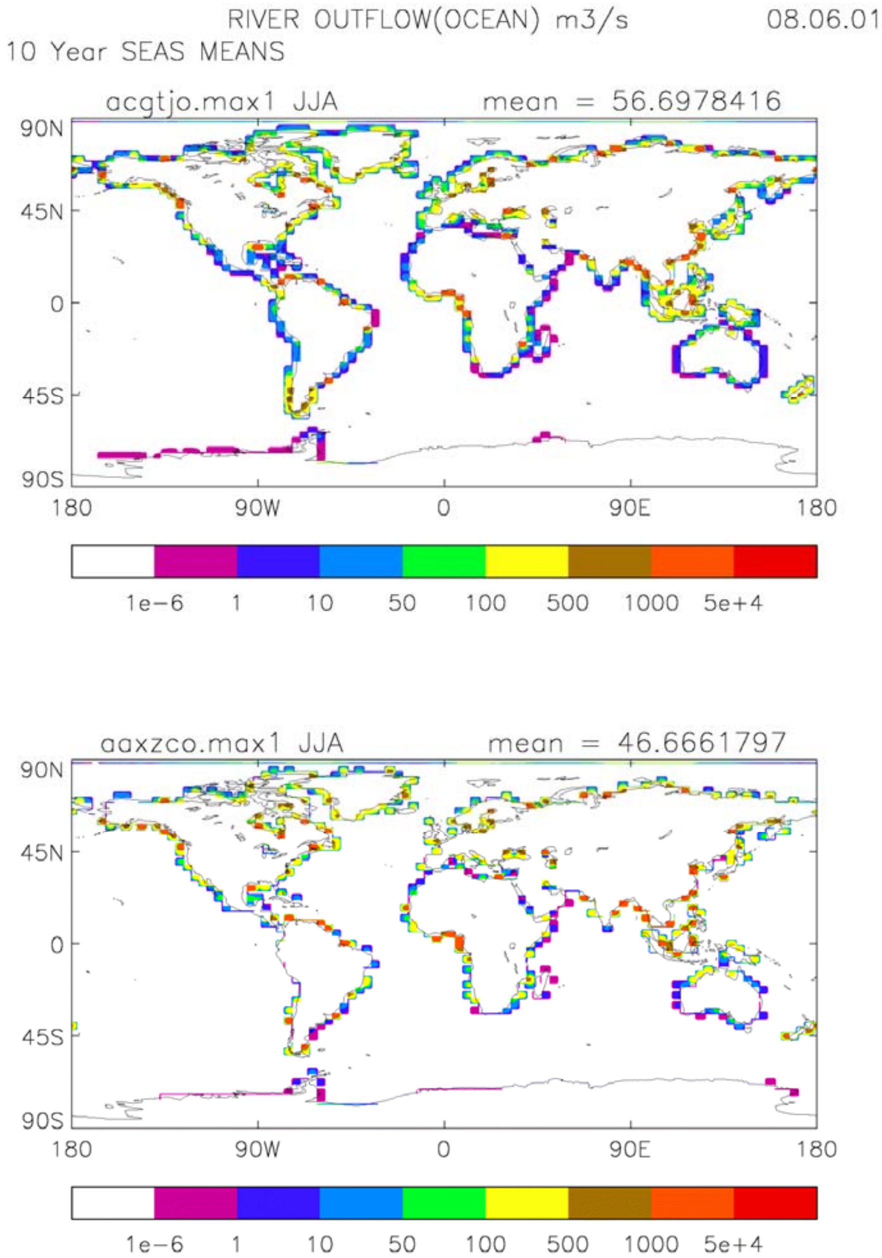


Figure 15: Comparison of the long-term mean seasonal outflow to the ocean

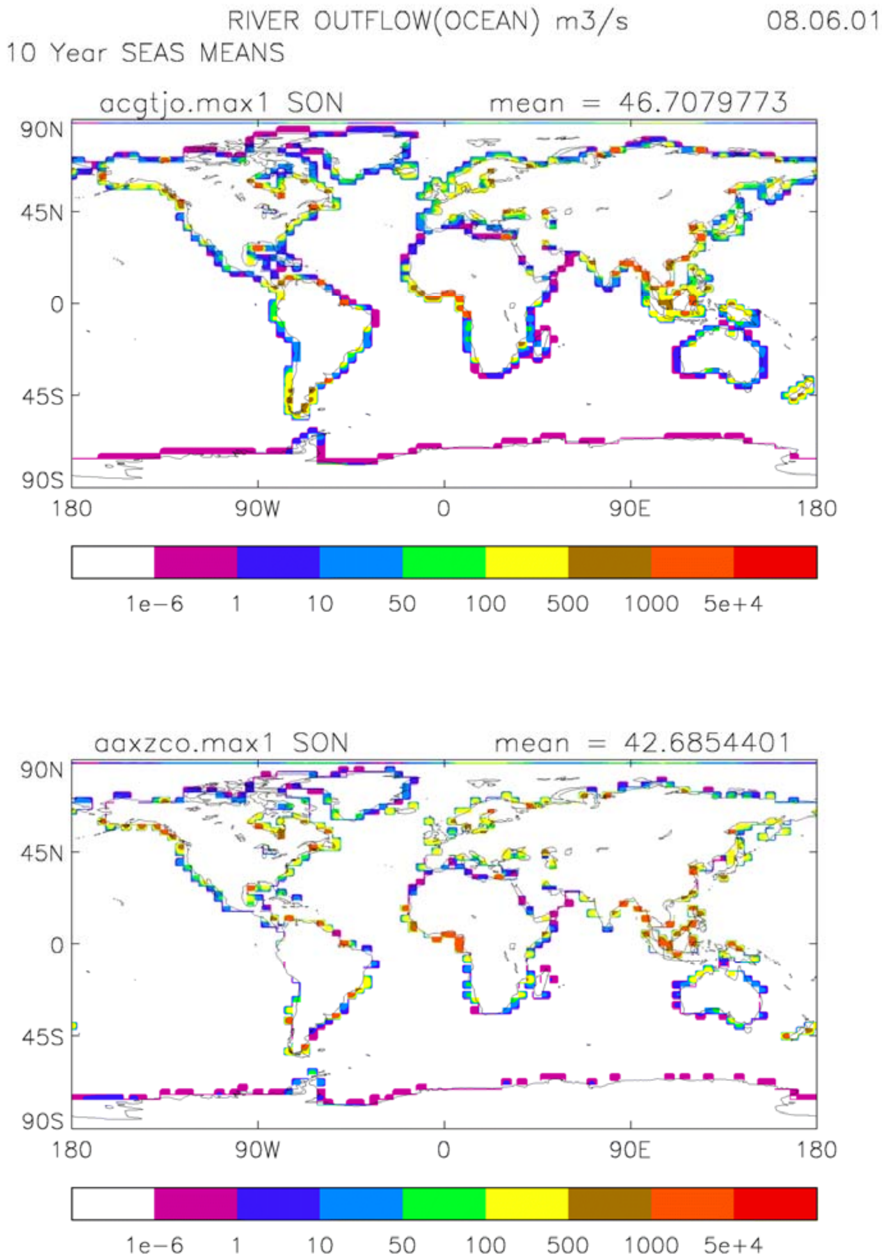


Figure 16: Comparison the seasonal flow produced using different effective velocities of 0.4 m s^{-1} (green line HadAM3, blue line HadCM3) and 0.3 m s^{-1} (yellow line HadAM3, purple line HadCM3) reflecting the difference in runoff production between HadAM3 and HadCM3.

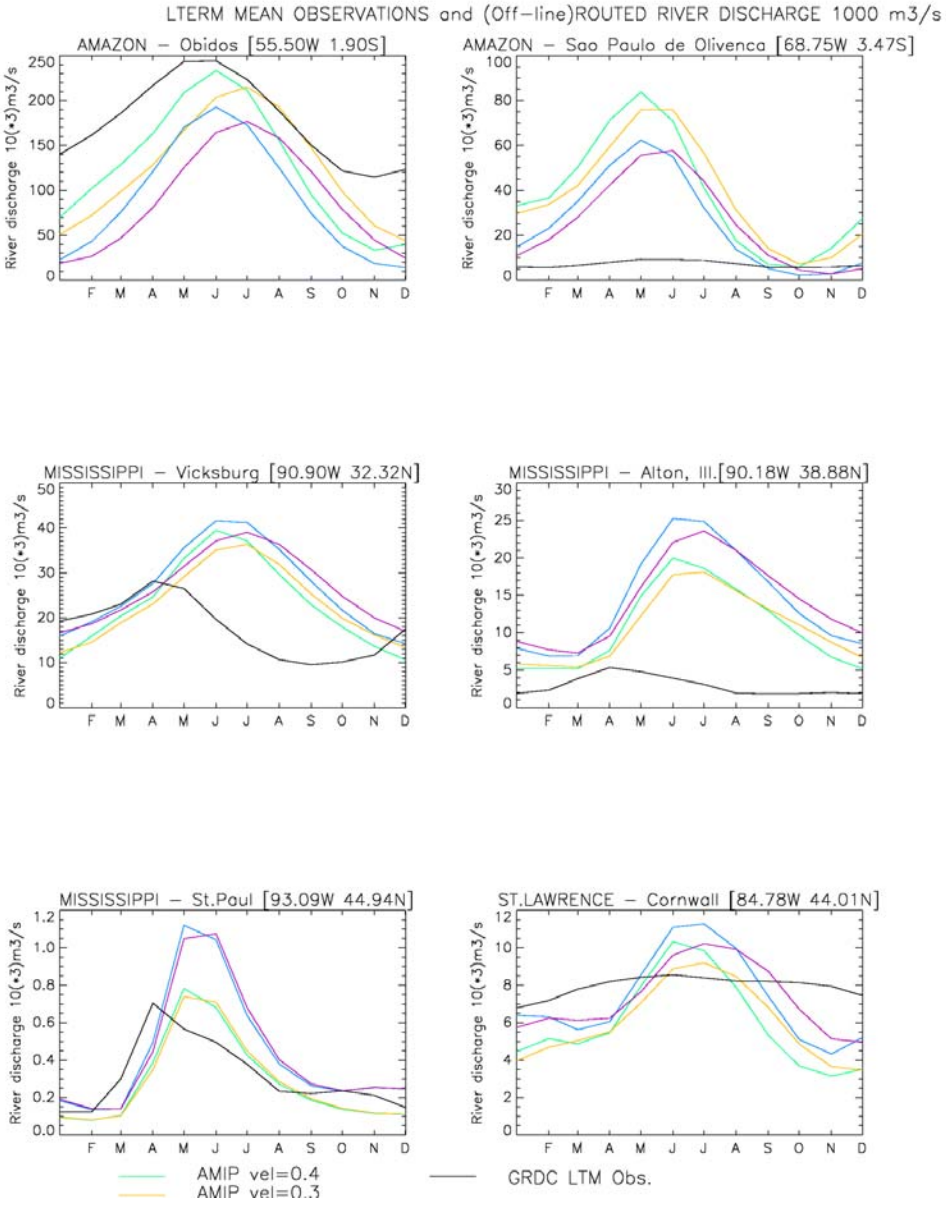


Figure 17: Comparison the seasonal flow produced using different effective velocities of 0.4 m s^{-1} (green line HadAM3, blue line HadCM3) and 0.3 m s^{-1} (yellow line HadAM3, purple line HadCM3) reflecting the difference in runoff production between HadAM3 and HadCM3

