Introduction to the current routing scheme and its ongoing evolutions in the land-surface model ORCHIDEE

Matthieu Guimberteau
CEA/LSCE
matthieu.guimberteau@lsce.ipsl.fr

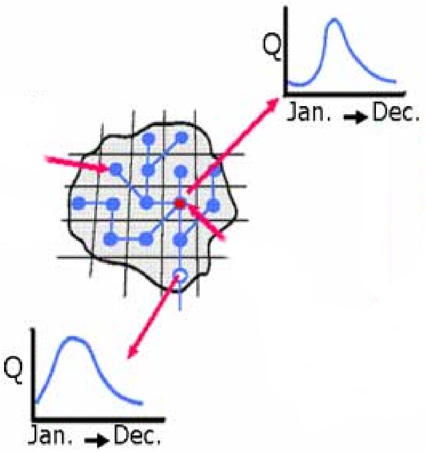
ORCHIDEE training course. Orsay, 11/25/2016.

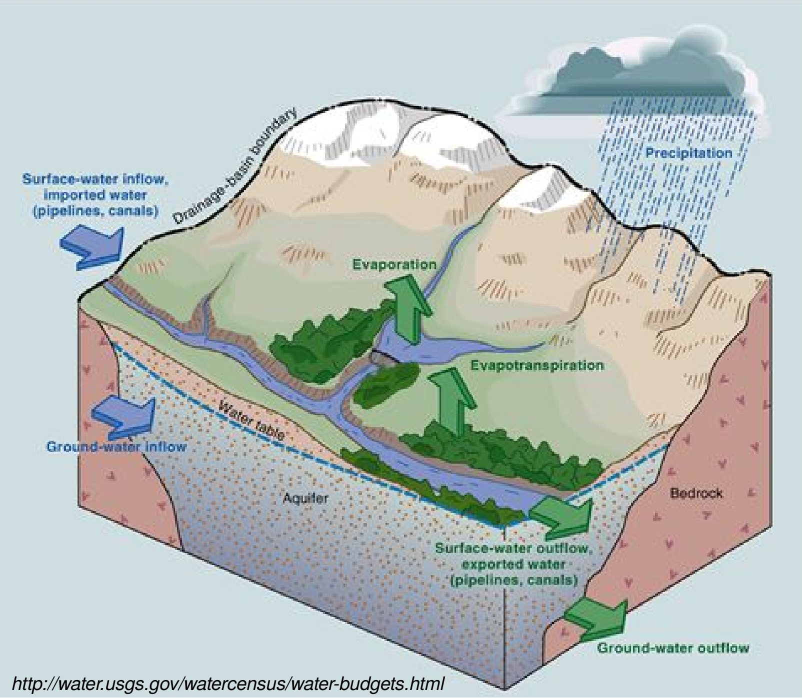
1

Generalities

ORCHIDEE
LAND SURFACE MODEL

What is a flow routing?



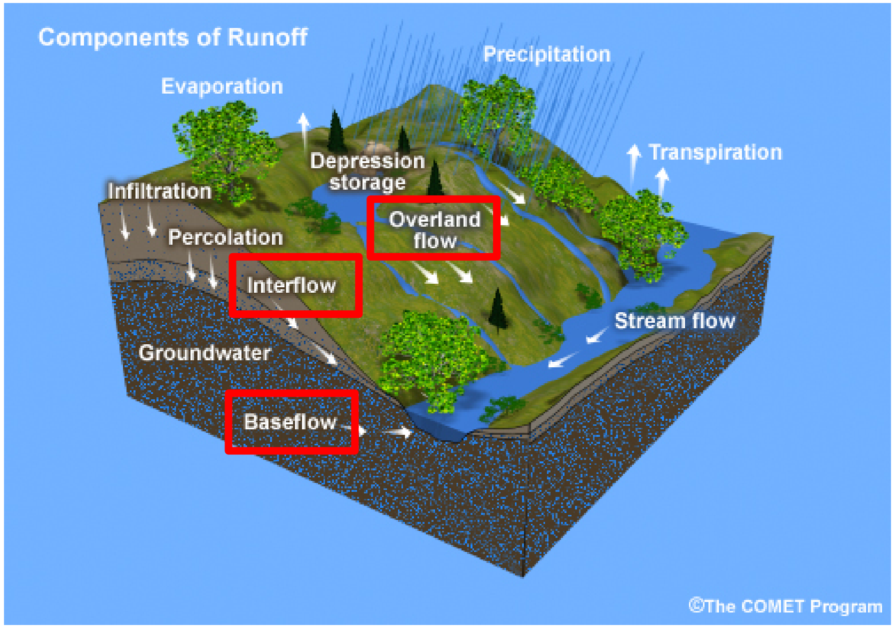


http://water.usgs.gov/watercensus/water-budgets.html

- “It is a computational procedure for predicting the changing magnitude, speed, and shape of a flood wave as a function of time (hydrographs) at one or more points along a watercourse” (Fread, Handbook of hydrology, 1992)

- It simulates the transport of runoff through river networks across continents (streamflow, river discharge) into the oceans

Lateral waterflow components



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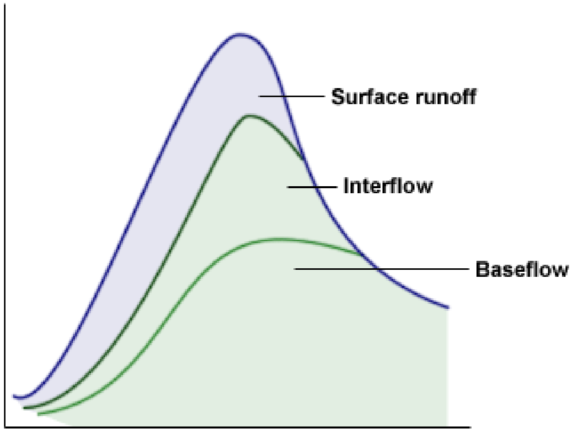
Surface Flow from Runoff Hydrograph



