Prediction of water surface elevation by a global river model: A case study for tidal effect in the Amazon River

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Joint Hydrology
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(1) INTRODUCTION

Development of a phisically-based model for explaining the variations in water surface elevation (WSE) is essential for understanding surface water dynamics. However, prediction of WSE in continental-scale rivers is difficult because surface waters dynamics are regulated by much smaller-scale topography than the resolution of continental-scale models.

Here, we developed a global river-floodplain model, CaMa-Flood, which describes smaller-scale topography as sub-grid parameters. CaMa-Flood explicitly predicts WSE by describing the relationship between surface water storage and WSE based on 90-m resolution DEM, HydroSHEDS.

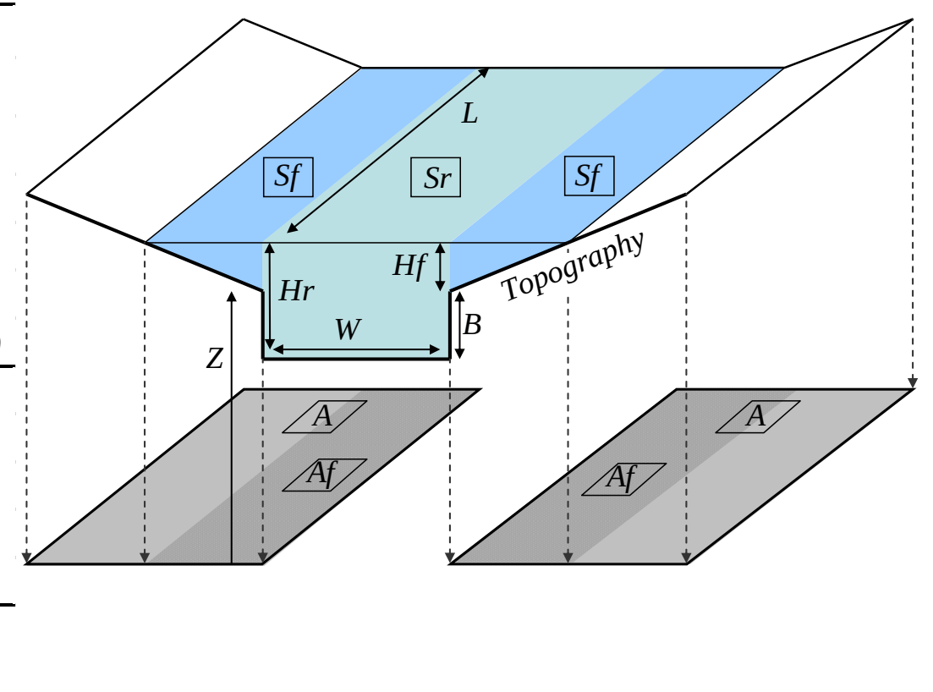
CaMa-Flood is applied to simulate tidal effect on surface water dynamics in the Amazon River. Because the Amazon basin is extremely flat, water level change in downstream propagates to upstream (backwater effect). Hence, precise prediction of WSE and induction of the diffusive wave equation are essential for representing surface water dynamics in the Amazon.

Simulation for the entire Amazon River basin is executed using CaMa-Flood. Water level change at river mouth due to ocean tide is given as the boundary condition of the model. The Impact of ocean tide on river discharge and WSE are discussed below.

