Representation of Continental land surface waters in global climate and weather prediction models

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With contributions from

M Ek (NCEP NOAA), J Polcher (LMD, Paris), B Decharme and V Pedinotti (CNRM-GAME, Météo-France), A Getirana (LEGOS, Toulouse) and others!

Global Earth System Models

Modes of usage:

• Medium Range Forecasts (10-16 km) ➔ 10days

• Seasonal Forecasts ➔ months

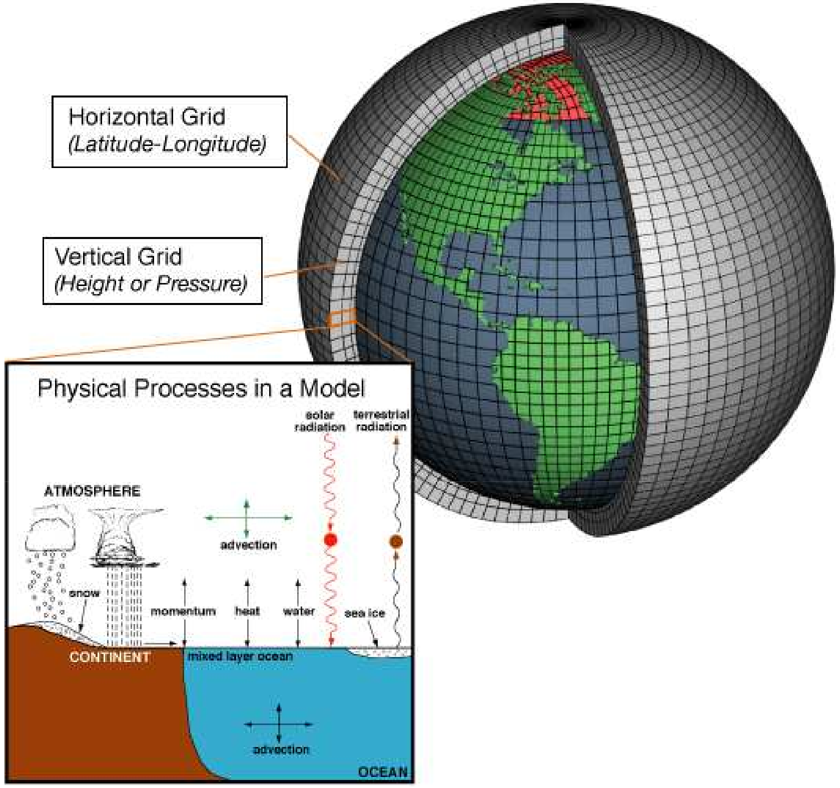
• High resolution (~50 km) ➔ 10 years

• Climate Projection (~1-5 deg) ➔ 100 + years

(fixed SSTs OR fully coupled OGCMs)

• Long term, paleo-climate 1000+ years…

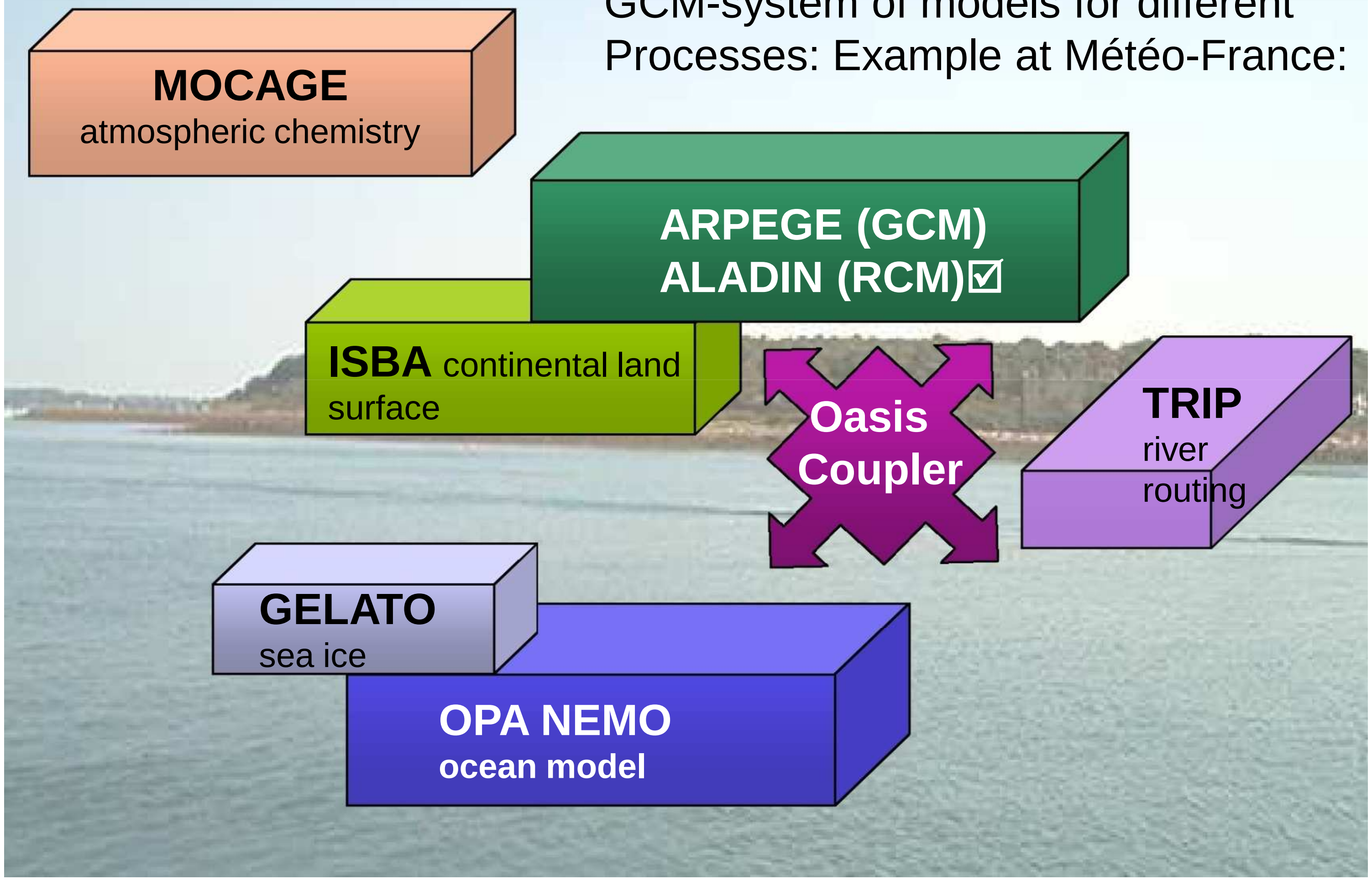
• Regional (RCM) : downscaling. Large scale forcing imposed (possibly by re-analysis data) ➔ process studies



State-of-the-art climate models now include interactive representations of the **ocean**, the **atmosphere**, the **land**, **hydrologic** and **cryospheric** processes, terrestrial and oceanic **carbon** cycles, and **atmospheric chemistry**.

Global Earth System Models

GCM-system of models for different Processes: Example at Météo-France:



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Global Earth System Models

Cimate Projections:

Projected climate change: a sample of IPCC Météo-France results…(2xemissions scenario)☑

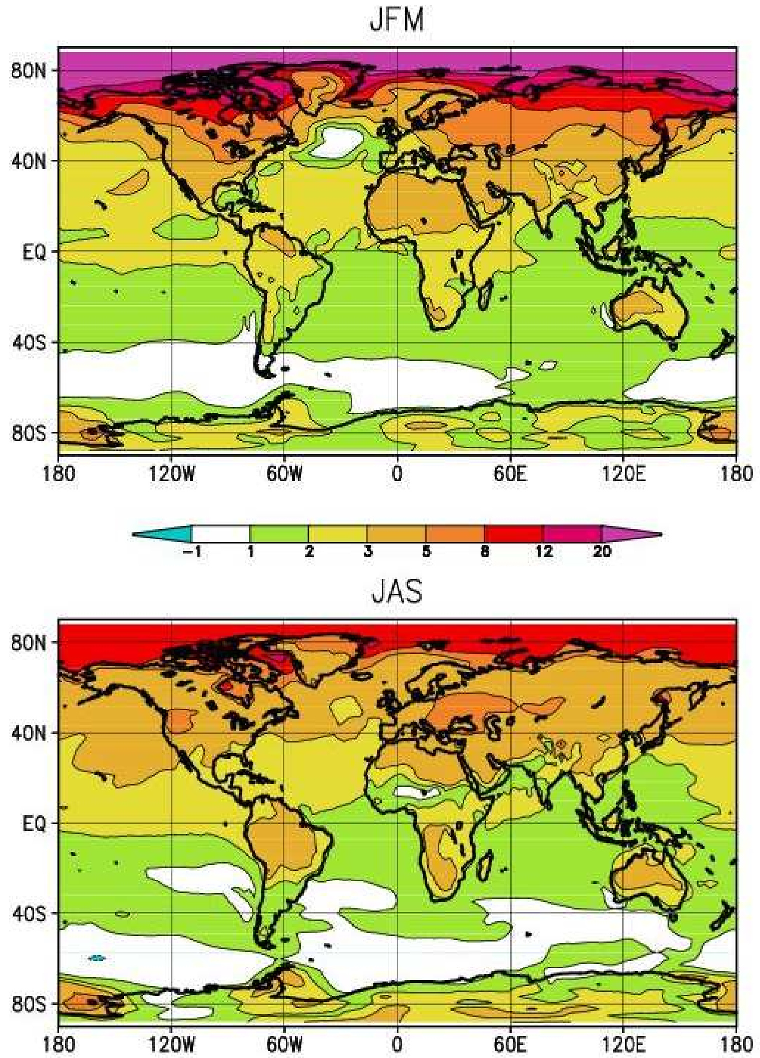
Significant Change in regimes for:

• Wetlands, flooded zones

• Lakes, rivers, snow (glaciers)

• Discharge (potential feedbacks with ocean and ice….)☑

• Wetland Carbon, Methane emssions…

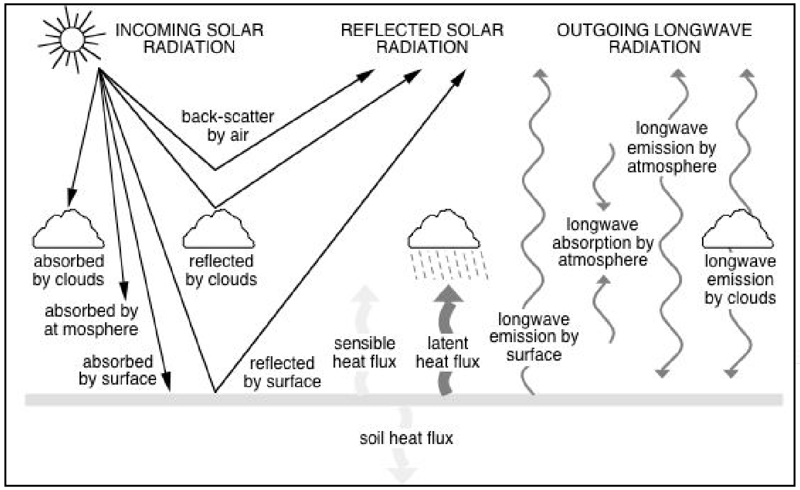


Need global scale data to develop & improve parameterizations for useful climate projections of hydrological impacts!

Role of Land Models

- Traditionally, from a **coupled NWP and climate modeling perspective**, a land-surface model provides four quantities to a parent atmospheric model:
  - surface sensible heat flux,
  - surface latent heat flux (evapotranspiration)
  - upward longwave radiation (or skin temperature and surface emissivity),
  - upward (reflected) shortwave radiation (or surface albedo, including snow effects)
  - Momentum sink

...to provide the bottom boundary condition in terms of the surface energy budget.



