Observing Global and Continental Terrestrial Water and Energy Budgets Using Satellite Remote Sensing

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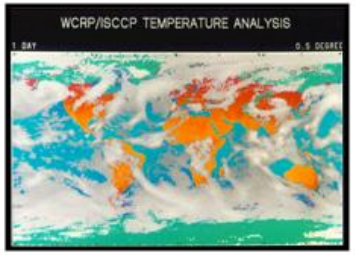
Princeton University

NASA Energy and Water Cycle Study (NEWS)
Science Team Meeting
December 2-3, 2009

NEWS/GEWEX strategy: close the budget though observations, which at the global scale requires remote sensing

GEWEX WCRP

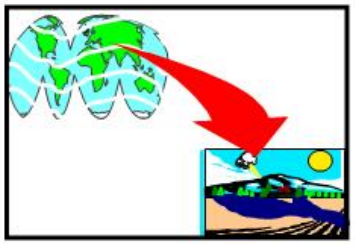
Research Strategy



-- Observe Globally

-- Initially Close Energy/Water Budgets at Continental-Scale

-- Couple (land/hydro - atmos) at the Mesoscale



-- Model & Predict Globally w / NWP

[upgrade land sfc/hydro & cloud physics]

-- Apply Locally to Water Resources

Background to the recent GEWEX activities.

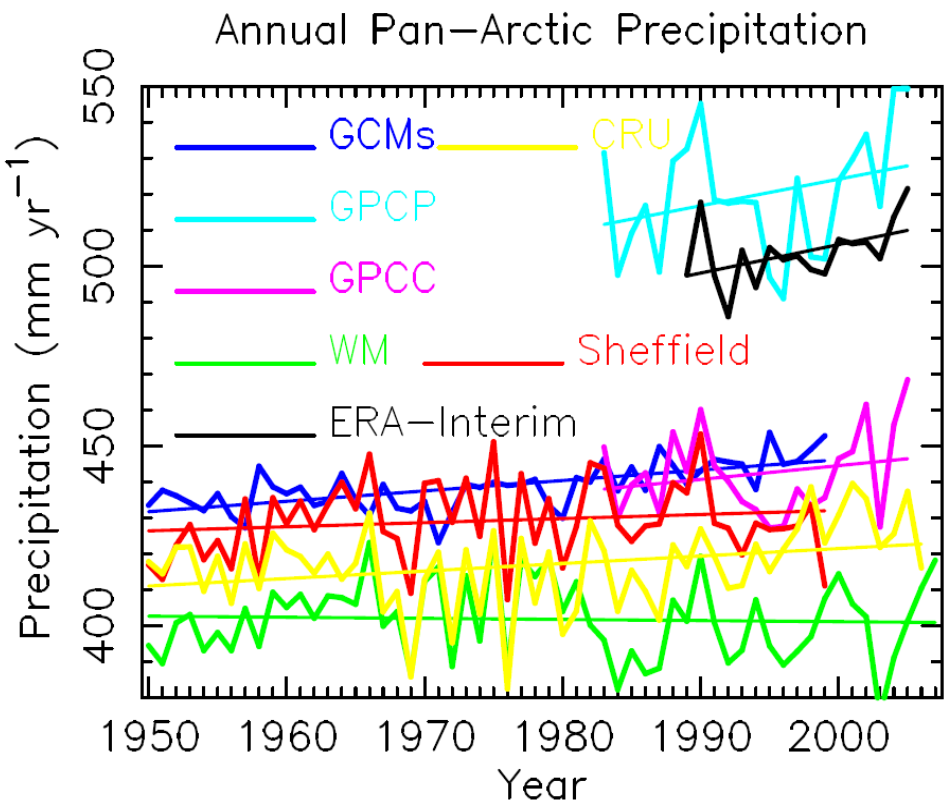
1. GEWEX Radiation Panel initiated the LandFlux initiative (2007) to "develop the needed capabilities and to produce a global, multi-decadal surface turbulent flux data product" to meet GEWEX's goal "to obtain a quantitative description of the weather-scale variations of the global energy and water cycle over a period of at least 20 years to allow for diagnostic studies of the causes of these variations and to develop predictive capability."

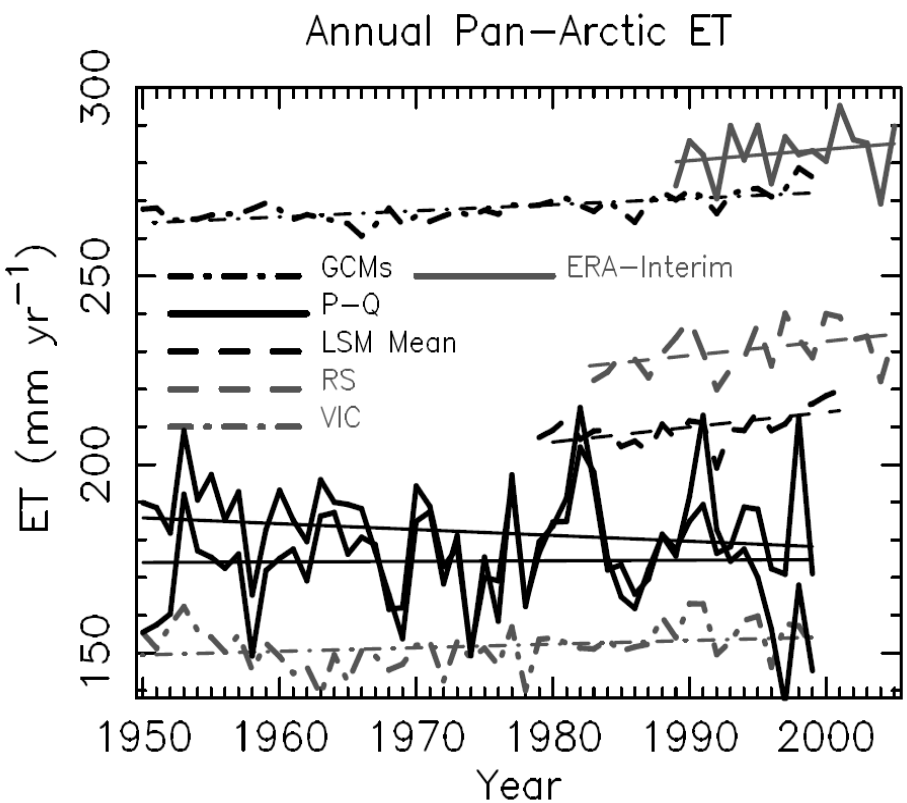
2. GCM Benchmark Activities. To effectively manage adaptation to climate change, the uncertainty in future climate projections must be reduced. Consequently, there is need to create observation-based benchmarks of GCM performance that can be used to guide climate model improvements and to select among (the most accurate) projections.

3. Workshops:
   2007, May: Initial LandFlux workshop (Toulouse).
   2009, July: GEWEX Symp. on Land Surface ET and Climate (Wallingford)
   2009, August: LandFlux Workshop (Melbourne)
   2010, June: LandFlux Evaluation Workshop (Tokyo)

The scope of the challenge: Determining the water cycle in the pan-Arctic

Estimates of water cycle variables over the pan-Arctic from observations, coupled GCMs, uncoupled LSMs, and remote sensing vary widely.





(from Rawlins, et al "Analysis of the Arctic System for Freshwater Cycle Intensification", in review)

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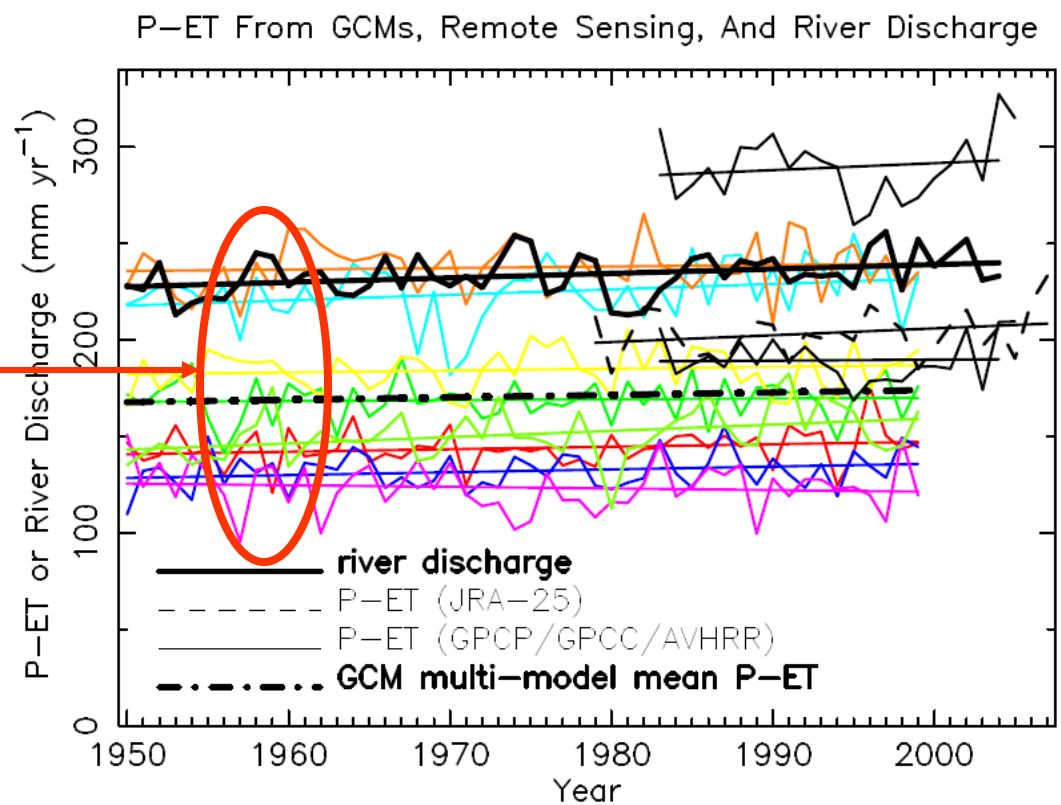
Range of 8 GCM estimates



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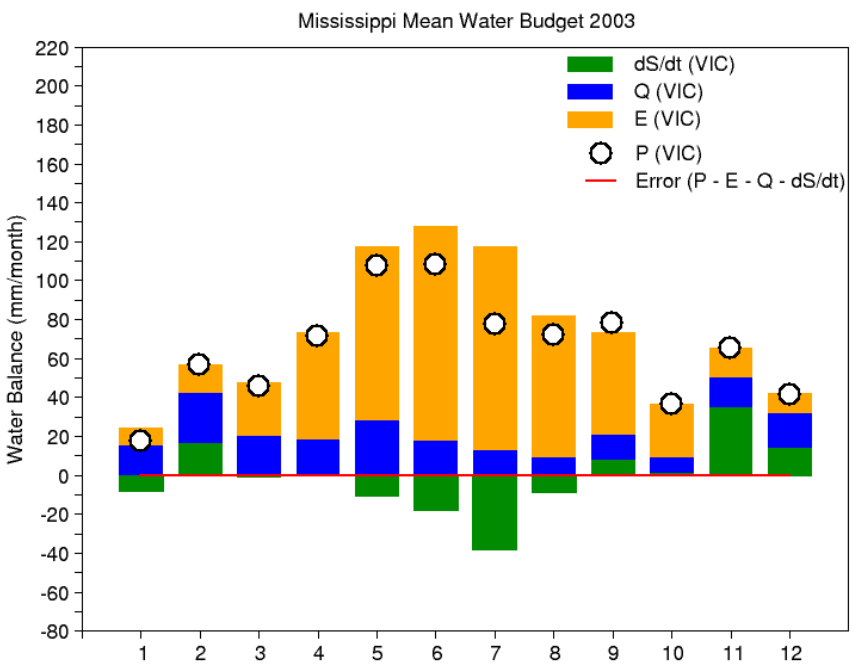
Grand challenge to Hydrology:
Can we close the land water budget using remote sensing observations?

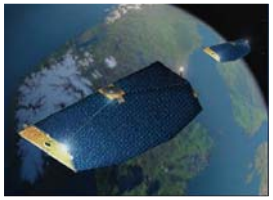
$$\frac{dS}{dt} = P - E - Q$$

What the budget should look like?
(from off-line modeling, forced closure)

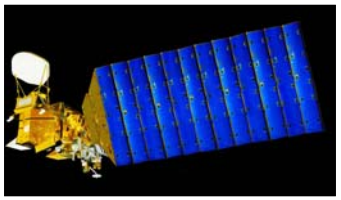


Potential Datasets

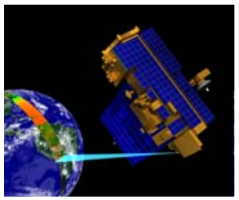
dS/dt from GRACE



E from
CERES / MODIS / AIRS
→ LandFlux



P from TRMM/CMORPH
PERSIANN → GPM



Q from
TOPEX/POSEIDON/JASON
→ SWOT

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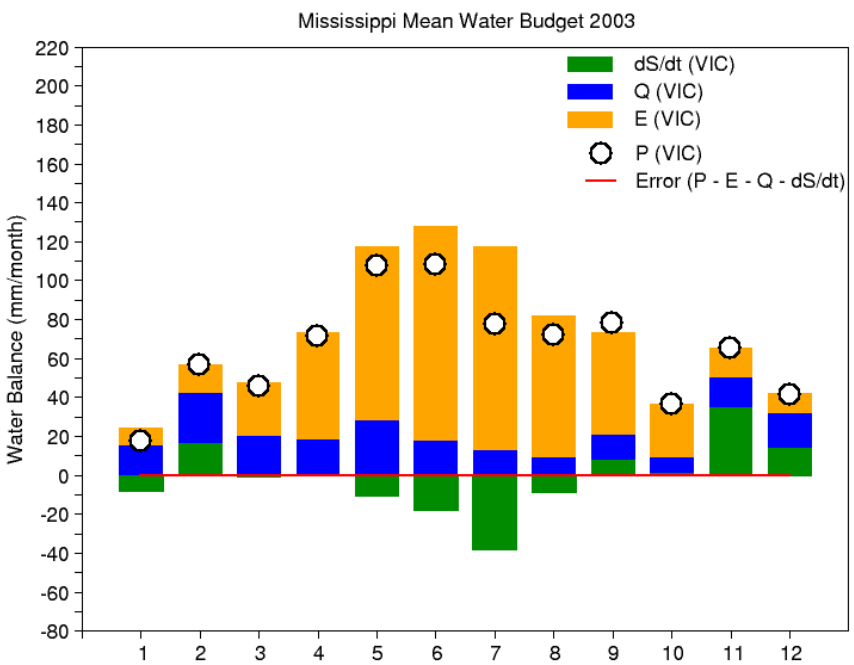
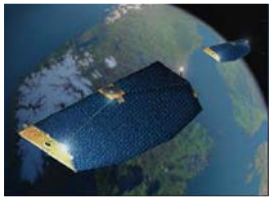


Potential Datasets

dS/dt from GRACE



E from
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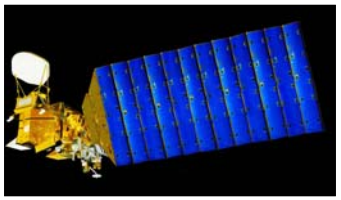

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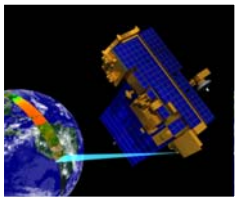

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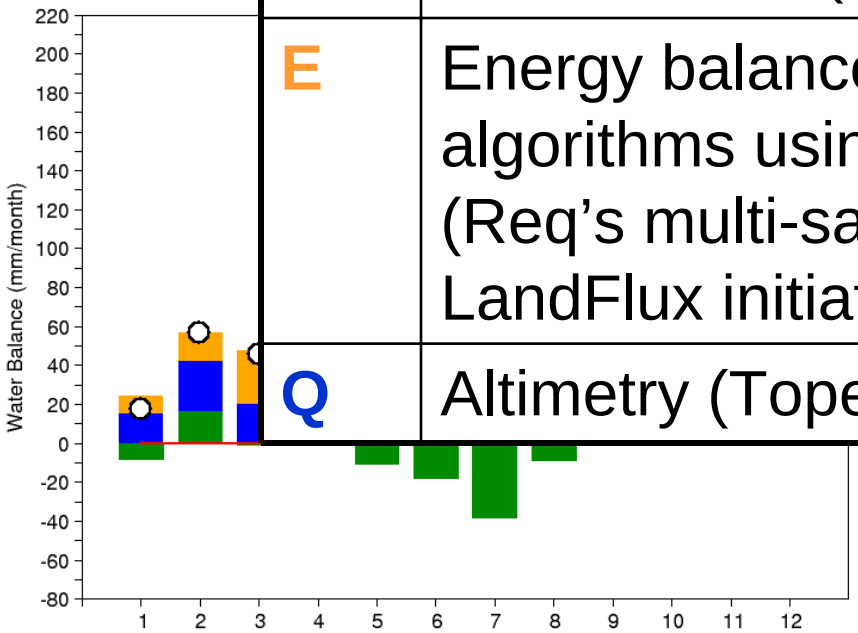
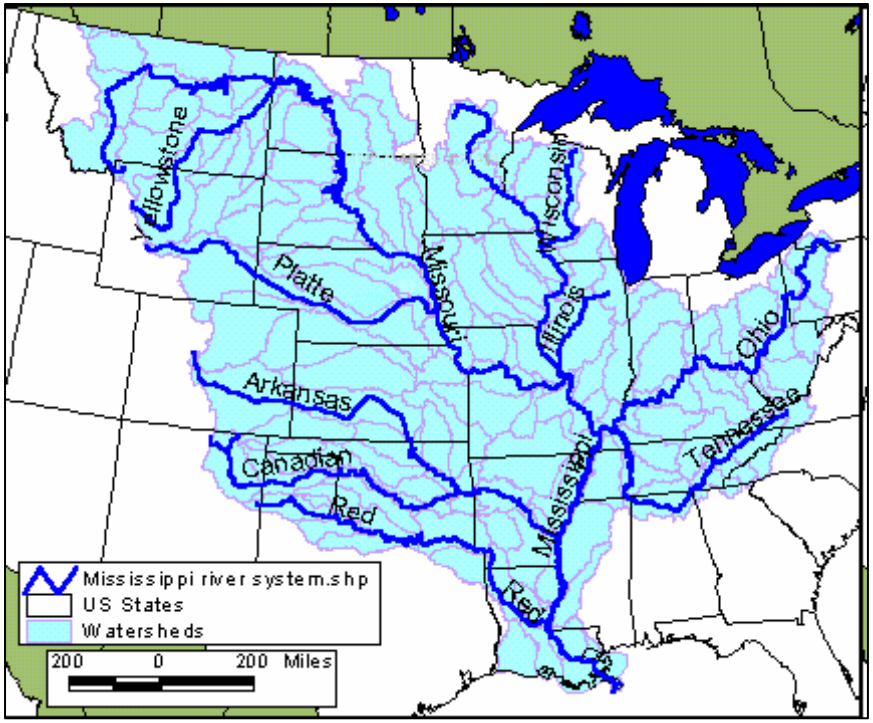