(2) MODEL FRAMEWORK

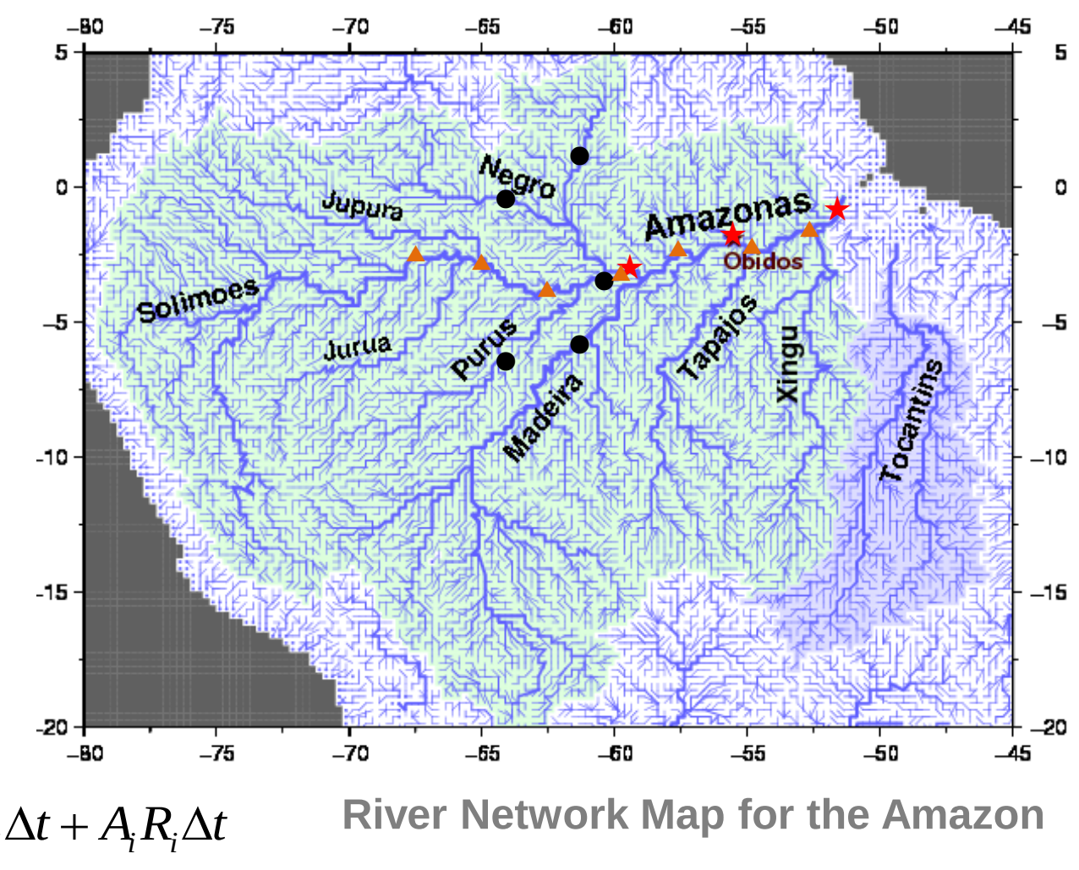
CaMa-Flood [Yamazaki, 2010] is a distributed river routing model which is forced by LSM runoff and predicts water storage, water surface elevation, inundated area, and river discharge. Spatial resolution is set to 25 km.

Parameter	Channel Elevation	Z
	Channel Length	L
	Channel Width	W
	Embankment Height	B
	Catchment Area	A
	Floodplain Elevation Profile	$f(Topography)$
Variables	River Storage	S_r
	Floodplain Storage	S_f
	River Water Depth	H_r
	Floodplain Depth	H_f
	Inundated Area	A_f



[2-1] River channel and floodplain storages are defined as continuative reservoirs in each grid. Total water storage in each grid is divided into river channel and floodplain storage to balance water surface elevation of both reservoirs.

[2-2] River discharge (i.e. flux between grids) is calculated along with a prescribed river network map. Diffusive wave equation is adopted as the governing equation for representing backwater effect. Water storage in next time step is predicted by continuity equation using inflow from upstream, outflow to downstream, and forcing runoff from LSM.



River Network Map for the Amazon

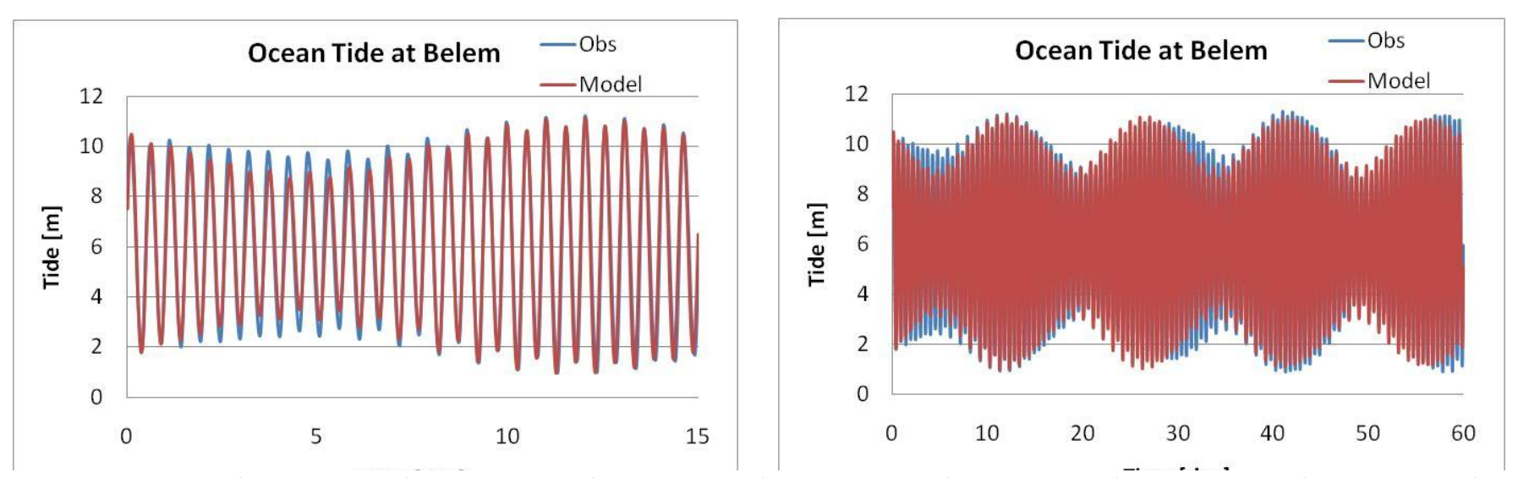
$$\underbrace{\frac{1}{g}\frac{\partial v}{\partial t}+\underbrace{\frac{v}{g}\frac{\partial v}{\partial x}+\underbrace{\frac{\partial h}{\partial x}+i_0-i_f}_{\text{Kinematic}}}_{\text{Diffusive}}}_{\text{Dynamic}}=0$$

