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U.S. DEPARTMENT OF ENERGY | Office of Science

FY 2015 First Quarter Performance Metric: Use Climate Models to Capture Seasonal to Decadal Changes in Surface Water Dynamics

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1.0 Product Definition

New model developments for dynamically representing changes in river flow have led to important advances in capturing seasonal to decadal changes in surface water dynamics and will be critical for associated changes in nutrients and regional climate. Through freshwater discharge, sediment, carbon, and nitrogen fluxes to the ocean, and outgassing of CO_2 to the atmosphere, rivers play an important role in the water and biogeochemical cycles of the coupled earth system. Surface water transport is also closely linked to human activities as water resources are managed to balance supply and demand through regulations of streamflow. Understanding and predicting natural hazards such as flooding and its hydrological and ecological consequences have required improved understanding and modeling of surface water dynamics.

In response to these requirements, the Model for Scale Adaptive River Transport (MOSART) has now been coupled with the Community Land Model (CLM) and implemented and evaluated globally. Decadal simulations of streamflow are shown to reproduce reasonably well the observed daily and monthly streamflow at over 1,600 world’s major river stations in terms of annual, seasonal, and daily flow statistics. In contrast to the River Transport Model (RTM) currently used in the standard version of CLM that assumes a constant river velocity in space and time, numerical experiments show that the spatial and temporal variability of river velocity simulated by MOSART is necessary for capturing streamflow seasonality and the annual maximum flood.

2.0 Product Documentation

MOSART is a physically based runoff-routing model designed for applications across watershed, regional, and global scales with relatively consistent performance at different resolutions (Li et al. 2013). All model parameters are physically based and only a small subset of them requires calibration. MOSART has been coupled with CLM (Lawrence et al. 2011) in the same manner as standard runoff routing module, River Transport Model (RTM) (Branstetter and Erickson, 2003). CLM simulates the surface runoff and baseflow for each grid cell at each time step. The gridded CLM-simulated surface runoff and baseflow is transferred to MOSART at the end of the time step and MOSART routes the runoff across hillslope and through sub-network and main channels. While RTM uses globally uniform and constant river velocity, MOSART explicitly simulates both spatial and temporal variability of flow velocity.

The coupled CLM-MOSART model has been applied globally using land surface parameters and atmospheric forcing (Qian et al. 2006) provided with the NCAR-I2000 configuration for 1995-2004. CLM simulation is performed on a $0.9^{o}\times1.25^{o}$ grid at 30-minute time step. MOSART is applied at 0.5 degree resolution for runoff routing. To assess the impacts of the added model complexity in MOSART, five successive simulations are performed by turning off the subgrid routing and removing the temporal and spatial variability of channel flow velocities. Results show that representing the spatial and temporal variations of flow velocities has important effects on simulating seasonality of streamflow and magnitude of annual maximum flood. Each level of complexity enabled by MOSART compared to a simpler model can lead to statistically significant differences in simulating streamflow. The more process-oriented MOSART overall captures the dynamics of surface water and provides a framework for modeling stream temperature, river biogeochemistry, and inundation dynamics that provide key linkages with other Earth system and human system components for a more holistic representation of global and regional water and carbon cycles.