S	Gravity field measurements (GRACE)
P	MW, MW+IR (e.g. TMPA → GPM)
E	Energy balance and turbulent transfer algorithms using RS radiation and meteorology (Req's multi-satellite algorithms – GEWEX LandFlux initiative.)
Q	Altimetry (Topex/Poseidon → NASA SWOT

Q from
TOPEX/POSEIDON/JASON
→ SWOT

Application to the Mississippi River Basin



- Mississippi River basin (one of the best observed regions)
- 2003-2005
- Estimate Q as a residual of the land water budget:

$$Q = P – E - dS/dt$$

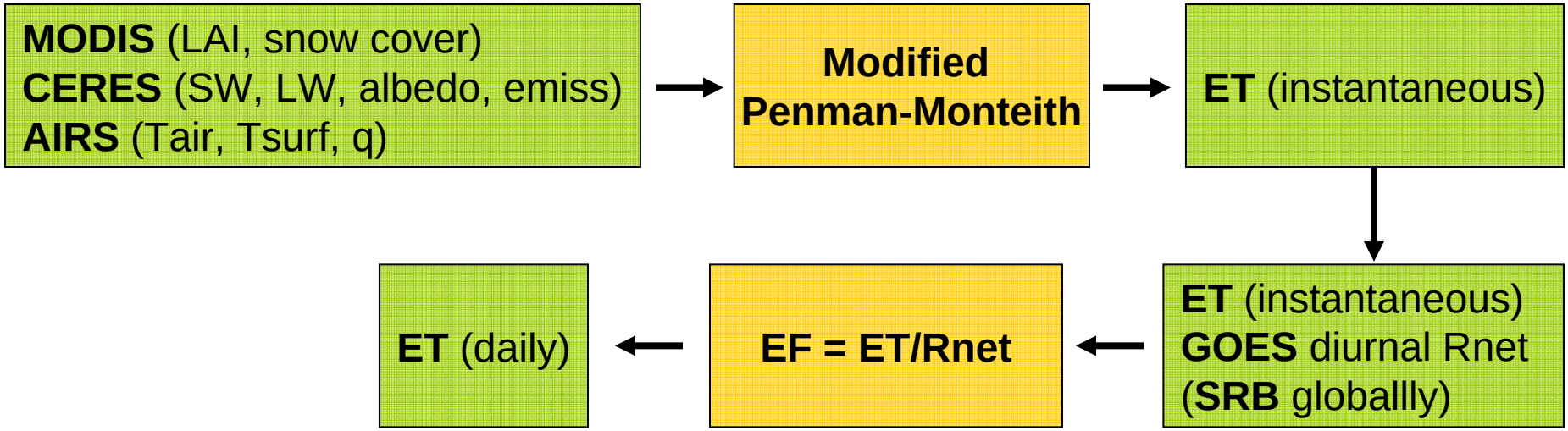
Remote Sensing Data

- **S** from **GRACE**
- **P** from **TRMM TMPA**, **CMORPH, PERSIANN**
- **E** from **Penman-Monteith** with Remote Sensing of radiation, Tair, humidity

Evaluation Data

- **P, E, Q, dS/dt** from **VIC NLDAS** observation-forced hydrologic simulation
- **E** from **NARR** (inferred values from atmospheric budget)
- **Q** from **USGS/USACoE gauge data**

ET from Remote Sensing



Mu, Q., F. A. Heinsch, M. Zhao, S. W. Running, 2007: Remote Sensing of Environment, 111, 519-536 (doi: 10.1016/j.rse.2007.04.015)

ET from Remote Sensing

Data Type	Variable	Unit	Source	Platform	Resolution
Surface Meteorological Data	Air temperature	°C	AIRS[2]	Aqua	45 km
	Pressure	KPa	AIRS[2]	Aqua	45 km
	Wind	m/s	4-DDA	GEOS-3	
	Vapor Pressure	KPa	AIRS[2]	Aqua	45 km
Radiative Energy Flux	Incident Shortwave Radiation	W/m^2	MODIS[1]	Aqua/Terra	5 km
	Incident Shortwave Radiation	W/m^2	CERES	Aqua/Terra	20 km
	Incident Longwave Radiation	W/m^2	CERES	Aqua/Terra	20 km
	Net Longwave Radiation	W/m^2	CERES	Aqua/Terra	20 km
	Net Radiation	W/m^2	CERES	Aqua/Terra	20 km
Surface Temperature	Composite Radiometric	K	MODIS	Aqua/Terra	1 – 5 km
	Temperature (Soil + Vegetation)	K	AIRS[2]	Aqua	45 km
Vegetation Parameters	Emissivity (MOD11)	-	MODIS	Aqua/Terra	1 – 5 km
	Emissivity (MOD11)	-	CERES	Aqua/Terra	20 km
	Albedo(MOD43)	-	MODIS	Aqua/Terra	1 – 5 km
	Broadband Albedo	-	CERES	Aqua/Terra	20 km
	Leaf Area Index & fPAR (MOD15)	-	MODIS	Aqua/Terra	1 – 5 km
	Vegetation Type (MOD12)	-	MODIS	Aqua/Terra	1 – 5 km

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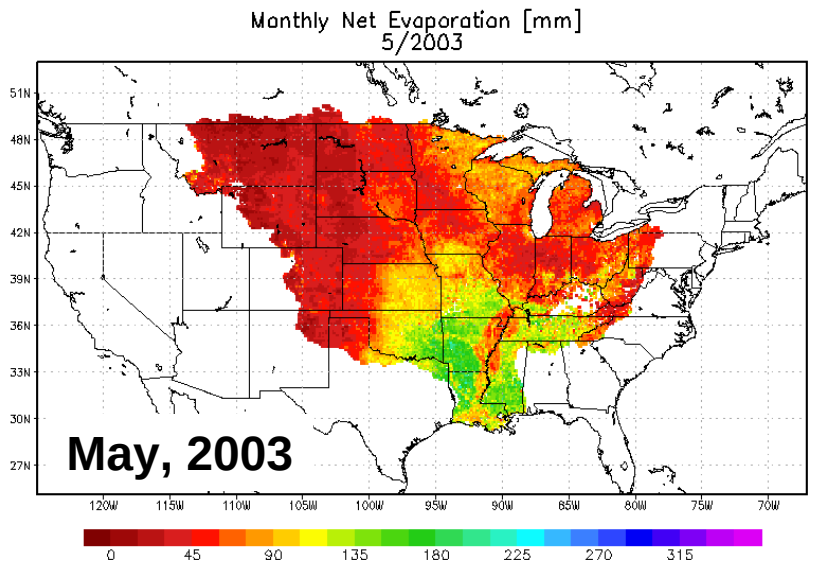
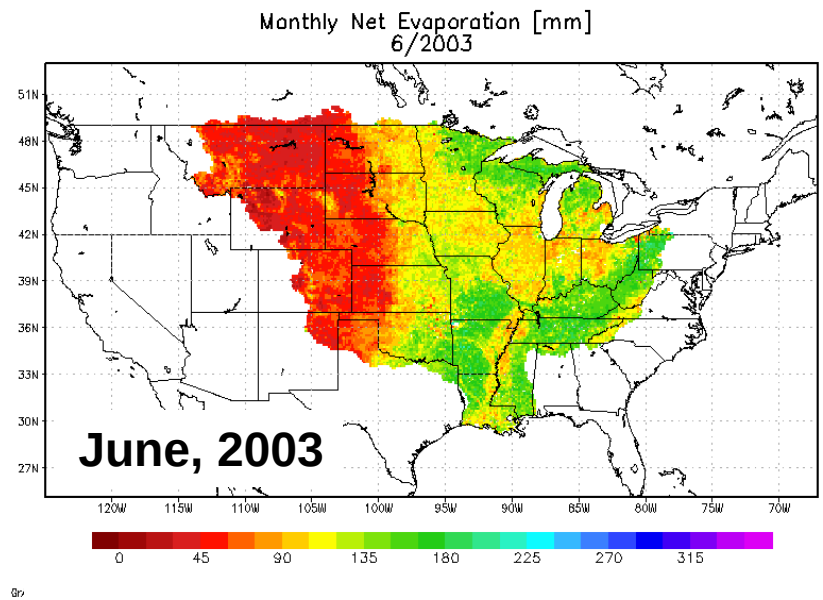
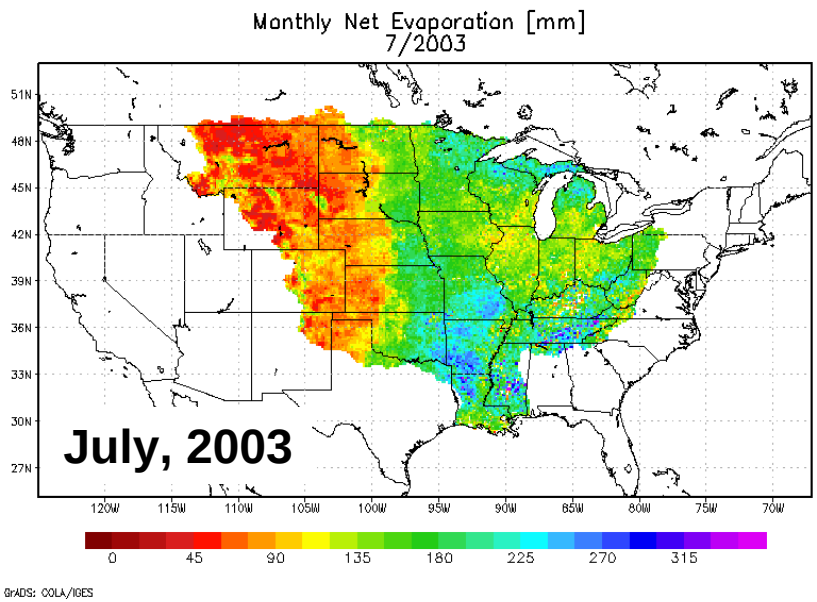
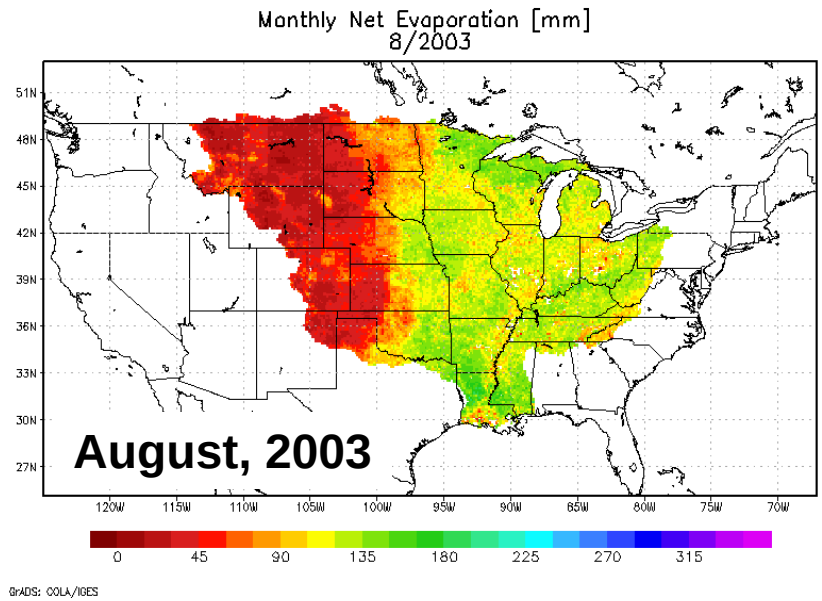
Penman-Monteith **retrievals over the Mississippi**



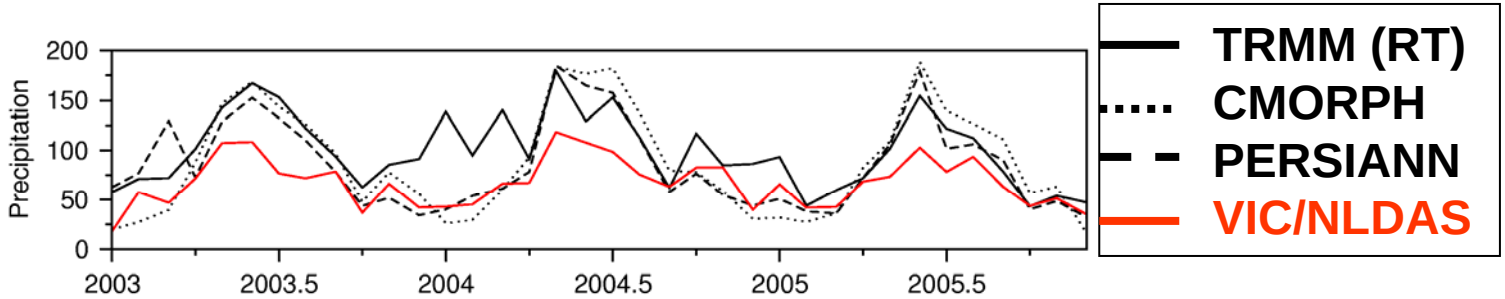




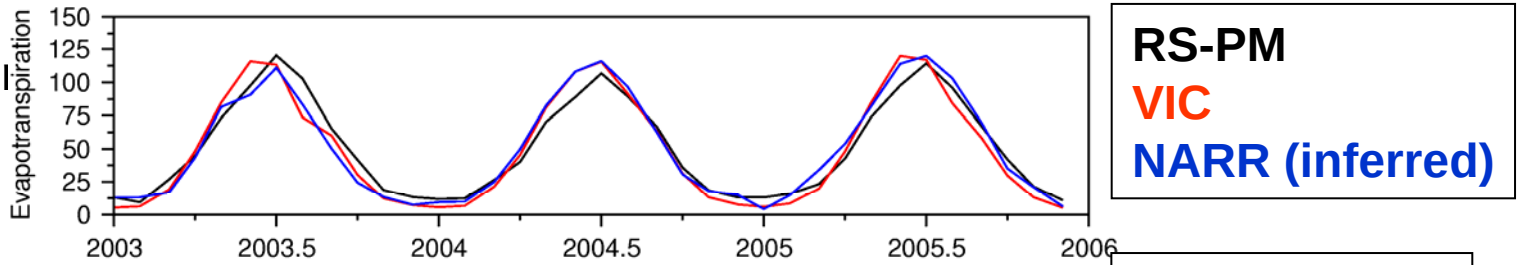


Summary of Budget Component Evaluations

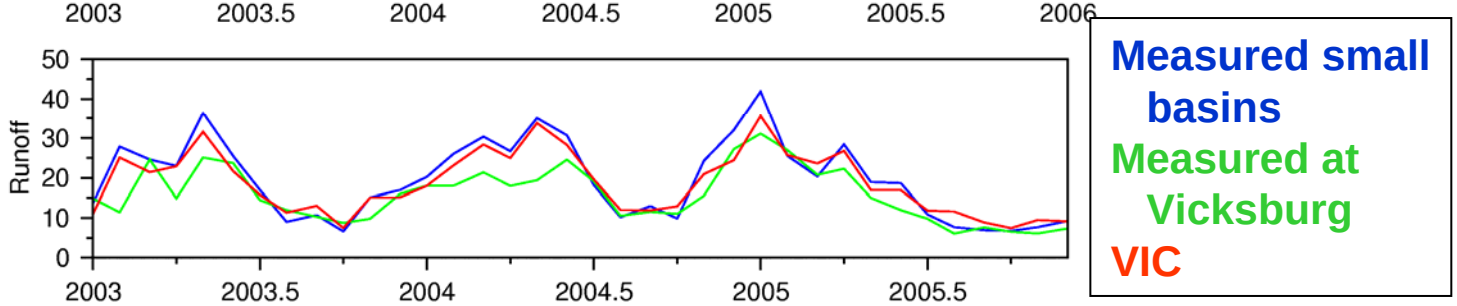
Large bias in RS P for all three datasets



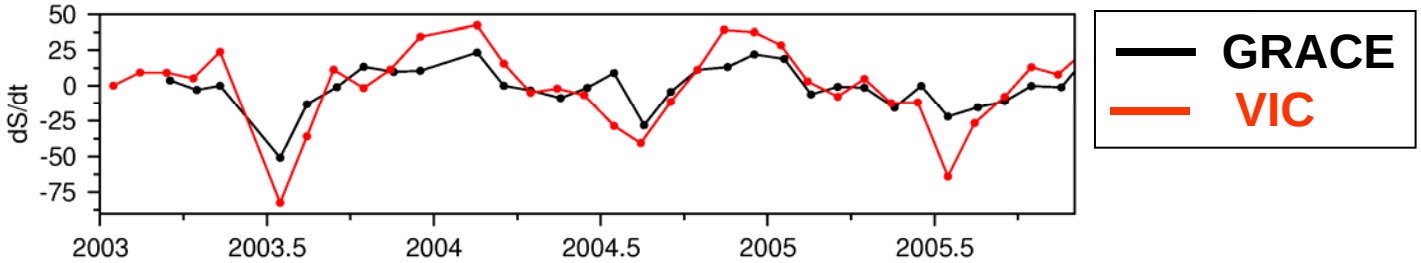
Under estimation in summer (canopy E?)