From M Ek

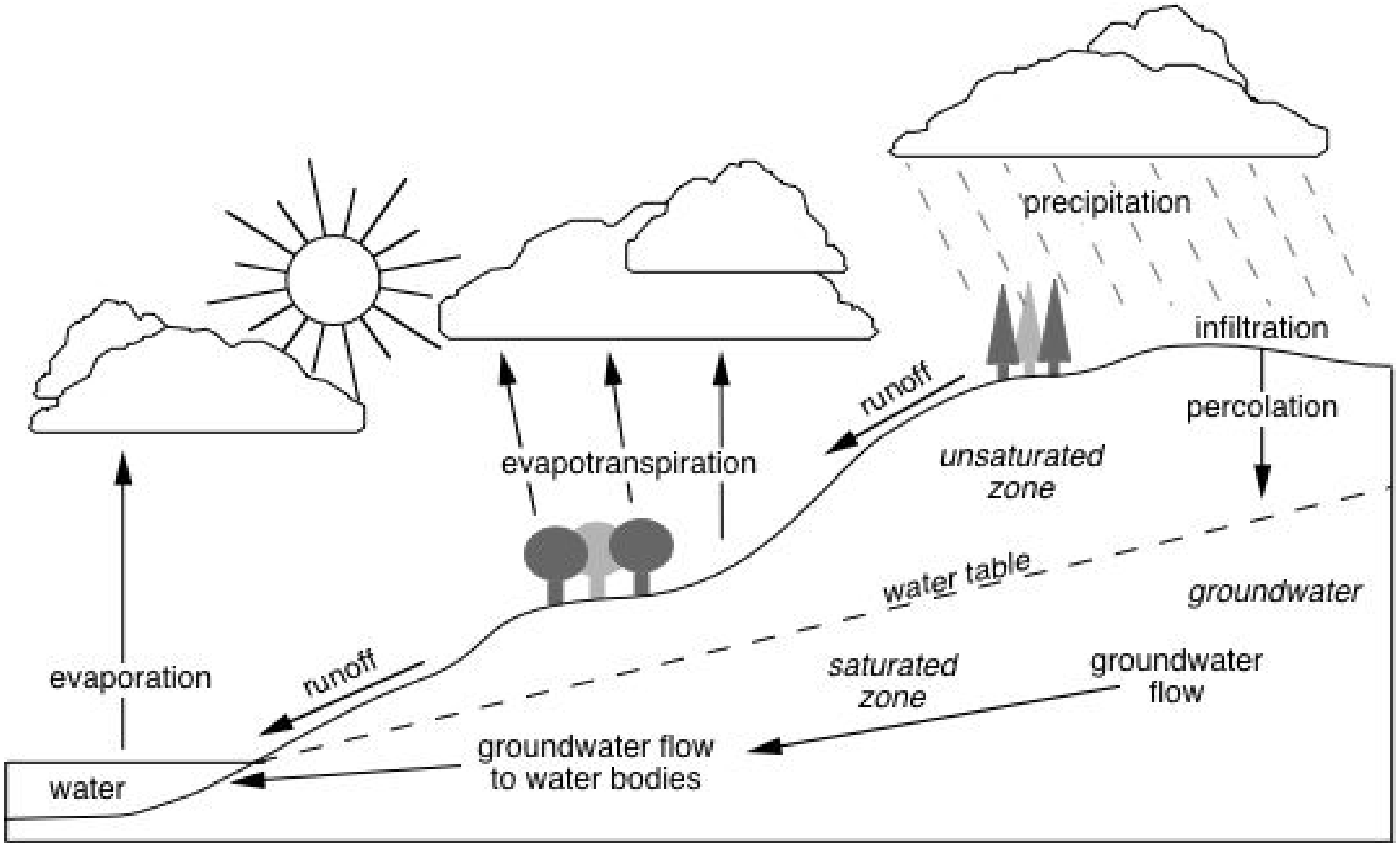
Changing Role of Land Models

- In a more fully-coupled ***Earth System***, this role is changing, with **Weather & Climate** connections to:
  - ***Hydrology*** *(soil moisture & ground water/water tables, irrigation and groundwater extraction, water quality, streamflow and river discharge to oceans, flood/drought, lakes, and reservoirs with management, etc),*
  - **Biogeochemical cycles** (application to ecosystems--terrestrial & marine, dynamic vegetation and biomass, carbon budgets, etc.)
  - **Air Quality** (interaction with boundary-layer, biogenic emissions, VOC, dust/aerosols, etc.)
- **More constraints**, i.e. we must close the energy budget, & now the water budget, and those related to biogeochemical cycles & air quality.

LSM parameterization of hydrology was recently highlighted at the Pan-GEWEX Conf as an area of research emphasis for the future, as need increases to interface with water resource managment

Representing the Hydrological Cycle

- **Land models** now more than just an atmospheric boundary condition; they **must close** the **water budget** (soil moisture, snow, runoff, streamflow).
- Draw upon experience with **hydrological models**.



From M Ek

GCM representation of continental hydrology:

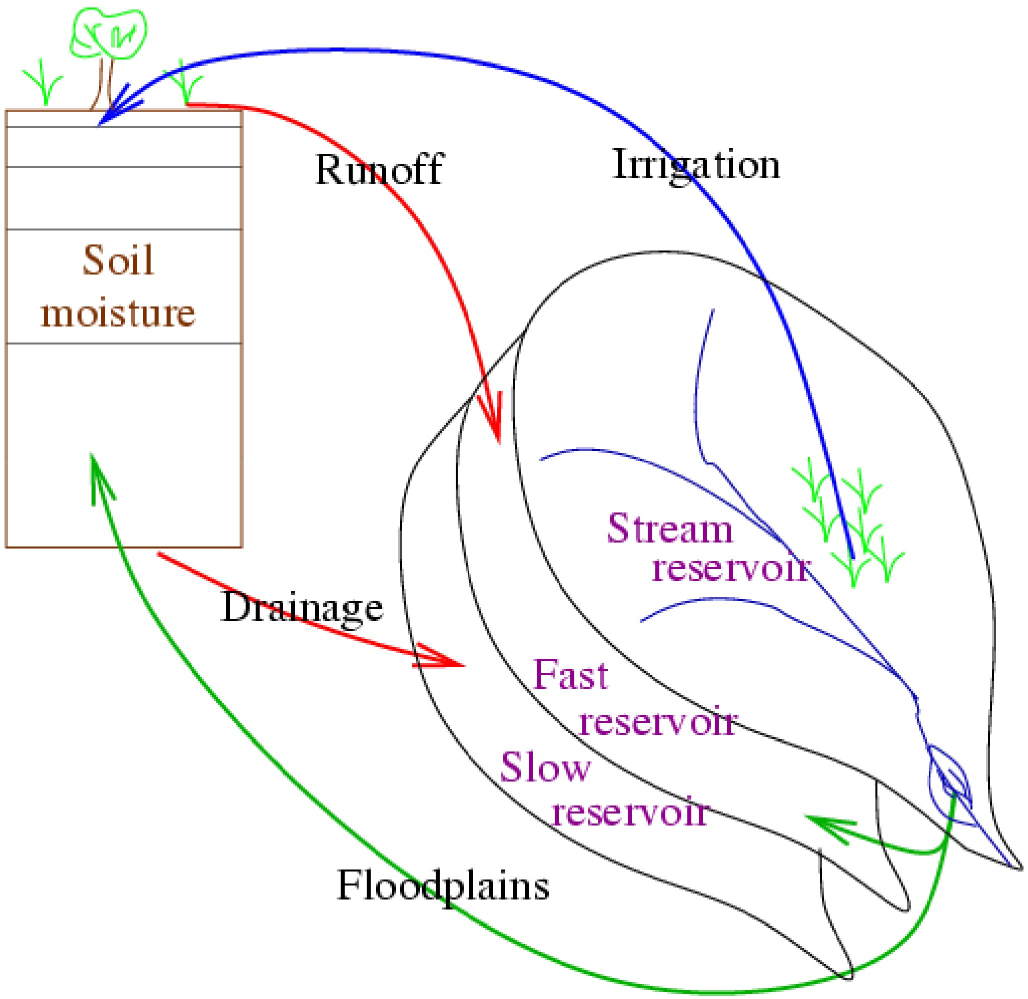
- Representation of wetlands, bogs
- Lake parameterizations
- Flooded zones: dynamics, interactions with lakes, rivers
- Freshwater discharge into sea/oceans
- River/Groundwater exchanges
- Irrigation (exchange with rivers, ground water/aquifers)
- Representation of Aquifers
- Precipitation spatial distribution at the surface
- Snow, ice (permafrost) representations
- Soil moisture, energy balance (evapotranspiration…)☑
- Runoff (Dunne and Horton) and baseflow

GCM representation of continental hydrology:

- Representation of wetlands, bogs generally not accounted for explicitly
- Lake parameterizations often prescribed Tsfc or 1D thermal transfer
- Flooded zones: dynamics, interactions with lakes, rivers few GCMs
- Freshwater discharge into sea/oceans…explicit, implicit, just a diagnostic
- River/Groundwater exchanges few GCMs
- Irrigation (exchange with rivers, ground water/aquifers) few GCMs
- Representation of Aquifers few GCMs?
- Precipitation spatial distribution at the surface few GCMs
- Snow, ice (permafrost) representations
- Soil moisture, energy balance (evapotranspiration…)☑
- Runoff (Dunne and Horton) and baseflow

- Important to keep in mind: the above are primarily **sub-grid parameterizations**, and there are restrictions on the complexity. Also, resulting **feedback mechanisms** must be studied carefully…

Example: The ORCHIDEE implementation



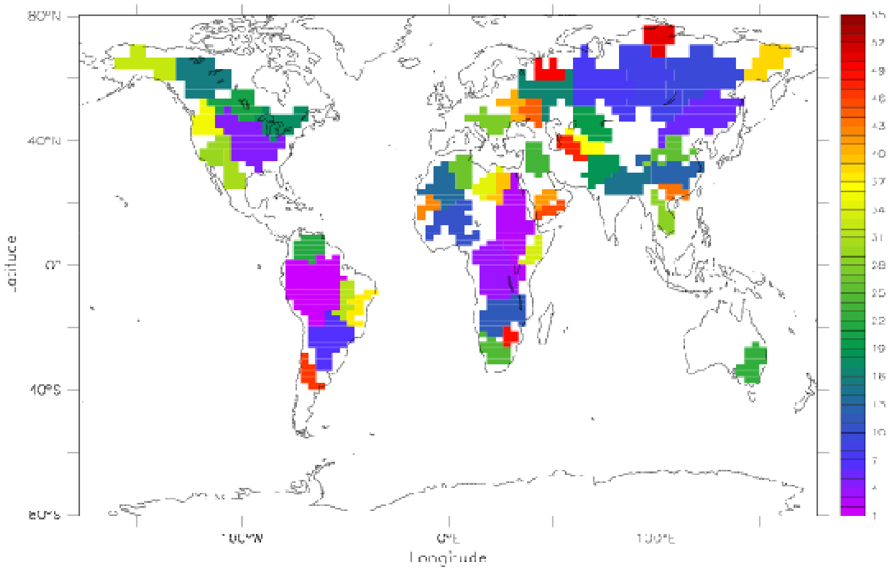
- Each grid-box can contain up to m basins.
- The *n* largest basins are identified as rivers and produce a river flow on the grid box closest to the ocean. Other basins contribute to a diffuse coastal flow.
- Endorehic basins contribute water to the lower soil moisture reservoir. Water can then return to the atmosphere through evaporation.
- In such a system floodplain and irrigation can be taken into account in a coherent way.

With this approach Earth system models can simulate the horizontal movement of water at the surface.

From J Polcher

Runoff routing

For the moment in Earth system models very little attention has been paid to routing. This will change and lead to some new developments in LSMs



LSMs have 3 possible approaches :

- Simply close the water budget and distribute the runoff over all oceans.
- Build pipelines to the ocean.
- Allow horizontal transport at the surface through a full integration in the LSM.

A Only the third approach allows for the parametrization of floodplains, anthropogenic use of water, ... -> a feedback of the land on climate through the oceans.