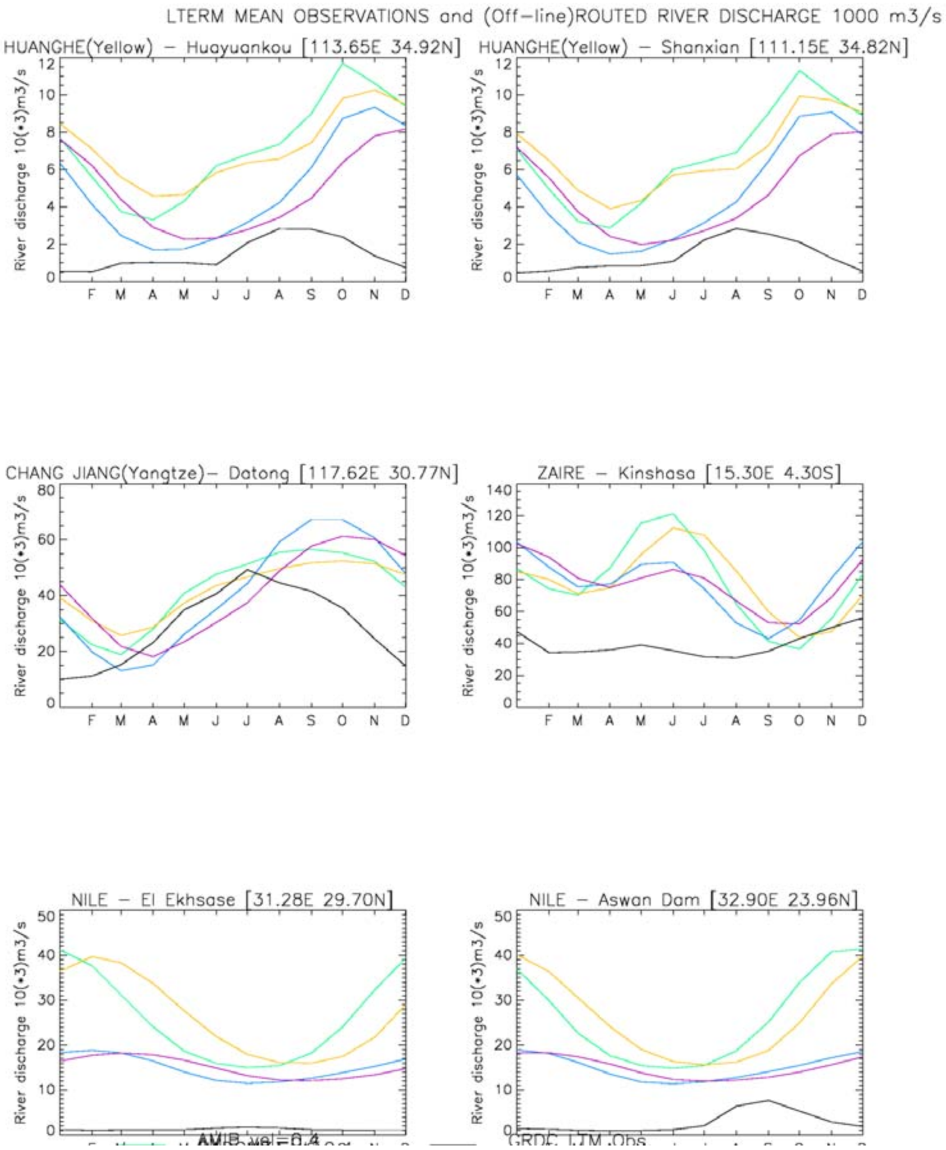
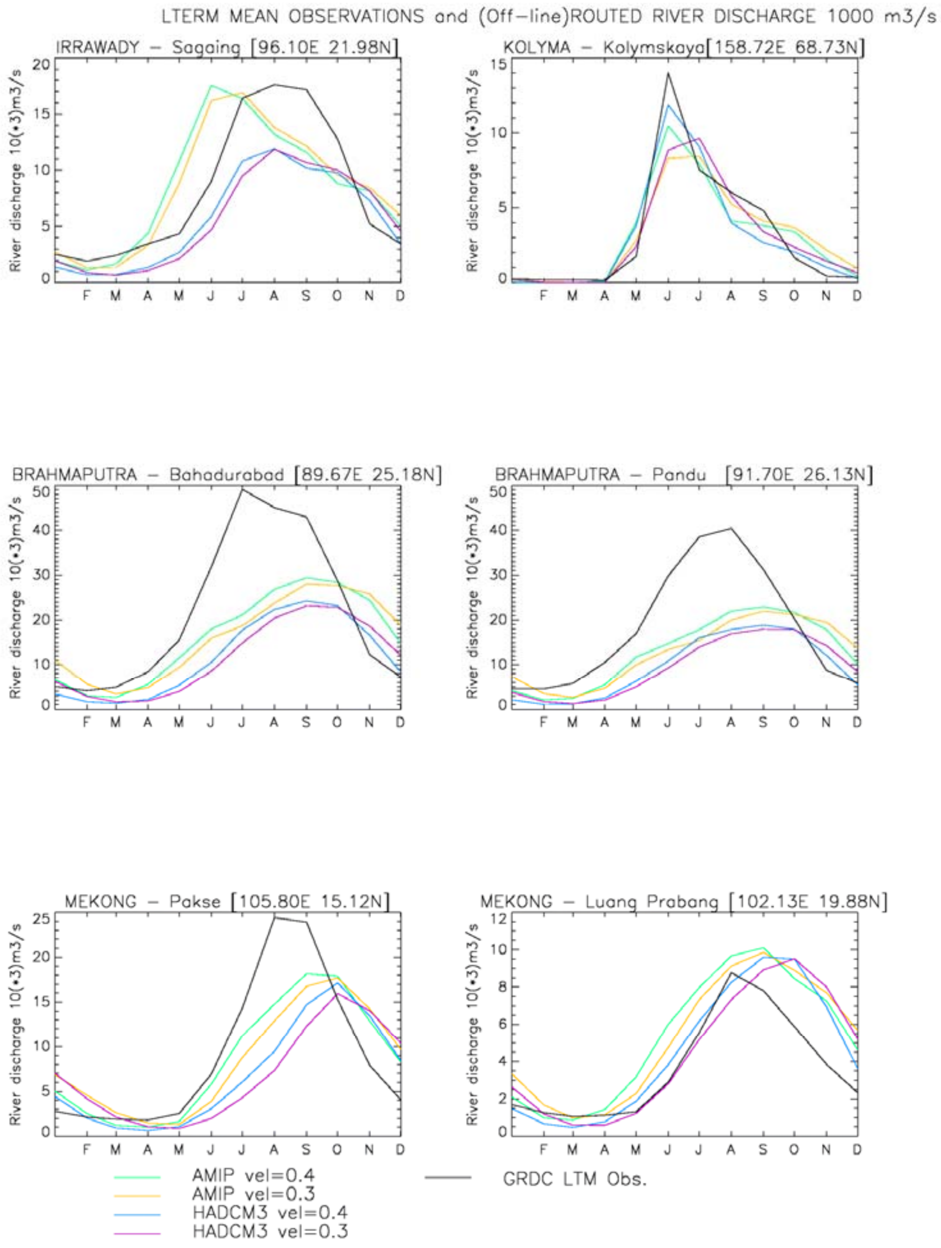


Figure 18: Comparison the seasonal flow produced using different effective velocities of 0.4 m s^{-1} (green line HadAM3, blue line HadCM3) and 0.3 m s^{-1} (yellow line HadAM3, purple line HadCM3) reflecting the difference in runoff production between HadAM3 and HadCM3.