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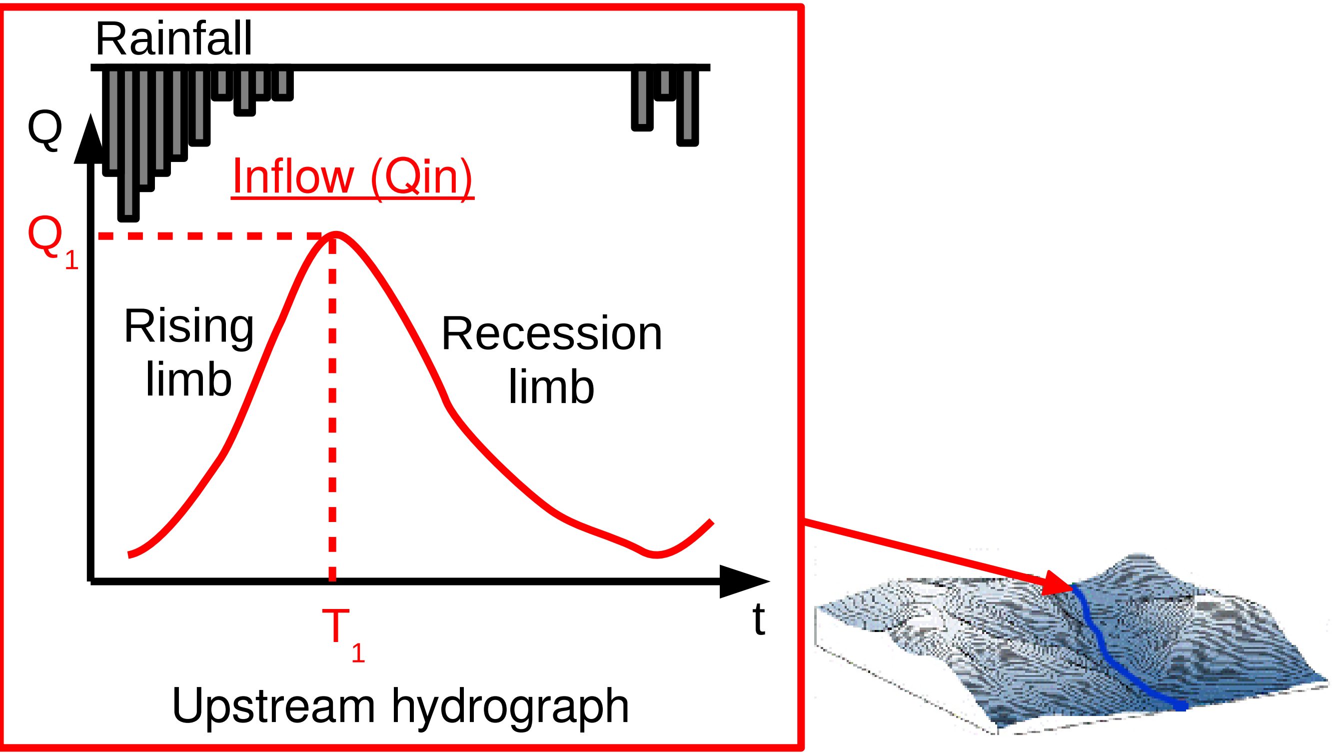
Lateral waterflow components

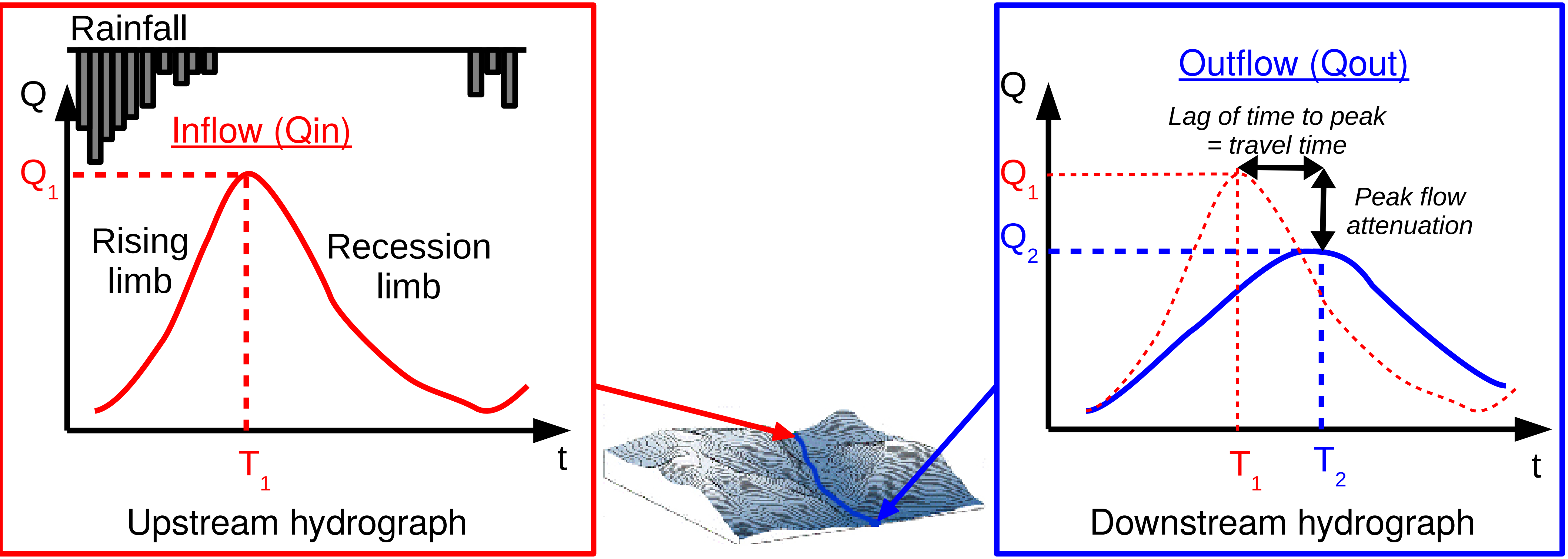
- **Overland flow (surface runoff)**: flow of water that does not infiltrate and travels relatively quickly towards the stream channel
- **Interflow (subsurface runoff)**: portion of infiltrated throughfall that moves laterally through the upper soil layers until it reaches the stream channel
- **Baseflow (groundwater runoff)**: portion of infiltrated throughfall that reaches water tables by deep drainage and then discharges into streams