From J Polcher

River Network

Large scale hydrology:

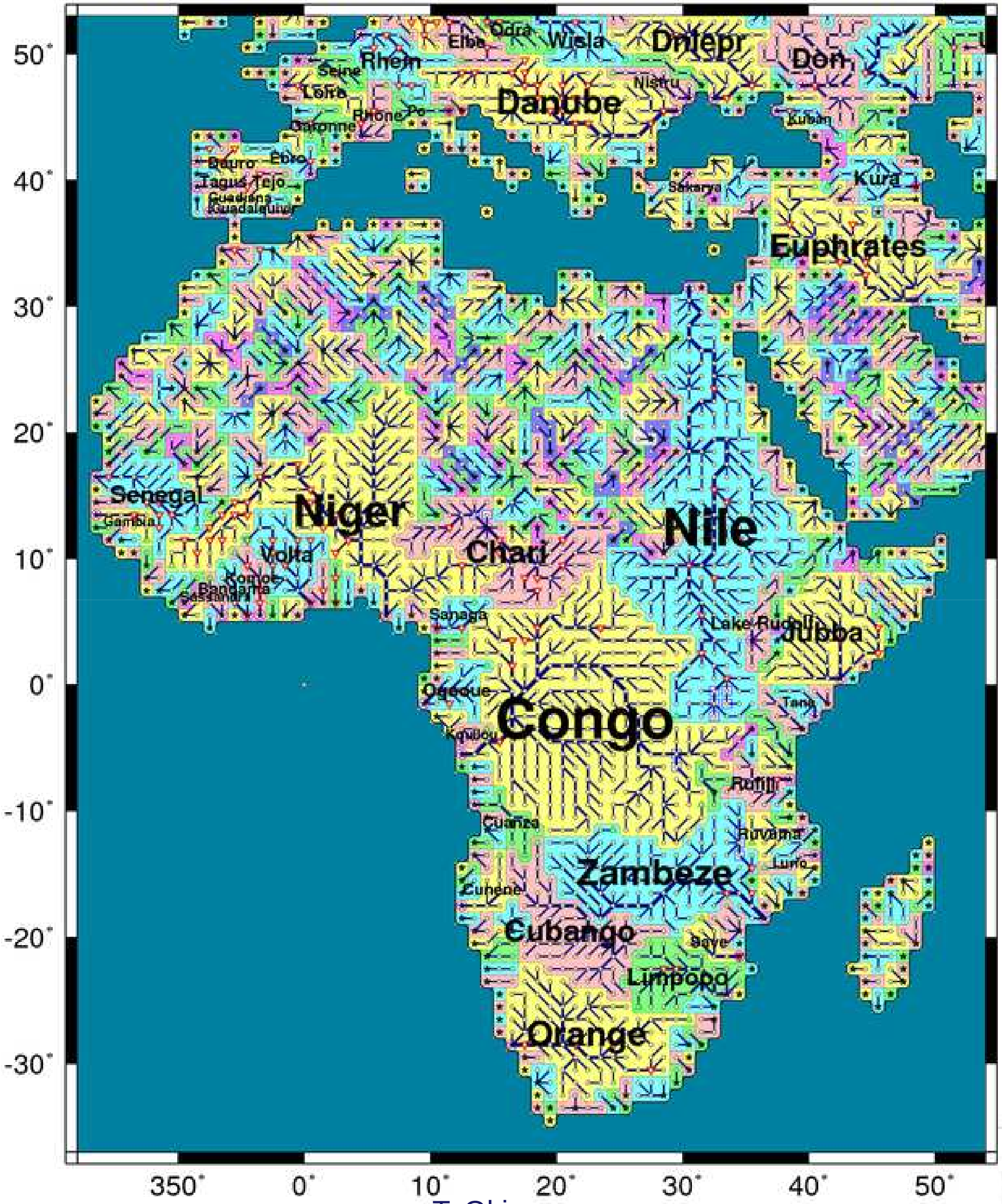
•Land surface model genrates runoff

• River routing using TRIP (1 or 0.5 degrees)☑

• Many fixed parameters (e.g. river meander factor…)

• Use simple geomorphological relationships (e.g. river width a fn of distance to ocean/sea)

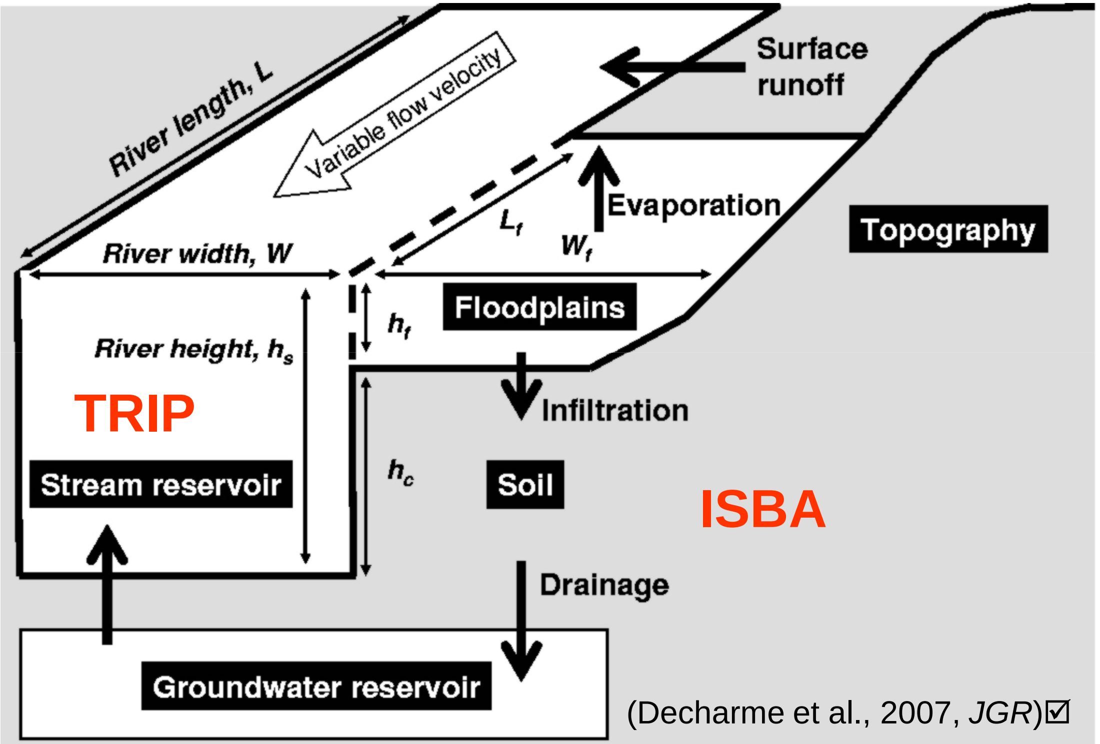
Rivers in Africa on TRIP in 1°x1° mesh



T. Oki

Parametrization of floodplains

The ISBA-TRIP coupling system



(Decharme et al., 2007, *JGR*)☑

Rivers and Floodplains increases locally evaporation and reduced the amount of water in the river.

<u>Prognostic variables:</u>

•The river height, h_s

•The river flow velocity, *v* (Manning formula)☑

•The floodplain volume (calculated using the sub-grid topography)☑

<u>Other important variables:</u>

•The flood fraction, f_{flood}

•The flood height, h_f

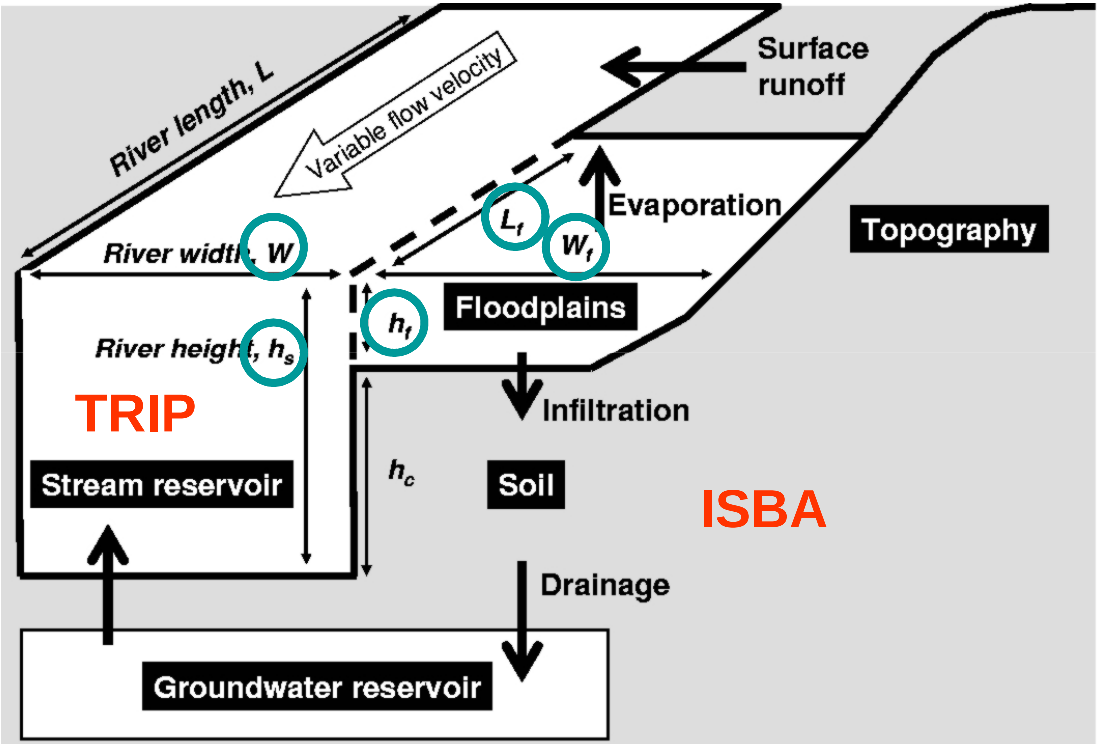
<u>Evaluations:</u>

•In-situ river discharge

•Satellite-derived wetland estimates (Prigent et al., JGR, 2007)☑, Cretaux

• **Altimeter-derived slope, depths, floodplain water depth and extent**

The ISBA-TRIP coupling system



Key variables from satellite ➔ SWOT!

Key scientific question for SWOT: better quantify the echange between rivers and floodplains for improved prediction

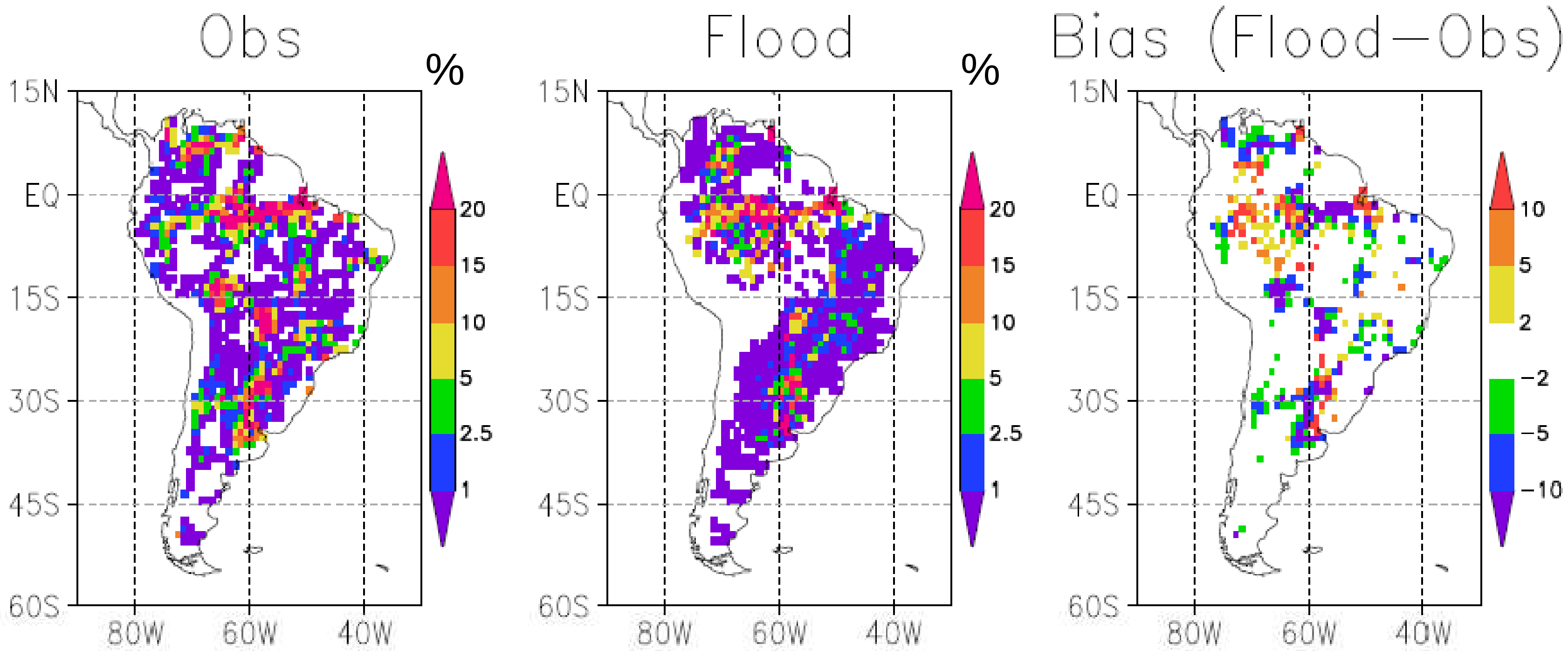
Development Methodology

- Improve in « offline » mode ➔ validation with obs and/or assimilation
- Use in (fully-coupled) projection ➔ extrapolate in n,t !