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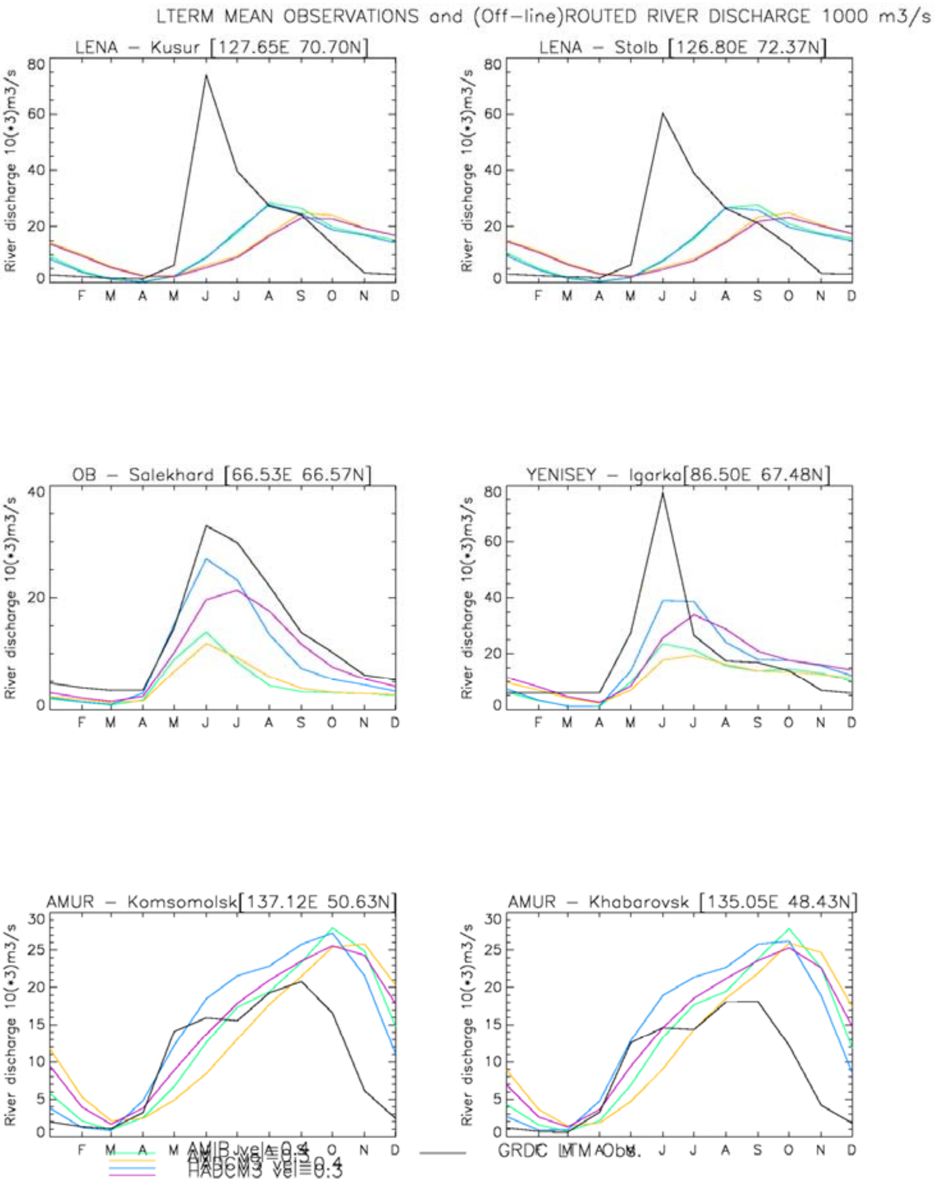


Figure 20: Comparison the seasonal flow produced using different effective velocities of 0.4 m s^{-1} (green line HadAM3, blue line HadCM3) and 0.3 m s^{-1} (yellow line HadAM3, purple line HadCM3) reflecting the difference in runoff production between HadAM3 and HadCM3.

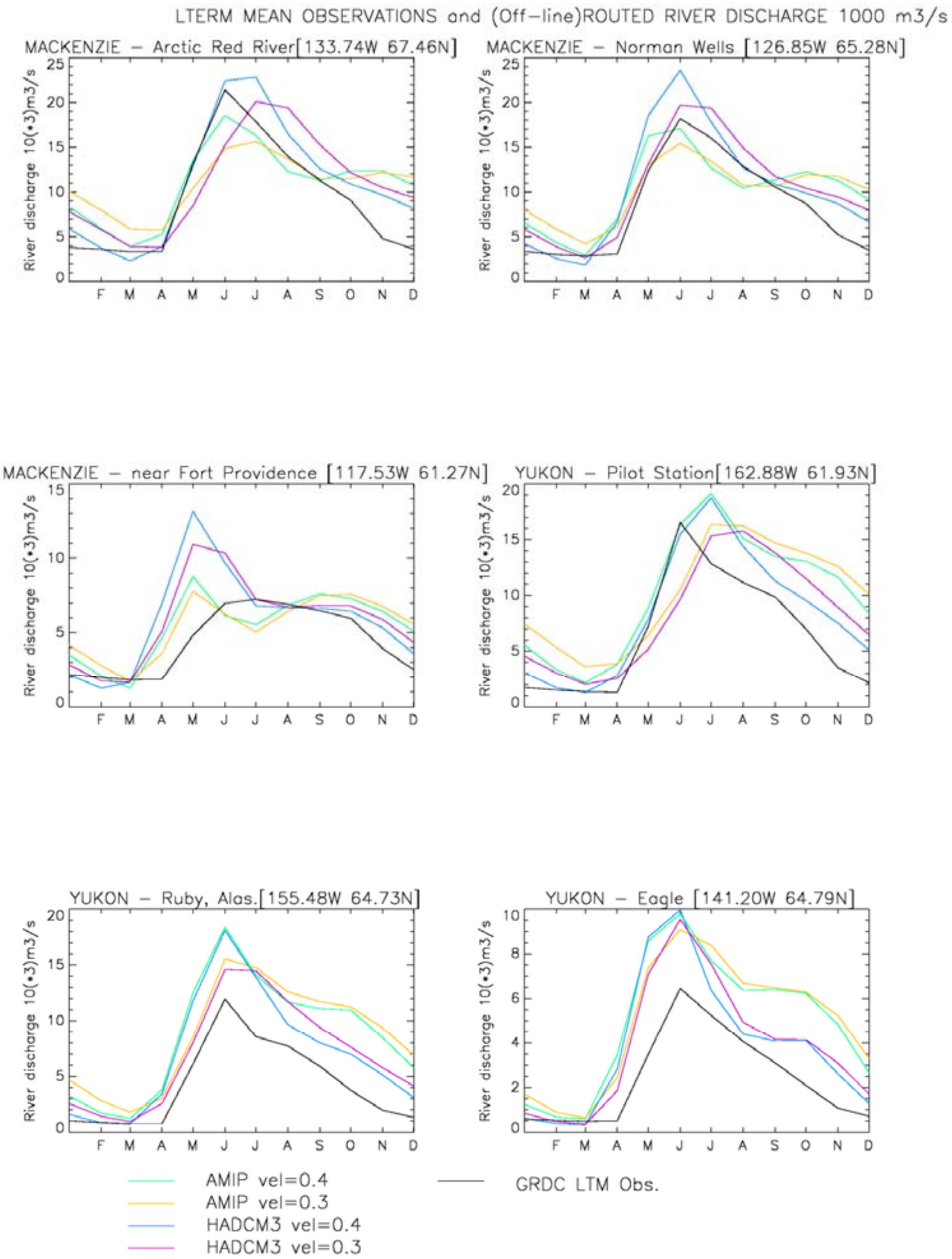


Figure 21: Comparison the seasonal flow produced using different effective velocities of 0.4 m s^{-1} (green line HadAM3, blue line HadCM3) and 0.3 m s^{-1} (yellow line HadAM3, purple line HadCM3) reflecting the difference in runoff production between HadAM3 and HadCM3.

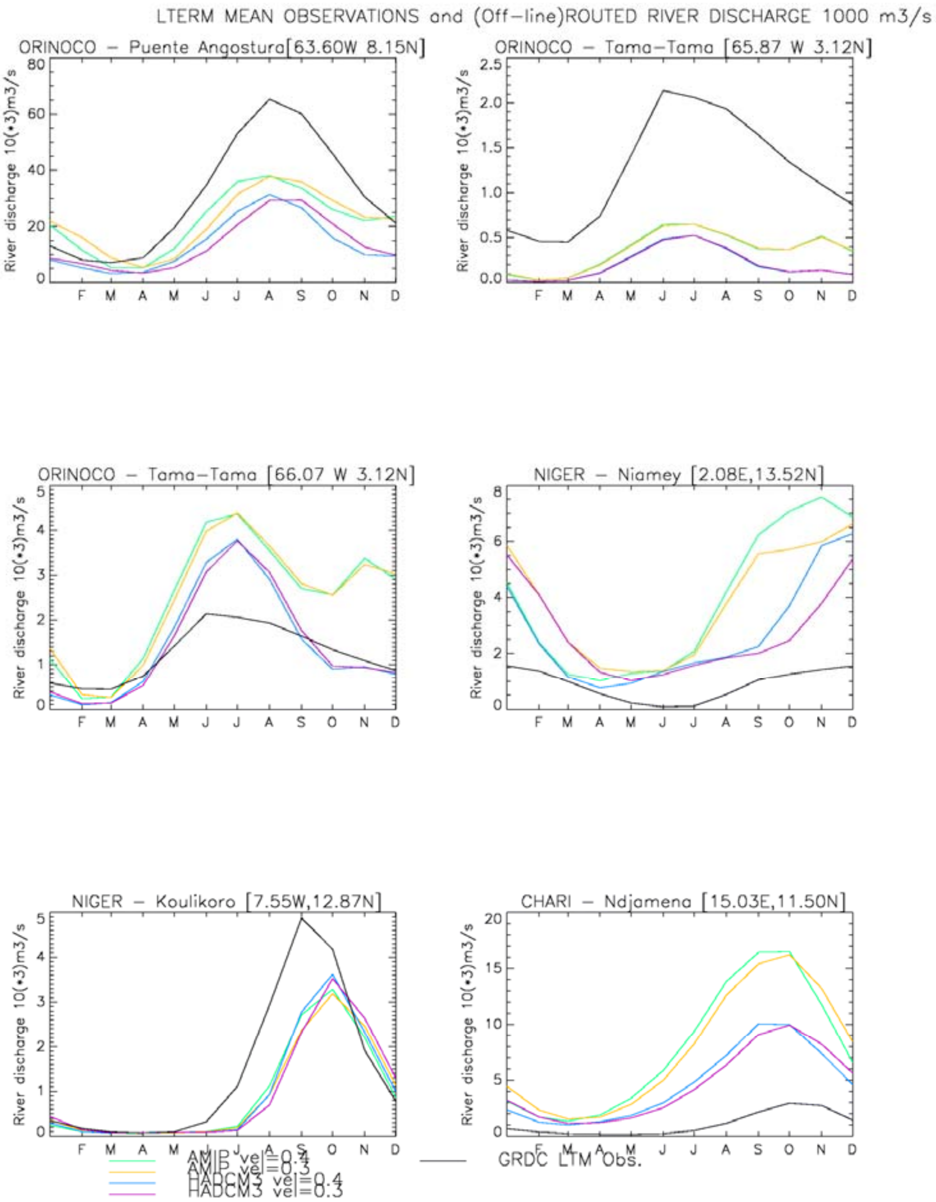
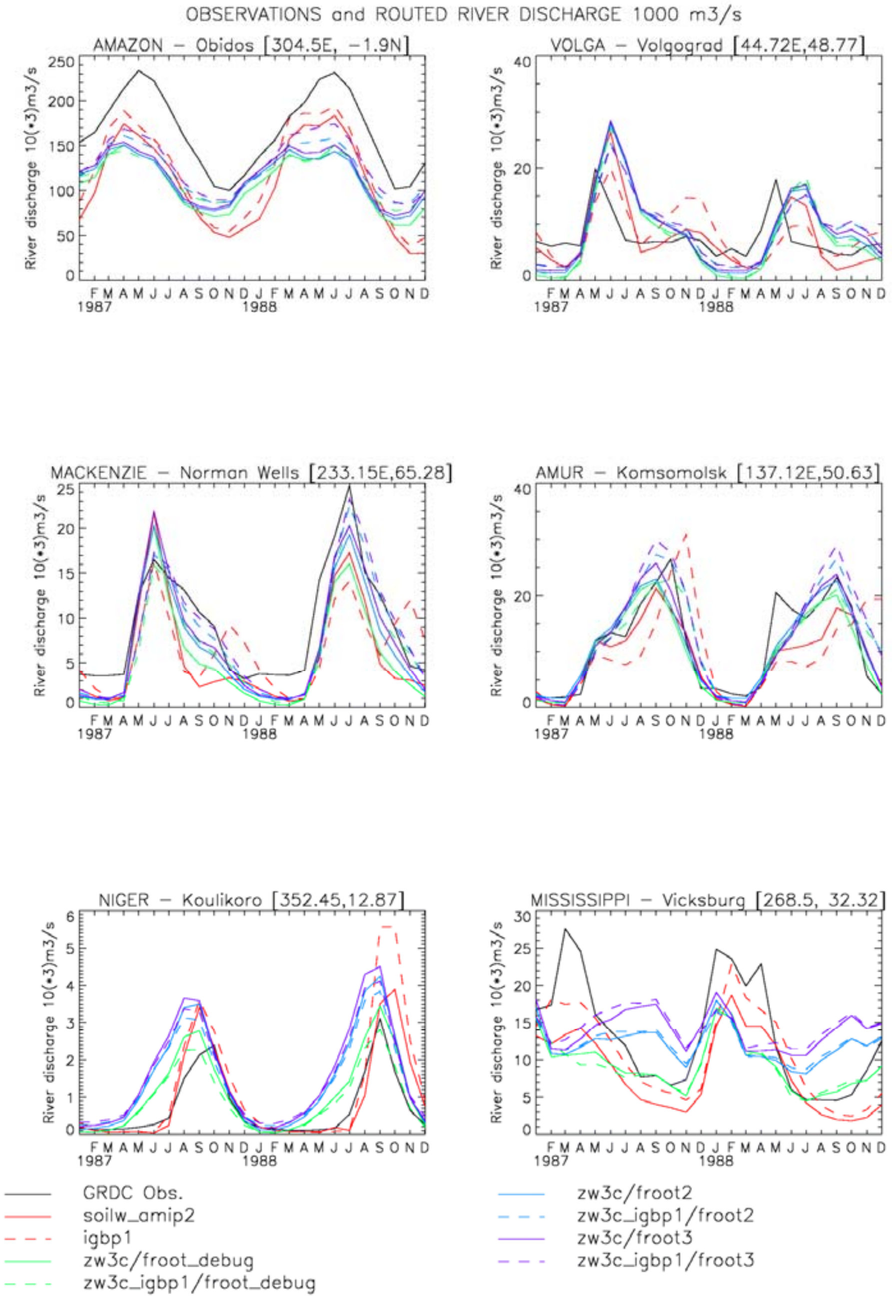