St. Venant Momentum Equation

$$S_i(t+\Delta t)=S_i(t)+\sum_j^{upstream}Q_j\Delta t-Q_i\Delta t+A_iR_i\Delta t$$

Continuity Equation

[2-3] Boundary condition of ocean surface elevation is given as a cyclic function empirically derived from the observation. The four major components of the tide is used.



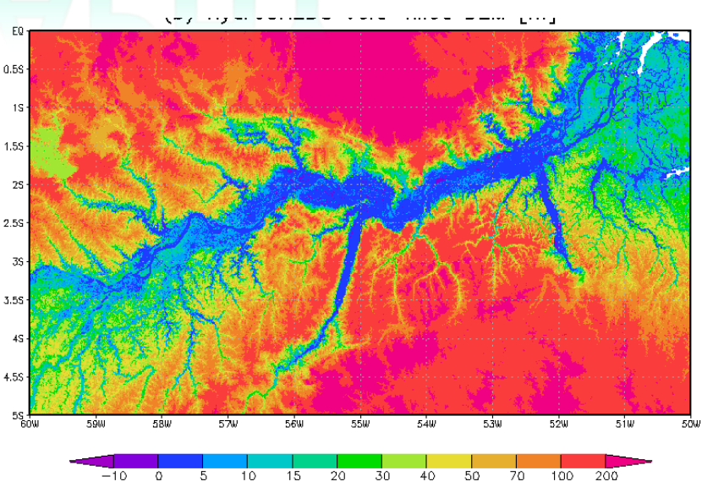
$$f(t)=3.83\cos\left(\frac{t-3.21}{12.42}2\pi\right)-0.18\cos\left(\frac{t-7.02}{23.93}2\pi\right)+1.07\cos\left(\frac{t-0.85}{12.00}2\pi\right)+0.19\cos\left(\frac{t-4.30}{25.82}2\pi\right)+a$$

Boundary condition for ocean surface elevation

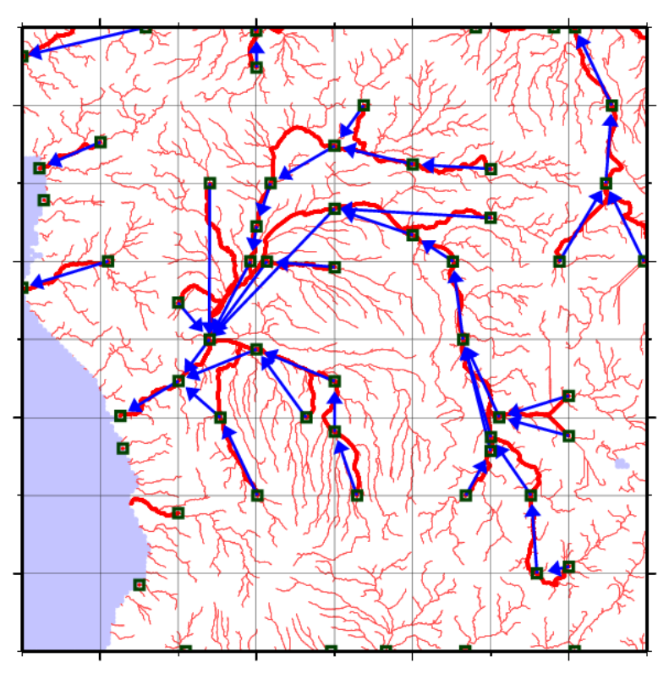
	Component	Cycle θ [h]	Factor(s)
M_2	Principal lunar semi-diunal tide	12.42	Relative position of the Earth - Moon
K_1	Luni-solar diurnal tide	23.94	Relative position of the Earth - Moon - Sun
S_2	Principal solar semi-diurnal tide	12.00	Relative position of the Earth - Sun
O_1	Principal lunar diurnal tide	25.82	Earth - Moon: 2nd mode of Spherical Harmonics