* NEED Global scale data!

Parametrization of floodplains

Spatial comparison between the Flood experiment
and the Satellite-derived wetland estimates



Satellite-derived wetland estimates from Prigent et al. (2007, JGR).

ISBA-TRIP flood-plain simulation

Difference

Decharme, Prigent

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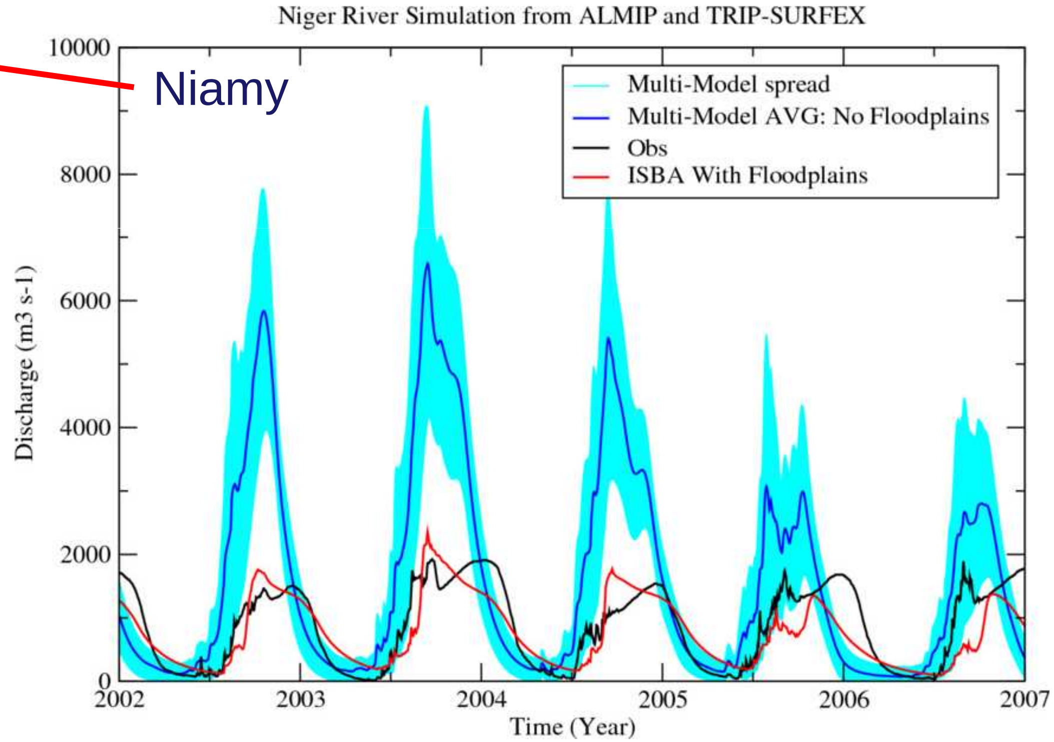
ISBA/TRIP modeling of the Niger basin

Niger Basin

- Using TRIP alone (offline) with LSM runoff: overestimate of discharge, rapid recession
- Coupled system: better timing and volume

- Force ensemble of LSMs with best estimate of meteo (observed/remote sensing)



Pedinotti, Boone, Decharme, Mognard

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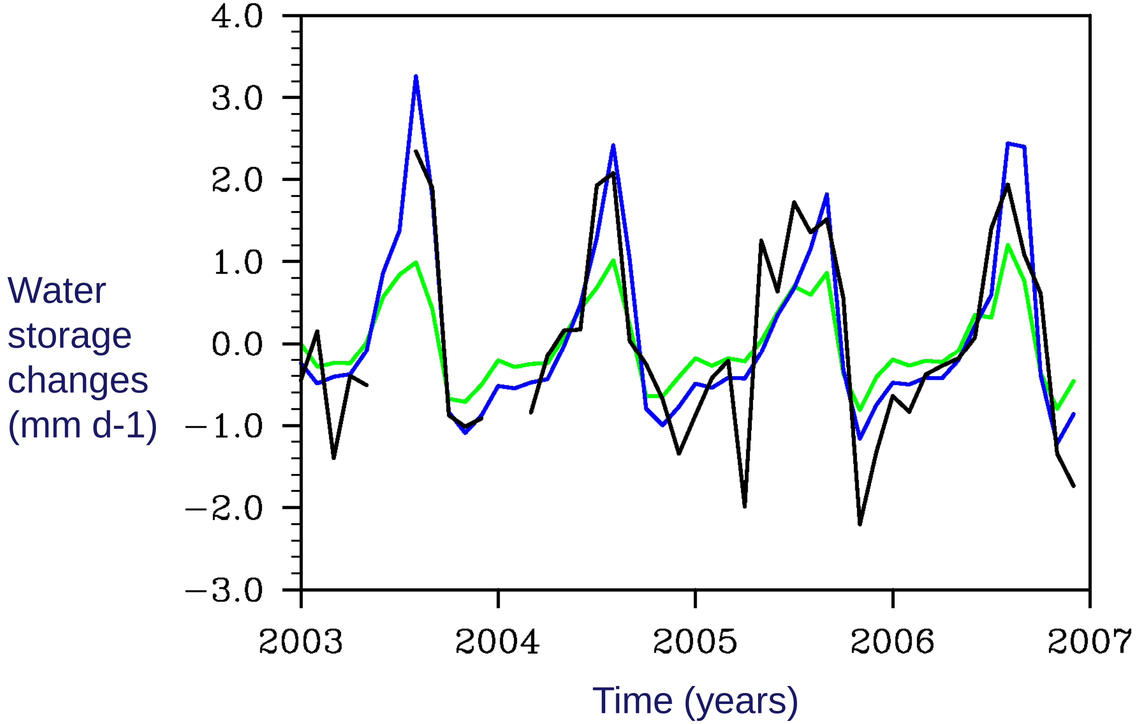
ISBA/TRIP modeling of the Niger basin

GRACE Water Storage Estimate
(CSR product)



- GRACE estimate
- Near surface soil
- Near surface + ground water + river store + flooded zone + deep aquifers

- Use GRACE to better estimate/constrain water budget components
- Perform more sensitivity tests towards parameter estimation optimization
- Use to help develop a parameterization of deep water storage/aquifers

Pedinotti, Boone, Decharme, Mognard

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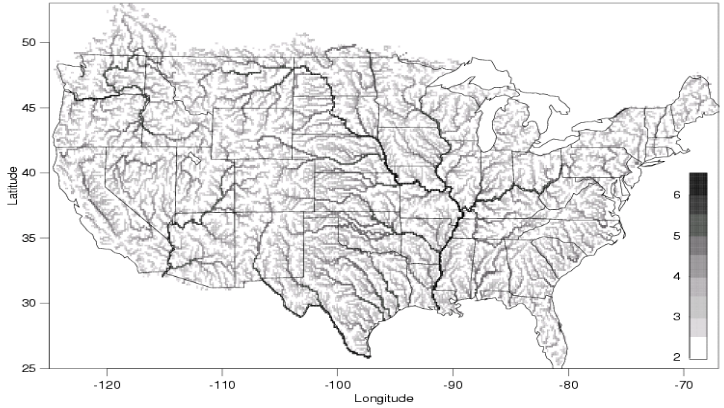
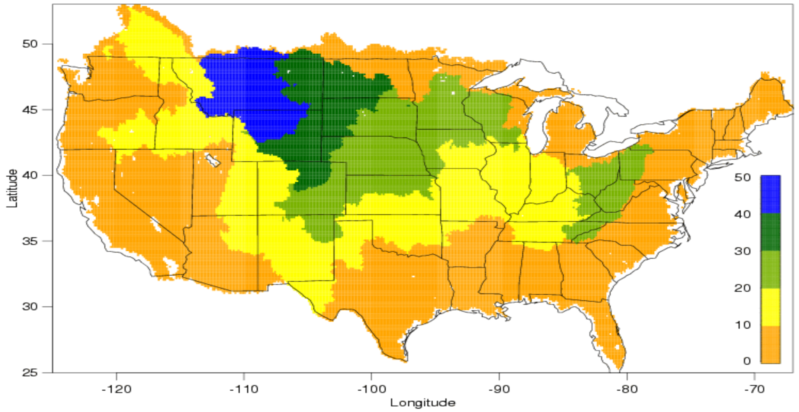
NLDAS Simulated River System

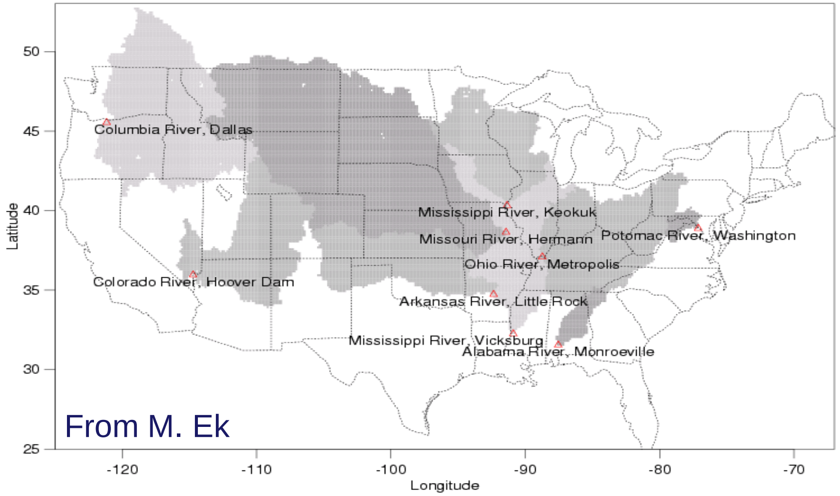
Upstream area [log10(km^2)]



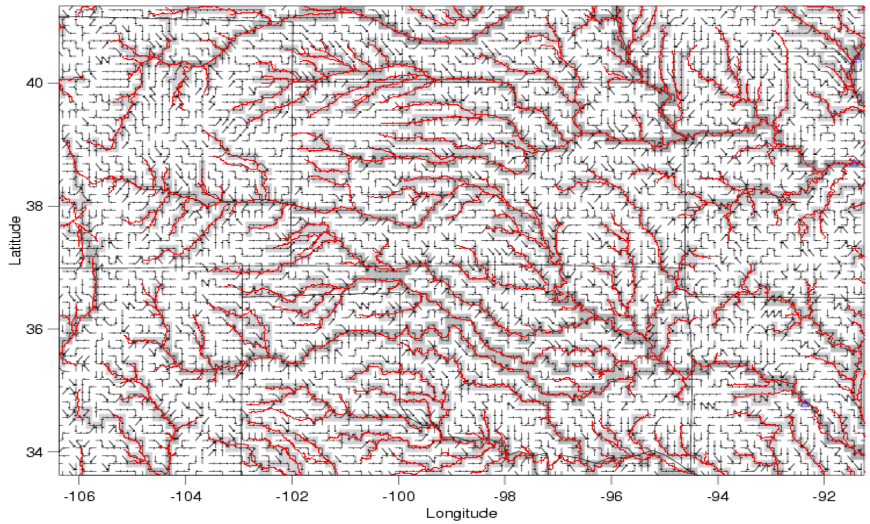
Travel time to outlet [days]