3.0 Results: Global Implementation of MOSART

The global implementation of MOSART is evaluated using observed runoff and streamflow data. To assess the impacts of the added model complexity in MOSART, five successive simulations are performed by turning off the subgrid routing and removing the temporal and spatial variability of channel flow velocities. The five numerical experiments include: (0) Baseline simulation, representing all within- and between-grid routing processes included in MOSART. (1) Turning off the within-grid routing processes (by delivering the surface and subsurface runoff instantaneously into the main channels) but fully representing the spatiotemporal variation of the main channel velocity simulated by the kinematic wave method. (2) Turning off the within-grid routing processes and removing the temporal variation of channel velocity. The spatial velocity map is derived by averaging the time series of channel velocity for each grid generated in (0). (3) Turning off the within-grid routing processes and removing the spatiotemporal variation of channel velocity. The spatially uniform and temporally constant velocity field is derived from the global average velocity value from (2), which is ~0.21m/s. (4) similar to (3), but the velocity value is 0.35m/s, same as that used in the RTM algorithm in CLM. These five simulations are denoted as “MO_baseline”, “MO_wgoff”, “MO_wgoff_vXY”, “MO_v0.21”, “MO_vRTM”, respectively, with “MO_vRTM” being a replication of RTM, except for a different underlying network map and compared to evaluate the impacts of model complexity on the simulated streamflow.

3.1 Three Metrics to Evaluate MOSART

Three metrics are used here to capture different effects of the routing processes, annual mean streamflow, mean monthly streamflow and annual maximum flood. Annual mean streamflow (AMS) is most useful in describing the accumulating effect largely affected by the annual water balance of the upstream drainage area (of a gauge station where the streamflow is measured or simulated). Mean monthly streamflow captures both the accumulation (particularly for small areas where the residence time of surface water is much less than a month) and dispersion (particularly for large regions where the residence time of surface water is close to a month). Annual maximum flood (AMF, the maximum discharge in a calendar year, usually derived from daily or sub-daily time series) captures both the accumulating and dispersion effects particularly during major storm events.

Observations to evaluate the CLM-MOSART simulations include monthly runoff maps and observed streamflow data from about 6,900 stations provided by the Global Runoff Data Center (GRDC). For each station, the upstream area value provided by GRDC is compared to that estimated from the upstream area map used as input to MOSART. If the two upstream area values differ by no more than 10%, the station passes the geo-referencing test and is selected for the subsequent evaluation. There are 3,195 GRDC stations that meet the upstream drainage area criterion, of which 1,674 are selected with no less than 10 years of complete records of daily streamflow observation in 1980-2004 (Figure 1). For each station, long-term averages of the mean and maximum values within each calendar year are calculated for the years with complete daily streamflow observations.

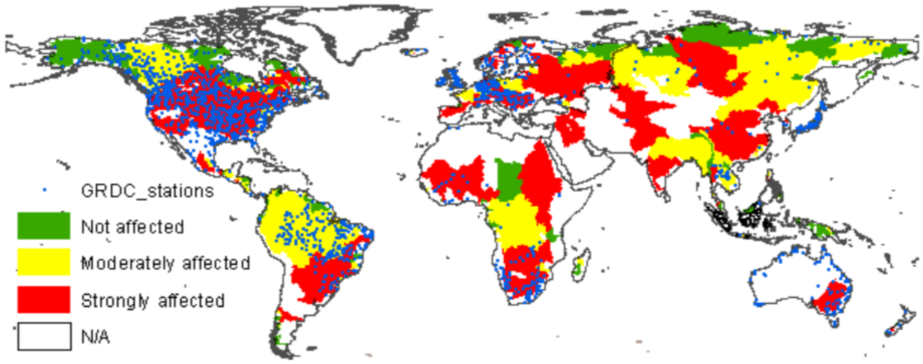


Figure 1.Distribution of 1,674 GRDC stream gauge stations (blue circles) used to evaluate the simulated streamflow. The GRDC stations are overlaid with the classification map based on the level of streamflow regulation (adapted from Nilsson et al., 2005).

For evaluation of the simulated streamflow, Table 1 lists the resulted R^2, slope values, and root-mean-square error (RMSE) from linear regression between the simulated and observed AMS and AMF at the 1,674 GRDC stations. All the slope values are statistically significant based on t-test with a p-value less than 0.001. The CLM-MOSART model reproduces well the long-term averaged AMS and AMF, as indicated by all the R^2 values higher than 0.75. The slope values for the AMS differ only slightly among all the simulations, but the differences for the AMF are more substantial. For AMF, the difference between the R^2 values from MO_wgoff (0.830) and MO_wgoff_vXY (0.805) is comparable to the difference between the R^2 values from MO_wgoff_vXY, MO_v0.21 (0.758), and MO_vRTM (0.78). Similar results are found for the slope and RMSE. Hence the effects of temporal variability of channel velocity on the simulated AMF are as important as those of the spatial variability of channel velocity and values of the global uniform channel velocity.