(3) SUB-GRID-SCALE TOPOGRAPHY

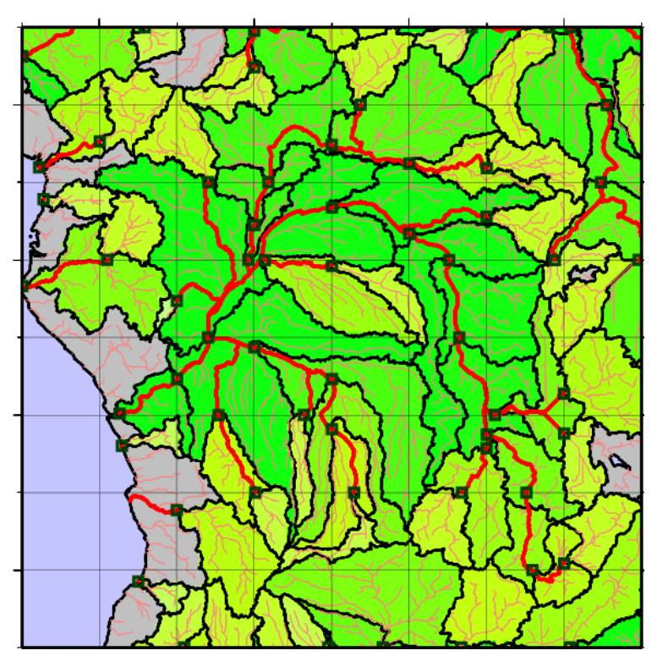
The river network map and sub-grid topographic parameters are objectively extracted from the HydroSHEDS flow direction map and DEM at 90-m resolution using FLOW method [Yamazaki, 2009].



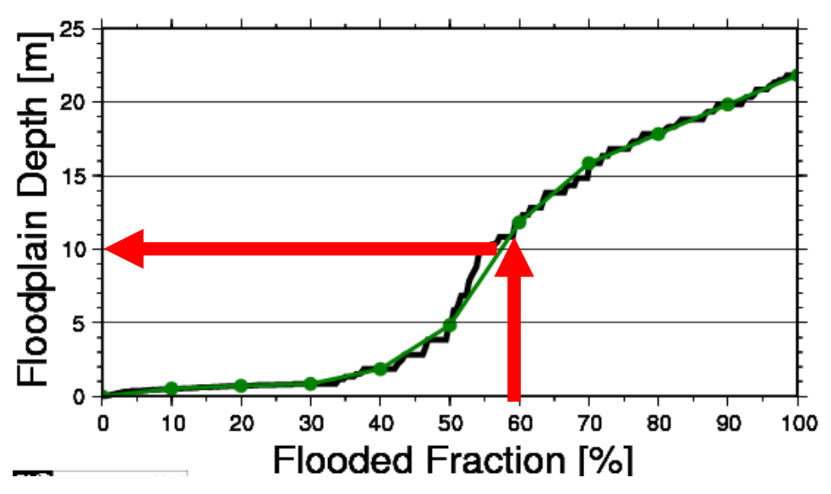
HydroSHEDS DEM



[3-1] "Outlet pixel" is decided for each coarse-resolution cell. channel elevation (green), river network map (blue) are extracted from 90-m resolution flow direction map and DEM.



[3-2] Channel length (red) is calculated for each cell considering meandering at 90-m scale. Unit-catchment (black tick boundaries) is decided for each coarse-resolution cell based on the flow direction map.



[3-3] Elevations of the pixels within an unit-catchment is sorted to generate a floodplain elevation profile, which is used to objectively describe the relation among floodplain water storage, floodplain water depth, and inundated area.

[Ex] Water depth is 10m when 60% of the catchment area is inundated

[3-4] Channel Width and Channel Embankment Height, which are not represented in 90-m fine-resolution dataset, are decided empirically.