VIC is calibrated to interpolated USGS runoff

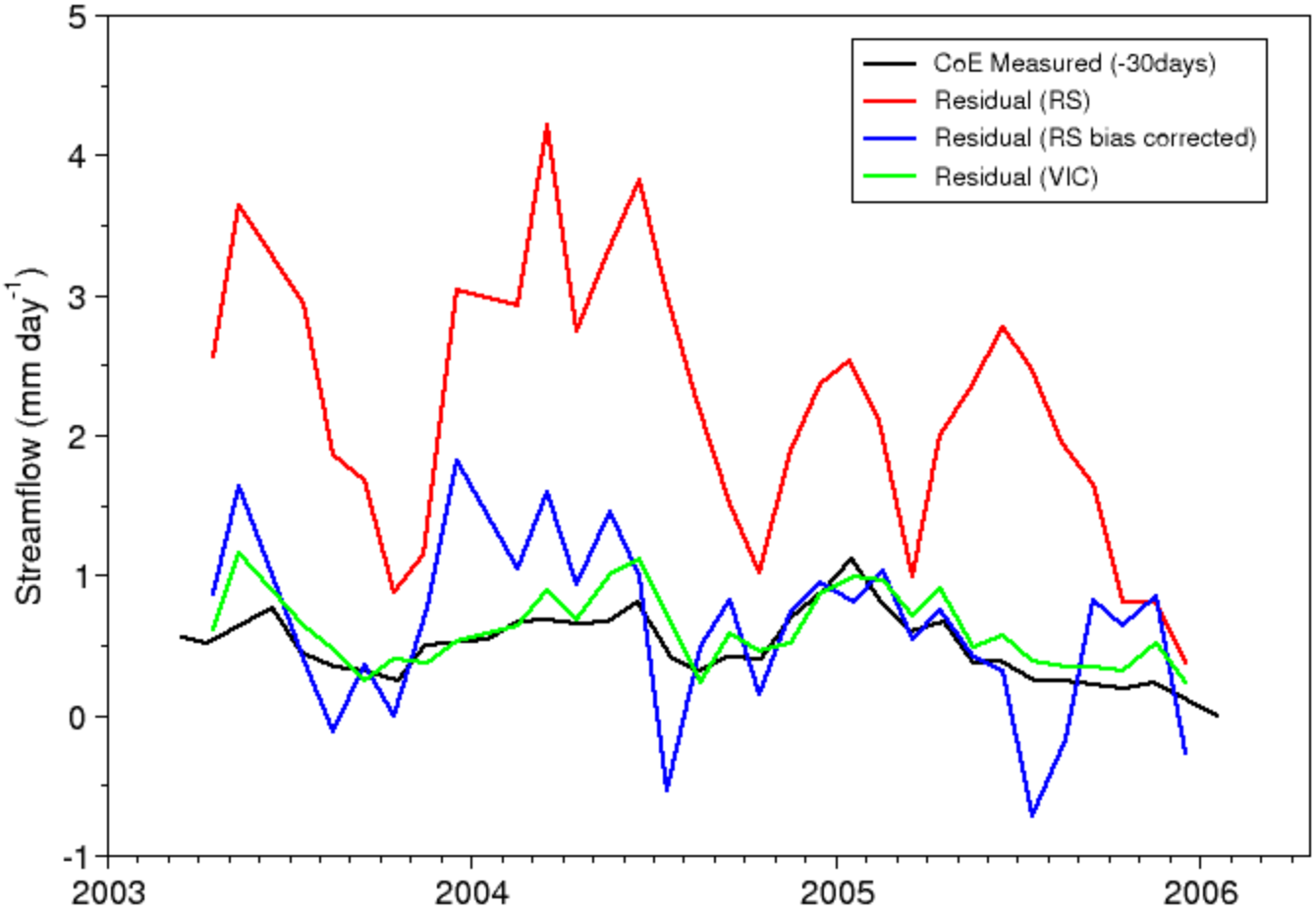


GRACE slightly underestimates VIC in summer and winter



Inferred Streamflow from RS

Q = P (TRMM,CMORPH) **– E** (CERES,MODIS,AIRS) **– dS/dt** (GRACE)



USACoE Obs. **shifted by 30 days for travel time**

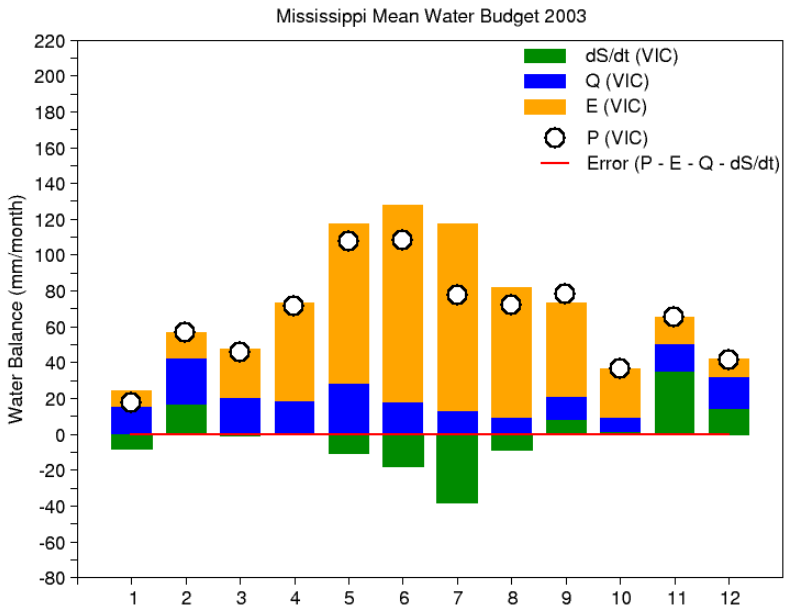
Inferred from RS Overestimation due to high bias in RS Precipitation

Inferred from RS with bias corrected P and E

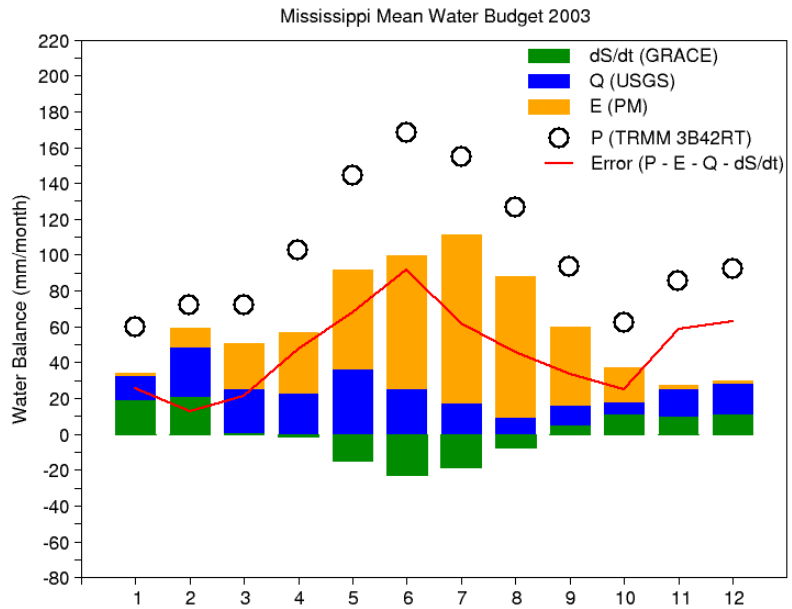
Inferred from VIC shown for comparison

Budget Closure: Comparison with VIC

VIC



RS

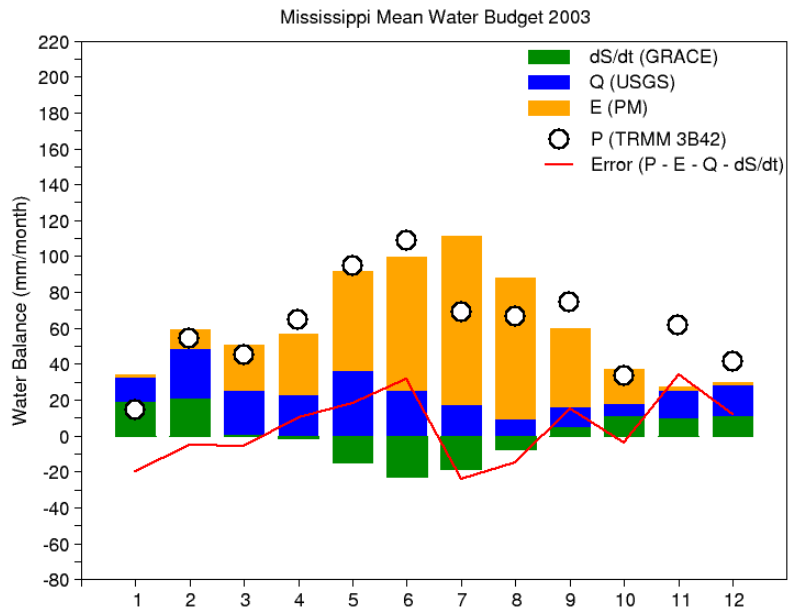


P: gauges
E, Q, dS/dt: VIC

TRMM 3B42RT

TRMM 3B42

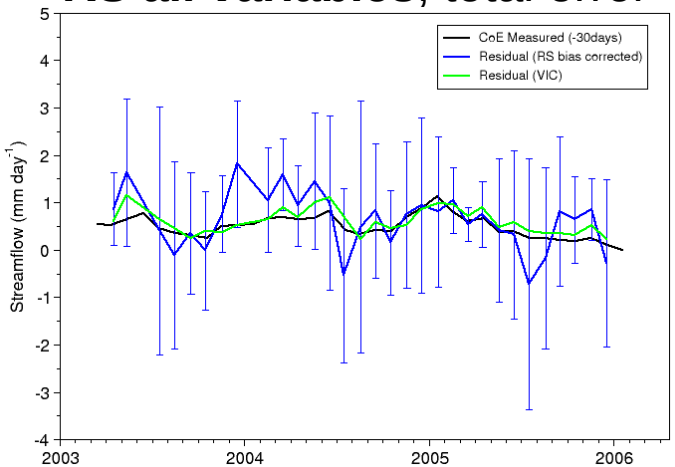
P: TRMM
E: PM (CERES/AIRS/MODIS)
Q: USACoE
dS/dt: GRACE



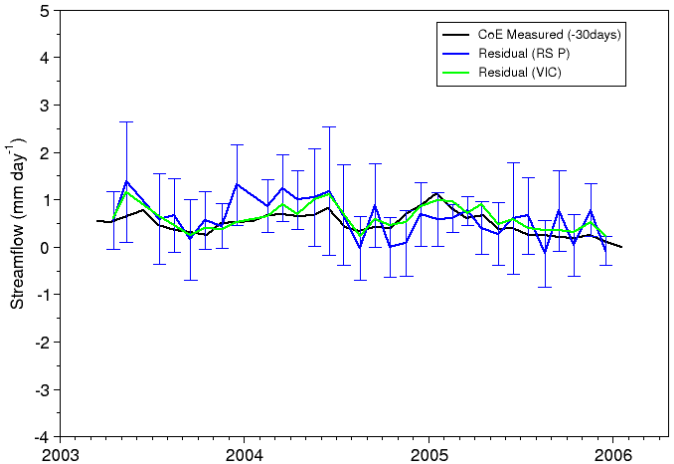
Uncertainties due to RS Data

Streamflow (mm/day)

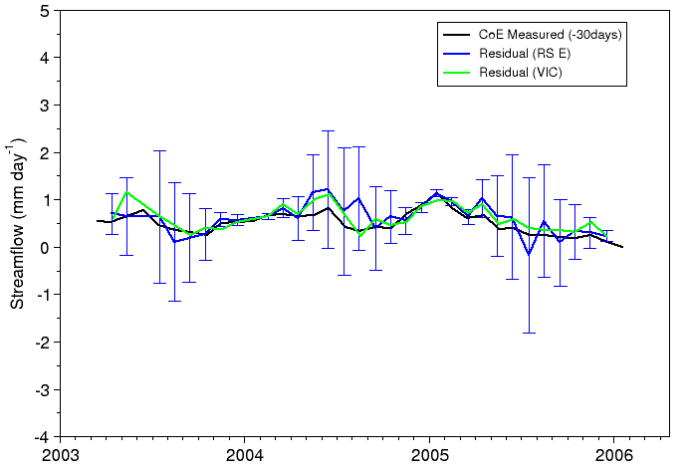
RS all variables, total error



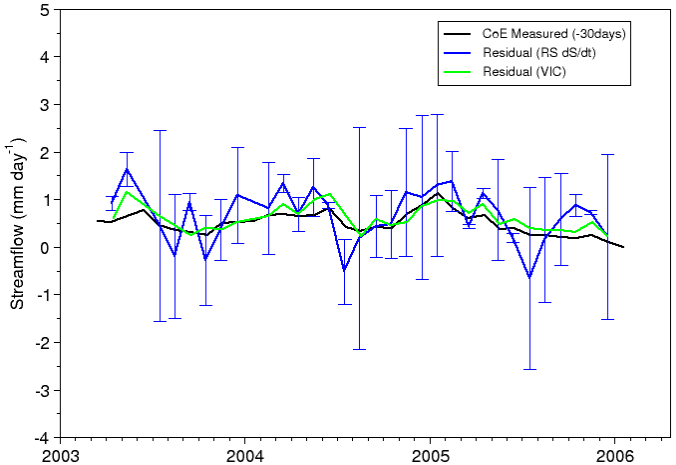
RS P, VIC E and dS/dt error in P only



RS E, VIC P and dS/dt, error in E only

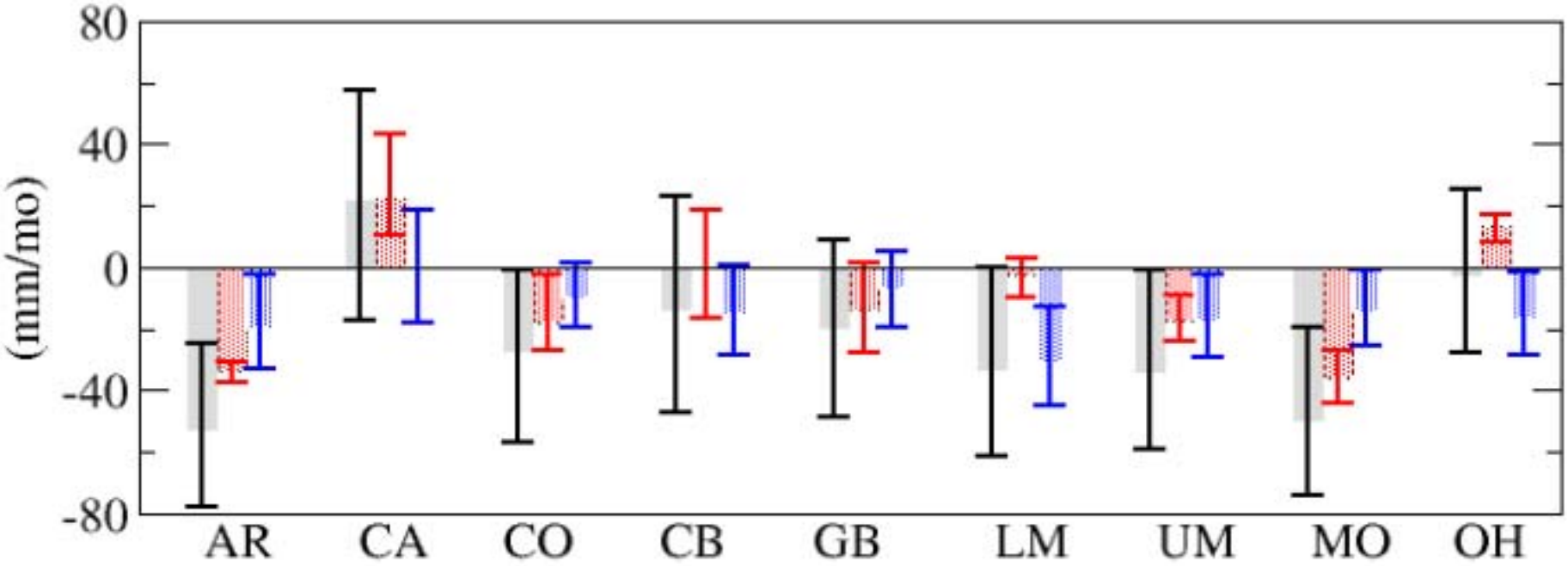


RS dS/dt, VIC P and E, error in dS/dt only



- **RS P and ET bias corrected, dS/dt unaltered**
- **RS P errors estimated from differences between TRMM and CMORPH**
- **RS ET errors estimated from sensitivity of RS-PM to different RS inputs**
- **RS dS/dt errors taken from standard GRACE instrument/sampling error**

Extension of water budget analysis to other US basins



Non-closure over 9 basins/regions. Black, **all terms from remote sensing**; **red, errors only from precipitation RS**; **blue using RS ET and storage with observed precipitation.**