Table 1. Evaluation of model simulated AMS and AMF against the GRDC observations

	AMS			**AMF**		
	R^2	**Slope**	**RMSE (m^3/s)**	**R^2**	**Slope**	**RMSE (m^3/s)**
MO_baseline	0.855	0.694	3192.0	0.832	0.896	5148.1
MO_wgoff	0.856	0.703	3149.8	0.830	0.897	5200.3
MO_wgoff_vXY	0.856	0.703	3152.0	0.805	0.781	5469.1
MO_v0.21	0.856	0.701	3156.8	0.758	0.599	6527.4
MO_vRTM	0.856	0.702	3154.5	0.780	0.697	5924.8

The R^2 and slope values are from the linear regression between the model simulations and observations. The slope values all passed the t-test with a p-value less than 0.001. RMSE is the root-mean-square error between the simulated and observed series.

The impacts of the sub-grid routing processes appear to be much less than those of the spatial and temporal variability of channel velocity. This is mainly because the sub-grid routing processes are mostly local, i.e., affecting discharge from local grid into main channel, while other processes have direct impacts on main channel routing, which are captured by the GRDC streamflow observations because they are exclusively provided at gauges located on the main channels. The major effects of both spatial and temporal variability of channel velocities are also confirmed by the RMSE values. Although subgrid routing has less impact on the main channels, they are important for riverine biogeochemistry as sediments and nutrients are mobilized more effectively by high flows and in headwaters where subgrid hillslope processes are important.

To better present the effects of model structure, Taylor diagram (Taylor 2001) is used to visualize the statistical relationship of simulated monthly streamflow between the baseline simulation, MO_baseline, and other simulations, as shown in Figure 2. This comparison highlights the impacts of model complexity rather than compare model biases between observed and simulated streamflow, which are more affected by factors such as biases in the runoff simulations and human impacts that are not directly related to model complexity. Three major statistics are captured in this diagram: correlation (dashed straight lines), centered root-mean-square difference (proportional to the distance from the reference point on the horizontal axis, REF, shown as solid arc lines) and amplitude of variations (proportional to the distance from the origin, shown as dashed arc lines). MO_baseline is used as the reference, and each marker represents comparison of monthly streamflow time series for 1995-2004 at one GRDC station simulated by MO_wgoff, MO_wgoff_vXY, MO_v0.21 or MO_vRTM, with MO_baseline. Overall, at the monthly time scale, the effects of within-grid processes are minor since all the red markers corresponding to MO_wgoff are close to the reference point. The blue (MO_wgoff_vXY), green (MO_v0.21) and golden (MO_vRTM) markers are increasingly further away from the reference point, indicating increasing differences from the baseline simulation.