Average Upstream Runoff $\overline{R}_{up}$

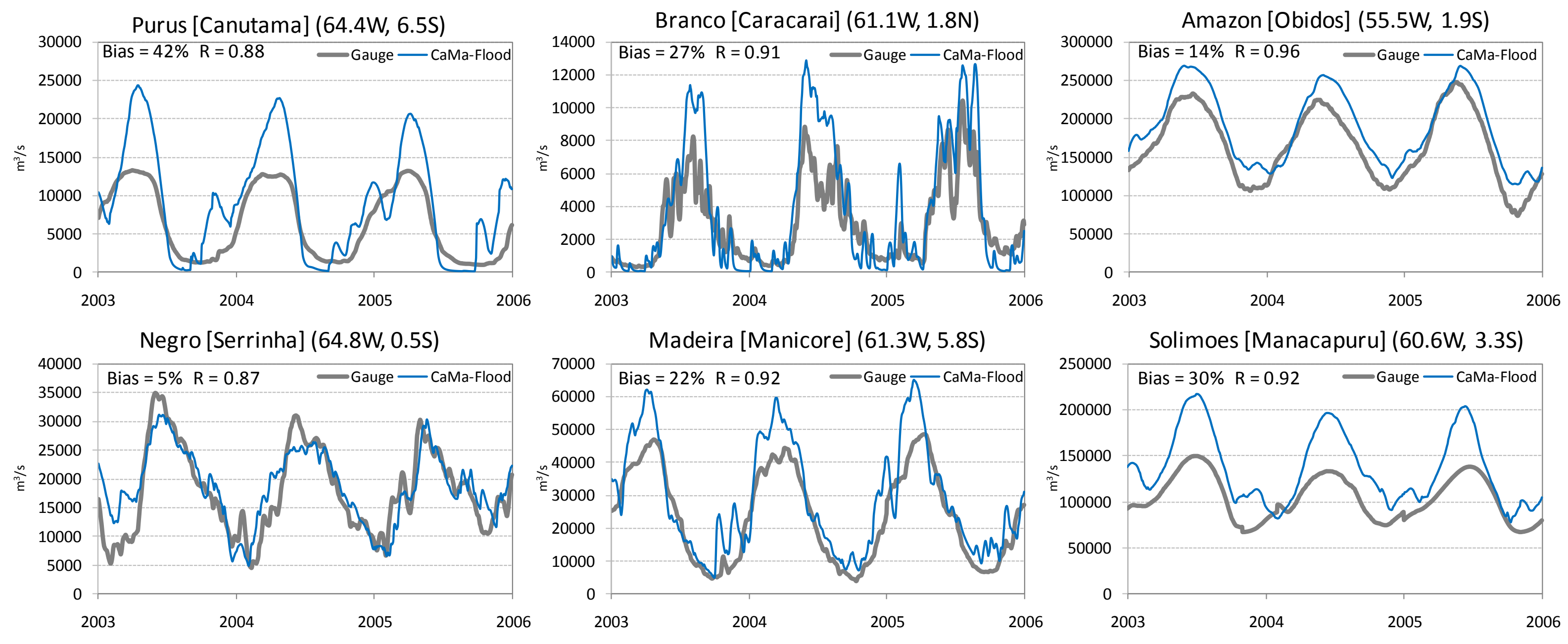
$$W=\max[10.0,1.0\times\overline{R}_{up}{}^{0.7}]$$