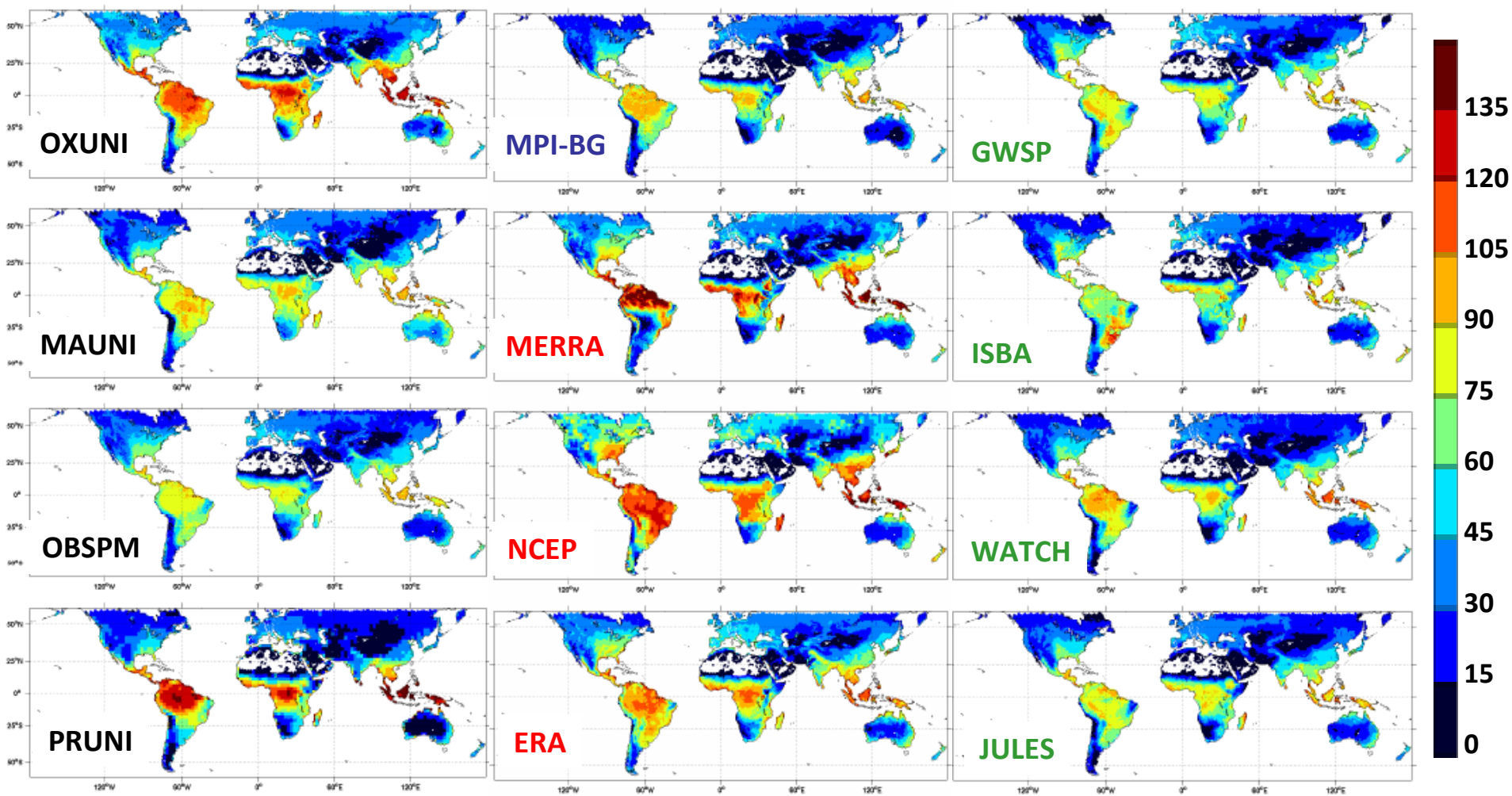
(from Gao et al "Estimating the water budget of major U.S. river basins via remote sensing, IJRS, in press)

Global LandFlux ET Data products (from Jimenez et al analysis)

1.Introduction
2.Products
3.Examples
4.Annual means
5. Zonal means
6. Basins
7. Summary

	INSTITUTION	LE	H	Rn	Resolution
‘simple’ PHYSICAL/EMPIRICAL MODELS [driven by observational data]					
OXUNI	University of Oxford	Priestley-Taylor ET, data from ISLSCP-II (SRB, CRU, AVHRR)	Rn - LE	SRB	1986-95 monthly 1º x 1º
MAUNI	University of Maryland	Empirical, calibrated with Ameriflux, satellite data from ISLSCP-II (SRB, CRU, AVHRR)	Rn - LE	SRB	1986-95 monthly 1º x 1º
PRUNI	Princenton University	Penman-Montheith ET, data from ISCCP, AVHRR	Rn - LE	ISCCP-FD	1992-99 monthly 1/4º x 1/4º
OBSPM	Paris Observatory	Empirical, calibrated with GSWP fluxes, data from ISCCP, ERS, SSMI, AVHRR …		ISCCP-FD	1986-06 daily 2.5º x 2.5º
MPIBGM	MPI Biogeochemistry	Empirical, global upscaling of FluxNet, data from CRU, GPCC, AVHRR ….		Rn~ LE+H	1982-08 monthly 1/2º x 1/2º
‘complex’ LAND SURFACE MODELS [coupled with an atmospheric model assimilating observational data]					
MERRA	NASA-GMAO	MERRA reanalysis, GEOS-5 atmospheric model coupled with NSIPP land model			1979- 6-hourly 1/2º x 2/3º
NCEP	NCEP/NCAR	NCEP-DOE reanalysis, atmospheric model coupled with OSU land model			1979- 6-hourly 1/2º x 2/3º
ERA	ECMWF	ERA Interim reanalysis, atmospheric model coupled with TESSEL land model			1989-98 6-hourly 1.5º x 1.5º
‘more complex’ LAND SURFACE MODELS [forced off-line with model and/or observational data]					
GSWP	GLASS/ISLSCP	Multi-model ensemble, forced with ISLSCP-II		↓Rn SRB	1986-95 monthly 1º x 1º
NOAH	NCAR/OSU/AFWA/HL	Equally forced participating models under the GLDAS land data assimilation system		↓Rn AGRMET data & RT model	1979- 3-hourly 1º x 1º
CLM	NCAR +				
MOSAIC	NASA-GSFC				

Initial Landflux ET comparisons (1993, total)



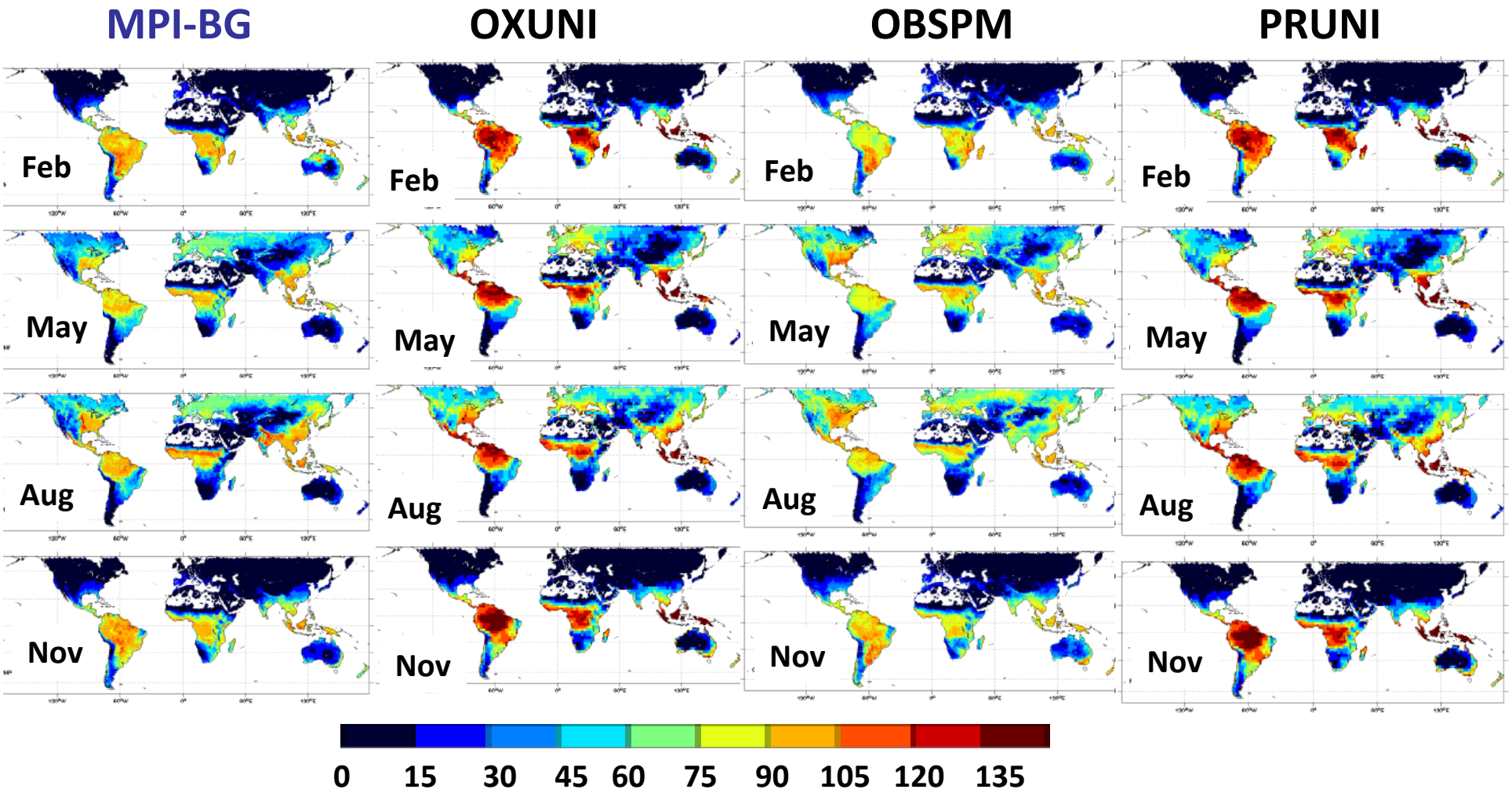
Remote sensing: OXUNI, MAUNI, OBSPR, PRUNI

Fluxnet: MPI-BG

Reanalysis: MEERA, NCEP, ERA

Land Surface Models: GSWP, ISBA, WATCH, JULES

Initial Landflux ET comparisons (1993, selected months)



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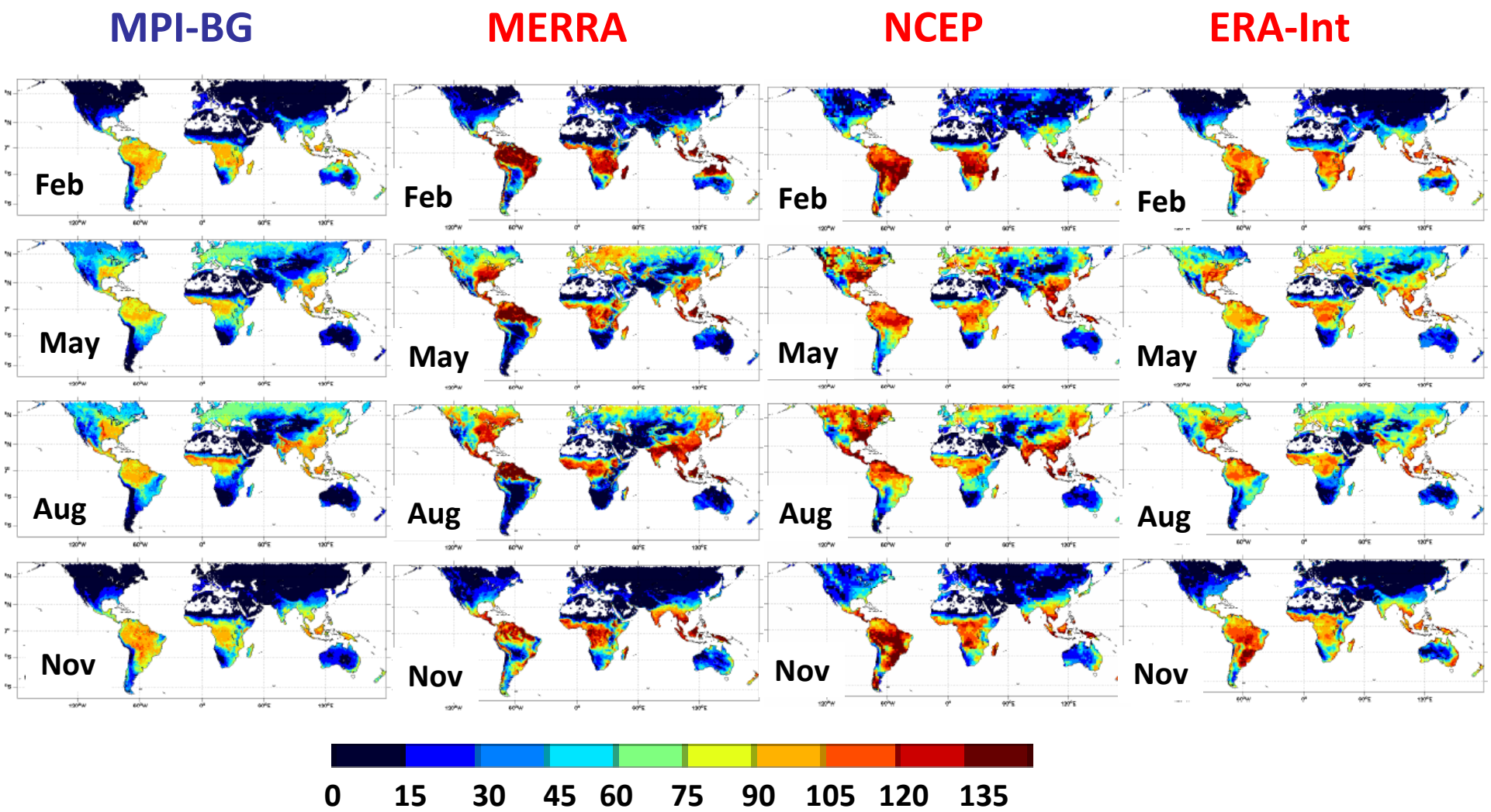