Streamflow hydrographs [L T^{-1}]



Upstream hydrograph

Streamflow hydrographs [L T^{-1}]

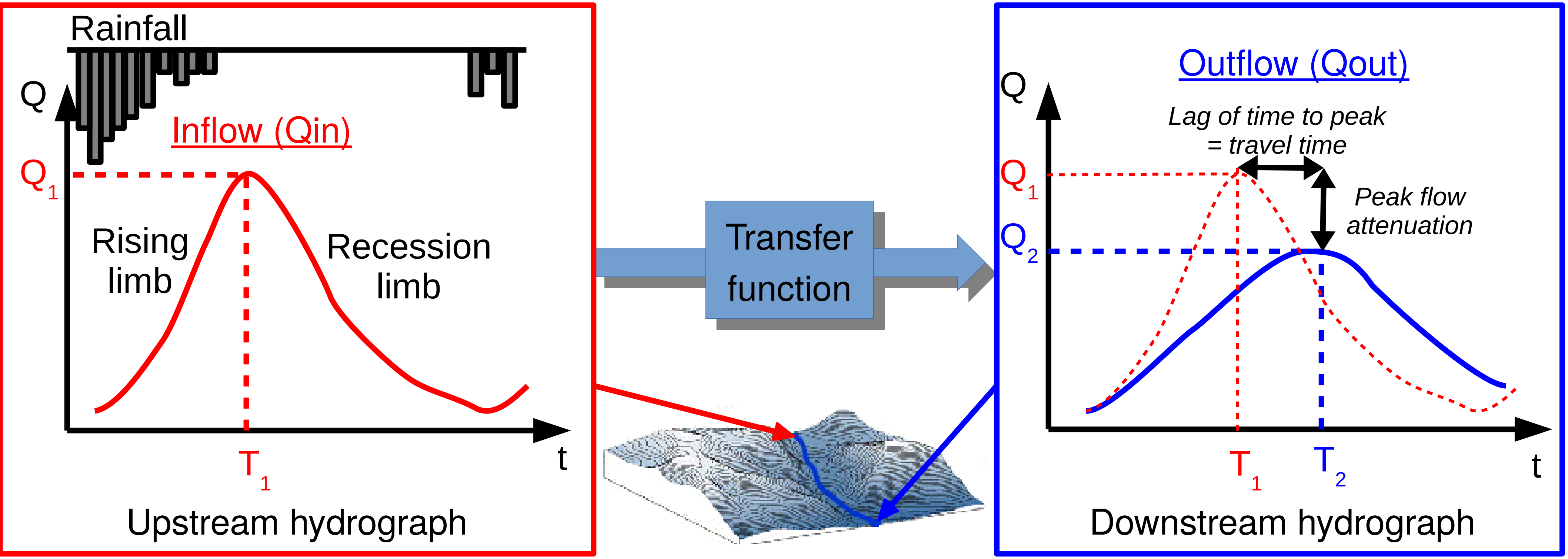


Upstream hydrograph

Downstream hydrograph

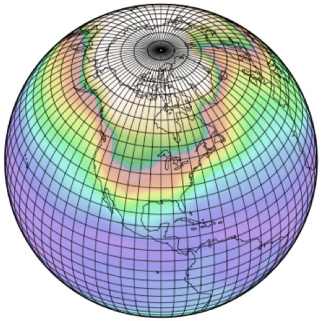
- As flood wave travels downstream, it undergoes:
  - outflow peak attenuation ($Q_2 < Q_1$)
  - outflow timing delay ($T_2 > T_1$)

Streamflow hydrographs $[L\ T^{-1}]$



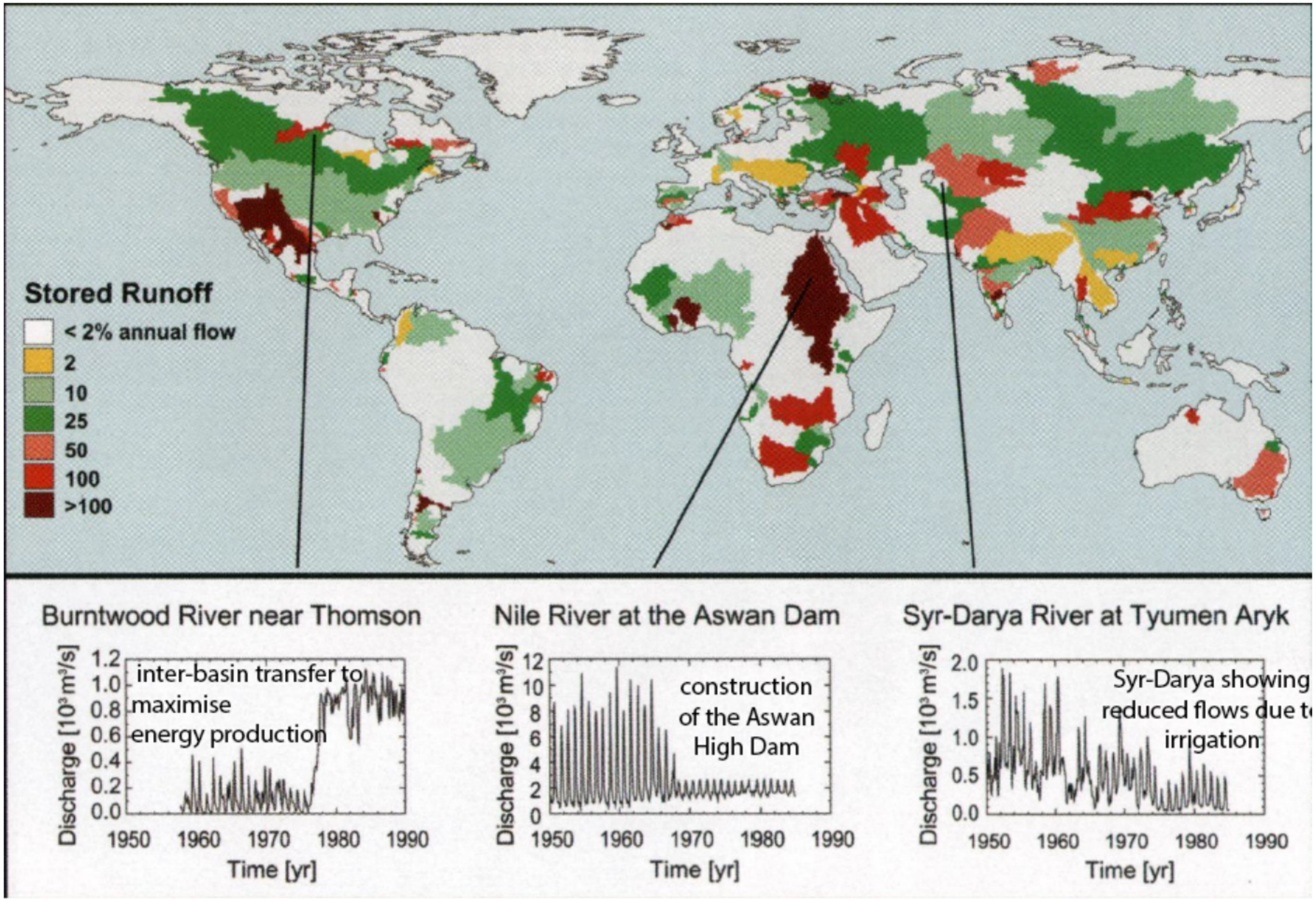
- As flood wave travels downstream, it undergoes:
  - outflow peak attenuation ($Q_2<Q_1$)
  - outflow timing delay ($T_2>T_1$)