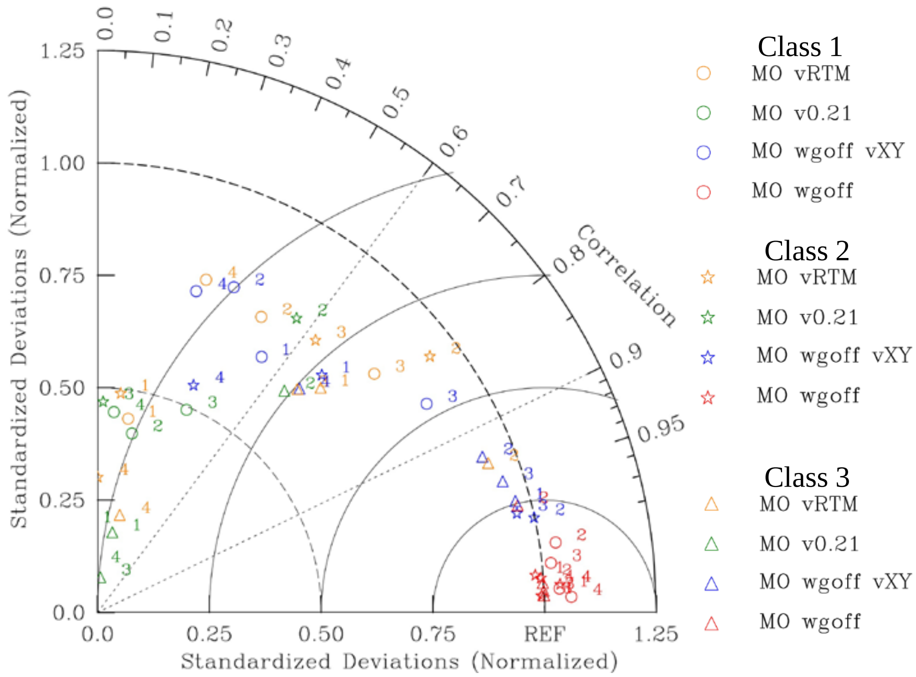


Figure 2. Taylor diagram of monthly streamflow simulations using different model structures with the baseline simulation as reference. For each class, four GRDC stations are plotted and labeled as 1, 2, 3 and 4.

The increasing distances of the various plotted points from the origin is associated with both reductions in the correlations from 1.0 to less than 0.1, and reductions in the normalized standard deviations from 1.0 to less than 0.25, indicating increasing differences in seasonal timing and reducing seasonal variability from the baseline simulation. More specifically, from MO_wgoff, MO_wgoff_vXY, to MO_v0.21 or MO_vRTM, the distances of the markers from the origin consistently decrease. The lowest correlation and variability are associated with vRTM and v0.21. Clearly, variations of the river velocity are increasingly removed by stepwise reduction of the model structure complexity. The time lag between MO_baseline and MO_wgoff is clearly less than that between MO_baseline and MO_wgoff_vXY, but it is not always clearly less than that between MO_baseline and MO_v0.21 or MO_vRTM. This suggests that turning off the temporal variability of channel velocity will certainly change the seasonal cycle compared to the baseline simulation, but further turning off the spatial variability might have some compensating effects on the timing of monthly streamflow. More investigation to elucidate the timing aspect is thus needed. Mean monthly streamflow curve, or regime curve, is a good indicator of the timing of streamflow at the monthly scale, which is discussed next.

Figure 3 shows the simulated mean monthly streamflow from the five numerical experiments at 12 selected GRDC gauge stations with complete monthly streamflow records within the period of 1995-2004 and representative of river basins that are “not affected”, “moderately affected” and “strongly affected” by human activities. The difference due to various model structures manifests consistently across all stations, despite the fact that the stations are very diverse with respect to the geographic locations, climate regimes and human influences. The mean monthly hydrographs from the “MO_wgoff” simulation show slightly higher peaks than those from the “MO_baseline” simulation. This is because neglecting the within-grid routing processes leads to reduced dispersion effect. The effects of temporal variation of channel velocity (indicated by the difference between the MO_wgoff_vXY and MO_wgoff simulations) are clearly more important than the within-grid routing processes at the monthly scale (the latter are important at daily or sub-daily scales as illustrated by Li et al. 2013).