Large River basins



River flow direction mask



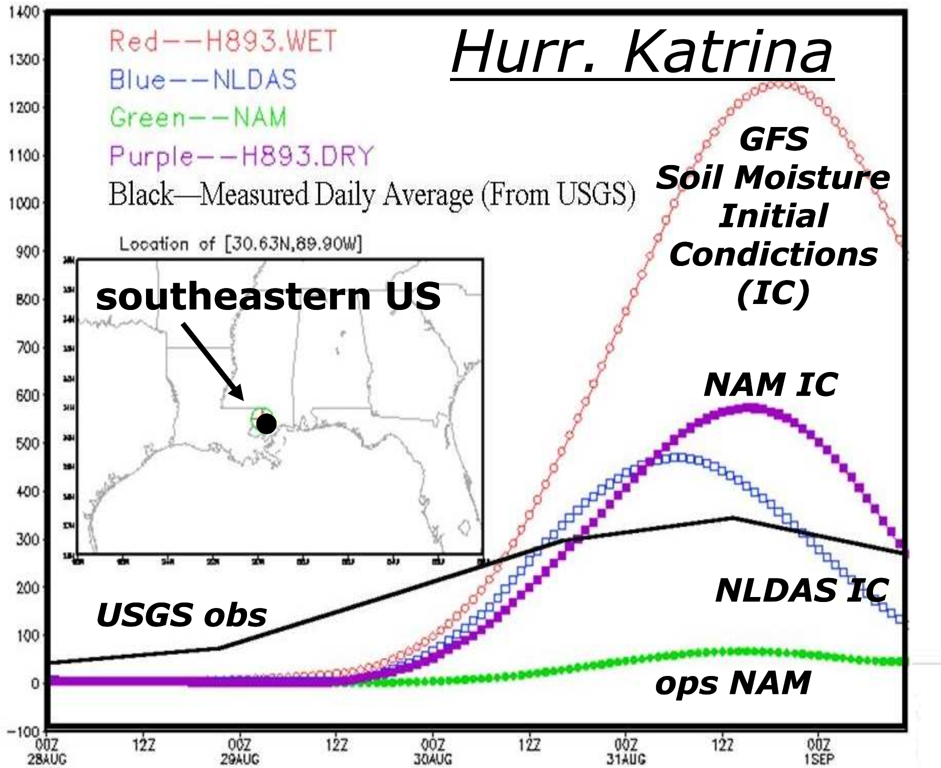
Hurricanes and Inland Flooding

More physical **Noah replaces "slab" land model** in the Hurricane (mesoscale) Wea. Research & Forecast. model.

Many hurricane cases tested, both "*out at sea*" and repeated for *near land-fall* to assure **no degradation** in hurricane track and intensity (including precip) compared to operational HWRF.

Coupled land model runoff with river-routing model; comparison with USGS river gauges demonstrates potential for **inland flood forecasting** (*not possible with "slab" land model*).

Use coupled land and river-routing models in **global & climate models** (*river discharge to ocean*).



From M. Ek

Towards a global river routing system ➔ SWOT app

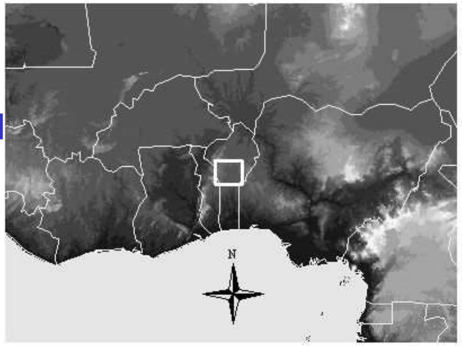
ALMIP2 AMMA Land Surface Model Intercomparison Project

Goal:
Develop a simple routing scheme for the mesoscale which can be used to transfer LSM runoff through a river network.

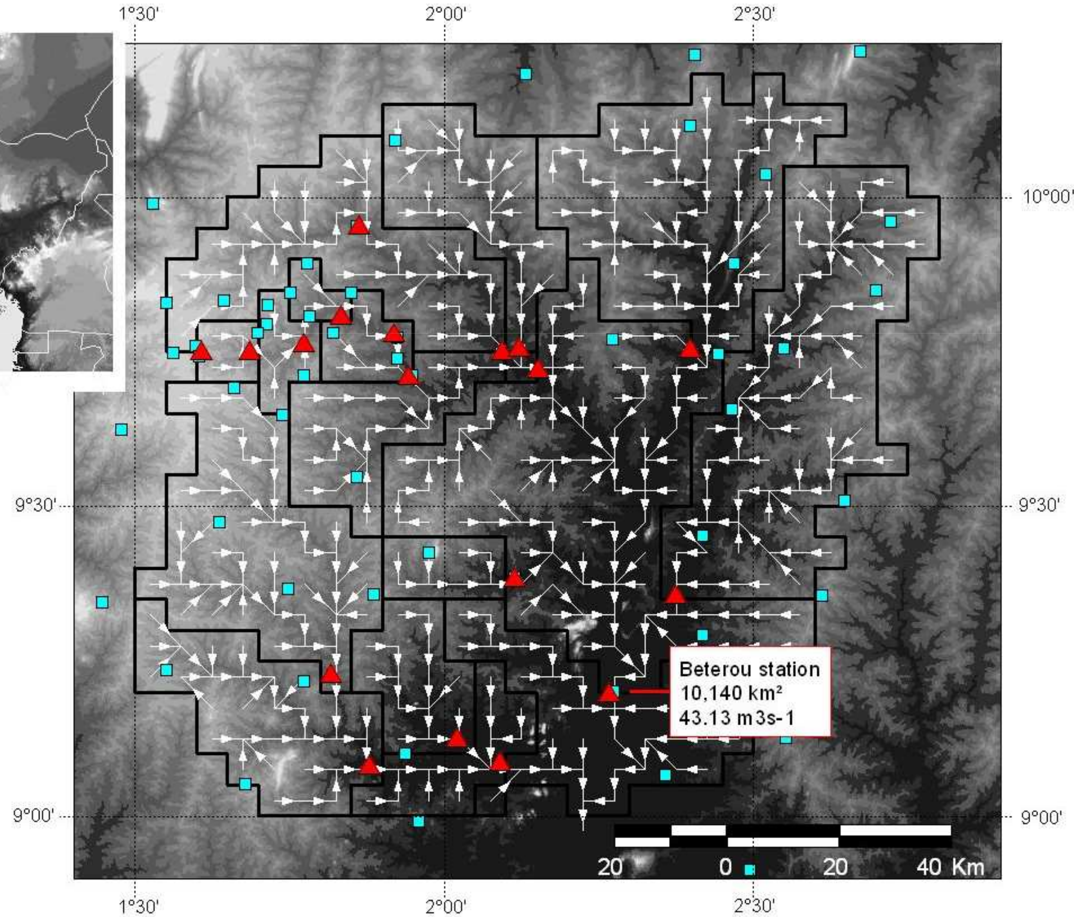
Used to **evaluate** and **intercomppare** hydrology from multiple LSMs (Météo-France, NCEP, ECMWF, UKmetOff etc…) and **compare to « pure » hydrological models** (e.g. TOP-AMMA etc.)

Getirana, Boone, Creteaux

Benin meso-square



River Routing Network: Ouémé basin, Benin



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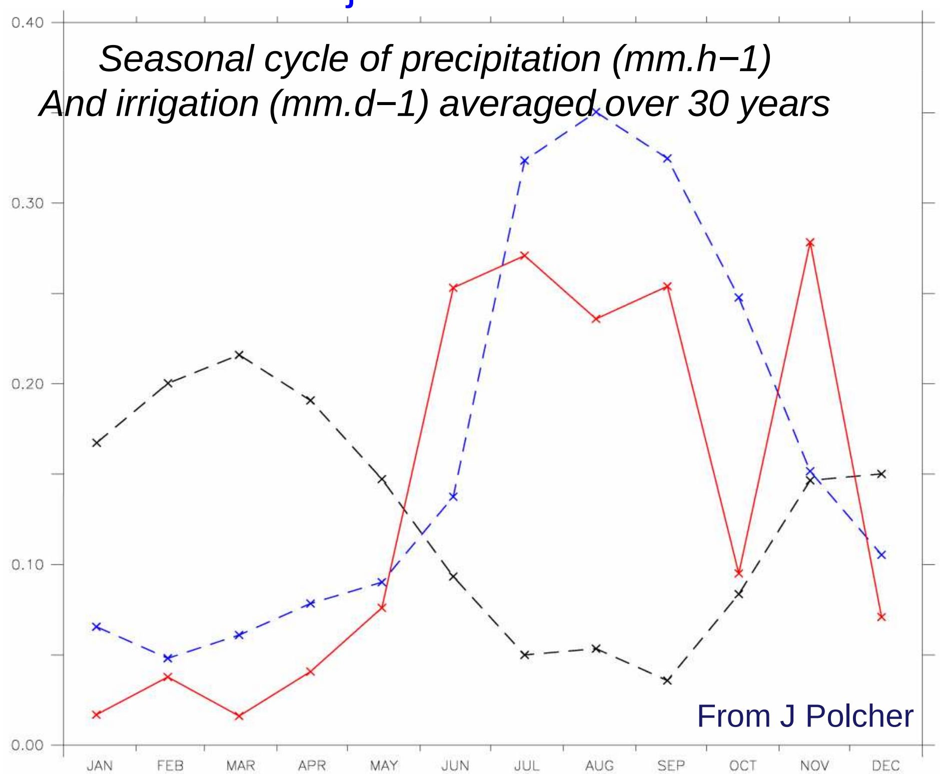
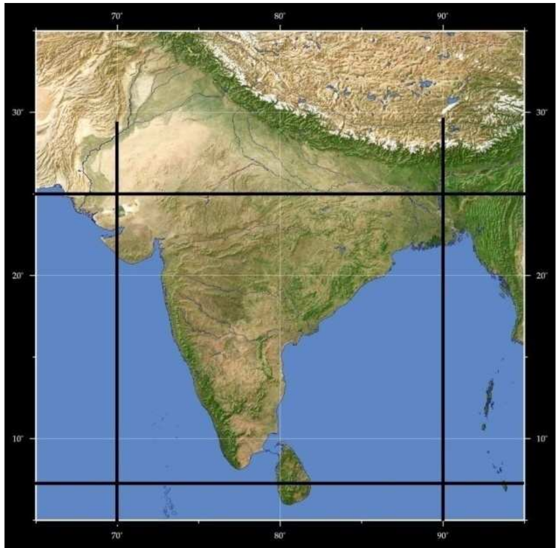
Irrigation and its impact on climate

- 2 simulation have been carried out with LMDZ/ORCHIDEE :
  - Without Irrigation (Control run) : SIr
  - With Irrigation : Air
- The difference between the 2 runs allow us to quantify the impact of irrigation.

Irrigation occurs all year long

Maximum is just before the monsoon





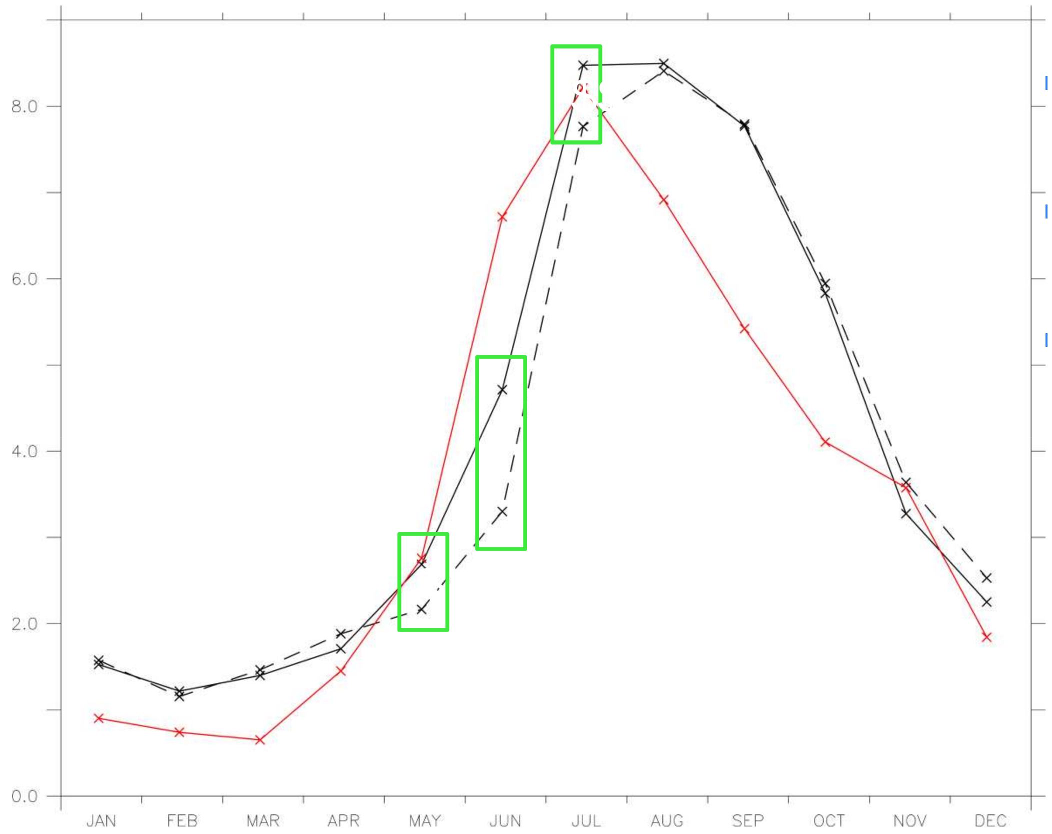
LEGENDE

-x- irrigation in AIr

-x- rainfall in AIr

-x- observed rainfall

Irrigation and its impact on climate



Seasonal cycle of precipitation (mm.d−1)
30 year average

In coupled mode (feedbacks via rain & Evap):

Ocean/land gradients weaker with irrigation in early June

➔ impacts the onset of the monsoon.