Why do we need it in GCMs ?



- Validation tool
  - river discharge is an integrator of the land hydrology
  - independent measure of the performance of the hydrological cycle of the GCM: simulated streamflow vs river gauge data (with very long-time series)
  - if both streamflow and precipitation are given with reasonable accuracy => check of evaporation accuracy
- Crucial for the closure of the global water cycle (in full-coupled GCMs)
  - fresh water input to the oceans (affects ocean salinity, sea surface temperature, thermohaline circulation...)
- It enables studies of climate change and human impacts (irrigation, dams, water diversion...) on water resources and the hydrology of the basins
- ...

Human activities on river discharge



Flow distortion caused by water engineering in three heavily-regulated rivers

Vorosmarty et al., 2004

2

The routing scheme in ORCHIDEE

- Overview
- River network
- Transfer between reservoirs

2.1

The routing scheme in ORCHIDEE

- Overview
- River network
- Transfer between reservoirs

ORCHIDEE
LAND SURFACE MODEL

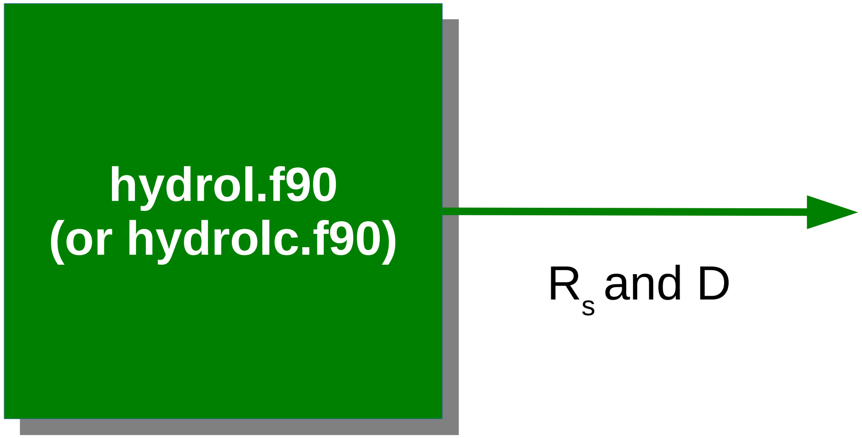
Basic functioning

- Based on existing routing schemes:
  - Ledoux (Phd Thesis, 1980)
  - Miller et al. (J. Climate, 1994)
  - Hagemann and Dümenil (Clim. Dyn., 1998)
  - Ducharne et al. (J. Hydrol., 2003)
- routing .f90 introduced by Jan Polcher (HDR, 2003) in SECHIBA

Basic functioning

- “Cell-to-cell” or “cell-based” methodology
  - simulation of the transport of runoff generated <u>within the modeling units (e.g. grid cells)</u>, through river networks across continents into the oceans
  - a watershed can be represented as a single grid cell, a cascade of n equal grid cells, or a network of n equal grid cells (based on Singh (Hydrologic systems, 1989))
    - division of a watershed into a set of interconnected grid cells
    - each of the grid cell is approximated as a <u>cascade of n linear reservoirs</u>
- Computation of hydrographs at any grid cell and not only at the outlet

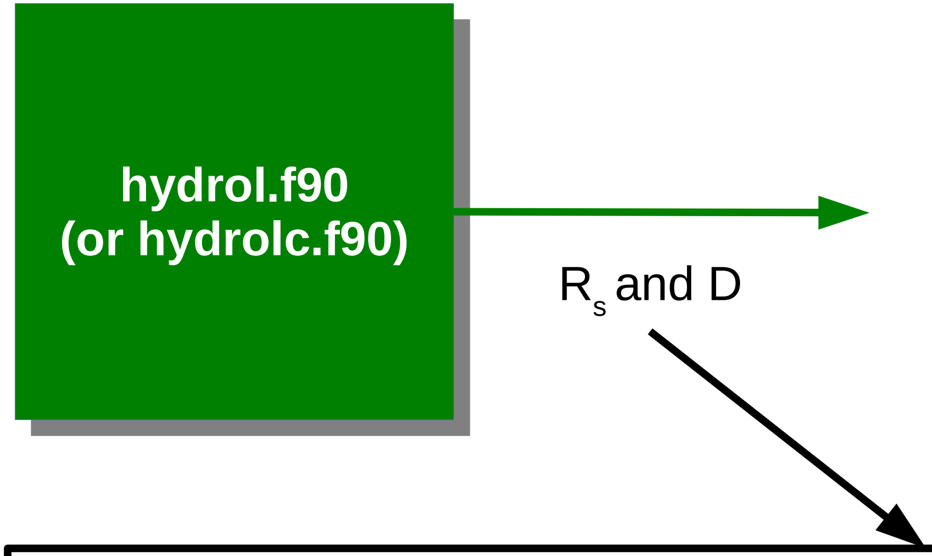
The routing scheme in ORCHIDEE: routing.f90



hydrol.f90
(or hydrolc.f90)