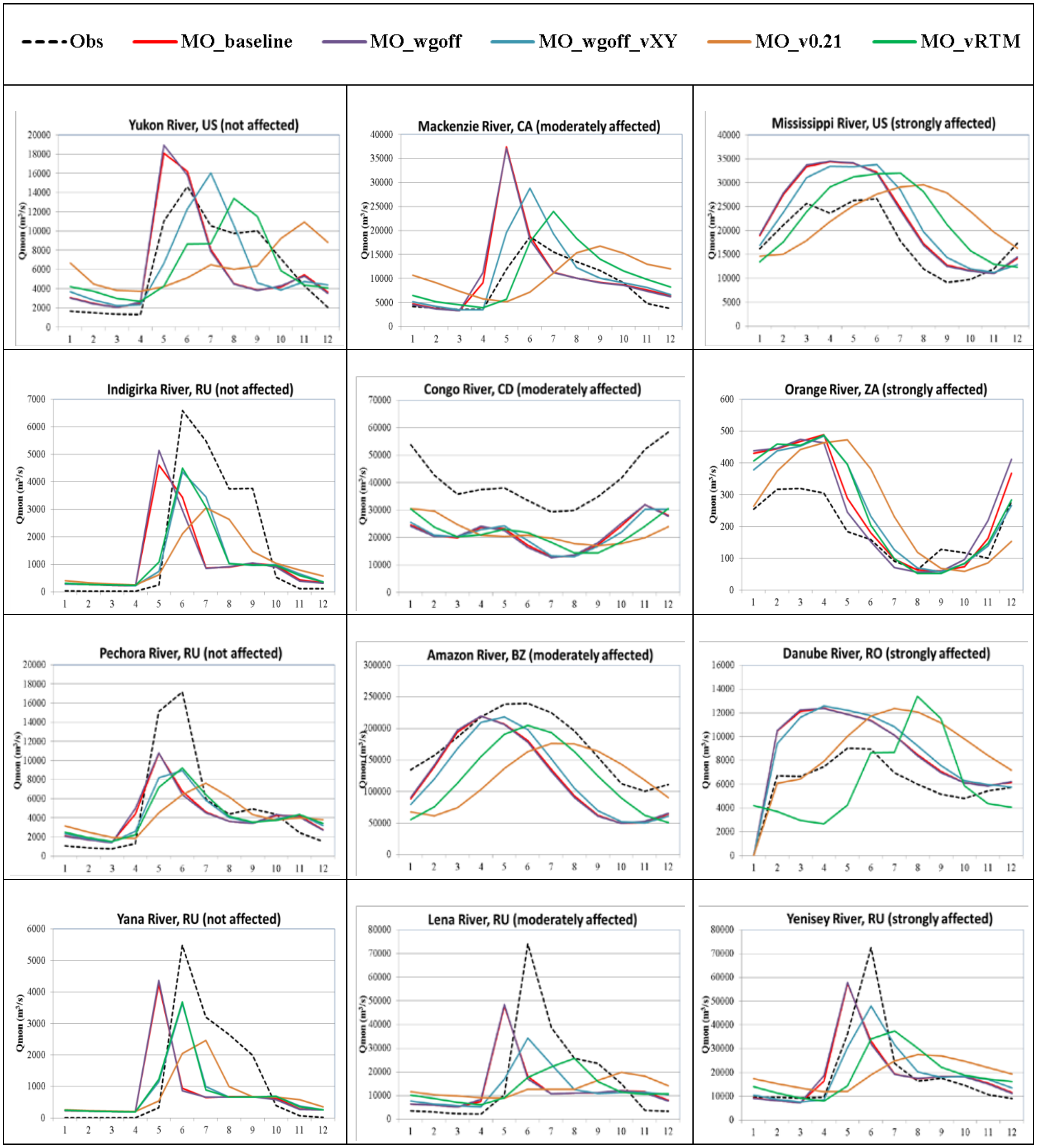
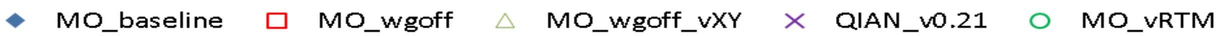