$$B=\max[1.0,0.04\times\overline{R}_{up}{}^{0.5}]$$

(4) RESULTS

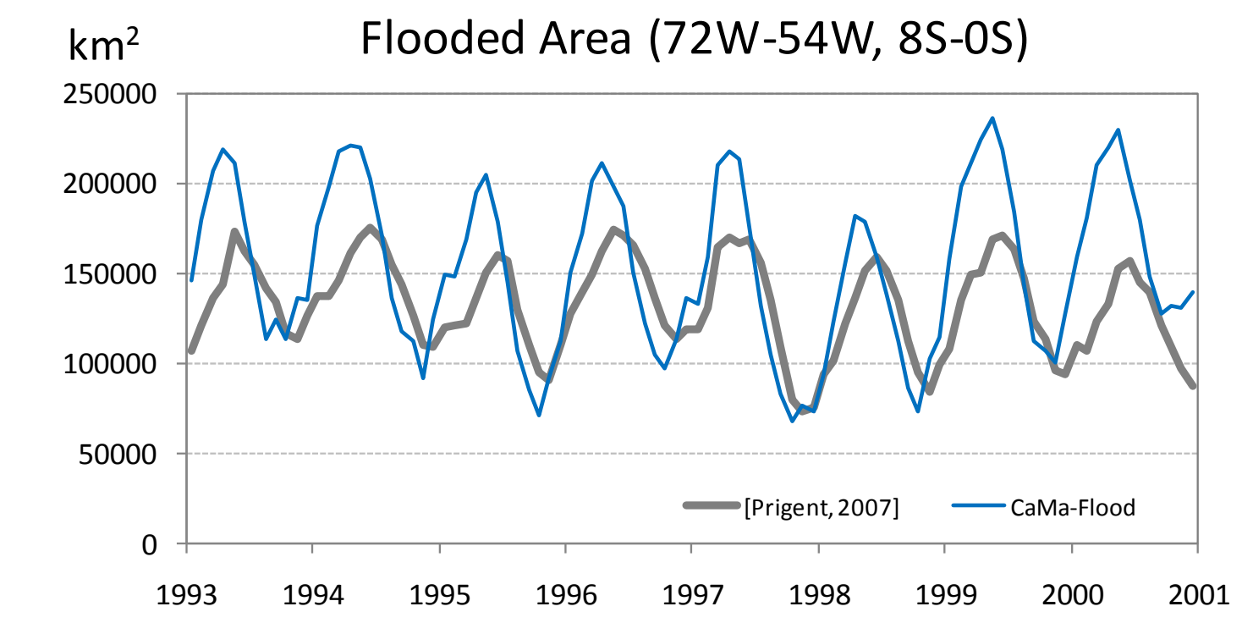
[4-1] DISCHARGE

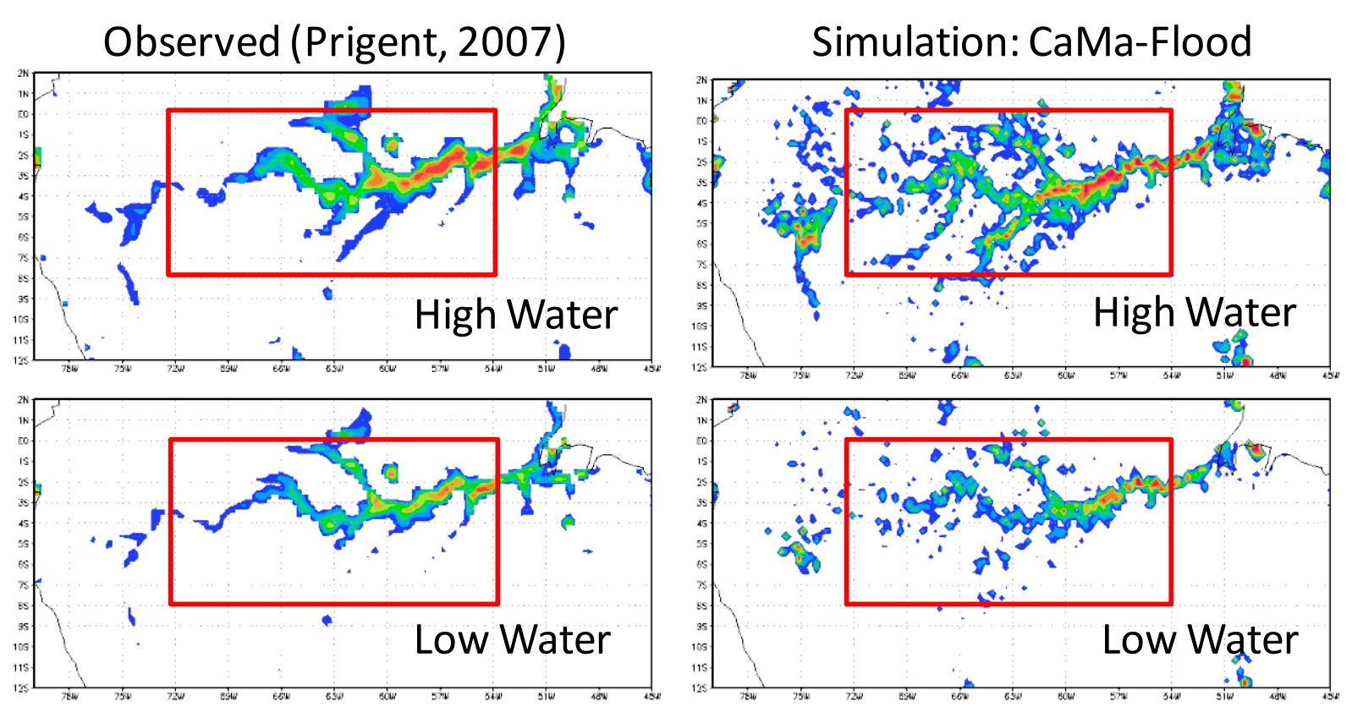
Simulated river discharge is compared against in-situ gauge observation. CaMa-Flood captures seasonal cycle of river discharge both in the mainstem and tributaries, though the input runoff from LSM is overestimated.



[4-2] FLOODED AREA

The Spatial pattern and seasonal cycle of flooded area are compared to satellite observation [Prigent, 2007]. They are well simulated, though the amplitude is overestimated.