Figure 22: Comparison the seasonal flow produced using soil parameters which affect the amount of runoff produced.



Other Uses of Off-line TRIP

The off-line model can be run very quickly to test routing velocities, timesteps and spin-up. Figures 16–22 show both differences in the flow for different effective velocities and the difference in the production of runoff by HadCM3 and HadAM3. This was used to produce the initial water storage files for ancillary files for the routing scheme in the UM (spun-up using long-term monthly means of AMIP2 runoff). It is also a convenient tool for validating schemes affecting runoff. It was used successfully to test the effects of different soil hydrology schemes and soil parameters on runoff. To compare the production of runoff in the HadAM3 and HadCM3 experiments, see Figures 16-22.

Re-routing water from inland basins to soil moisture

The original implementation of TRIP in HadGEM did not conserve water since water flow from any inland outflow points was previously lost from the system on regridding. A series of modifications were added to the model at UM version 6.1 to re-route this lost water to the top level of soil moisture – the code is available from UM version 6.2 onwards. Details of how to use this modification are given in Appendix B.

Comparing results from HadCM3 and HadGEM1

10 year averaged river outflow values were taken from long-term baseline runs of HadCM3 and HadGEM1. The results of TRIP from the HadCM3 and HadGEM1 runs were compared with long-term observations from the Global Runoff Data Centre (GRDC). Simulated river flow was taken from the gridbox corresponding to the location of the gauging station used for observations. Validation for some rivers was inappropriate because of significant human intervention (such as dams) which is not yet accounted for in the model, such as the Nile. Table 3, and Figures 23 and 24 show the results of the validation for 40 gauging stations from the world's major rivers. In 28 out of the 40 gauging stations investigated here, prediction of total annual river flow was improved in HadGEM1 compared to HadCM3, in some cases considerably. HadGEM1 predictions for high latitude rivers were particularly good. Figure 24a shows that a considerable improvement in flow prediction for the Amazon mouth was obtained with HadGEM1 compared to HadCM3 – which is significant since the Amazon contributes the largest flux of freshwater to the oceans globally, approximately three times that of any of the other rivers investigated here. Predicted seasonality of river flow was generally improved in HadGEM1 compared to HadCM3 for the Mississippi, Huanghe (Yellow River), Zaire, Brahmaputra, Volga and downstream Orinoco. Predicted seasonality was generally worse from HadGEM1 in comparison with HadCM3 for the Mekong, upstream Amazon, Irrawady and downstream Orinoco.

Further investigation should be carried out for gauging stations with a difference between observed and predicted total annual flow >100%, such as the upstream Amazon, Mississippi, Huanghe, Nile, Mekong, Niger, Volga and Indus. Future work should concentrate on 1) errors in predicted flow arising from TRIP parameterisation (the model is not calibrated on a basin-by-basin basis) – a half degree grid model is also now available, 2) errors in predicted flow arising from errors in climate and input runoff and 3) implementing the impact of major human intervention into TRIP.