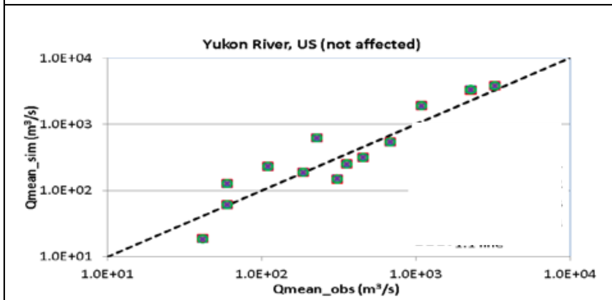
Figure.3. Impacts of model structure on seasonality of streamflow. The left, middle, and right columns are for river systems not affected, moderately affected, and strongly affected by flow regulation, respectively.

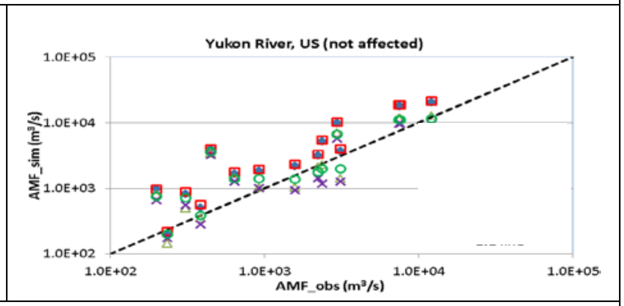
The effects of spatial variation of channel velocity (indicated by the difference between the MO_v0.21 and MO_wgoff_vXY simulations) are also apparent as shown in different river systems. It is interesting that in Indigirka, Pechora, Yana, and Orange River systems the monthly mean streamflow simulated by the MO_wgoff_vXY and MO_vRTM simulations are quite close. A first guess is that the actual long-term mean velocities averaged over all the grids within those river systems are close to 0.35m/s. The average velocities within the Yukon, Mackenzie, Mississippi, Lena, and Yenisey River systems are likely larger than 0.35m/s, as indicated by the earlier and higher monthly peak discharges. The impacts of different values of globally uniform and constant channel velocity are also clearly shown in all river systems, as expected. It is not feasible to use a single channel velocity to capture the diverse streamflow dynamics globally. Comparing the impacts of the different model complexity levels as demonstrated in Figure 3, it is clear the temporal variability of channel velocity is an important factor controlling also the timing of monthly streamflow simulations besides the AMF.

Figure 3 shows the streamflow simulation only at the outlets of the large river systems. Spatially, however, streamflow can be highly variable so it is interesting to find out how well the simulations reproduce the observed streamflow within large river systems. For this purpose one more criterion of river system selection is added on top of those used in Figure 3: only river systems including at least 10 GRDC stations with at least 8 years of complete daily streamflow records in 1995-2004 are selected. Only four river systems, Yukon, Mackenzie, Mississippi, and Danube, meet all the selection criteria. The impacts of routing model complexity on the AMS are expected to be negligible, as shown in Figure 4, since the travel time of surface water (particularly through river channels) is usually much less than one year. However, the impacts of routing model structure on the AMF peaks are clearly shown even from the log-log plots (right column in Figure 4). Note that each dot in Figure 4 is for the simulation at one GRDC station. The temporal variability of channel velocity is again a dominant factor on the simulated magnitude of annual flood peaks, as one can tell from the difference between the simulated flood peaks from the MO_wgoff simulation and those from the MO_wgoff_vXY simulation. Furthermore, the annual flood peaks simulated by the MO_vRTM case (uniform and constant velocity 0.35m/s) are always larger than those simulated by MO_v0.21 (uniform and constant velocity 0.2m/s), because larger channel velocity usually leads to larger flood peaks. This also explains the noticeable difference between the annual flood peaks simulated by MO_wgoff_vXY (spatially variable but temporally constant velocity) and MO_wgoff (spatiotemporally variable velocity), particularly in the Yukon and Mackenzie River systems, since the larger channel velocities associated with the flood peaks are well preserved in MO_baseline and MO_wgoff, but not in MO_wgoff_vXY, MO_v0.21 or MO_vRTM.