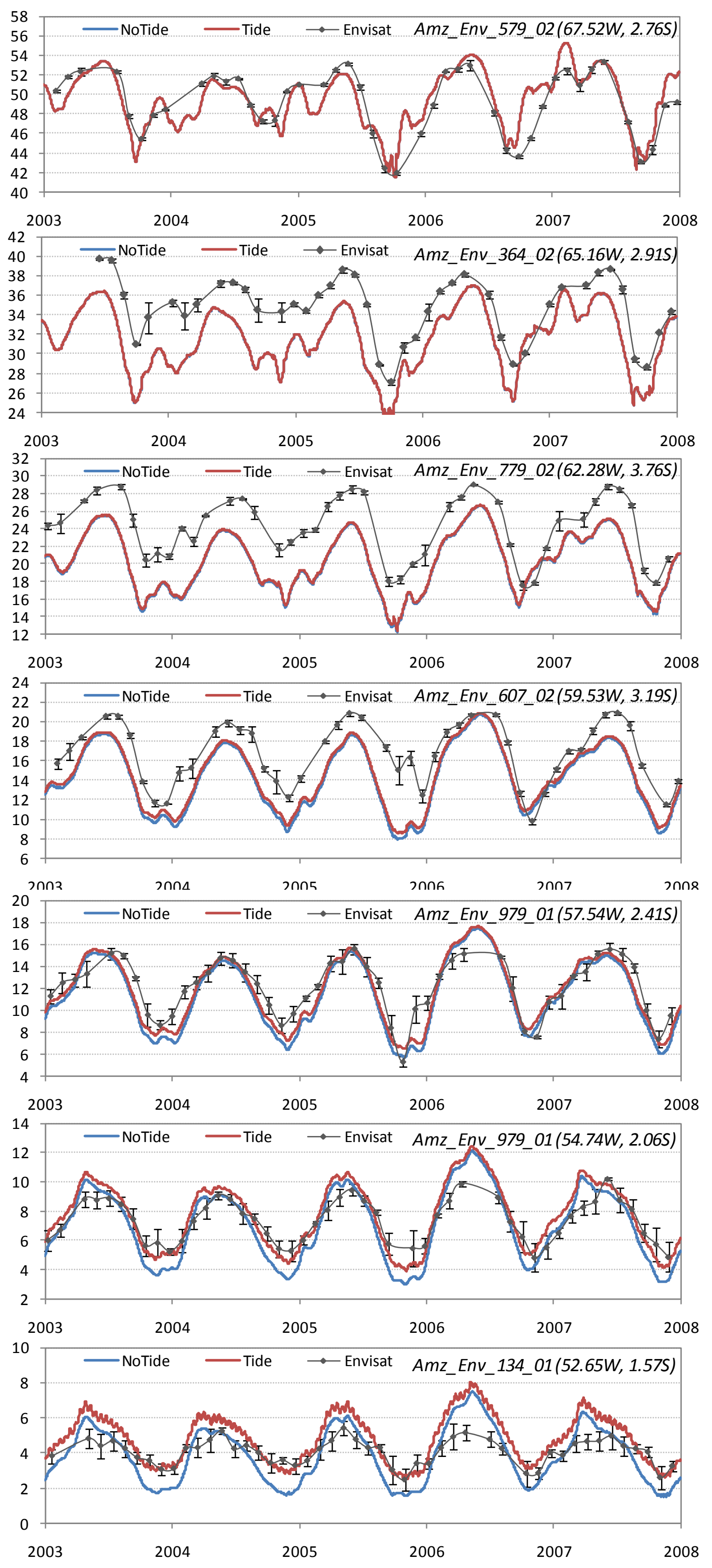




Flooded Fraction [%]

[4-3] WATER SURFACE ELEVATION

WSE is validated against Envisat observation. CaMa-Flood reproduces phase and amplitude of WSE along the mainstream. The bias seen in middle reach may be errors in DEM or parameterization. WSE in downstream reach is affected by the tidal (the difference between "Tide" and NoTide").