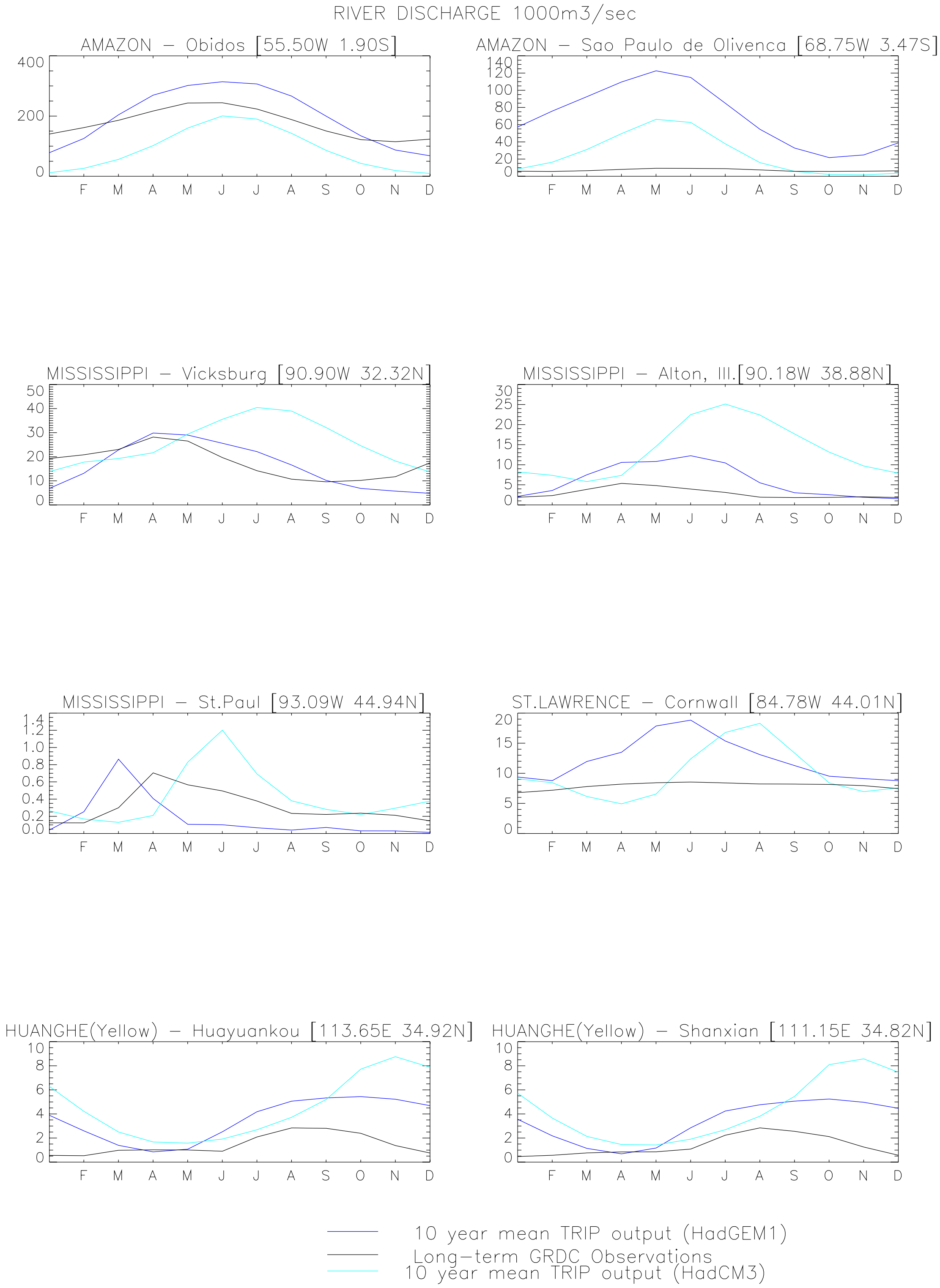
Conclusions

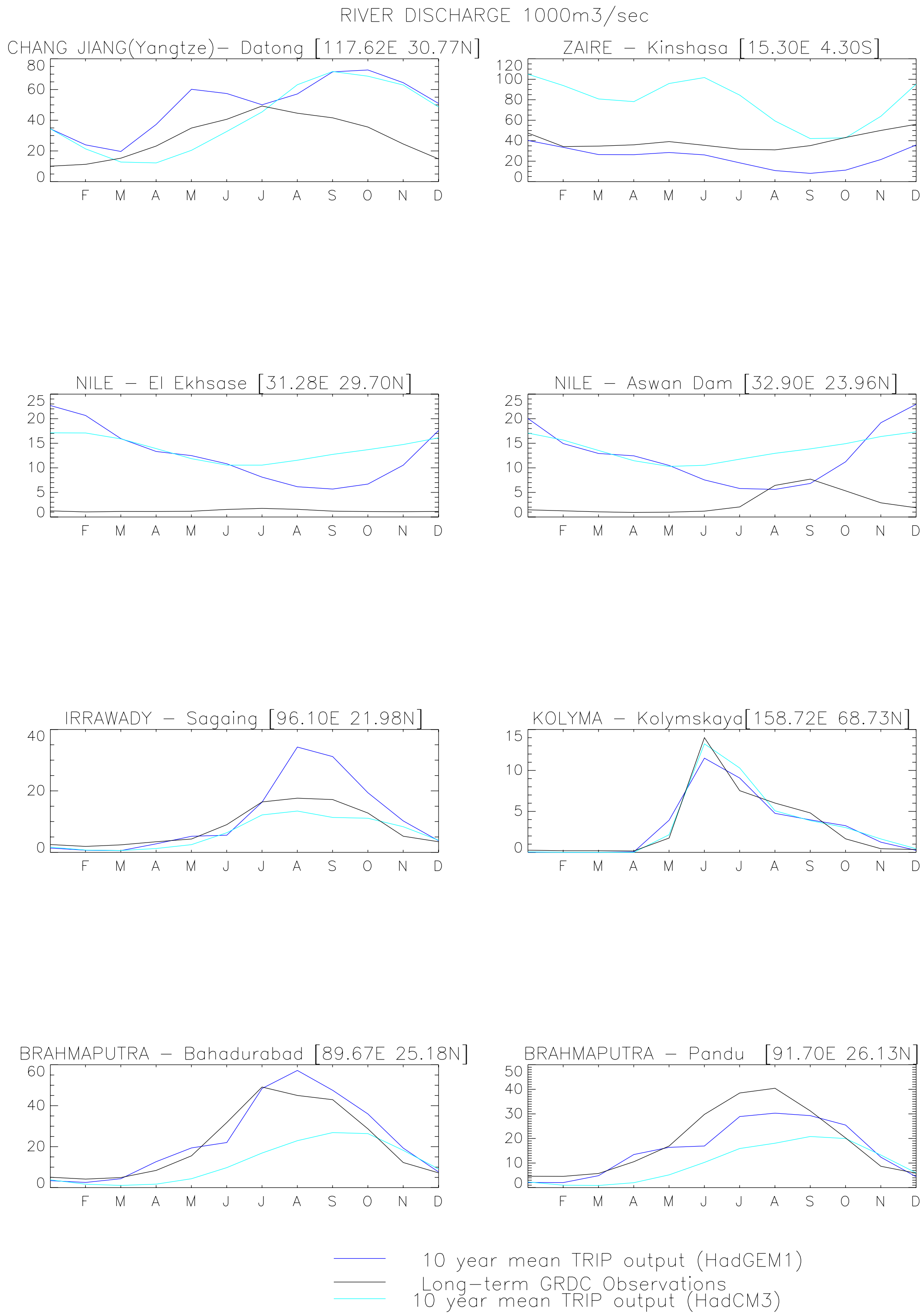
Coupling the TRIP river routing scheme to the Hadley Centre GCM has been found to improve the seasonality of river flow. Predicted river flow values from the TRIP river routing scheme has been improved from HadCM3 to HadGEM1 as a result of improved climate prediction and thus improvements to the annual mean runoff produced by the LSH hydrology scheme. HadGEM1 has been shown to give good simulations of river flow as input to the ocean and for investigating the hydrological effects of climate change, although further improvements can still be made for some major river basins. In addition the off-line routing model is proving very useful in testing parameters both for improved river routing and for other hydrology schemes.

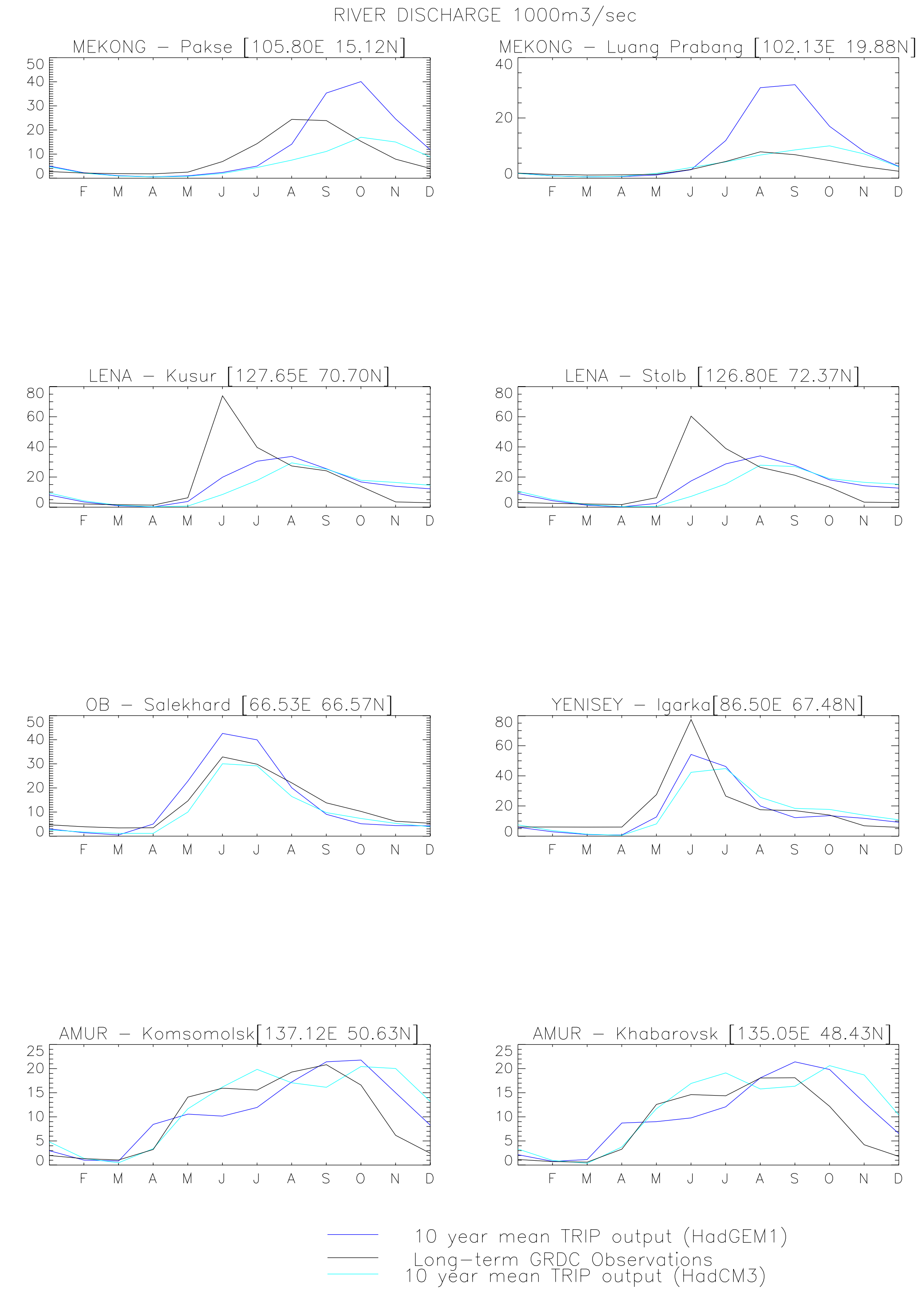
Table 3: Observed, HadCM3 and HadGEM1 long-term mean time-integrated total annual river discharge from major river gauging stations, $1000m^3 s^{-1}$.