LEGEND
— Rainfall : SIr
- - Rainfall : AIr
— observations
— Statistically Significant changes

From Guimberteau & Polcher

Summary: Generally speaking (1 of 2)

GOAL: *Estimates of river discharge from climate change simulations can aslo be used to assess the impact of climate change on water resources and the hydrology of the major river basins*. Arora and Boer, 1999, JGR

To Accomplish this Goal: Earth System model development ➔ multi-year data at the global scale of water storage, discharge, flood extent, water height and slope within the context of improving the hydrological & hydrodynamic parameterizations: notably in terms of exchanges between rivers and floodplains, changes in lakes/wetlands, and freshwater discharge into the oceans.

Some caveats:

- Precipitation generally not well predicted by GCMs, notably for monsoon circulations
- Not all GCMs include river/floodplain, lake, wetland models ← Partly due to a lack of adequate data…
- Ditto for carbon and methane wetland processes
- Increasingly using remotely sensed data BUT…Need multi-year records to develop robust GCM parameterizations (length of GRACE & SWOT missions?)☑

Summary: More specifically (2 of 2)

Have come a long way in the last 10+ years BUT…

I) Need to evaluate river routing and floodplain parameterizations for use in GCMs and regional scale modeling:

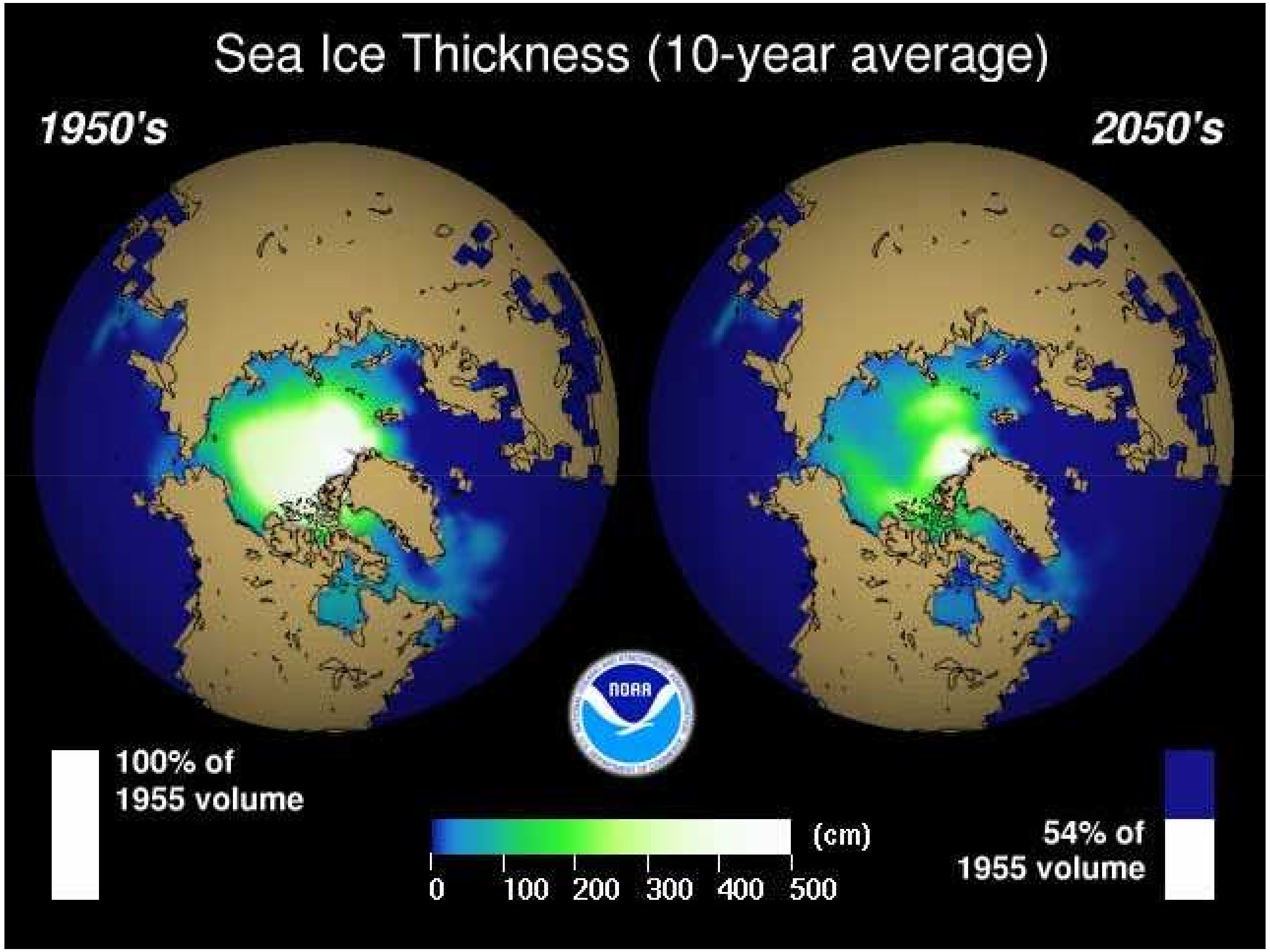
- **Used to study possible global climate change impacts on flood risk/frequency**
- **Long term impact on lake storage: possible aid to water resource planning (seasonal and long term)☑**
- **Better description of lake changes at high latitudes: links with freeze thaw, greenhouse gas release**
- **NEED river depth, floodplain depth/extent, river velocity: SWOT is part of the solution!**

***End Result: Better river discharge/routing, lake parameterizations to be utilized within fully-coupled OGCM model (complete description of water cycle)☑**

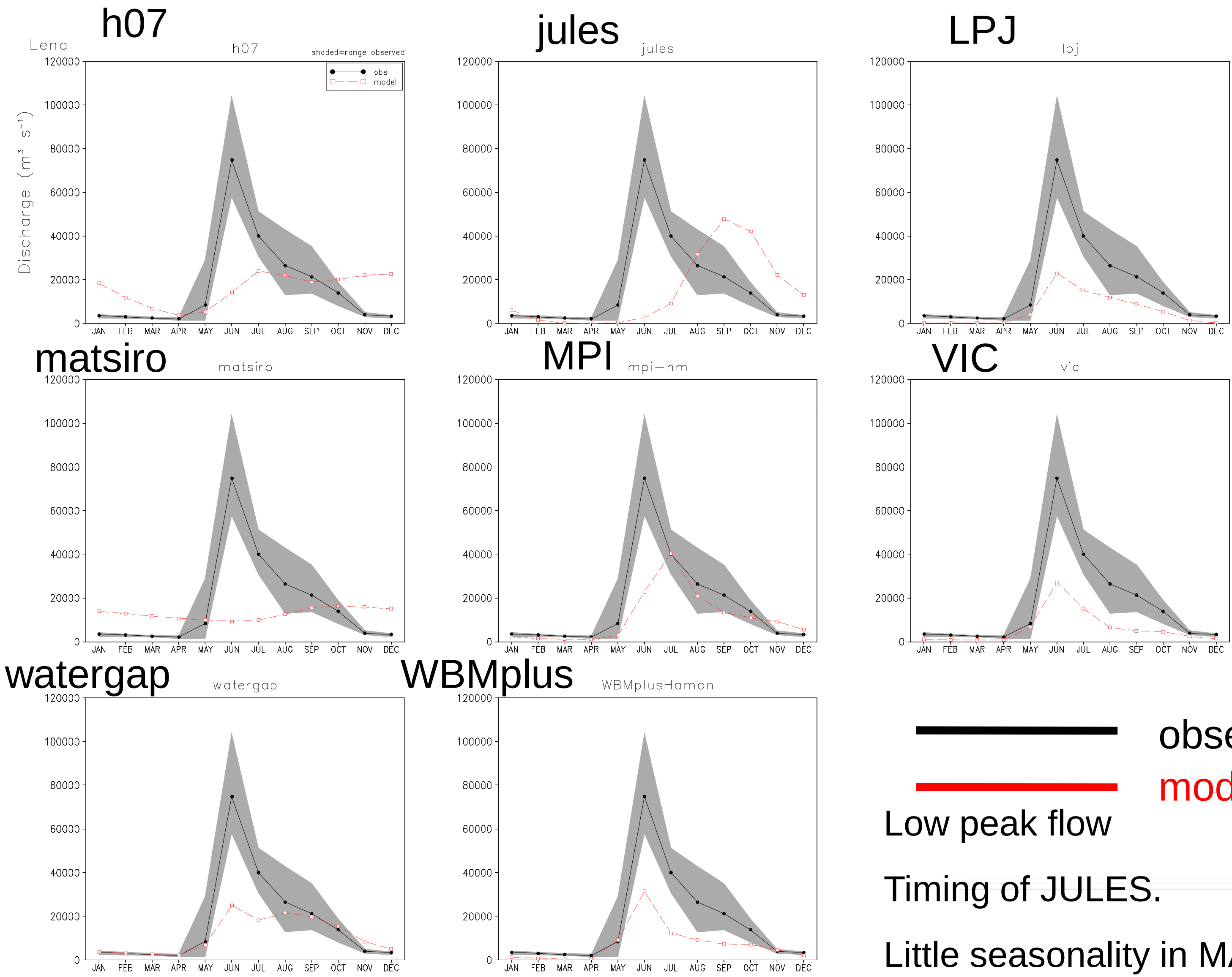
II) Operational Hydrological Forecasting:

- **Real-time monitoring of the water resources at the national level**
- **Ensemble streamflow forecast studies: initialized using current river heights: potential flood risk forcasted**
- **NEED high spatial resolution (100m probably not fine enough?) and daily (?) observations**
- **Potential uses in developing countries with relatively low spatial density observational discharge/river monitoring networks (eg. Western Africa)☑**

Extra…………..


Sea Ice Thickness (10-year average)
1950's
2050's
NOAA
100% of
1955 volume
(cm)
0
100
200
300
400
500
54% of
1955 volume

Average monthly discharge values for the Lena at Kyusyr



observed

modelled

Low peak flow

Timing of JULES.

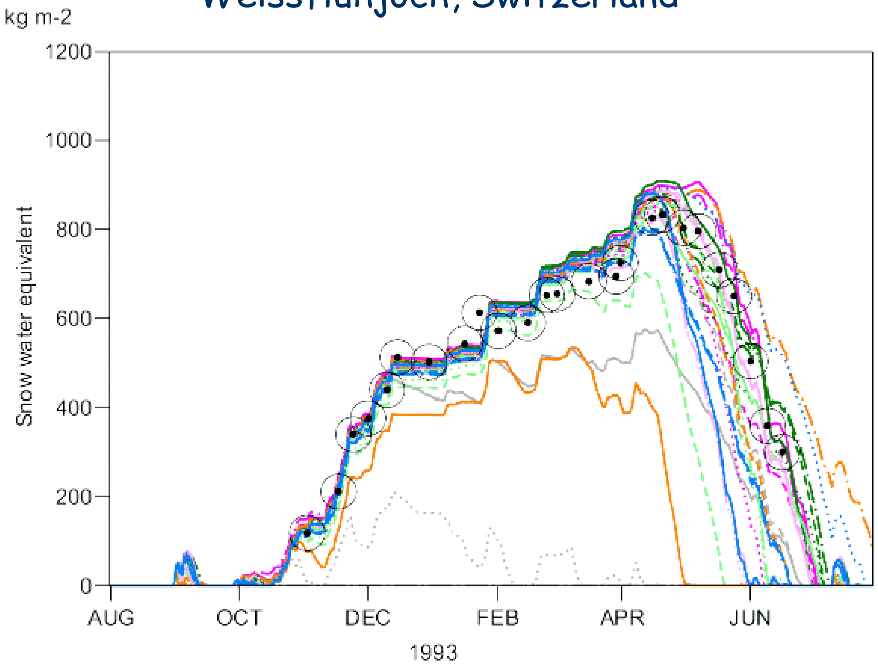
Little seasonality in MATSIRO.