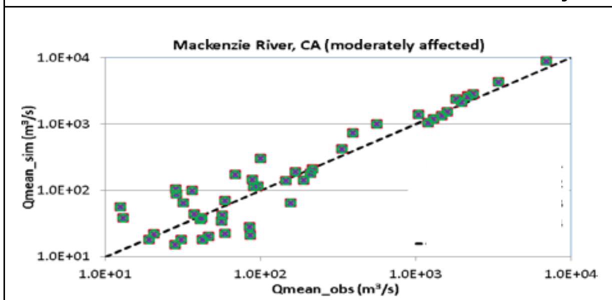


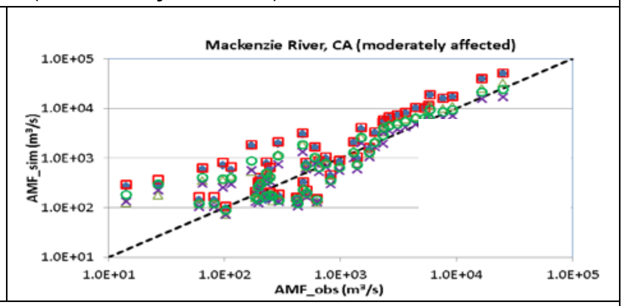
Yukon River system (not affected)



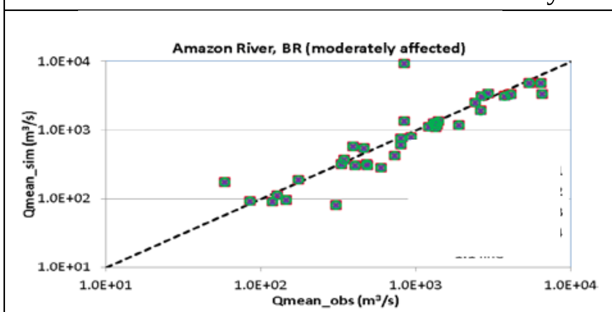


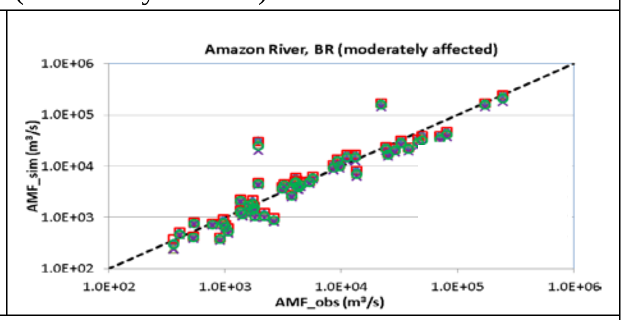
Mackenzie River system (moderately affected)



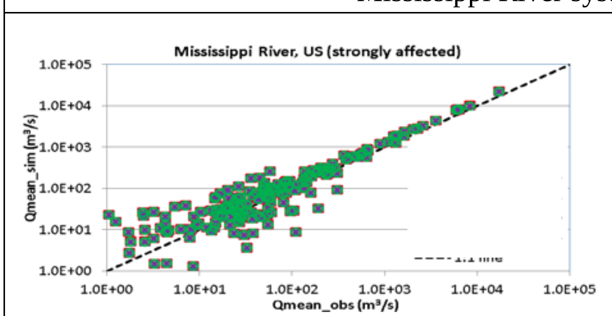


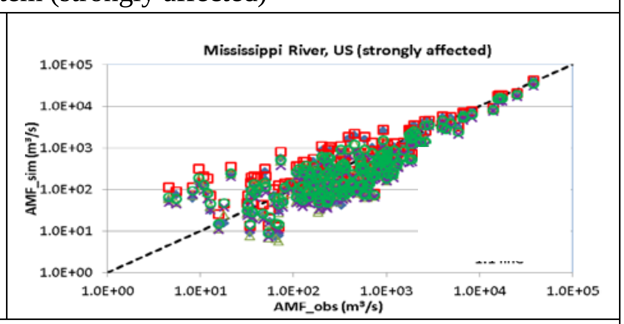
Amazon River system (moderately affected)