River/station/latitude/longitude	GRDC	HadCM3	Difference (GRDC-HadCM3)	% Difference (GRDC-HadCM3/ GRDC)	HadGEM1	Difference (GRDC-HadGEM1)	% Difference (GRDC-HadGEM1/ GRDC)
AMAZON - Obidos [55.50W 1.90S]	63423.63	31377.43	-32046.2	-50.53	70662.22	7238.59	11.41
AMAZON - Sao Paulo de Olivenca [68.75W 3.47S]	2532.44	9026.93	6494.49	256.45	24917.33	22384.88	883.92
MISSISSIPPI - Vicksburg [90.90W 32.32N]	6335.93	9160	2824.06	44.57	5802.36	-533.58	-8.42
MISSISSIPPI - Alton, Ill.[90.18W 38.88N]	1042.42	4852.52	3810.1	365.5	2153.52	1111.1	106.59
MISSISSIPPI - St.Paul [93.09W 44.94N]	112.24	151.41	39.17	34.9	60.65	-51.59	-45.97
ST.LAWRENCE - Cornwall [84.78W 44.01N]	2859.91	3567.57	707.66	24.74	4423.39	1563.48	54.67
HUANGHE(Yellow) - Huayuankou [113.65E 34.92N]	517.68	1623.94	1106.26	213.69	1267.42	749.74	144.83
HUANGHE(Yellow) - Shanxian [111.15E 34.82N]	484.81	1572.36	1087.54	224.32	1210.15	725.34	149.61
CHANG JIANG(Yangtze)- Datong [117.62E 30.77N]	10372.09	14833.19	4461.1	43.01	17991.25	7619.17	73.46
ZAIRE - Kinshasa [15.30E 4.30S]	14232.83	28297.32	14064.5	98.82	8621.73	-5611.09	-39.42
NILE - El Ekhsase [31.28E 29.70N]	450.48	4974.83	4524.36	1004.35	4521.7	4071.23	903.76
NILE - Aswan Dam [32.90E 23.96N]	993.54	4972.26	3978.72	400.46	4498.51	3504.96	352.77
IRRAWADY - Sagaing [96.10E 21.98N]	2888.81	2201.96	-686.85	-23.78	3938.42	1049.61	36.33
KOLYMA - Kolymskaya[158.72E 68.73N]	1119.22	1192.58	73.36	6.55	1139.7	20.48	1.83
BRAHMAPUTRA - Bahadurabad [89.67E 25.18N]	7653.92	4281.45	-3372.47	-44.06	8415.23	761.31	9.95
BRAHMAPUTRA - Pandu [91.70E 26.13N]	6515.83	3469.79	-3046.05	-46.75	5598.86	-916.97	-14.07
MEKONG - Pakse [105.80E 15.12N]	3240.36	2250.51	-989.85	-30.55	4300.72	1060.36	32.72
MEKONG - Luang Prabang [102.13E 19.88N]	1305.13	1610.11	304.99	23.37	3328.57	2023.44	155.04
LENA - Kusur [127.65E 70.70N]	5982.78	4363.86	-1618.92	-27.06	5061	-921.78	-15.41
LENA - Stolb [126.80E 72.37N]	5473.51	4383.77	-1089.74	-19.91	5107.49	-366.03	-6.69
OB - Salekhard [66.53E 66.57N]	4511.6	3550.46	-961.14	-21.3	4742.16	230.56	5.11
YENISEY - Igarka[86.50E 67.48N]	6498	5844.89	-653.11	-10.05	5714.03	-783.97	-12.06
AMUR - Komsomolsk[137.12E 50.63N]	3554.78	4338.63	783.86	22.05	3889.91	335.14	9.43
AMUR - Khabarovsk [135.05E 48.43N]	3050.78	4138.92	1088.14	35.67	3674.7	623.91	20.45
MACKENZIE - Arctic Red River[133.74W 67.46N]	3282.75	4091.09	808.34	24.62	3731.62	448.87	13.67
MACKENZIE - Norman Wells [126.85W 65.28N]	2996.62	3840.38	843.76	28.16	3460.62	463.99	15.48
MACKENZIE - near Fort Providence [117.53W 61.27N]	1578.44	2189.26	610.81	38.7	1815	236.56	14.99
YUKON - Pilot Station[162.88W 61.93N]	2284.86	2999.94	715.09	31.3	2579.04	294.18	12.88
YUKON - Ruby, Alas.[155.48W 64.73N]	1517.59	2540.62	1023.03	67.41	2083.31	565.72	37.28
YUKON - Eagle [141.20W 64.79N]	849.3	1394.2	544.9	64.16	1019.8	170.5	20.08
ORINOCO - Puente Angostura[63.60W 8.15N]	11023.47	4966.75	-6056.72	-54.94	10142.58	-880.89	-7.99
ORINOCO - Tama-Tama [66.07 W 3.12N]	441.74	498.32	56.58	12.81	1333.16	891.42	201.8
NIGER - Niamey [2.08E,13.52N]	321.51	934.61	613.1	190.69	657.8	336.28	104.59
NIGER - Koulikoro [7.55W,12.87N]	506.61	358.93	-147.68	-29.15	529.3	22.69	4.48
CHARI - Ndjamena [15.03E,11.50N]	381.38	1497.58	1116.2	292.67	378.68	-2.7	-0.71
ORANGE - Aliwal North [26.71E, 30.68S]	52.34	119.15	66.81	127.64	339.43	287.08	548.46
VOLGA - Volgograd [44.72, 48.77]	2988.06	2006.49	-981.56	-32.85	2706.73	-281.33	-9.42
INDUS - Kotri [68.37E, 25.37N]	905.07	942.3	37.23	4.11	2163.11	1258.04	139
SEVERNAY DVINA - Ust-Pinega [42.17E,64.1N]	1204.66	134.8	-1069.86	-88.81	115.75	-1088.92	-90.39
NIGER - Gaya [3.4E, 11.88N]	372.21	1007.36	635.15	170.64	679.81	307.6	82.64

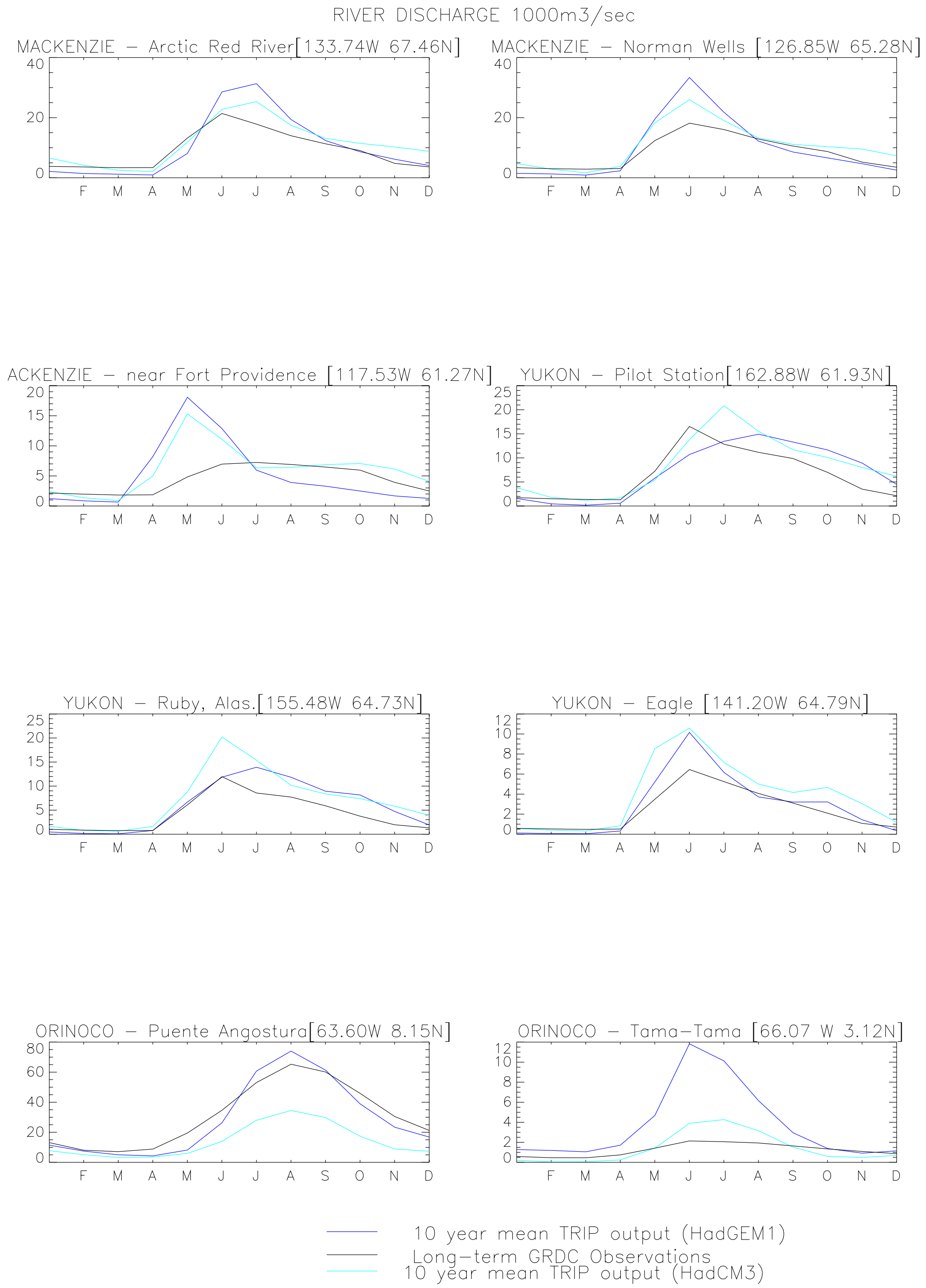
Figure 23: Mean seasonal cycle of river flow from gauging station measurements (black line) and from simulations by TRIP river routing scheme in HadCM3 (light blue line) and HadGEM1 (dark blue line)




RIVER DISCHARGE 1000m3/sec
CHANG JIANG(Yangtze)– Datong [117.62E 30.77N]
ZAIRE – Kinshasa [15.30E 4.30S]
NILE – El Ekhsase [31.28E 29.70N]
NILE – Aswan Dam [32.90E 23.96N]
IRRAWADY – Sagaing [96.10E 21.98N]
KOLYMA – Kolymskaya[158.72E 68.73N]
BRAHMAPUTRA – Bahadurabad [89.67E 25.18N]
BRAHMAPUTRA – Pandu [91.70E 26.13N]
F M A M J J A S O N D
10 year mean TRIP output (HadGEM1)
Long–term GRDC Observations
10 year mean TRIP output (HadCM3)



RIVER DISCHARGE 1000m3/sec
MEKONG – Pakse [105.80E 15.12N]
MEKONG – Luang Prabang [102.13E 19.88N]
LENA – Kusur [127.65E 70.70N]
LENA – Stolb [126.80E 72.37N]
OB – Salekhard [66.53E 66.57N]
YENISEY – Igarka[86.50E 67.48N]
AMUR – Komsomolsk[137.12E 50.63N]
AMUR – Khabarovsk [135.05E 48.43N]
F M A M J J A S O N D
10 year mean TRIP output (HadGEM1)
Long–term GRDC Observations
10 year mean TRIP output (HadCM3)


RIVER DISCHARGE 1000m3/sec
MACKENZIE – Arctic Red River[133.74W 67.46N]
MACKENZIE – Norman Wells [126.85W 65.28N]
ACKENZIE – near Fort Providence [117.53W 61.27N]
YUKON – Pilot Station[162.88W 61.93N]
YUKON – Ruby, Alas.[155.48W 64.73N]
YUKON – Eagle [141.20W 64.79N]
ORINOCO – Puente Angostura[63.60W 8.15N]
ORINOCO – Tama–Tama [66.07 W 3.12N]
F M A M J J A S O N D
10 year mean TRIP output (HadGEM1)
Long–term GRDC Observations
10 year mean TRIP output (HadCM3)