◆ Snow Model Intercomparison Project (SnowMIP)☑

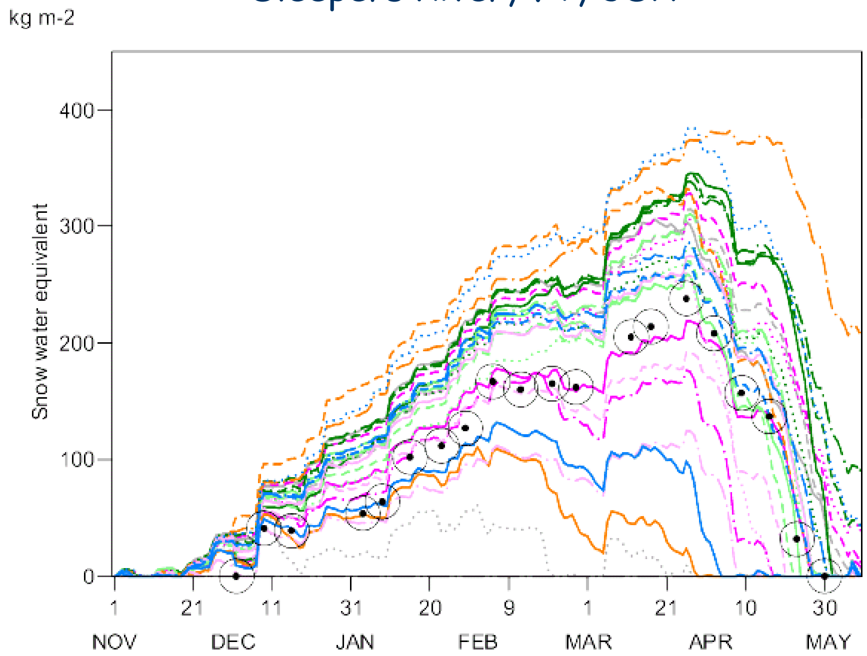
- www.cnrm.meteo.fr/snowmip

- considered two alpine sites in Europe and two sites in N. America.
  - point simulations at sites without tall vegetation.
  - simple snow schemes used in GCM and hydrological models as well as sophisticated schemes.

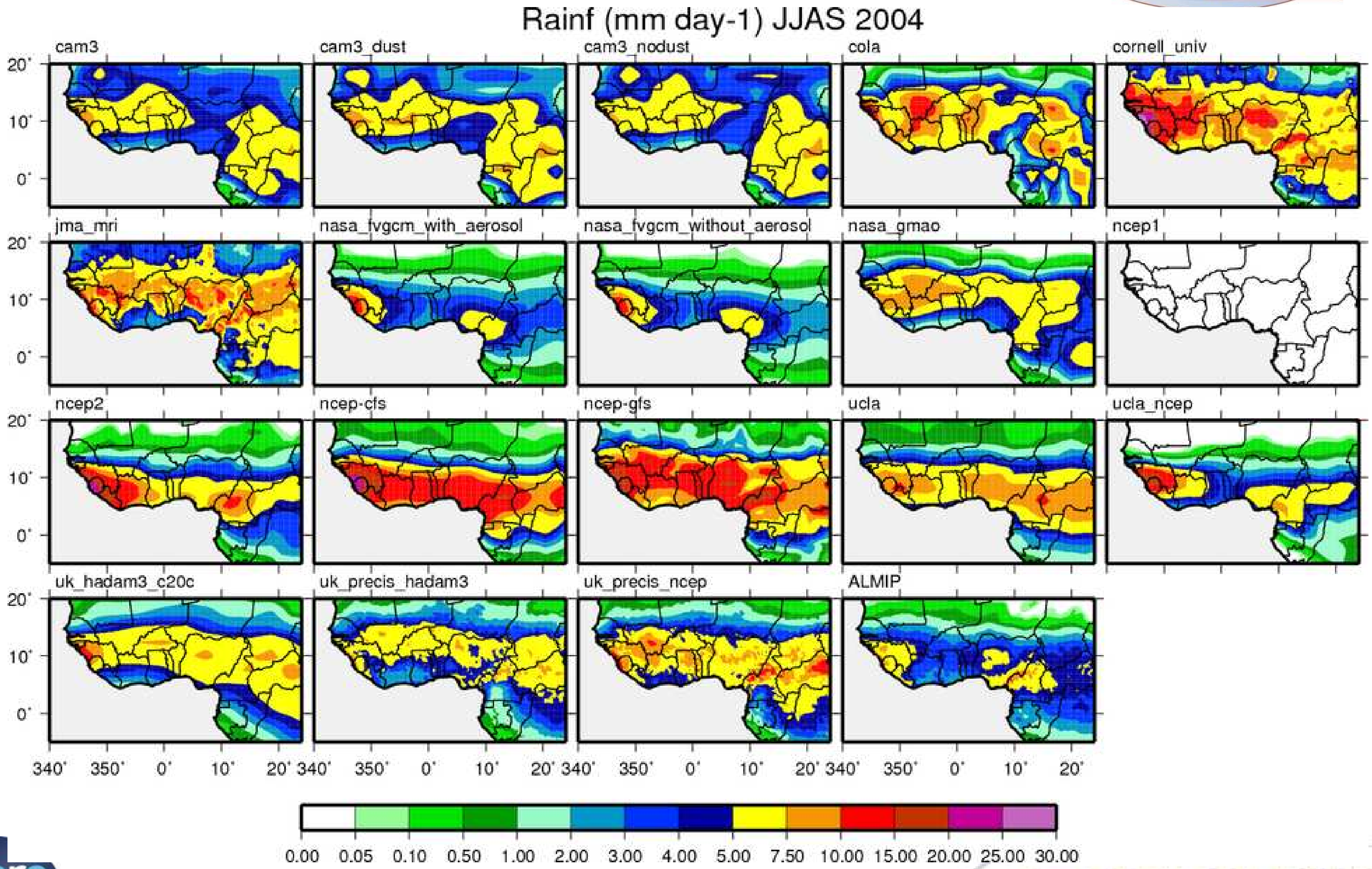
Weissfluhjoch, Switzerland

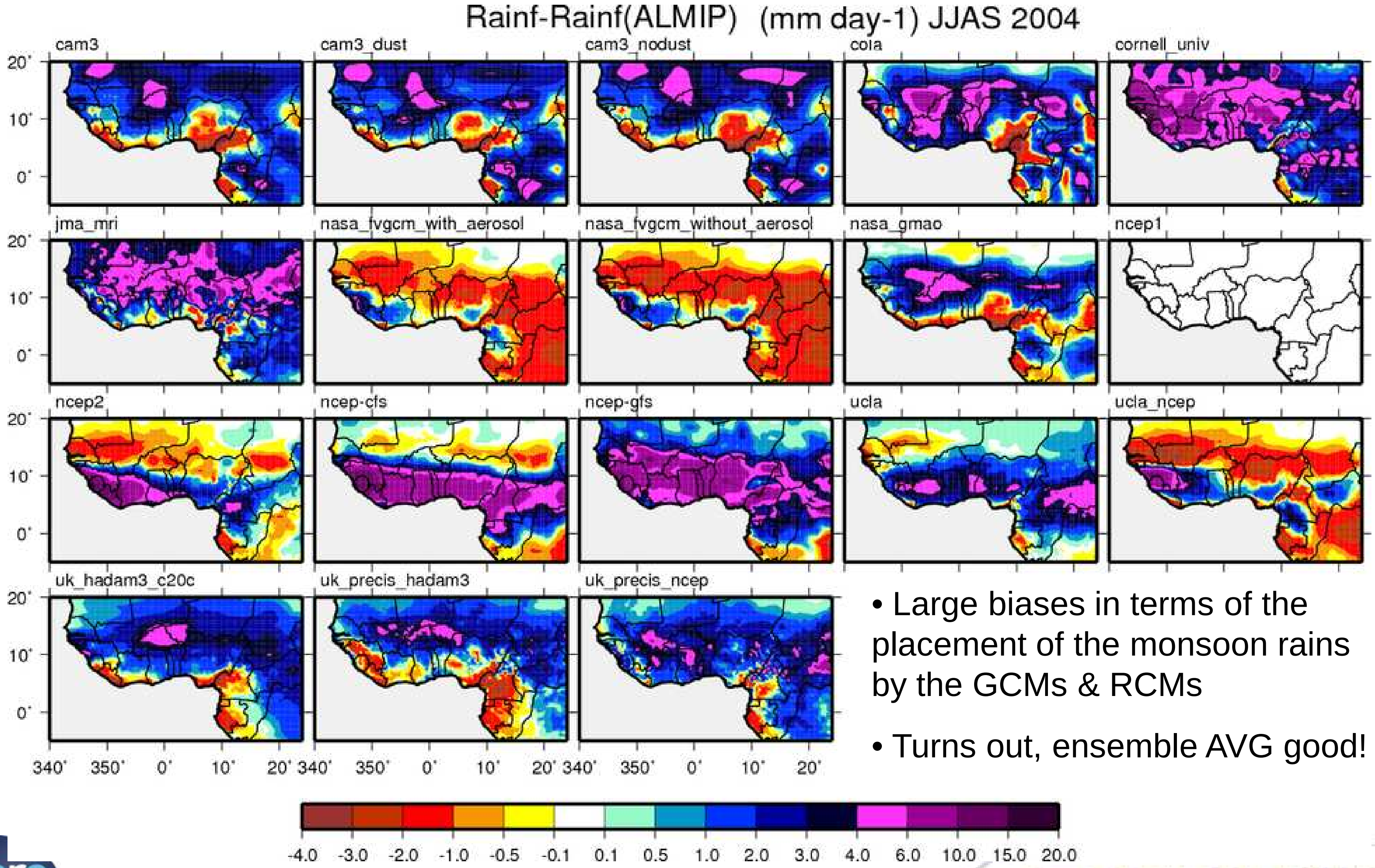


Sleepers River, VT, USA



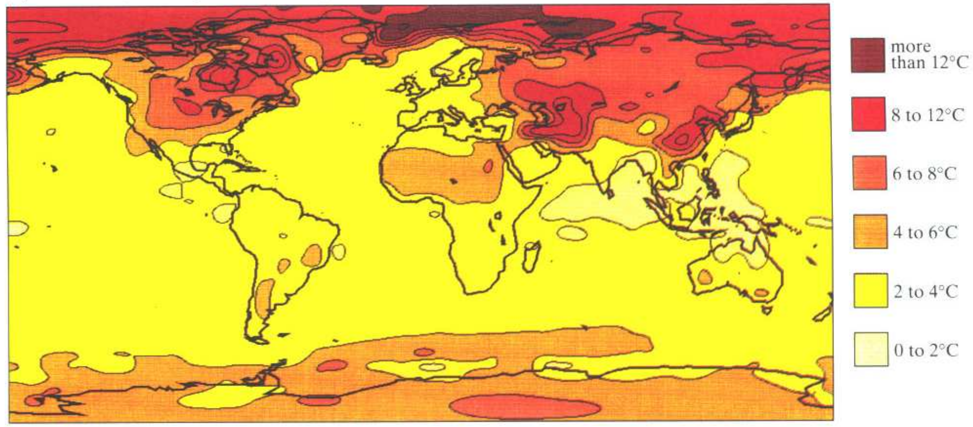
Large differences at Vermont site are attributed to differences in the representation of sublimation.