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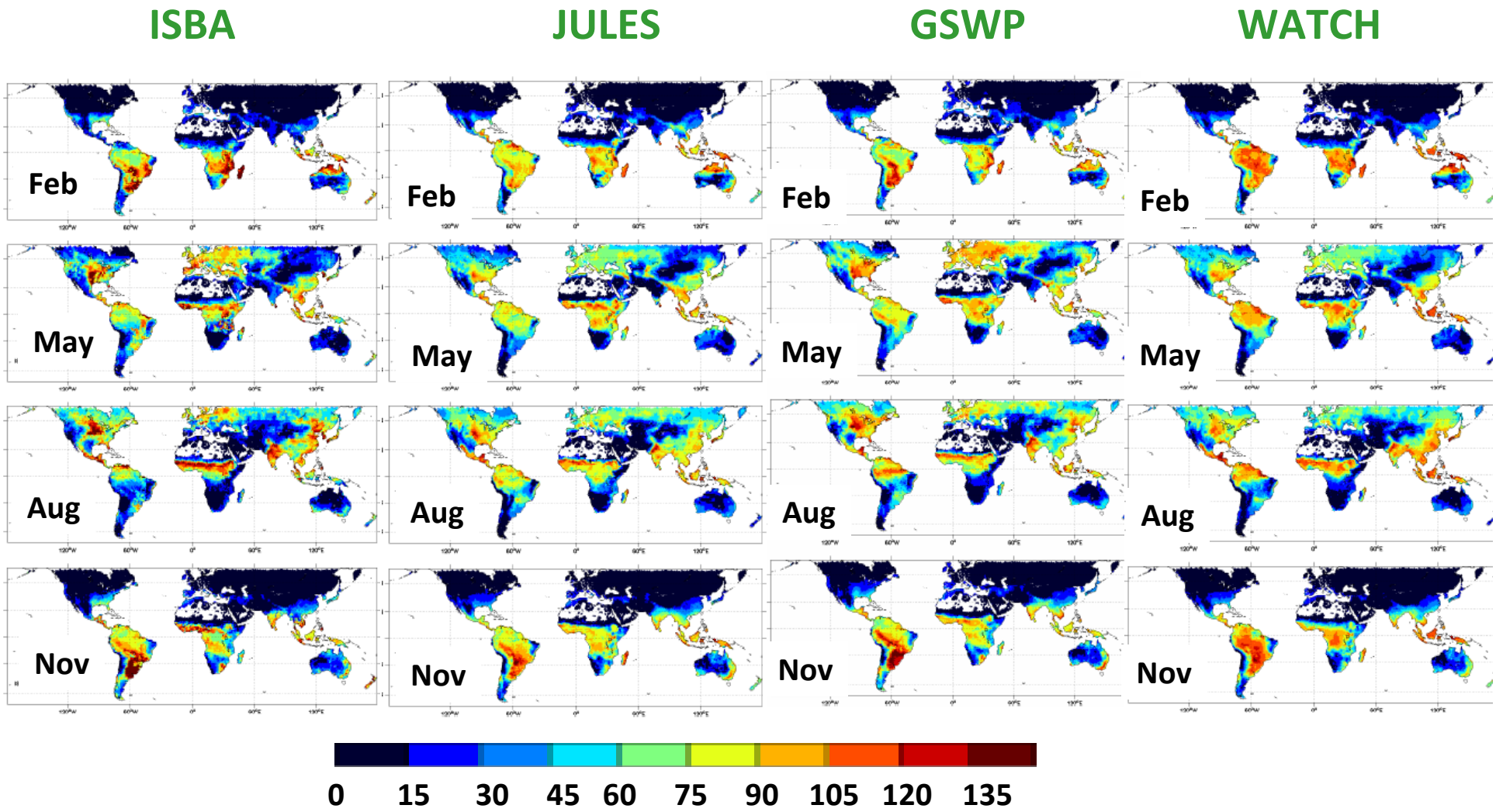
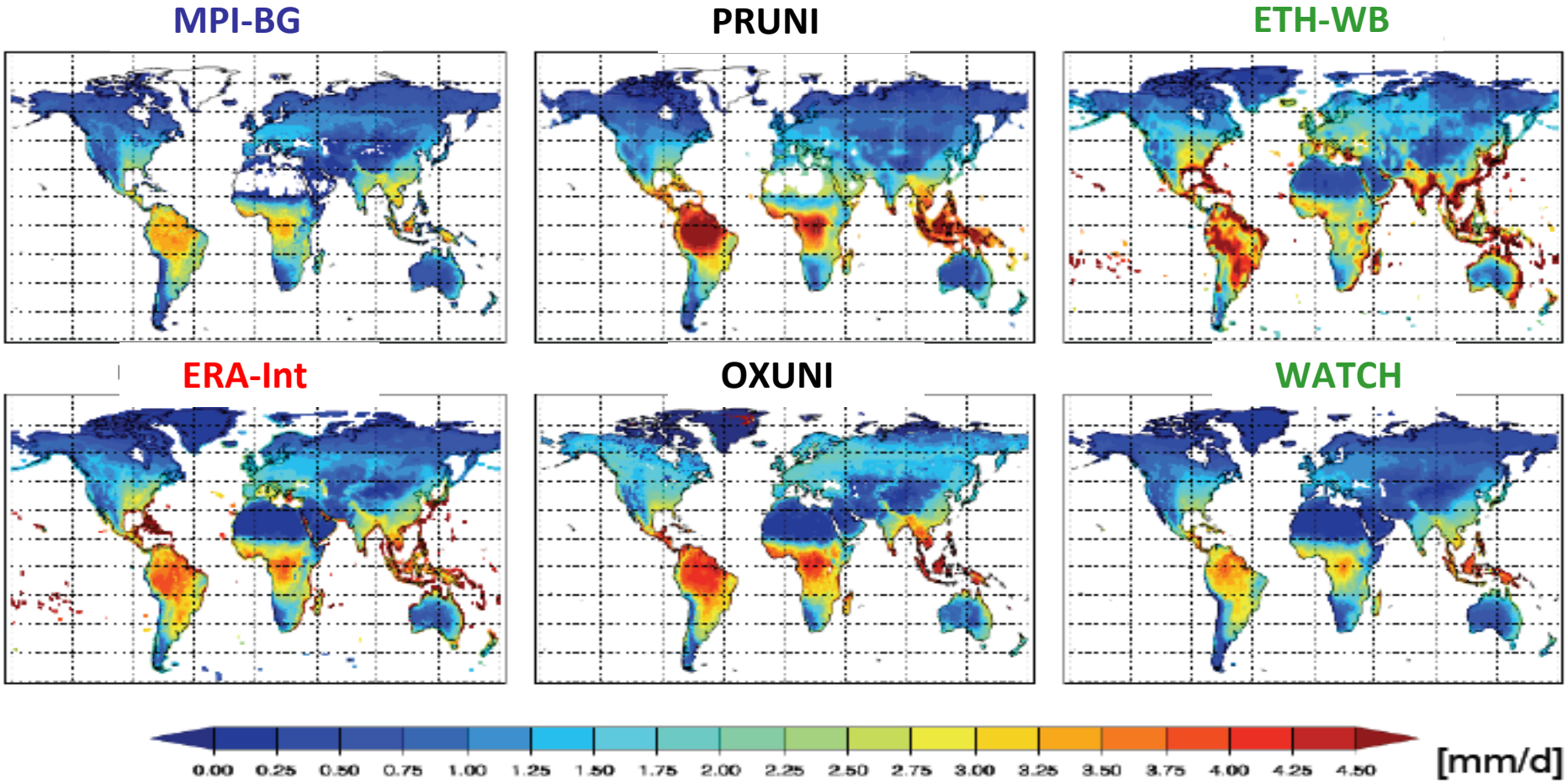
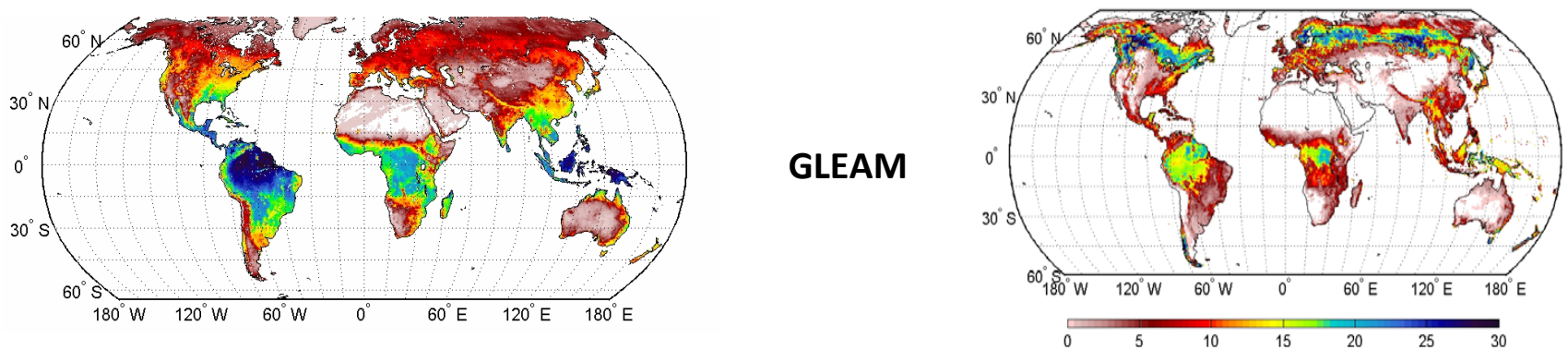
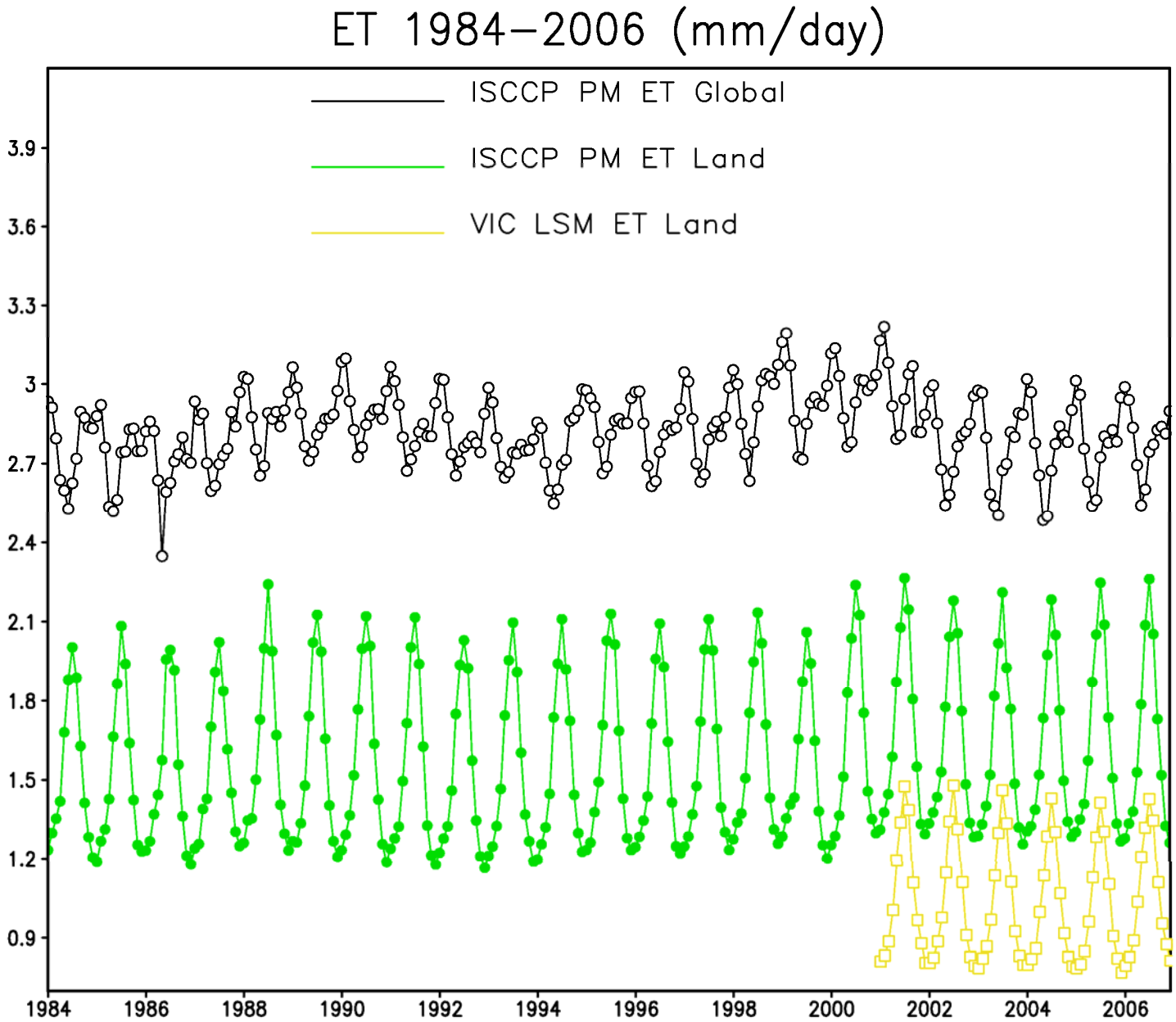


Initial Landflux ET comparisons (1989-2006, annual means)

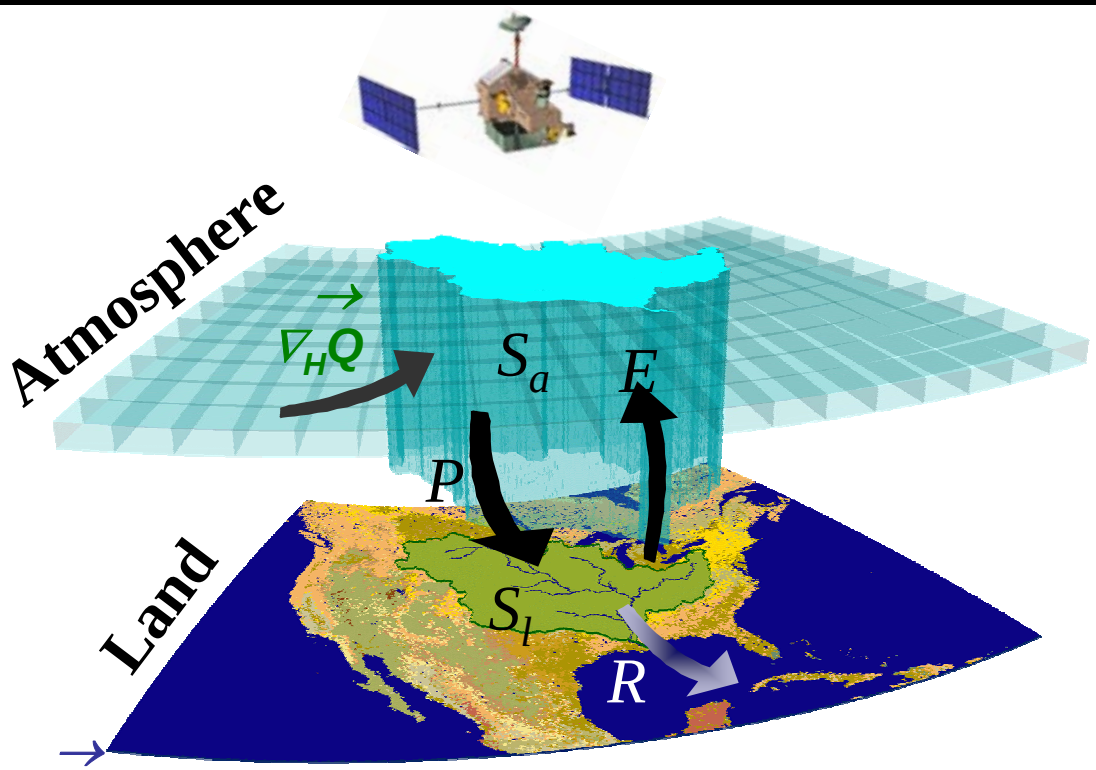




Global ET (Princeton P-M, ISCCP-inputs, 1984-2006)



Basin and continental-scale water budget studies to infer E



Atmospheric Budget

$$E = \frac{dS_a}{dt} - \vec{\nabla}_H Q + P$$

River Basin Water Budget

$$E = -\frac{dS_l}{dt} + P - D$$

Surface Radiation Budget

$$R_n = \lambda E + H + G$$

Land Surface Models

$\vec{\nabla}_H Q$: Moisture convergence

S_a : Atmospheric moisture storage

P : Precipitation

E: Evaporation

D : Surface and subsurface discharge

S_l : Land-moisture storage (soil, reservoirs, and groundwater)

R_n = Net radiation

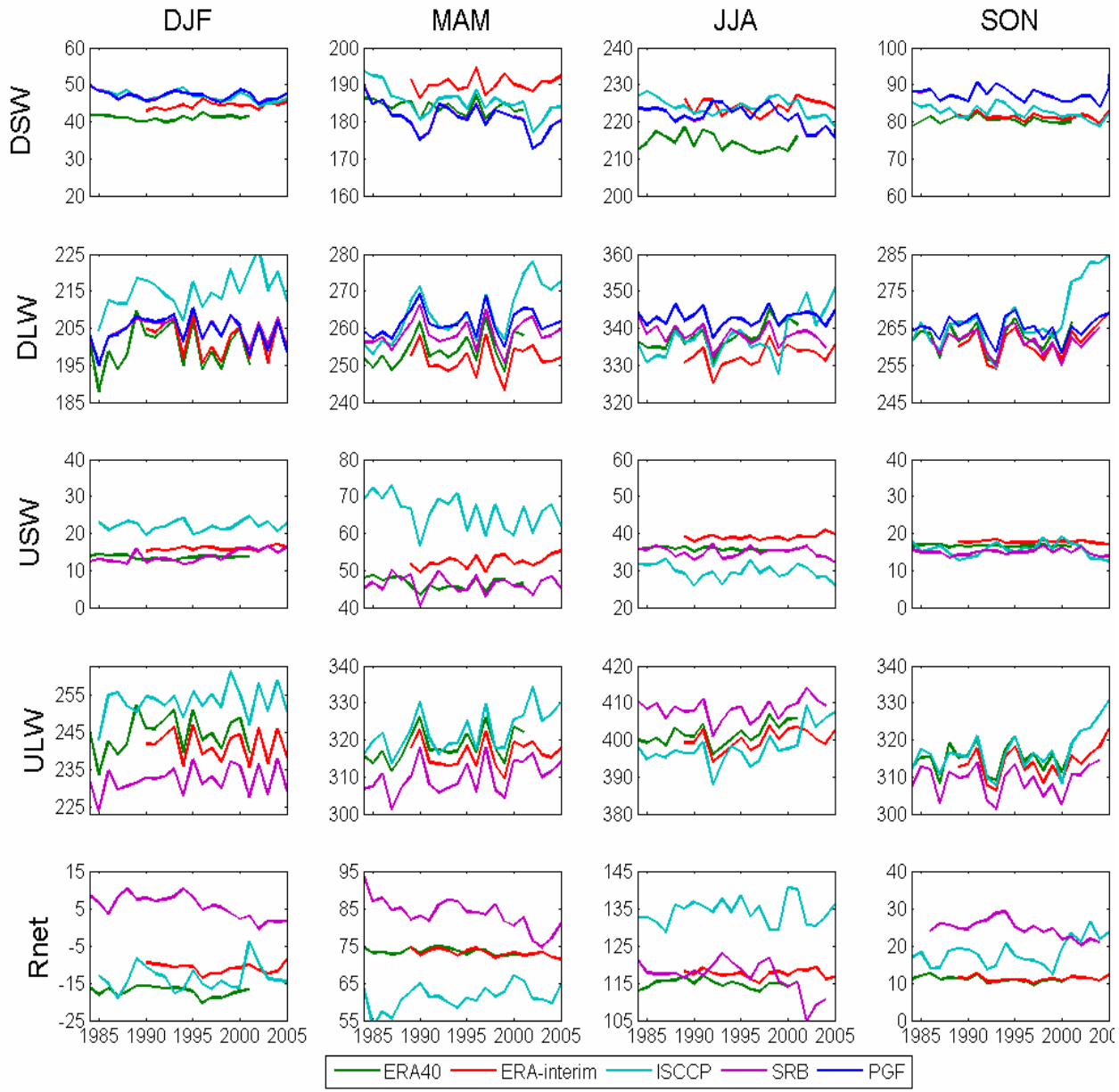
λE = Latent heat (evaporation)

H = Sensible heat

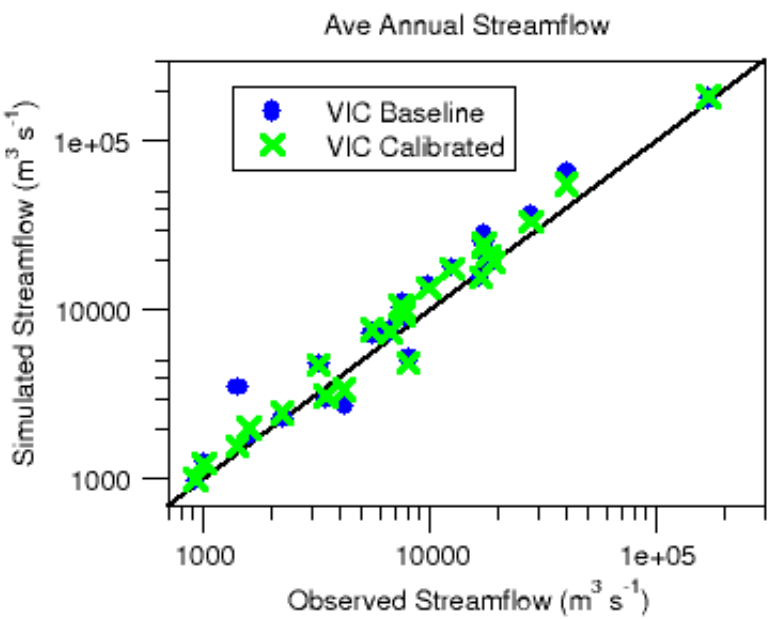
G= Ground heat flux

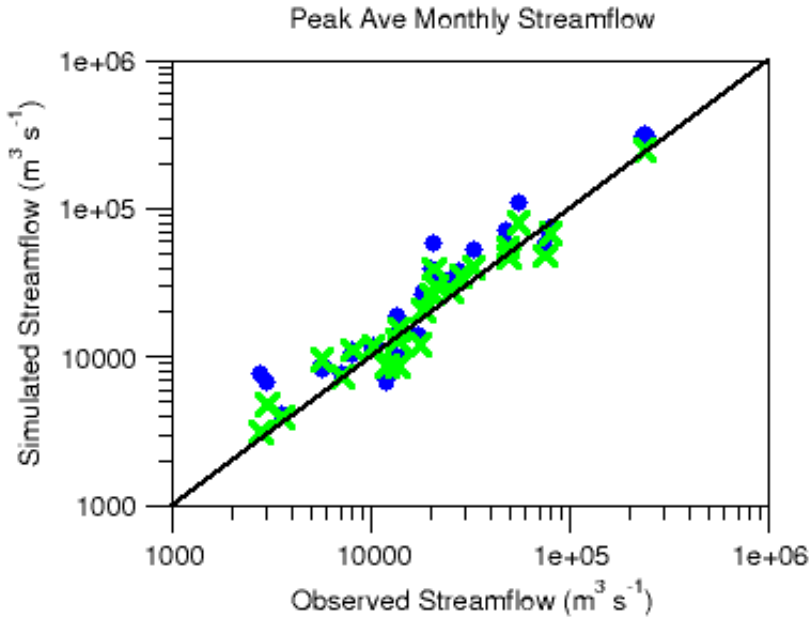
Comparison of Radiative Fluxes over NEESPI