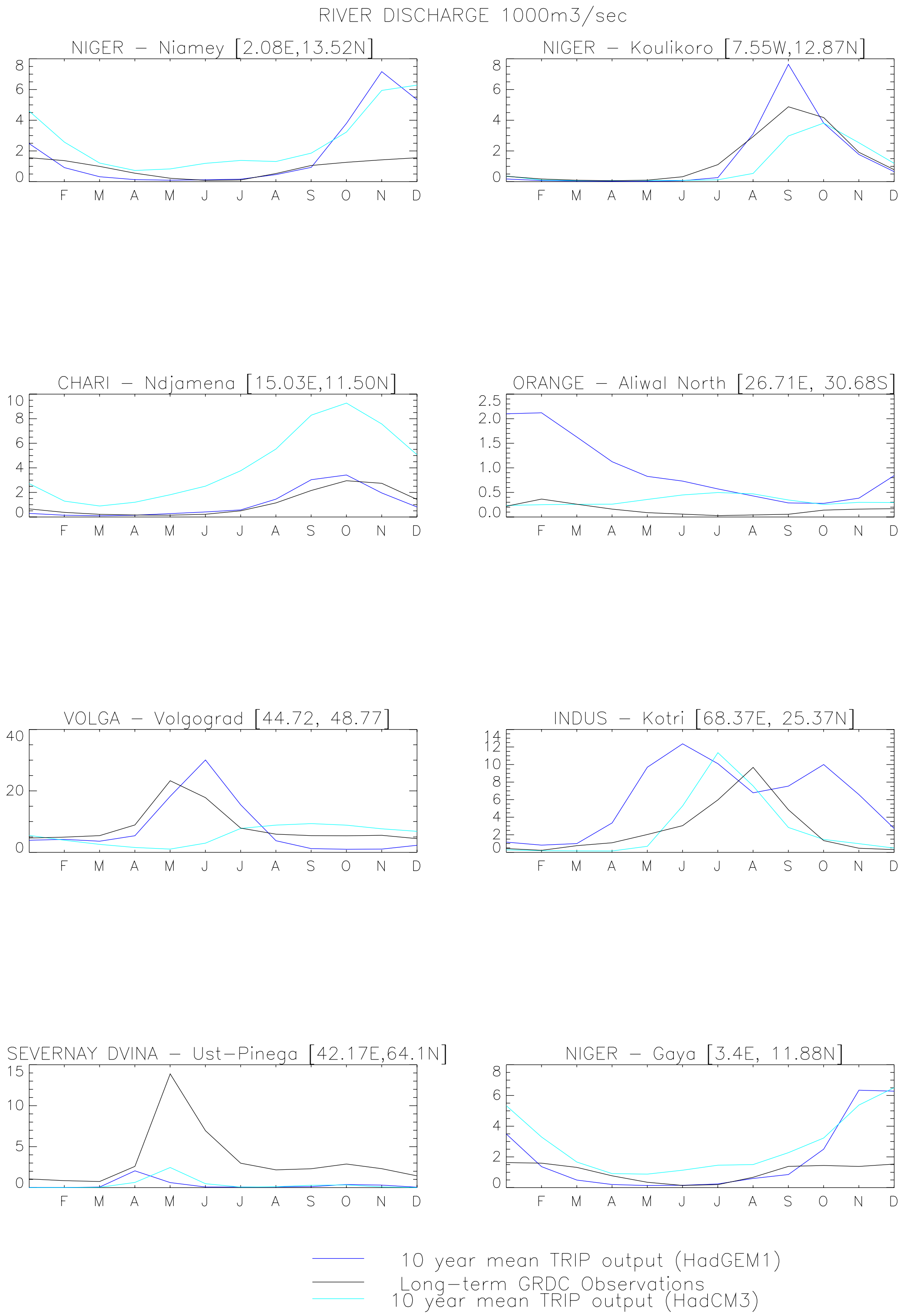
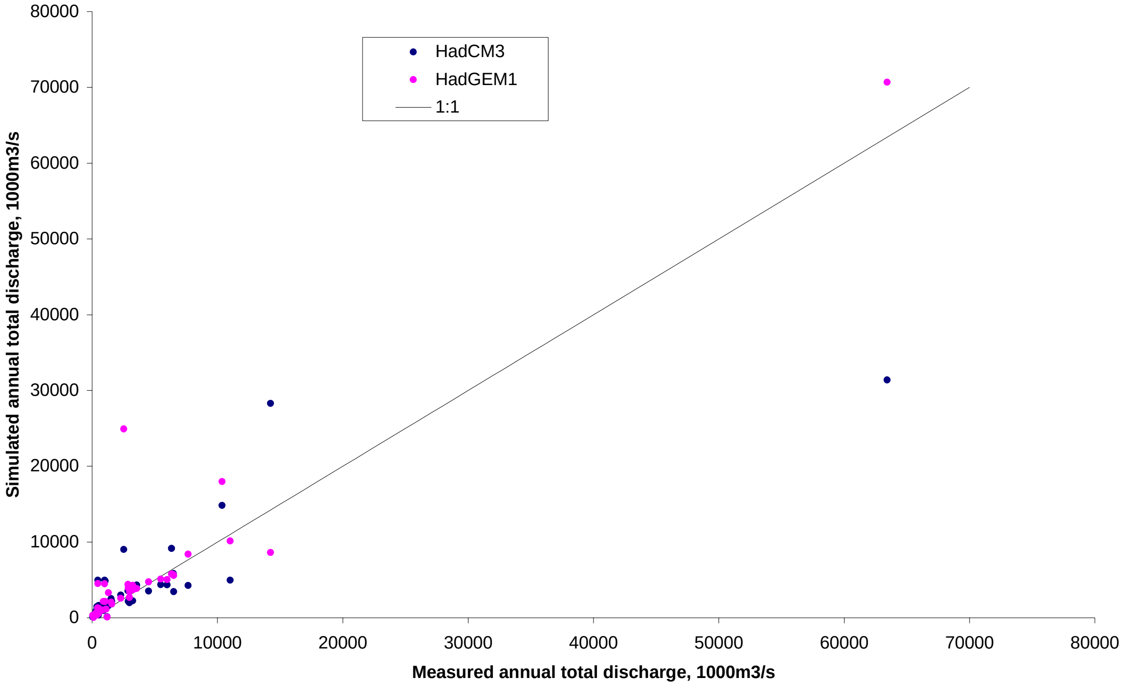
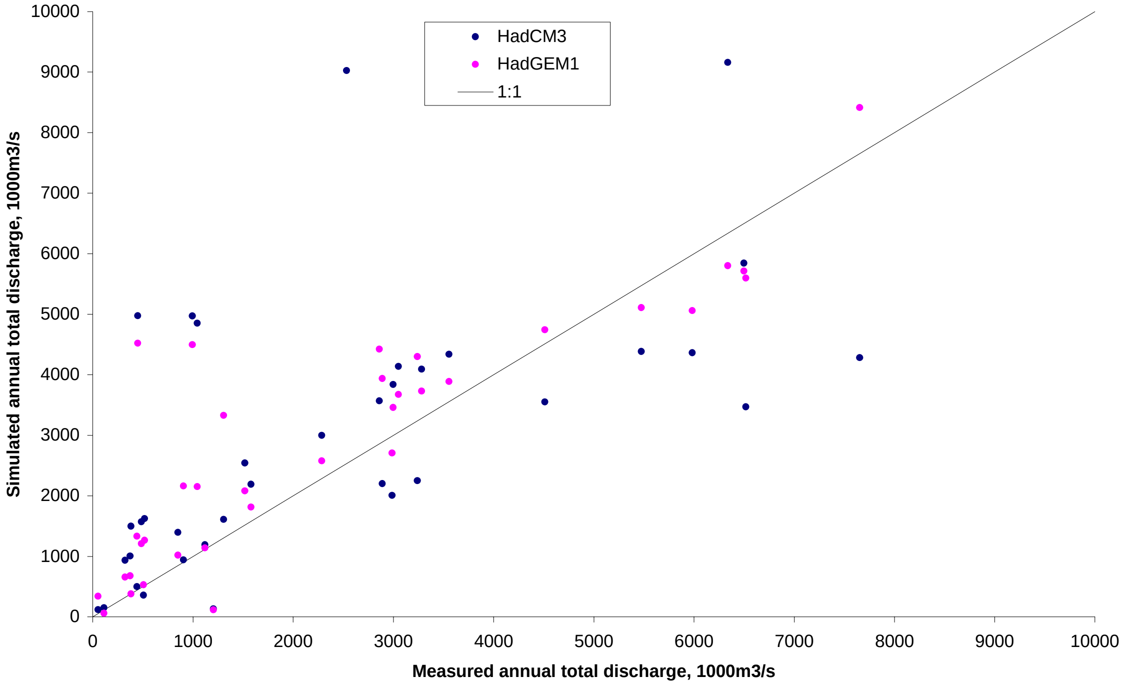

RIVER DISCHARGE 1000m3/sec
NIGER – Niamey [2.08E,13.52N]
NIGER – Koulikoro [7.55W,12.87N]
CHARI – Ndjamena [15.03E,11.50N]
ORANGE – Aliwal North [26.71E, 30.68S]
VOLGA – Volgograd [44.72, 48.77]
INDUS – Kotri [68.37E, 25.37N]
SEVERNAY DVINA – Ust–Pinega [42.17E,64.1N]
NIGER – Gaya [3.4E, 11.88N]
F M A M J J A S O N D
10 year mean TRIP output (HadGEM1)
Long–term GRDC Observations
10 year mean TRIP output (HadCM3)

Figure 24: Observed (GRDC) and simulated long-term mean annual total river discharge for a) full range of data and b) flows less than 10000 $m^3 s^{-1}$ (x1000)

a)



b)



Future Work

1) Some rivers e.g. Lena show less realistic flow in the new scheme which needs investigation.
2) When information on the position of dams becomes available, these could be inserted into the model.
3) Different meander ratios for each gridbox or river should be investigated.

References

Gedney, N. & Cox, P.M. (2002) The sensitivity of global climate simulations to the representation of soil moisture heterogeneity. Hadley Centre Technical Note 41, Hadley Centre for Climate Prediction and Research, Exeter, UK.

Oki, T. (1997) Validating the runoff from LSP-SVAT models using a global river routing network by one degree mesh. American Meteorological Society Abstracts, 1997, 319 – 322, 1997.

Oki, T. & Sud, Y.C. (1998) Design of Total Runoff Integrating Pathways (TRIP) – A global river channel network. Earth Interactions 2, 1-37.