R_s and D

The routing scheme in ORCHIDEE: routing.f90

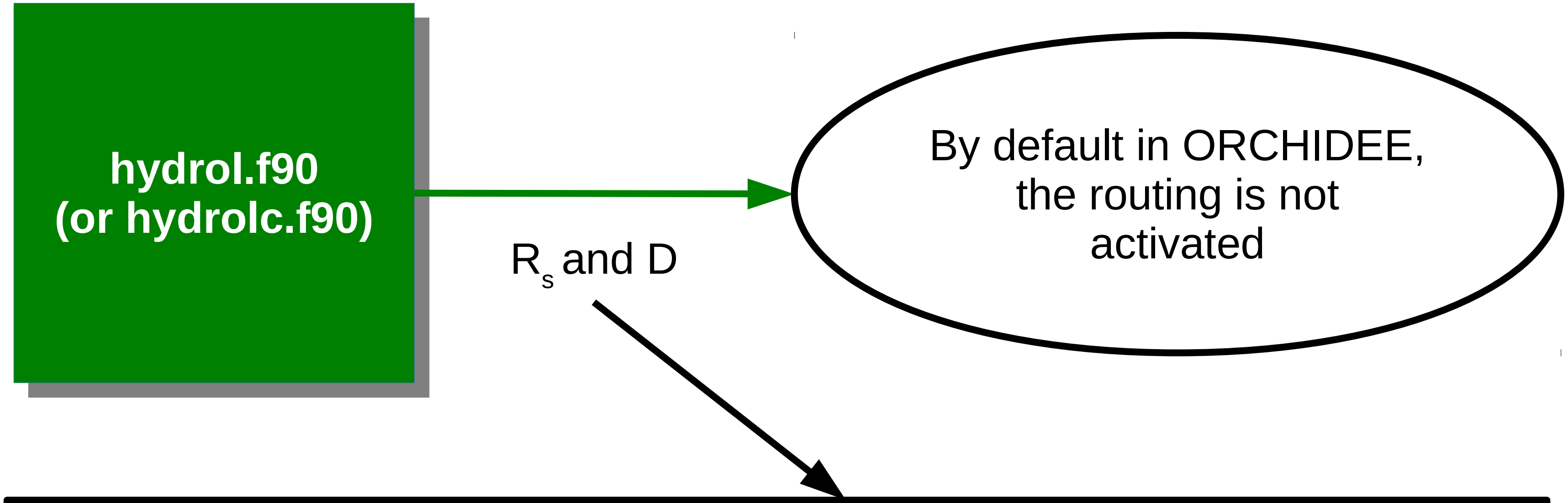


hydrol.f90
(or hydrolc.f90)

R_s and D

- 2-layer soil hydrology scheme (hydrolc.f90) => R (runoff)
  - 0.05*R = Rs (surface runoff)
  - 0.95*R = D (drainage)
- 11-layer soil hydrology scheme => Rs and D

The routing scheme in ORCHIDEE: routing.f90



hydrol.f90
(or hydrolc.f90)

R_s and D

By default in ORCHIDEE,
the routing is not
activated

- 2-layer soil hydrology scheme (hydrolc.f90) => R (runoff)
  - 0.05*R = Rs (surface runoff)
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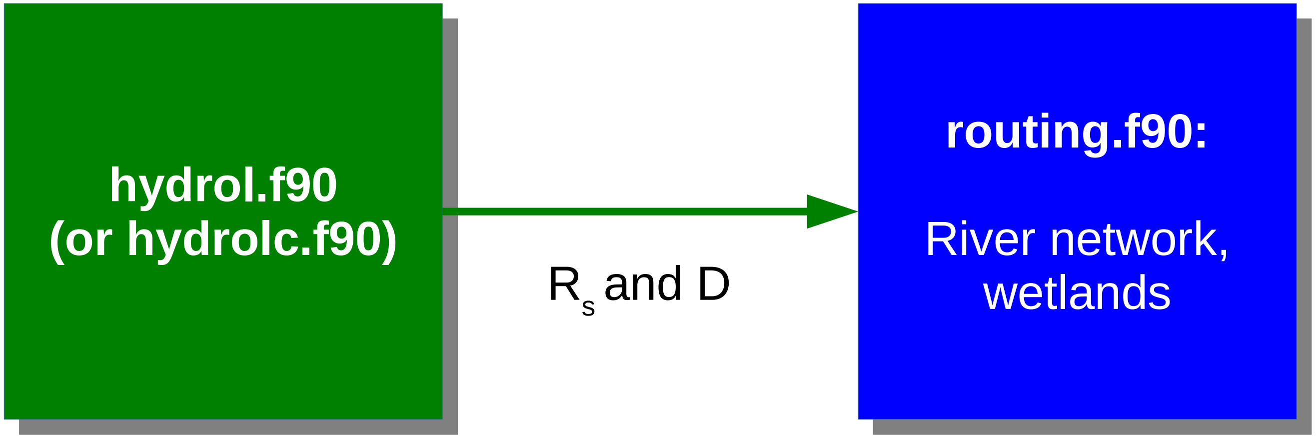
- 11-layer soil hydrology scheme => Rs and D

The routing scheme in ORCHIDEE: routing.f90



hydrol.f90
(or hydrolc.f90)