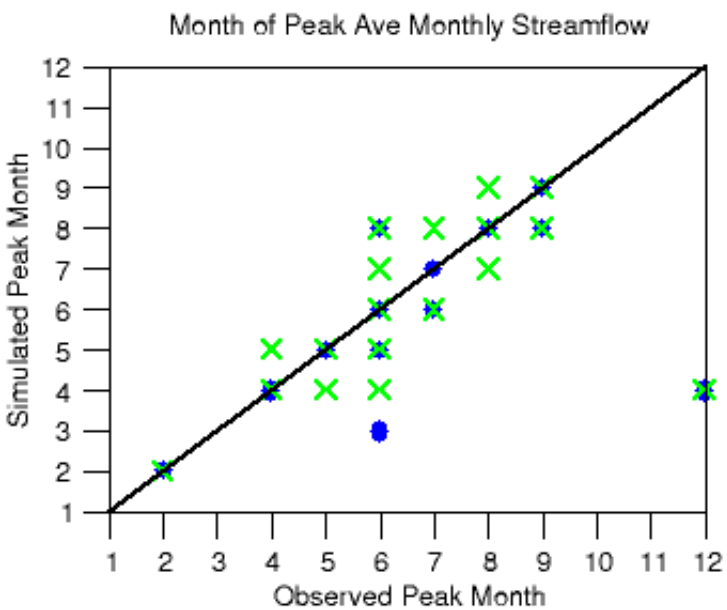
- Seasonal radiative fluxes averaged across region
- Biases exist in the radiative components, but interannual variability is similar between products
- Differences in winter & spring USW can be partially attributable to the snow albedo
- For ULW, differences of 2-4 K in skin temperature can lead to differences of 10-15 W/m^2, which could account for the spread in estimates.

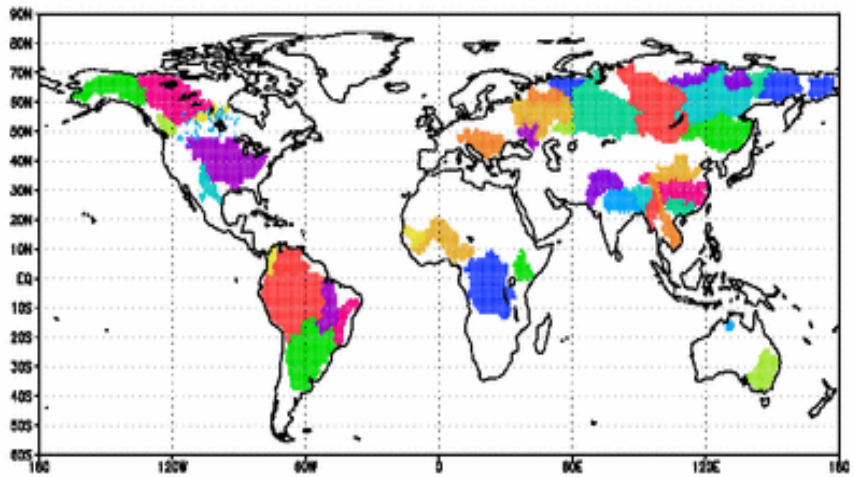


VIC LSM Evaluations: Large Basin Streamflow

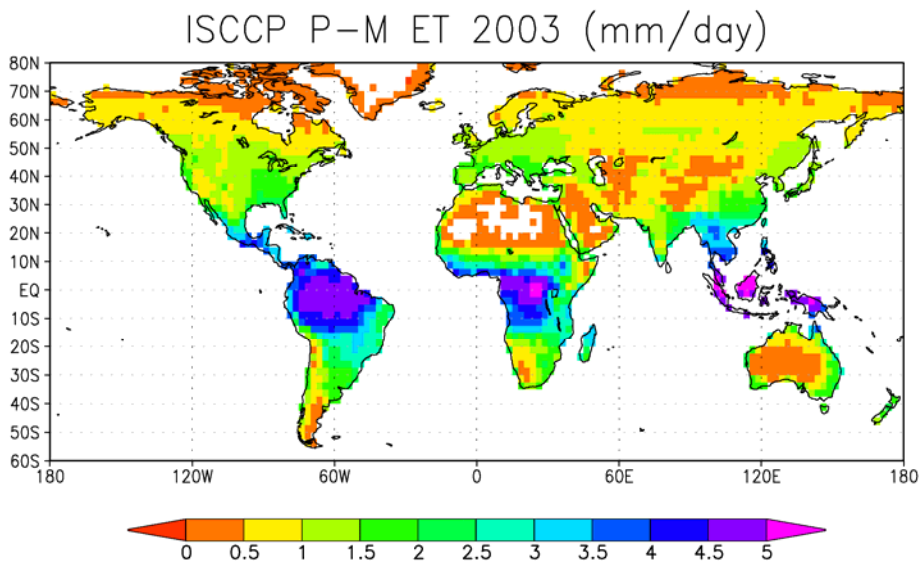


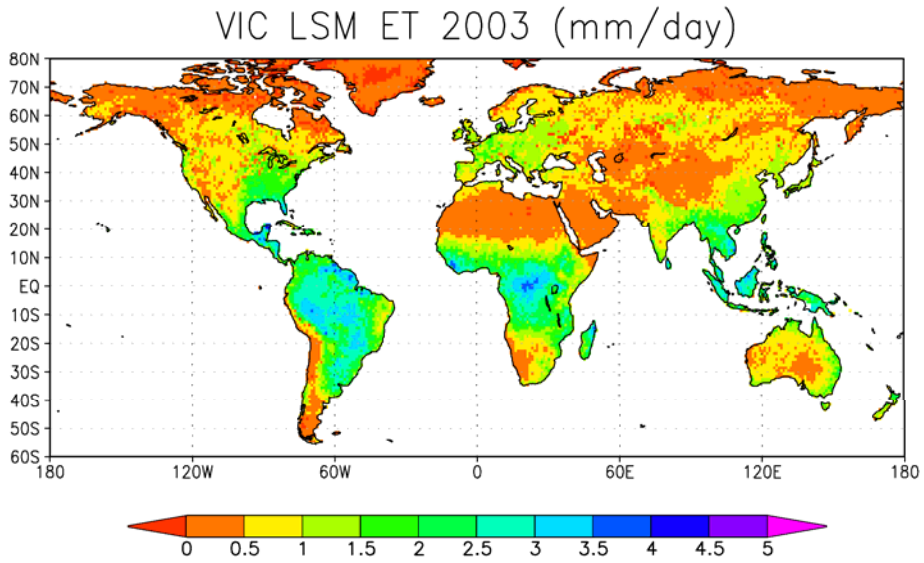




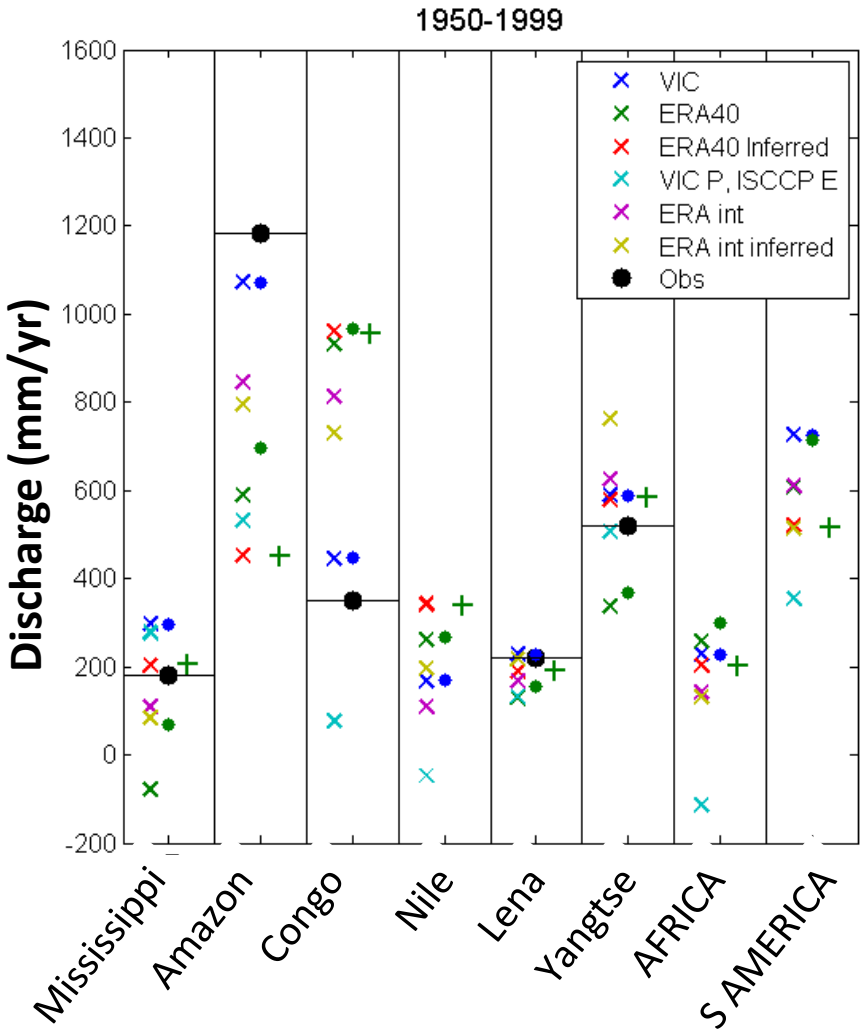


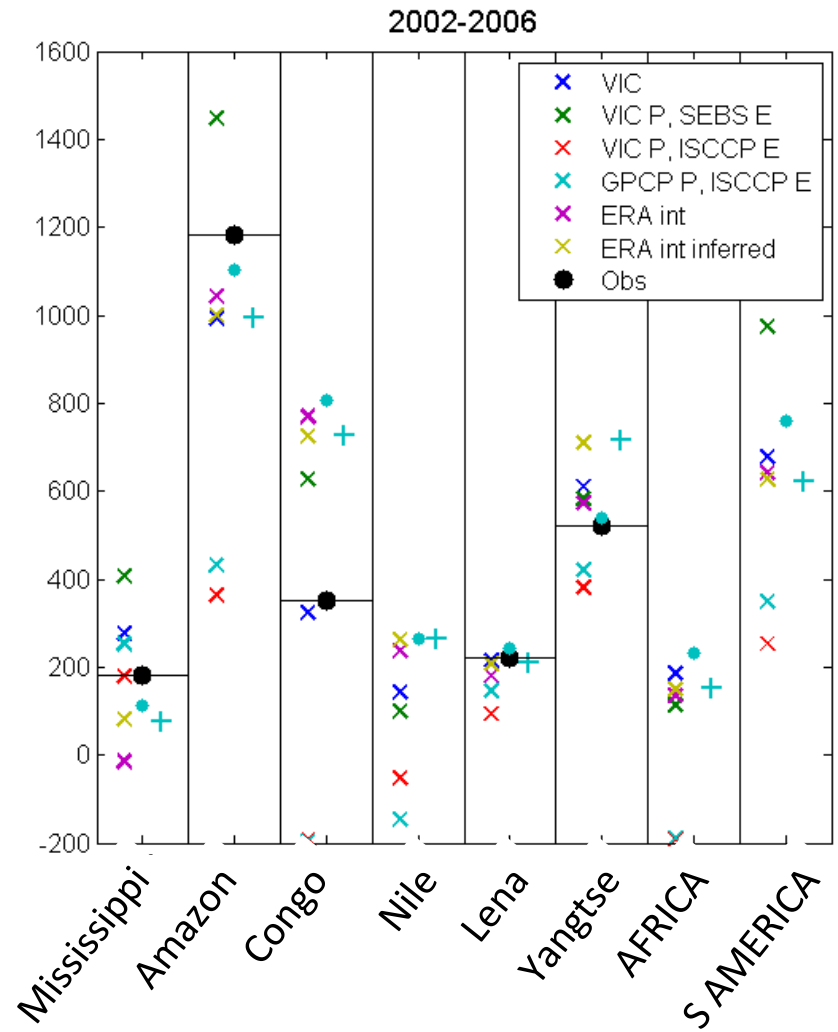
Global ISCCP Annual Mean vs VIC LSM





Discharge: observed and inferred, for ET 'validation'



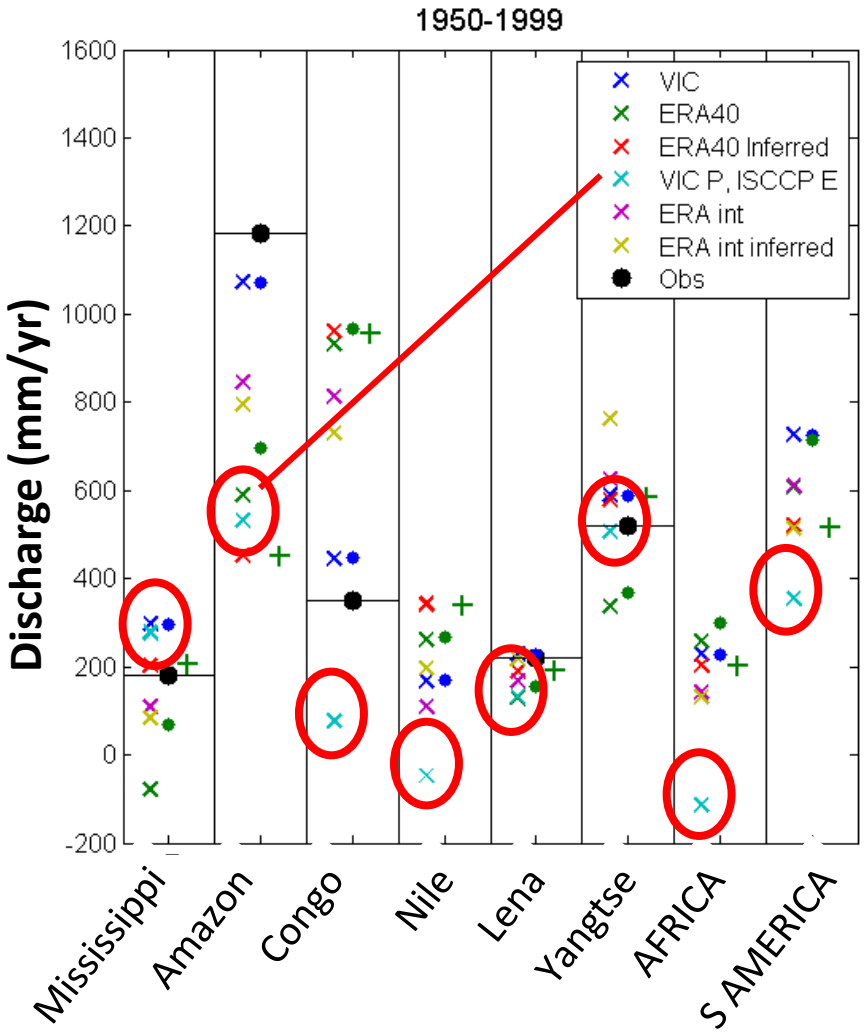


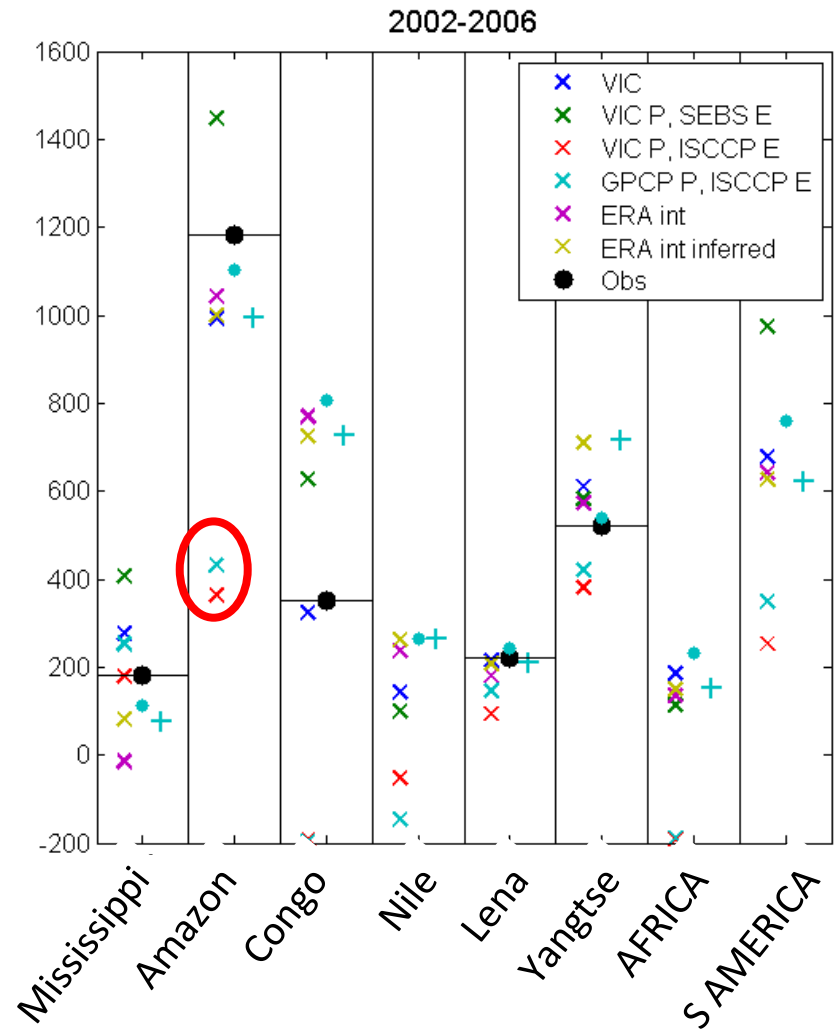
X's are estimates from P-E

Circles are estimates from runoff fields (simulated by VIC, reanalysis runof fields)