Global Runoff Data Centre (GRDC), Federal Institute of Hydrology, Koblenz, Germany. (www.bafg.de/grdc.htm)

APPENDIX A

The TRIP Scheme in UM version 5.5 onwards : Code Structure

The code structure for river routing is as follows:

	➔	RIV_IC1A ➔ RIVER1A➔ ROUTRIV1	A20_1A
ATMPHB2			
	➔	RIV_IC2A ➔ RIVER2A	A20_2A

1A is the TRIP global scheme and 2A is a Limited Area scheme (under development for regional modelling). These new routines and the new diagnostics are all part of the new Atmosphere Section 20.

Scheme 1A will be described:
After the call to HYDROLOGY in ATMPHB2, the surface and subsurface runoff is accumulated in the Atmosphere Dump until the river routing timestep is reached. This is passed into RIV_IC1A (from the initial dump) together with the river direction and sequence files, water storage and atmosphere gridbox areas. As river routing must be run on only one processor (the last one), the arrays required are gathered onto the one PE in RIV_IC1A. The gathered arrays are then passed to RIVER1A. In RIVER1A the surface and subsurface runoffs are totalled and regridded onto the 1 x 1 degree grid and passed into ROUTRIV1 as mmd^{-1}. Due to differences in the UM and TRIP land/sea masks, some runoff after regridding appears in TRIP sea points but this is simply added as instantaneous outflow to conserve water. The water is routed using the TRIP advection scheme. The gridbox outflow and inflow (runoff kgs^{-1}) are passed out to RIVER1A where the outflow at river mouths or seapoints is mapped onto UM atmosphere sea points as river outflow and converted to $kgm^{-2}s^{-1}$ as expected by the ocean. This, together with the total gridbox outflow and inflow and (updated) water storage are written out as requested diagnostics in DAGRIV1 (called by ATMPHB2). The updated water storage is also written to the Atmosphere dump for the next river routing timestep. The Atmosphere grid river outflow is carried to the Ocean dump via the Coupling routines (SWAPA2O and TRANA2O).

APPENDIX B

The TRIP Scheme in UM version 5.5 : UMUI

There is a new User Interface (Atmosphere) Scientific Section page (section 20) for river routing. As some diagnostics and prognostics are on the 1 x 1 degree grid, a new grid code (23) has been produced which is used in their new STASH entries. The new Diagnostics are:
Stash code 20 1 River Water storage (kg)
Stash code 20 2 Gridbox Outflow (kgs^{-1}) – available for every 1 x 1 degree gridbox
Stash code 20 3 Gridbox Inflow (kgs^{-1}) – available for every 1 x 1 degree gridbox
Stash code 20 4 River Outflow ($kgm^{-2}s^{-1}$) – on UM Atmosphere grid

Further Modsets are required for the Atmosphere Model and Reconfiguration to allow river diganostics to be stored in section 26 (instead of 20) for consistency with 6.0 and correct river grid prognostic and diagnostic field headers in the dump.

IN UMUI PAGE Sub-Model Independent => Compilation and Modifications => Modifications for the Model:

/u/m20/cprod/c20cb/mods506/acb0f506.mf77 Model modset
/u/m20/cprod/c20cb/mods506/acb0h506.mh " "
/u/m20/cprod/c20cb/mods506/acb0f506.mf77 Model modset

IN UMUI PAGE Sub-Model Independent => Compilation and Modifications => Modifications for the Reconfiguration:

/u/m20/cprod/c20cb/mods506/gcb0n506.mf90 Reconfiguration Modset

In addition the user stashmaster files:

In UMUI page Atmosphere => STASH => User Stashmaster files:

~hadcb/umui_jobs/prestash/river_routing_5.5_new2
~hadcb/umui_jobs/prestash/user_stashm_sect20
~hadcb/umui_jobs/prestash/user_stashm_sect26

river_routing_5.5_new2 contains a copy of the river routing prognostics to allow for their initialisation from the dump /u/m20/cprod/c20cb/ddafd/ddafd.astart which contains them.

Initialise them in UMUI page Atmosphere => STASH => Initialisation of User Prognostics:

Choose 3 for Accumulated Runoff, subsurface runoff and gridbox areas (no longer used)
Choose 7 for River direction, sequence and water storage from the dump

/u/m20/cprod/c20cb/ddafd/ddafd.astart.

There is curently no code to read in multifile ancilliary files of initial water storage.
Switch On River Routing:

UMUI page Atmosphere => Scientific Parameters and Sections=> Section by Section Choices => Section 20 River Routing

Note that at 5.5 the code is still in section 20 but the diagnostics are in section 26.
At 6.0 they are all in section 26.

Choose River Routing 1A Global.
The parameters are set for a one day timestep (to fit with the Atmos/Ocean Coupling)

If doing an Atmos/Ocean run follow the button to OCN_RIVER to switch on the river routing in the Ocean Model. The anciliary files are concerned with the Ocean circulation of freshwater.

Hand edit file - this runs automatically when listed in the
UMUI page Sub-model Independent => User hand edit files
~hadcb/umui_jobs/hand_edits_acqip.ed

Choose diagnostics:
Atmosphere => STASH => STASH specification of Diagnostic requirements:
Diagnostics button => load new diagnostics => section 26

26001 River Water storage (Kg) - Time profile TRIVDMP (or TDAILY)
26002 Gridbox Outflow (Kg/s) - Time profile TRIVDMP (or TDAILY)
26003 Gridbox Inflow (Kg/s) - Time profile TRIVDMP (or TDAILY)
26004 River Outflow (Kg/m2/s) - Time profile TRIVDMP (or TDAILY)
and Useage UPCOUP if a Coupled Run.

TRIVDMP is every river timestep (1 day at present) with no time processing.
26002 will be used for comparing individual rivers with guaging stations observations
26003 is essentially the total runoff regridded to the river grid

UM version 6.0

River routing has changed to Atmosphere Section 26.

Atmosphere => Scientific Parameters and Sections => Section by Section Choices => Section 26: River routing

Choose version: 1A Global model
The parameters are set for a one day timestep (to fit with the Atmos/Ocean Coupling)

If doing an Atmos/Ocean run follow the button to OCN_RIVER to switch on the river routing in the Ocean Model. The ancillary files are concerned with the Ocean circulation of freshwater.

The ancillary files must be set up via user prognostics as at version 5.5:

Add the user stashmaster files:

In UMUI page Atmosphere => STASH => User Stashmaster files:
~hadcb/umui_jobs/prestash/river_routing_5.5_new2
~hadcb/umui_jobs/prestash/user_stashm_sect20
~hadcb/umui_jobs/prestash/user_stashm_sect26

river_routing_5.5_new2 contains a copy of the river routing prognostics to allow for their initialisation from the dump /u/m20/cprod/c20cb/ddafd/ddafd.astart which contains them.

Initialise them in UMUI page Atmosphere => STASH => Initialisation of User Prognostics:

Choose 3 for Accumulated Runoff, subsurface runoff and gridbox areas (no longer used)
Choose 7 for River direction, sequence and water storage from the dump

/u/m20/cprod/c20cb/ddafd/ddafd.astart.

Choose diagnostics:
Atmosphere => STASH => STASH specification of Diagnostic requirements:
Diagnostics button => load new diagnostics => section 26

26001 River Water storage (Kg) - Time profile TRIVDMP (or TDAILY)
26002 Gridbox Outflow (Kg/s) - Time profile TRIVDMP (or TDAILY)
26003 Gridbox Inflow (Kg/s) - Time profile TRIVDMP (or TDAILY)
26004 River Outflow (Kg/m2/s) - Time profile TRIVDMP (or TDAILY)
and Useage UPCOUP if a Coupled Run.

TRIVDMP is every river timestep (1 day at present) with no time processing.
26002 will be used for comparing individual rivers with guaging stations observations
26003 is essentially the total runoff regridded to the river grid

<u>UM version 6.1</u>

In the UMUI go to:

Atmosphere => Scientific Parameters and Sections => Section by Section Choices => Section 26: River routing

Choose version: 1A Global model
The parameters are set for a one day timestep (to fit with the Atmos/Ocean Coupling)

Number of Columns (X direction) 360
Number of Rows (Y direction) 180
River Routing Timestep (sec) 86400
Effective velocity (m/sec) 0.400000
Meander ratio 1.400000

If doing an Atmos/Ocean run follow the button to OCN_RIVER to switch on the river routing in the Ocean Model. The ancillary files are concerned with the Ocean circulation of freshwater.

The river routing ancillary files can now be defined as ancillaries from within the UMUI.

Atmosphere => Scientific Parameters and Sections => Section by Section Choices => Section 26: River routing

Push ANC1A to define Global river routing ancillaries. Specify path and filenames for river direction and sequence (in one file) and initial river water storage (in a separate file).

Choose diagnostics:
Atmosphere => STASH => STASH specification of Diagnostic requirements:
Diagnostics button => load new diagnostics => section 26

26001 River Water storage (Kg) - Time profile TRIVDMP (or TDAILY)
26002 Gridbox Outflow (Kg/s) - Time profile TRIVDMP (or TDAILY)
26003 Gridbox Inflow (Kg/s) - Time profile TRIVDMP (or TDAILY)
26004 River Outflow (Kg/m2/s) - Time profile TRIVDMP (or TDAILY)
and Useage UPCOUP if a Coupled Run.

TRIVDMP is every river timestep (1 day at present) with no time processing.
26002 will be used for comparing individual rivers with guaging stations observations
26003 is essentially the total runoff regridded to the river grid

<u>UM version 6.2</u>

As at UM version 6.1, but a modification has been added to re-route water from inland basins (which was previously lost from the system on regridding) to the top level of soil moisture. To use this modification check the button :

Atmosphere => Scientific Parameters and Sections => Section by Section Choices => Section 26: River routing

Re-routing inland basin water back to soil moisture

Diagnostics of this quantity are also available on the river routing and atmosphere grids:

Choose diagnostics:
Atmosphere => STASH => STASH specification of Diagnostic requirements:
Diagnostics button => load new diagnostics => section 26
INLANDBASINFLOW TRIP GRID KG/S – Time profile TDAILY Domain profile DIAG Usage profile UPA

Atmosphere => STASH => STASH specification of Diagnostic requirements:

Diagnostics button => load new diagnostics => section 8

INLANDBASINFLOW ATM GRID KG/M2/S – Time profile TDAILY Domain profile DIAG Usage profile UPA