Mississippi River system (strongly affected)





Danube River system (strongly affected)

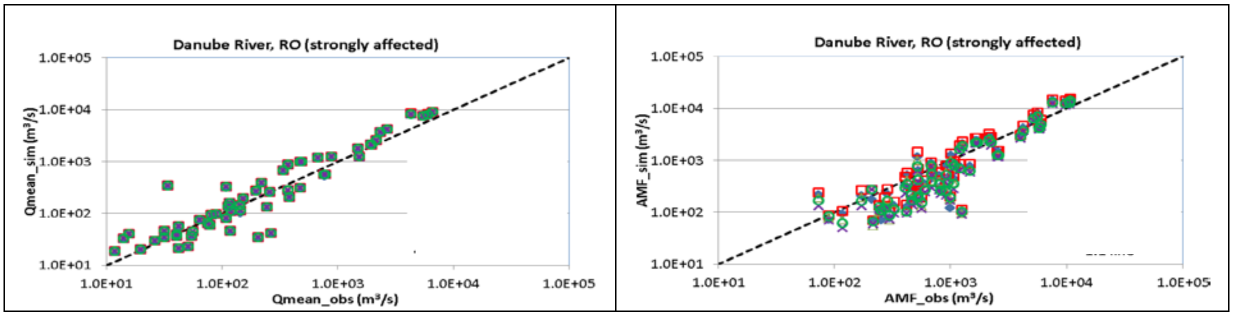


Figure 4. Scatterplots comparing observed and simulated AMS (left) and AMF (right) for simulations with different model structures (symbols).

3.2 MOSART P Streamflow Analysis Across Global Domain

Overall, it is shown that MOSART is able to simulate streamflow reasonably well across the global domain. Analysis suggests that representing the spatially and temporally varying flow velocities process in the routing model has important effects on simulating seasonality of streamflow and magnitude of AMF. Decharme *et al.* (2010) showed that realistic representation of channel velocity is important for global simulations of monthly streamflow. Here, we further show that the temporal variability of channel velocity has no less influence than the spatial variability of channel velocity, particularly with respect to the simulated magnitude of AMF. Each level of complexity enabled by MOSART compared to a simpler model can lead to statistically significant differences in simulating streamflow. Compared to the RTM implemented in CLM (as replicated by the MO_vRTM simulation), the more process-oriented MOSART overall captures the AMF better over the global domain and, to a certain degree, also captures the seasonality of streamflow better.

The modeling framework used in this study can be improved in several aspects. First, as many river basins are highly managed for flood control, irrigation, and other water uses, the impacts of reservoir operation and irrigation should be included. The reservoir operation scheme of Voisin *et al.* (2013a, 2013b) is being extended globally for coupling with CLM-MOSART. For rivers in high latitude areas, ice transport and jamming mechanism are known to have important effects on the timing of streamflow, and these are not included in MOSART yet. In other river systems (e.g., Amazon), representation of inundation dynamics (e.g., exchange between the main channel and floodplain) will lead to more realistic simulation of average channel velocity and will help to improve the simulation of timing and magnitude of streamflow at short time scale such as daily or subdaily (Getirana *et al.*, 2012). Extension of MOSART to incorporate inundation dynamics is being pursued for use in Earth system models, which will allow important climate feedbacks (e.g., inundation effects on methane and inundation induced changes in surface fluxes through albedo and soil moisture changes) to be captured more realistically.

4.0 References

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