+'s are estimates from moisture convergence fields

Discharge: observed and inferred, for ET 'validation'





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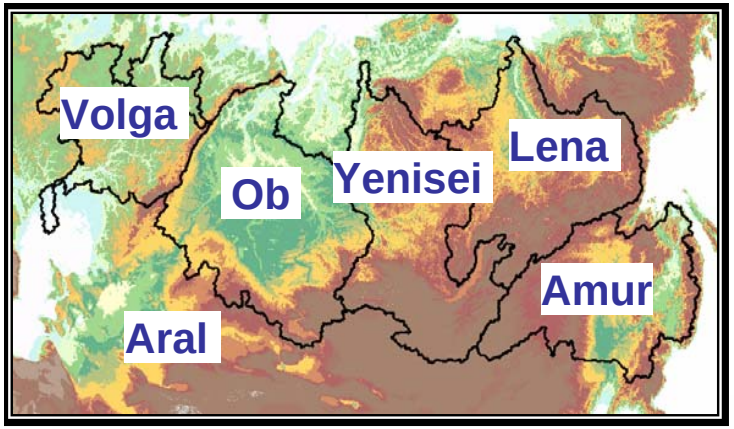
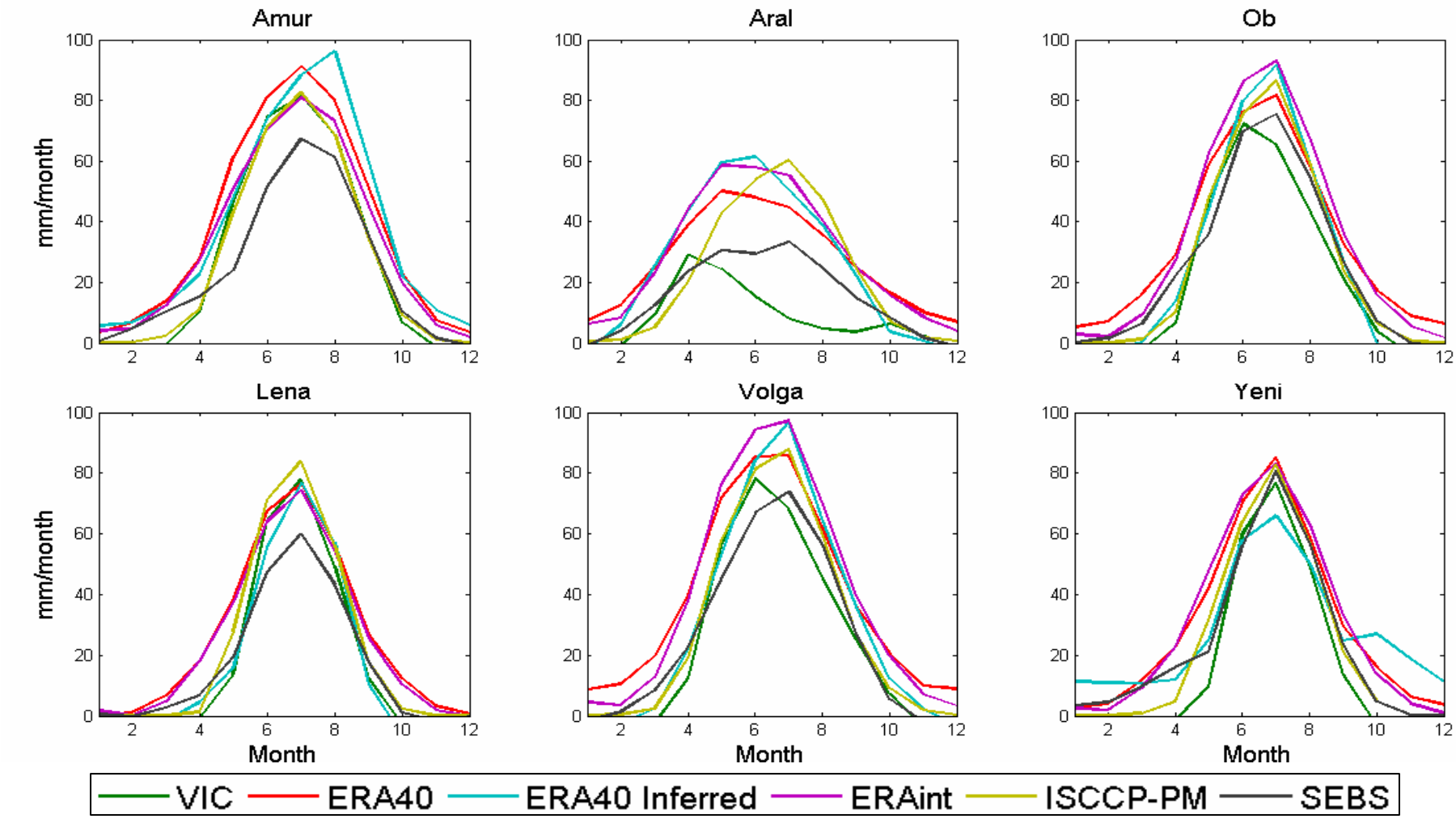
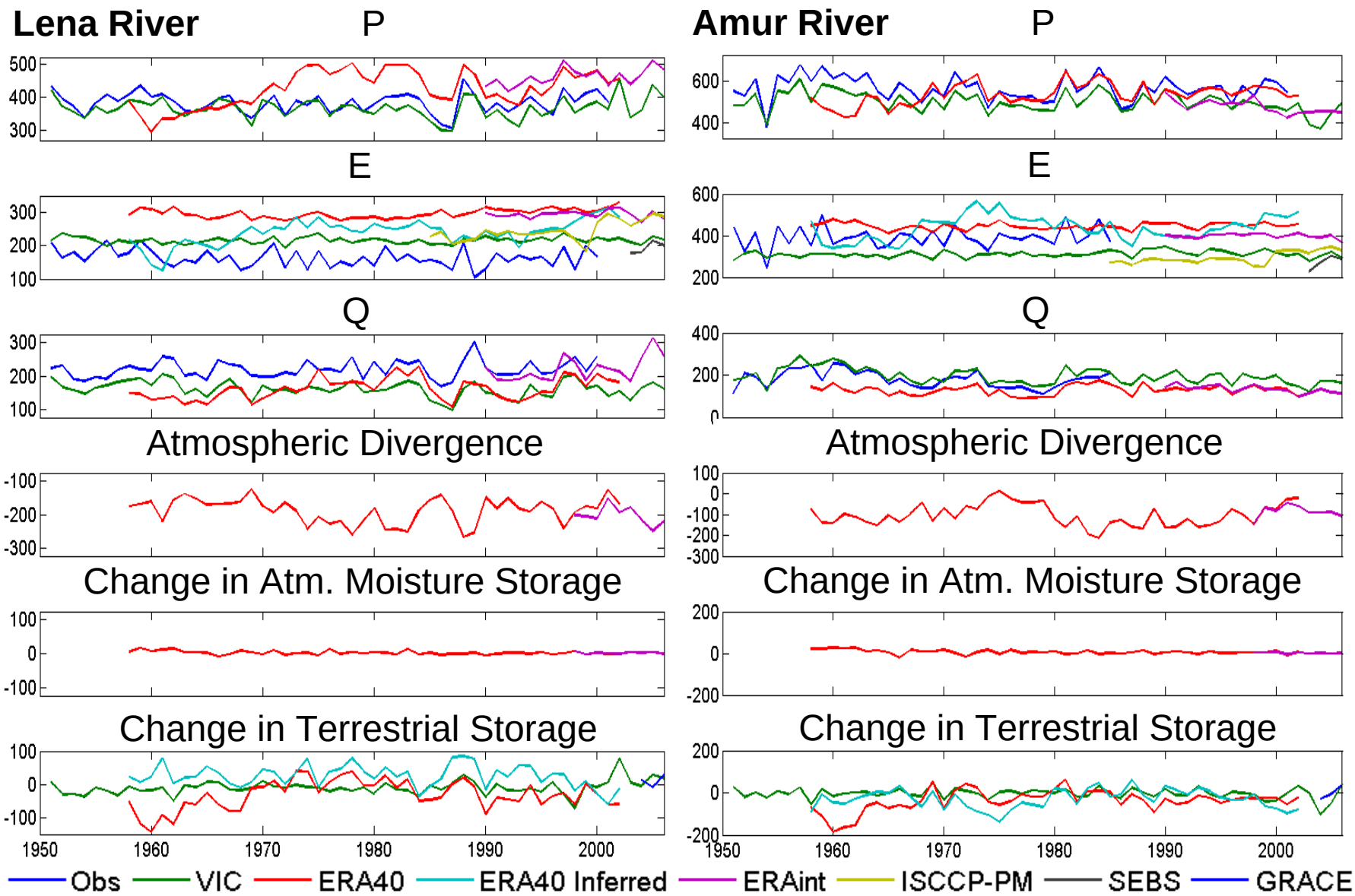


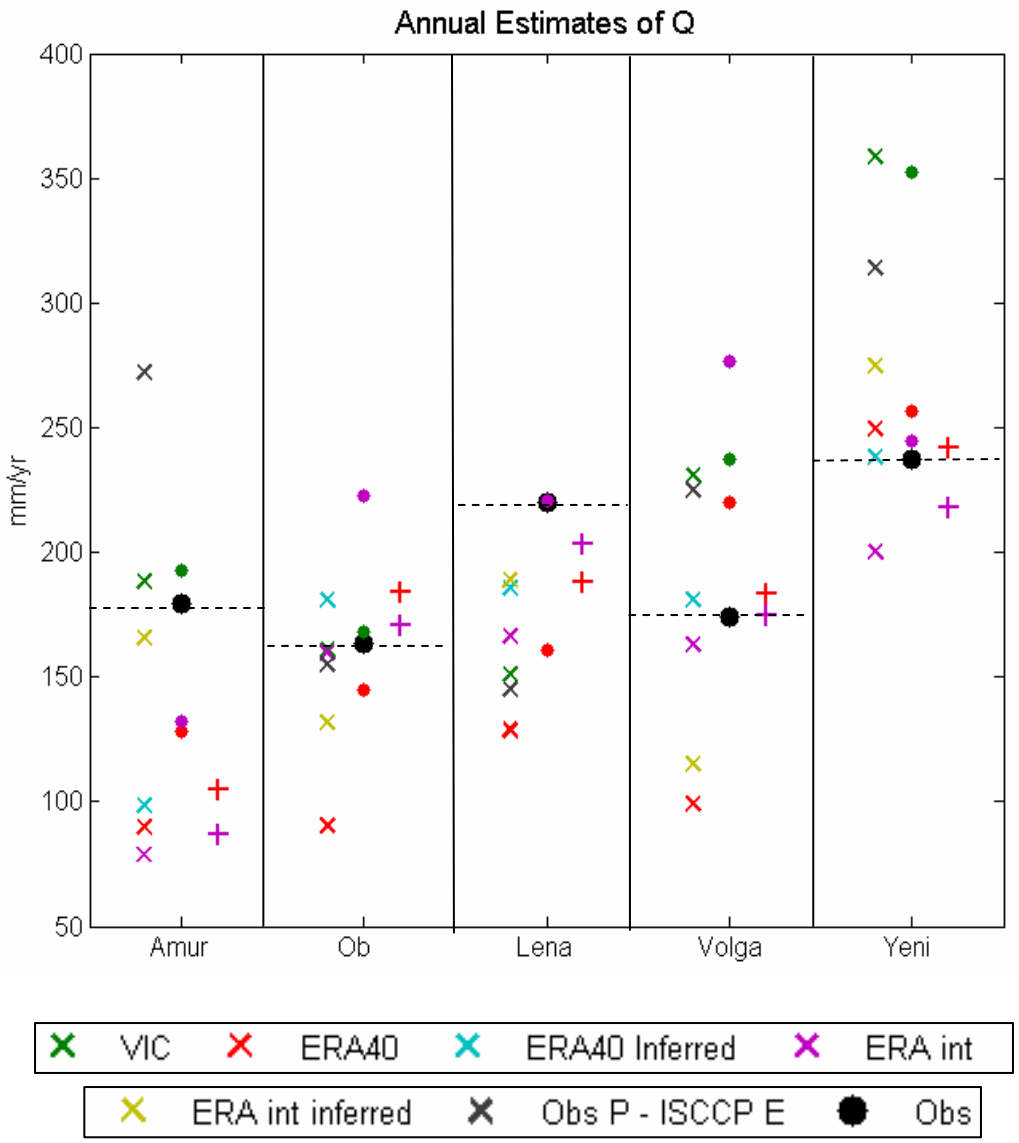
Monthly Estimates of ET over Northern Eurasia (NEESPI)



Annual WB Estimates for NEESPI basins

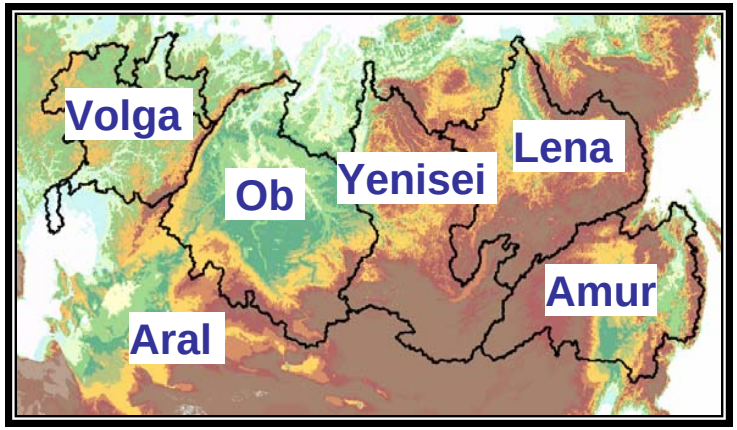


Inferred Estimates of Annual Q for NEESPI Basins

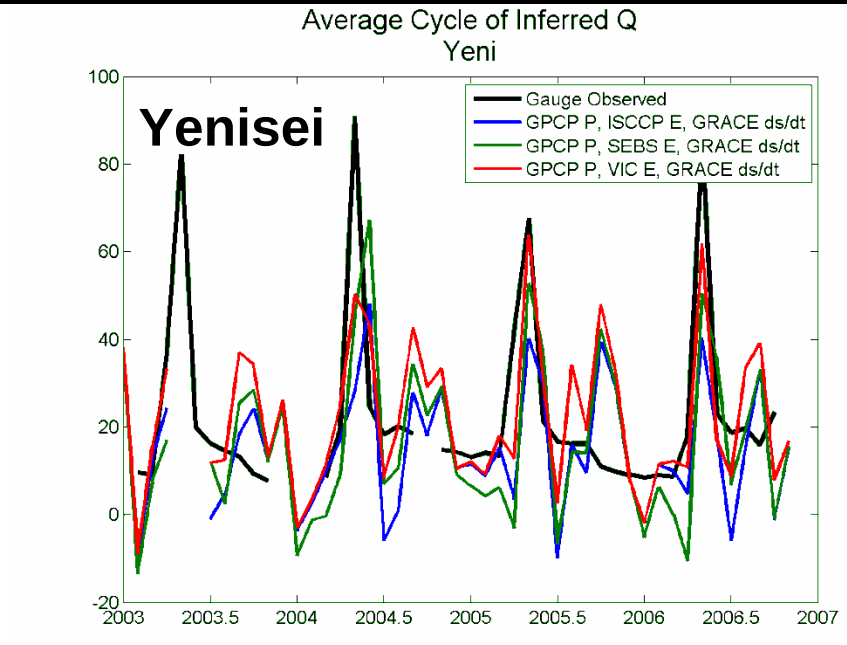


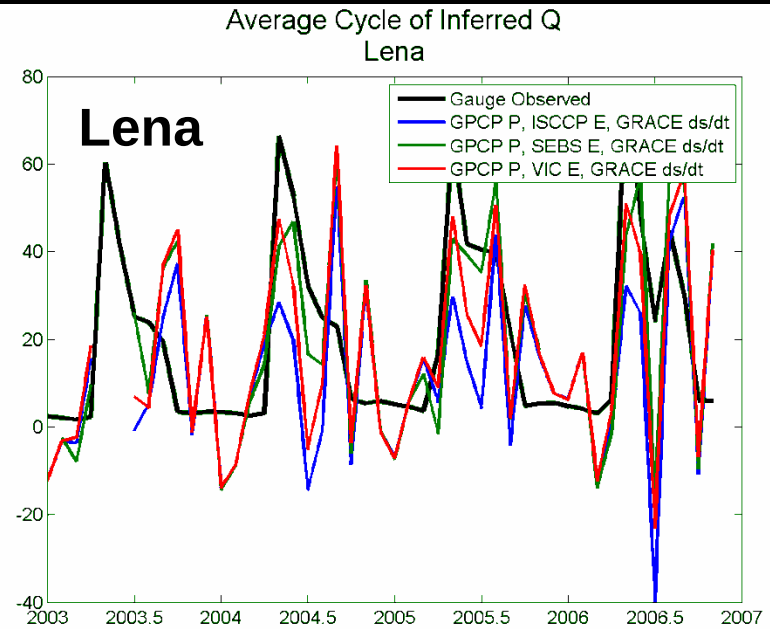
$$R = -\nabla \cdot qv = P - E$$

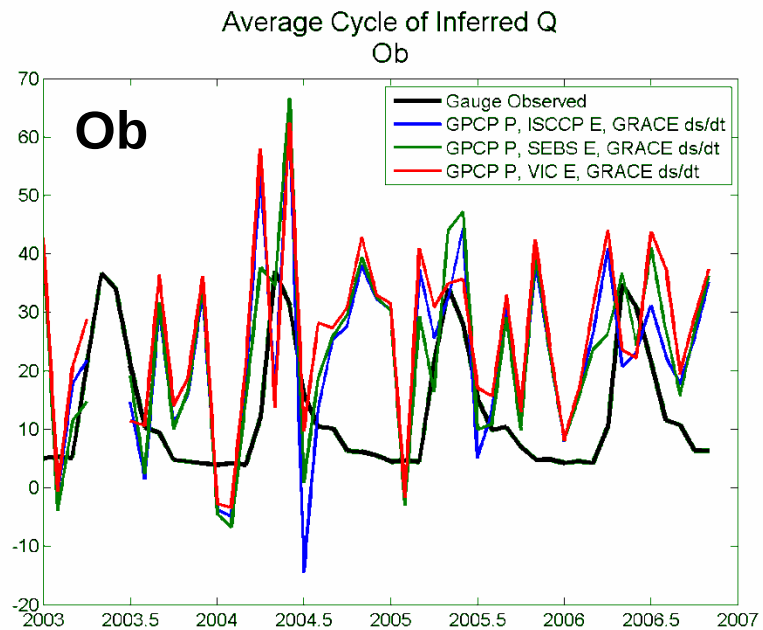
- Black dots: Gauge measurements of discharge
- Circles: Runoff fields
- X's: P-E
- +'s: Atmospheric Convergence