Rainf (mm day-1) JJAS 2004
cam3
cam3_dust
cam3_nodust
cola
cornell_univ
jma_mri
nasa_fvgcm_with_aerosol
nasa_fvgcm_without_aerosol
nasa_gmao
ncep1
ncep2
ncep-cfs
ncep-gfs
ucla
ucla_ncep
uk_hadam3_c20c
uk_precis_hadam3
uk_precis_ncep
ALMIP
20°
10°
0°
340° 350° 0° 10° 20°
0.00 0.05 0.10 0.50 1.00 2.00 3.00 4.00 5.00 7.50 10.00 15.00 20.00 25.00 30.00

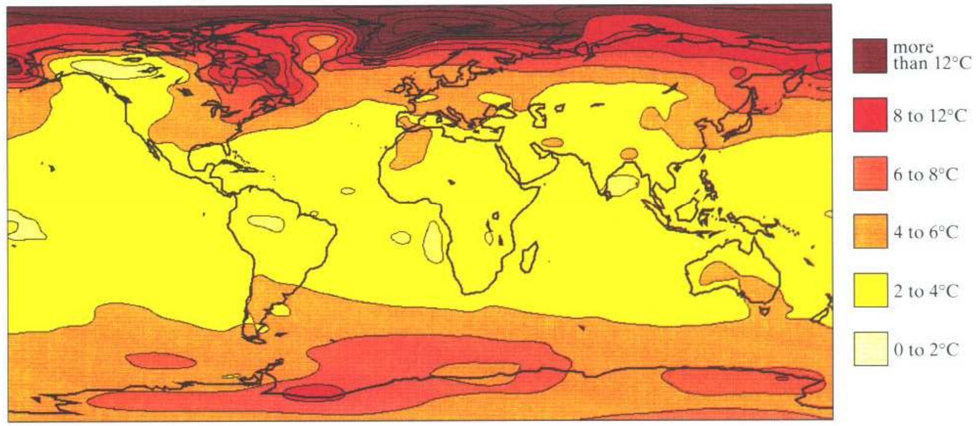


- Large biases in terms of the placement of the monsoon rains by the GCMs & RCMs
- Turns out, ensemble AVG good!

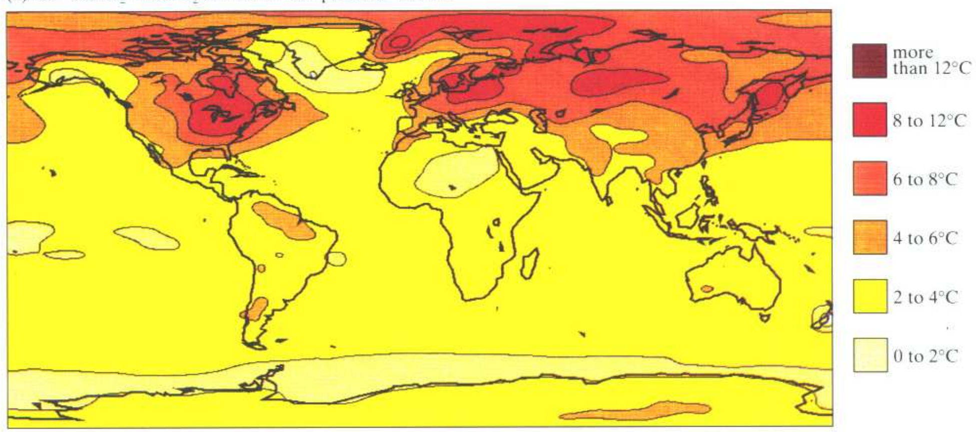
(a) DJF $2\times CO_2 - 1\times CO_2$ surface air temperature: CCC

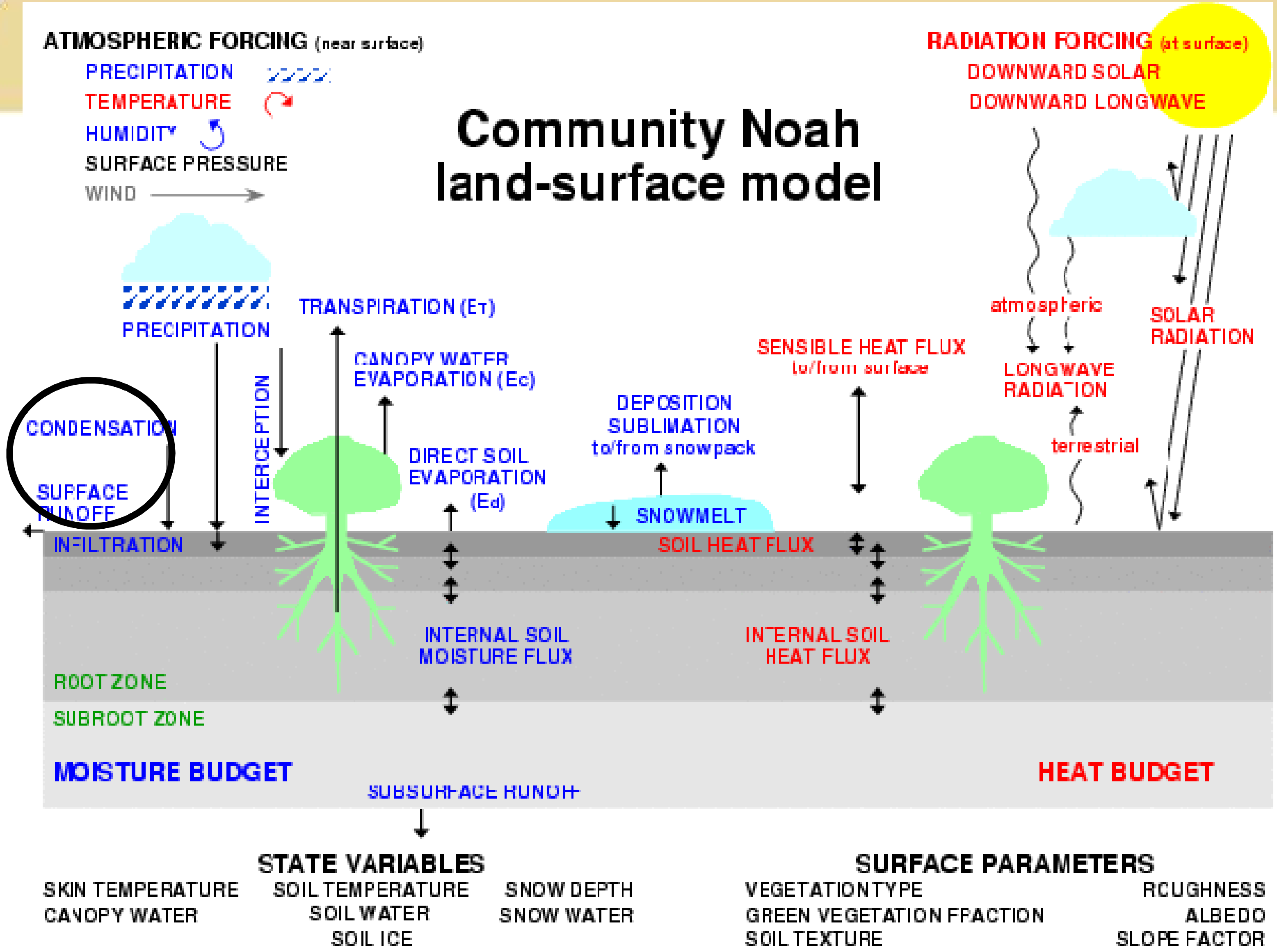


(b) DJF $2\times CO_2 - 1\times CO_2$ surface air temperature: GFHI



(c) DJF $2\times CO_2 - 1\times CO_2$ surface air temperature: UKHI

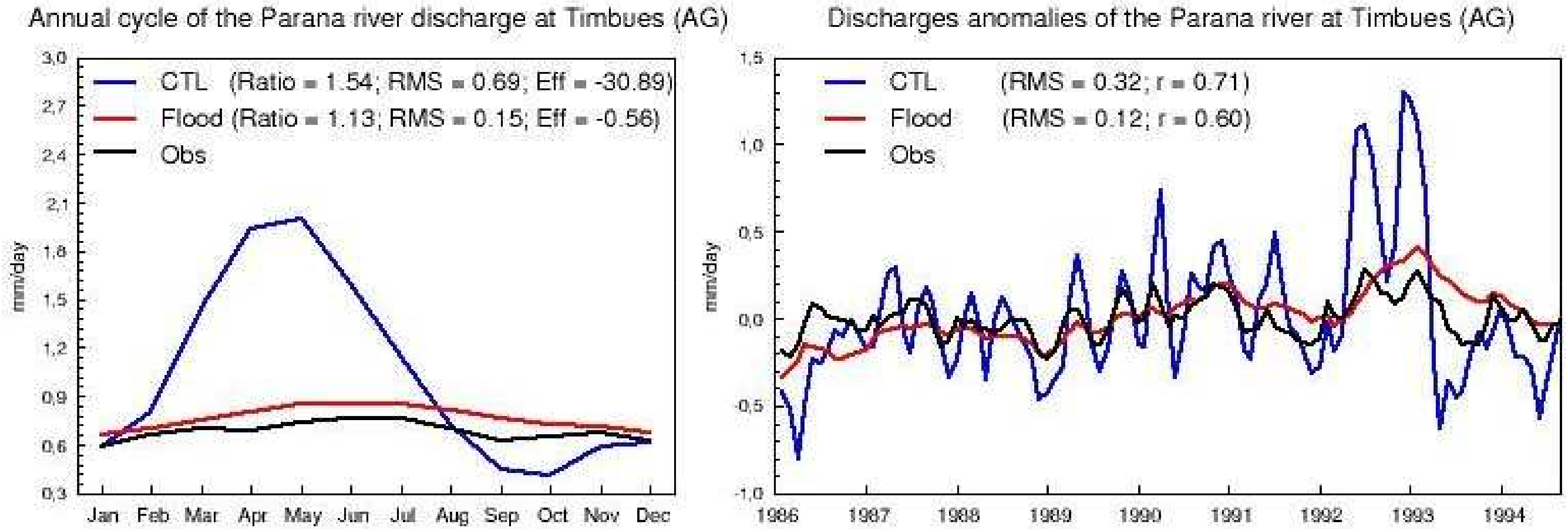




ftp://ftp.emc.ncep.noaa.gov/mmb/gcp/ldas/noahlsm

Parametrization of floodplains

2 simulations (10-years atmospheric forcing from GSWP-2 at 1⌖ by 1⌖):
with (Flood) and without (CTL) the flooding scheme



- Evaporation from floodplains quite significant for some regions: possible feedbacks with atmosphere…

GSWP-2, Dirmeyer et al., 2006

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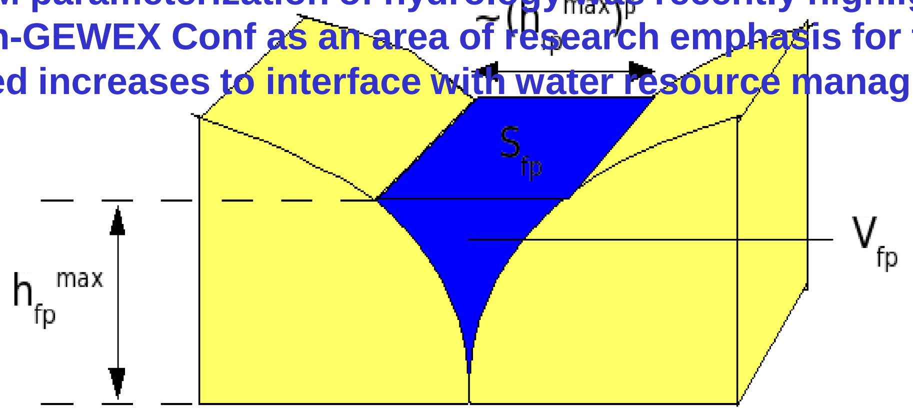
Parametrization of floodplains

- From the discharge into a known area of floodplains the volume lost by the river is computed.
- From this volume the flooded area is estimated
- This defines the grids over which soil moisture is increased and ponds are exposed to the atmosphere.

LSM parameterization of hydrology was recently highlighted at the Pan-GEWEX Conf as an area of research emphasis for the future, as need increases to interface with water resource managment



This increases locally evaporation and reduced the amount of water in the river.

From Orgeval, Polcher et al