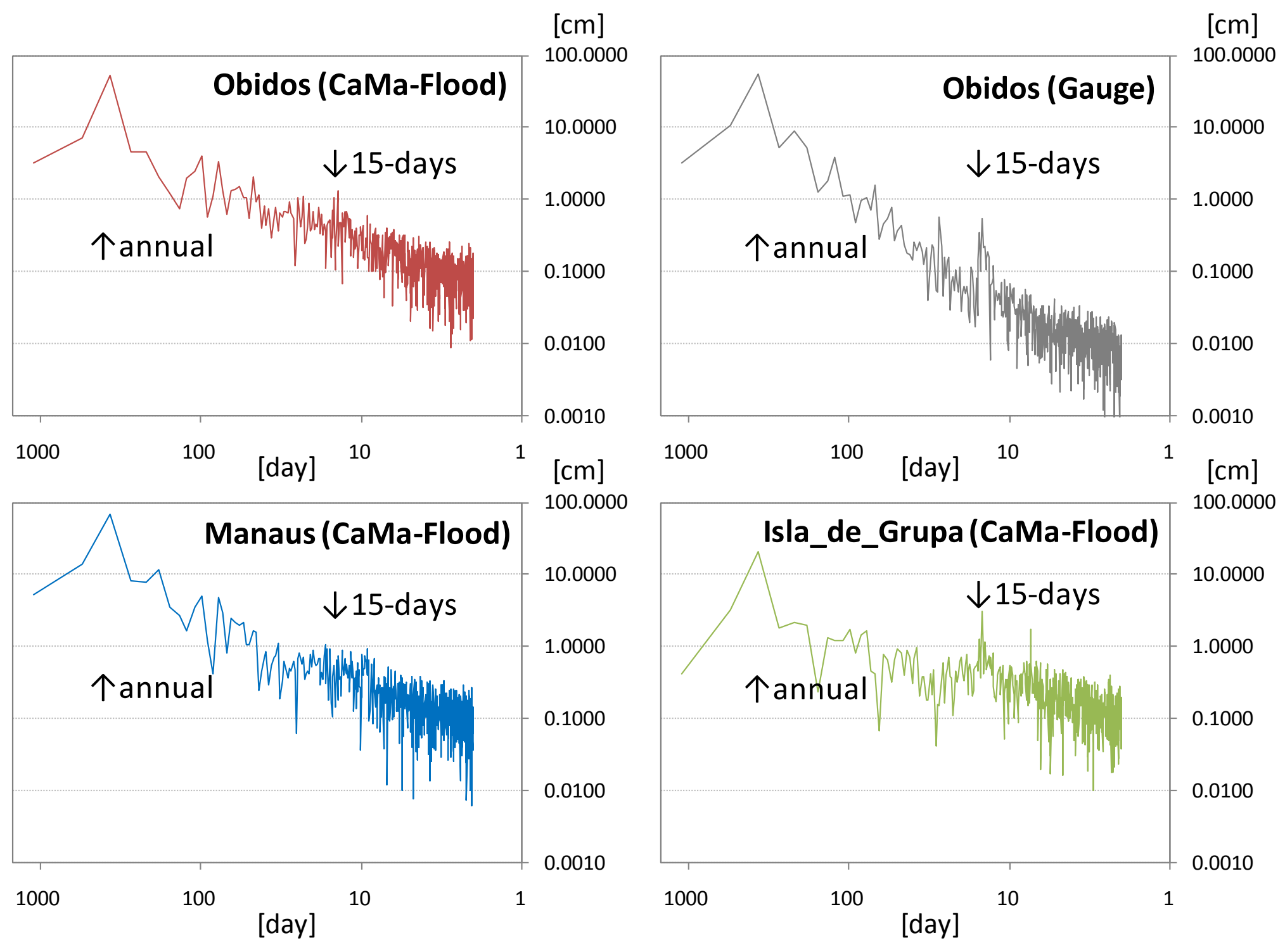


Water surface elevation [m]

[4-4] SPECTRA ANALYSIS

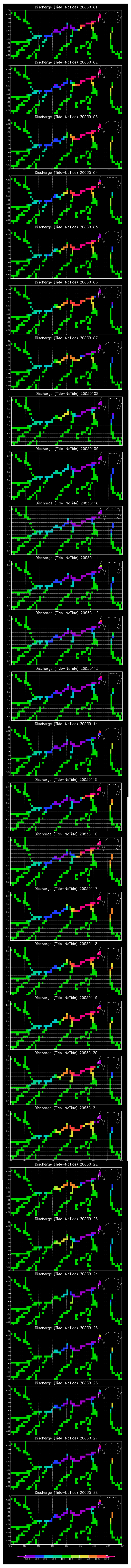
Power-spectra of simulated and observed WSE at Obidos (55.5W), Manaus (60.1W), and upstream of Isla de Grupa (51.0W) are analyzed. We can see significant 15-days cycle in WSE at Obidos and Isla de Grupa, but it disappears in Manaus. Amplitude of 15-day cycle is about 1cm at Obidos for both simulation and in-situ gauged observation.

Spectra analysis for water surface elevation



[4-5] DISCHARGE ANOMALY

Anomaly of river discharge between the simulation with and without the tidal effect is illustrated for 28 days. The anomaly is propagating upward from the river mouth. The of anomaly propagation is also about 15-days, and the speed of anomaly propagation is about 80 km/day.



(5) CONCLUSION

Variations in water surface elevations simulated by CaMa-Flood agreed with satellite observation at a certain level. When ocean tide information was given as the boundary condition, CaMa-Flood reproduced realistic 15-days cycle in WSE and river discharge. These results suggest the predictability of WSE in continental-scale rivers using a global river routing model.

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