Northern Eurasia: Closing the Budget







--- Gauge observed
--- GPCP P, ISCCP ET, GRACE dS/dt
--- GPCP P, EOS ET, GRACE dS/dt
--- GPCP P, VIC LSM ET, GRACE dS/dt

The Bigger Picture

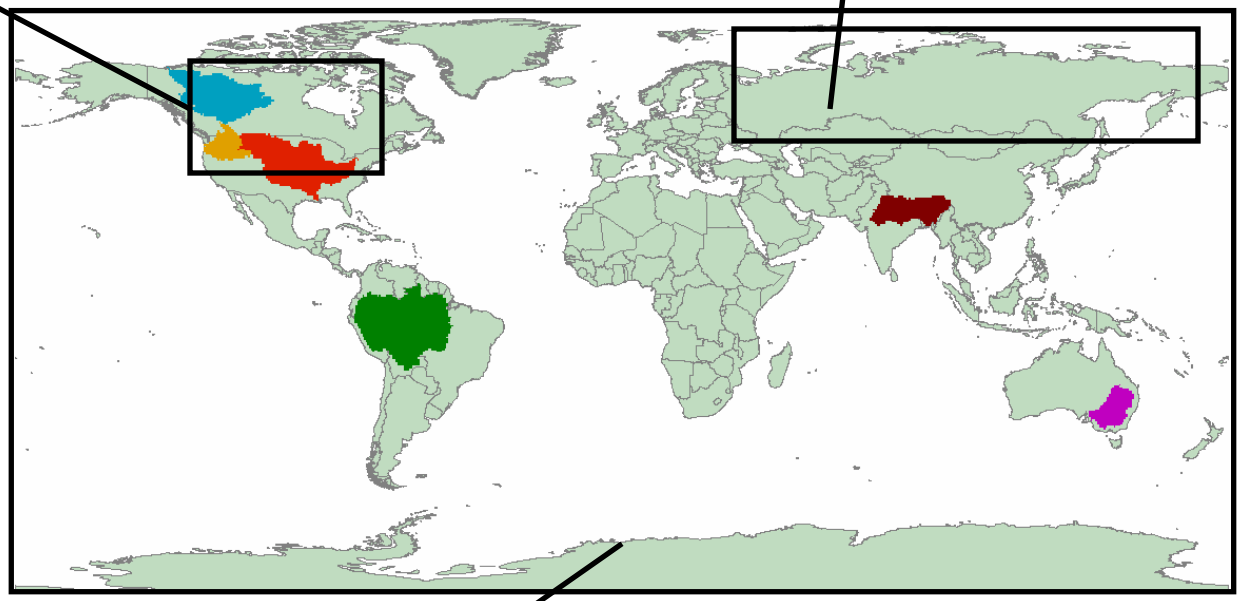
Can we analyze budgets at Global Scales?

USA

P: TRMM, CMORPH, PERSIANN
E: CERES, AIR, MODIS
S: GRACE
NLDAS VIC simulations
NARR

NEESPI

P: TRMM, CMORPH, PERSIANN (**50S-50N**), GPCP; **ERA40 / ERA-interim**
E: PM (CERES, AIR, MODIS)
S: GRACE
Q: GRDC / R-ArcticNet
Global VIC simulations



Global

P: TRMM, CMORPH, PERSIANN (**50S-50N**)
E: PM (CERES, AIR, MODIS)
S: GRACE
Global VIC simulations
ERA-40 interim

Global Evaluations: Potential Datasets

VIC Global Simulations

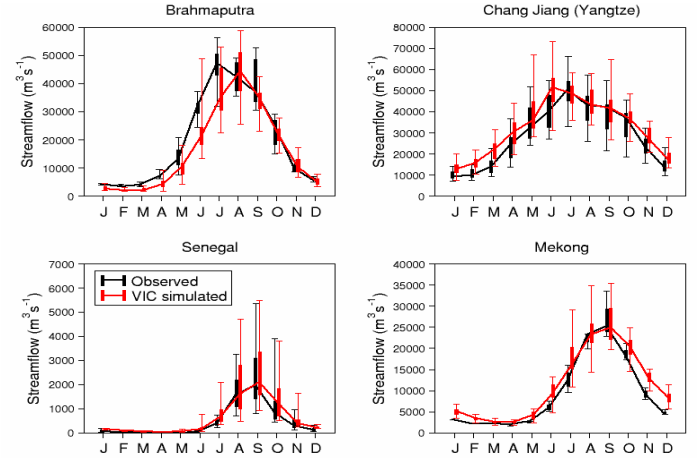
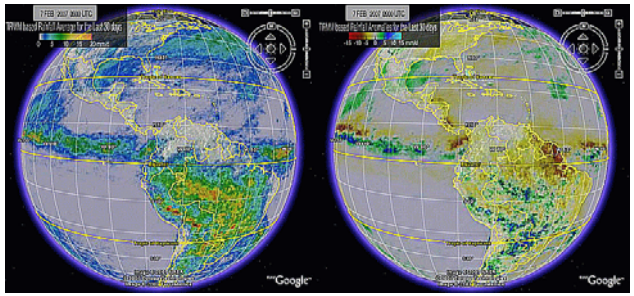
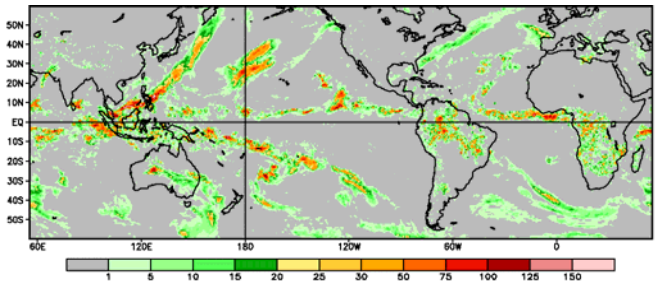


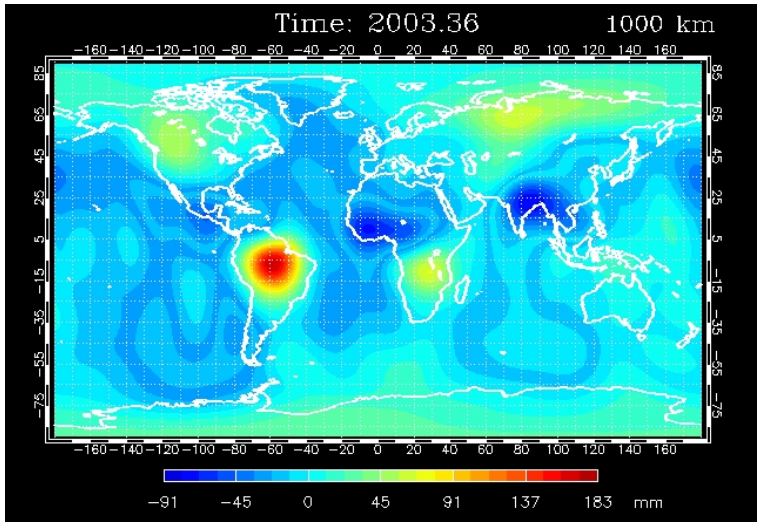
Figure: Simulated (using the VIC model) mean seasonal cycle and variability, and observations for four large global rivers.

TRMM, CMORPH (50S-50N) P

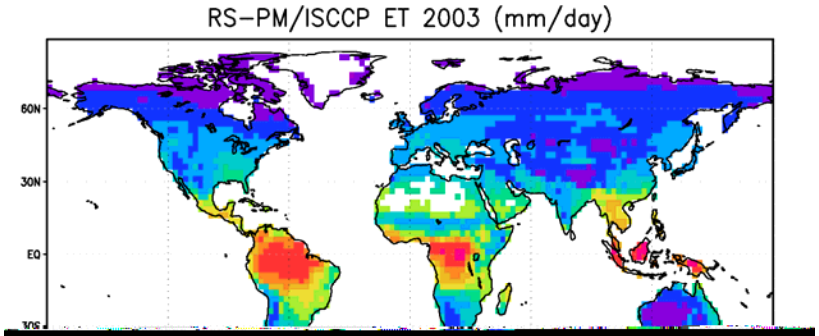




GRACE dS/dt



RS-PM / SEBS ET



Global Evaluations: Potential Datasets

VIC Global Simulations

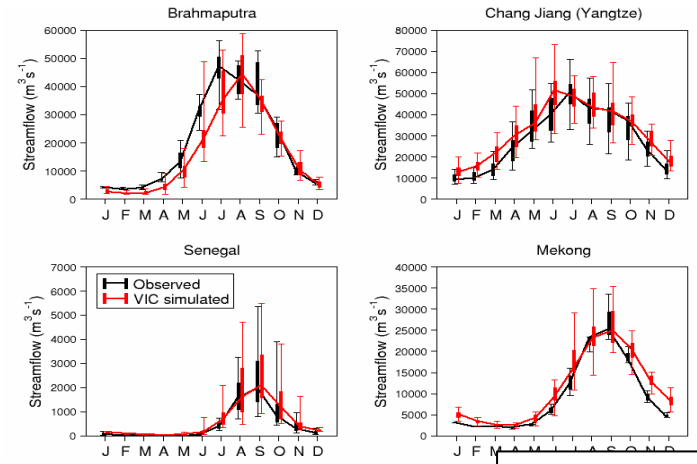
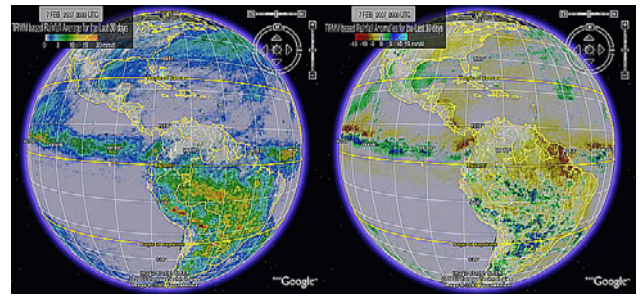
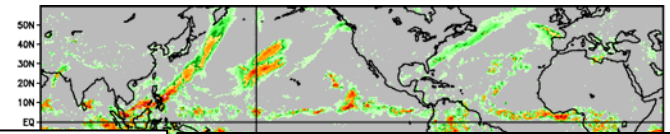


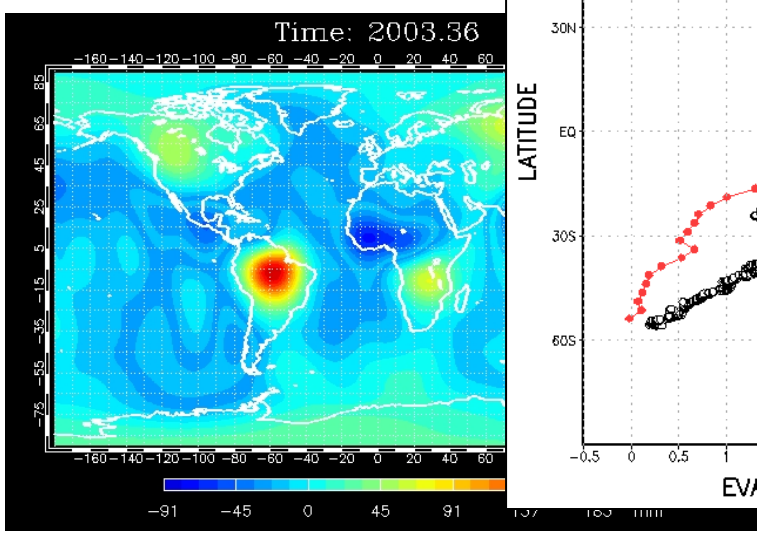
Figure: Simulated (using the VIC model) seasonal cycle and variability, and obser large global rivers.

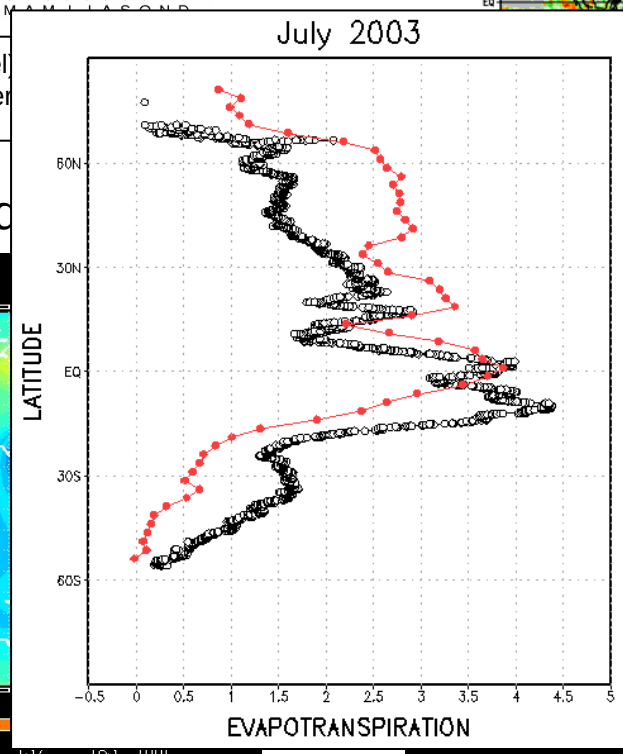
TRMM, CMORPH (50S-50N) P

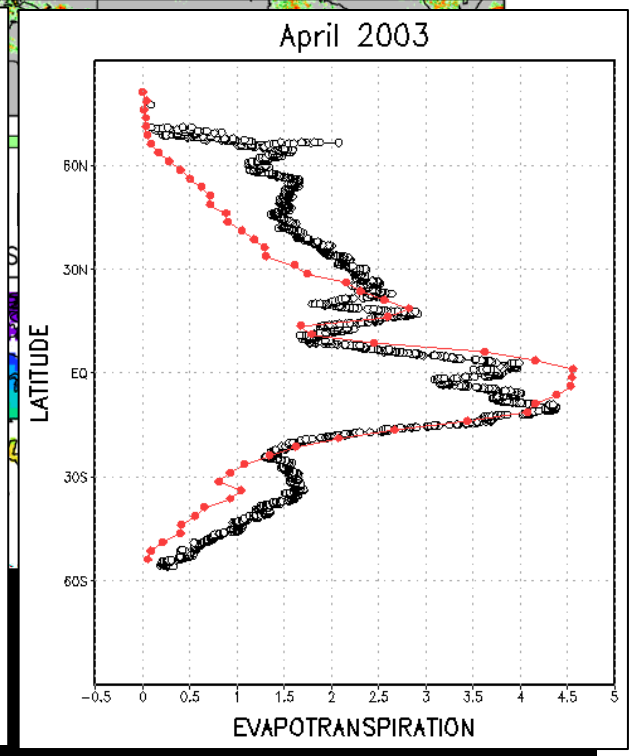




GRACE dS/d







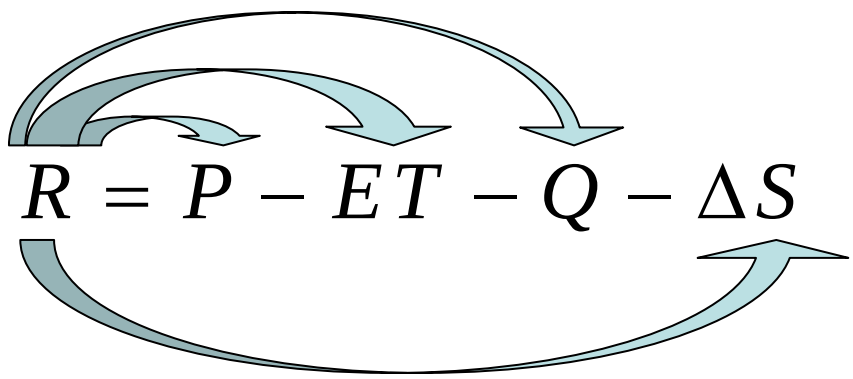
Closing the Budget: the Holy Grail

A closed water budget: $P = ET + Q + \Delta S$

Various errors lead to an unclosed budget with a residue term:

$$R = P - ET - Q - \Delta S$$

Force closure by redistributing the residue based on error statistics:



HOW? By passing the estimates through a Kalman filter where the closure constraint is introduced as an error free observation. (Pan and Wood, 2006 *JHM*, 7(3):534-547, June)