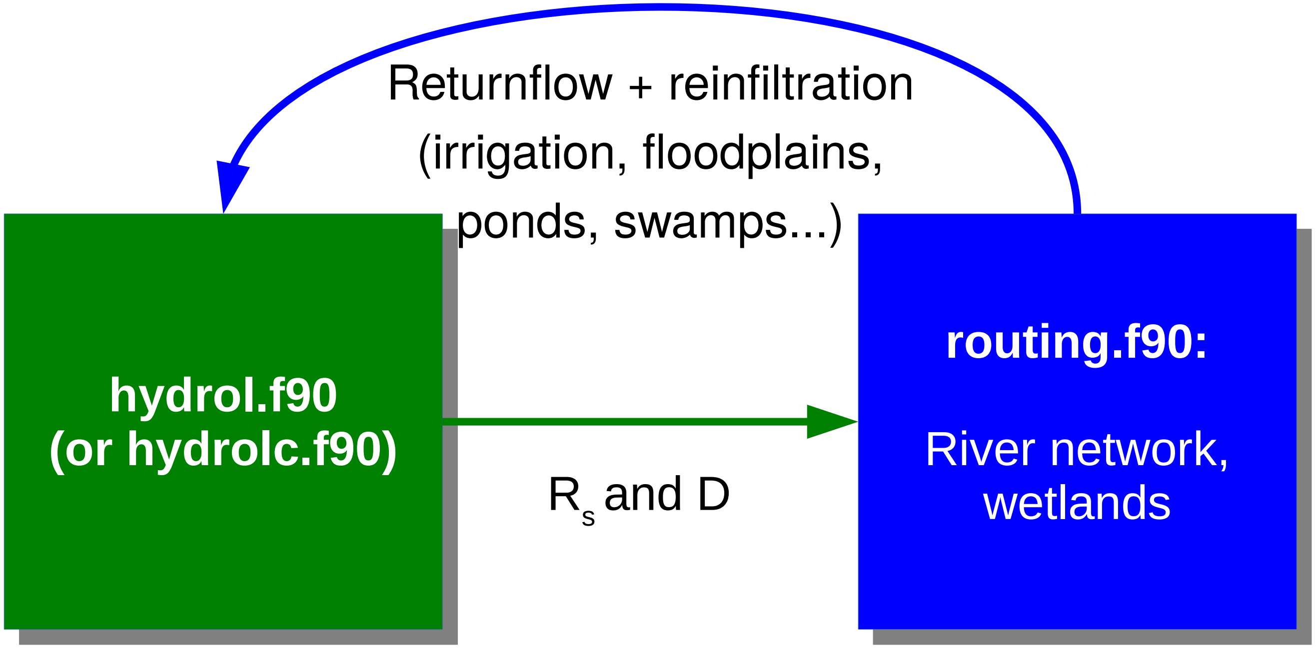
R_s and D

routing.f90:

River network,
wetlands

To activate it:
RIVER_ROUTING = y in the run.def

The routing scheme in ORCHIDEE: routing.f90



Returnflow + reinfiltration (irrigation, floodplains, ponds, swamps...)

hydrol.f90
(or hydrolc.f90)

R_s and D

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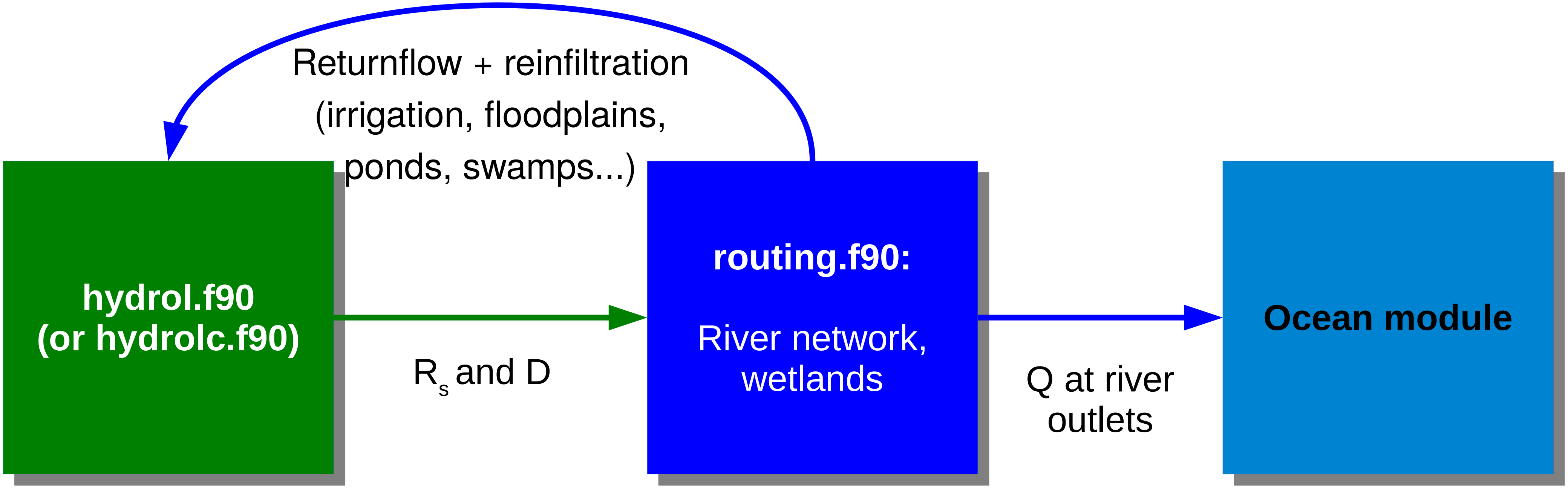
The routing scheme in ORCHIDEE: routing.f90



Returnflow + reinfiltration (irrigation, floodplains, ponds, swamps...)

hydrol.f90 (or hydrolc.f90)

R_s and D

routing.f90:

River network, wetlands

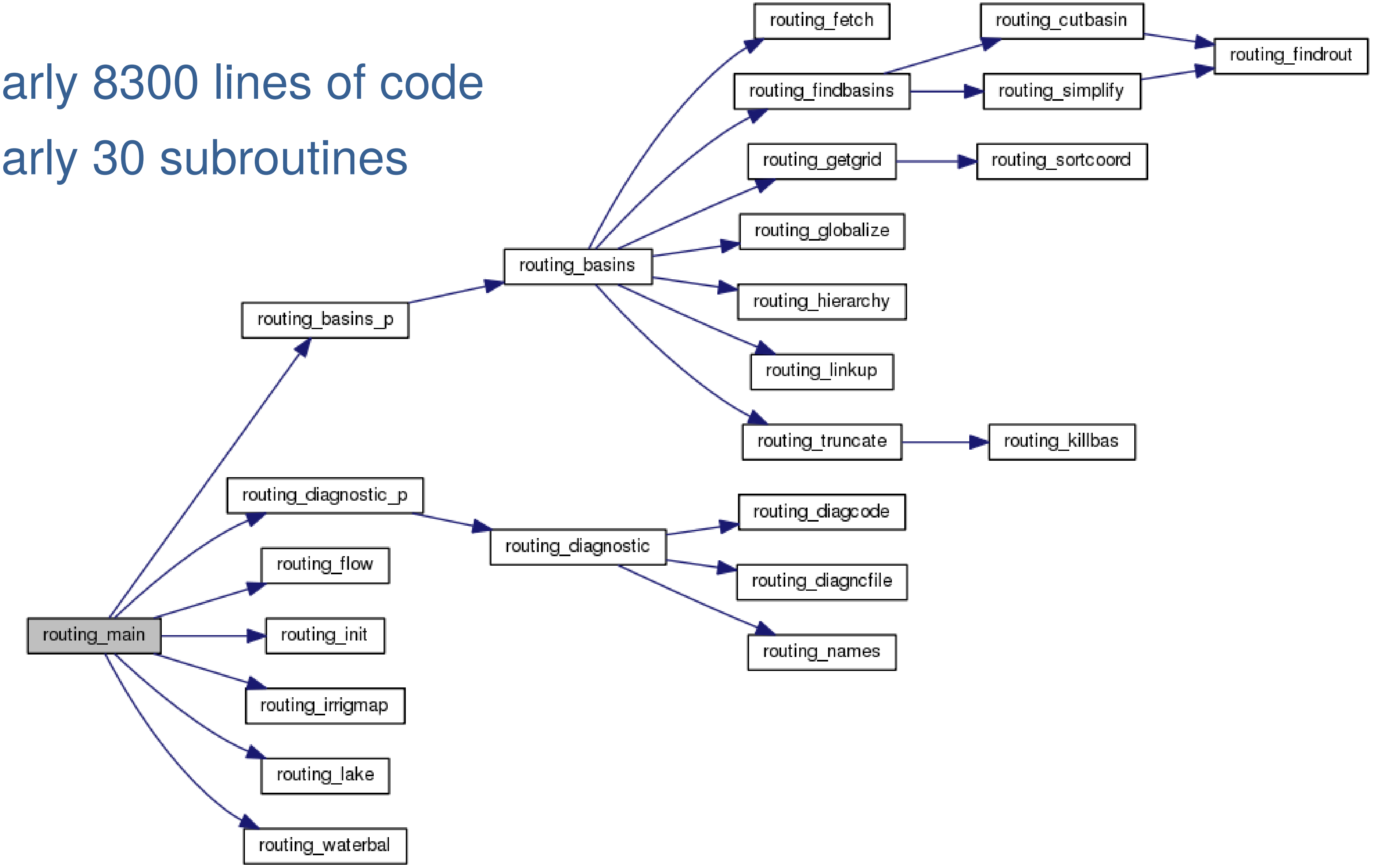
Q at river outlets

Ocean module

To activate it:
RIVER_ROUTING = y in the run.def

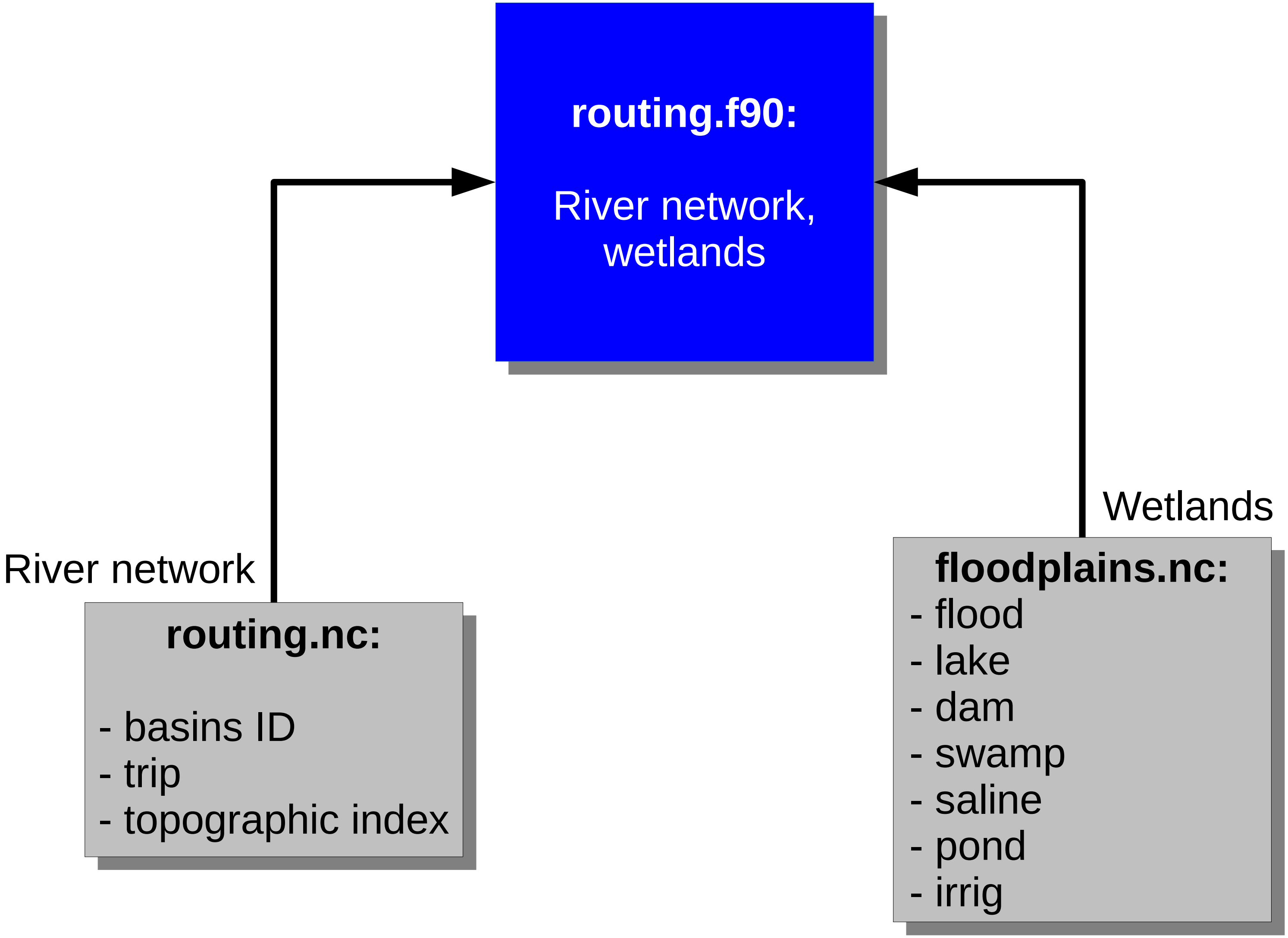
The routing scheme in ORCHIDEE: routing.f90

- Nearly 8300 lines of code
- Nearly 30 subroutines



Call graph of routing_main
http://dods.ipsl.jussieu.fr/orchidee/DOXYGEN/webdoc_1240/d3/d1e/namespacerouting.html

Maps read by routing.f90



routing.f90:

River network, wetlands

River network

routing.nc:

- basins ID
- trip
- topographic index

Wetlands

floodplains.nc:

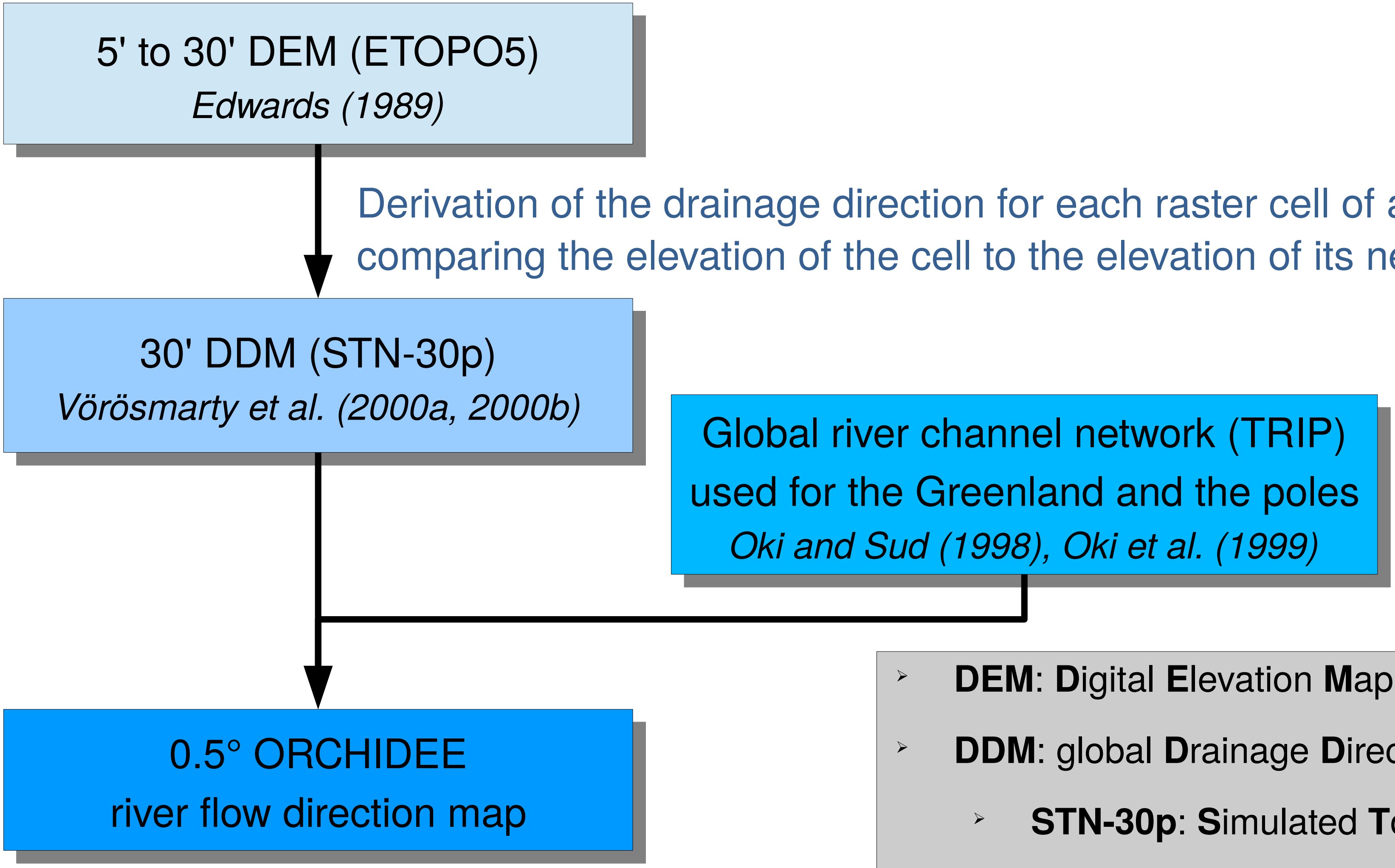
- flood
- lake
- dam
- swamp
- saline
- pond
- irrig

The routing scheme in ORCHIDEE

2.2

- Overview
- **River network**
- Transfer between reservoirs

The river flow direction map



5' to 30' DEM (ETOPO5)
Edwards (1989)

Derivation of the drainage direction for each raster cell of a **DEM** by comparing the elevation of the cell to the elevation of its neighboring cells

30' DDM (STN-30p)
Vörösmarty et al. (2000a, 2000b)

Global river channel network (TRIP) used for the Greenland and the poles
Oki and Sud (1998), Oki et al. (1999)

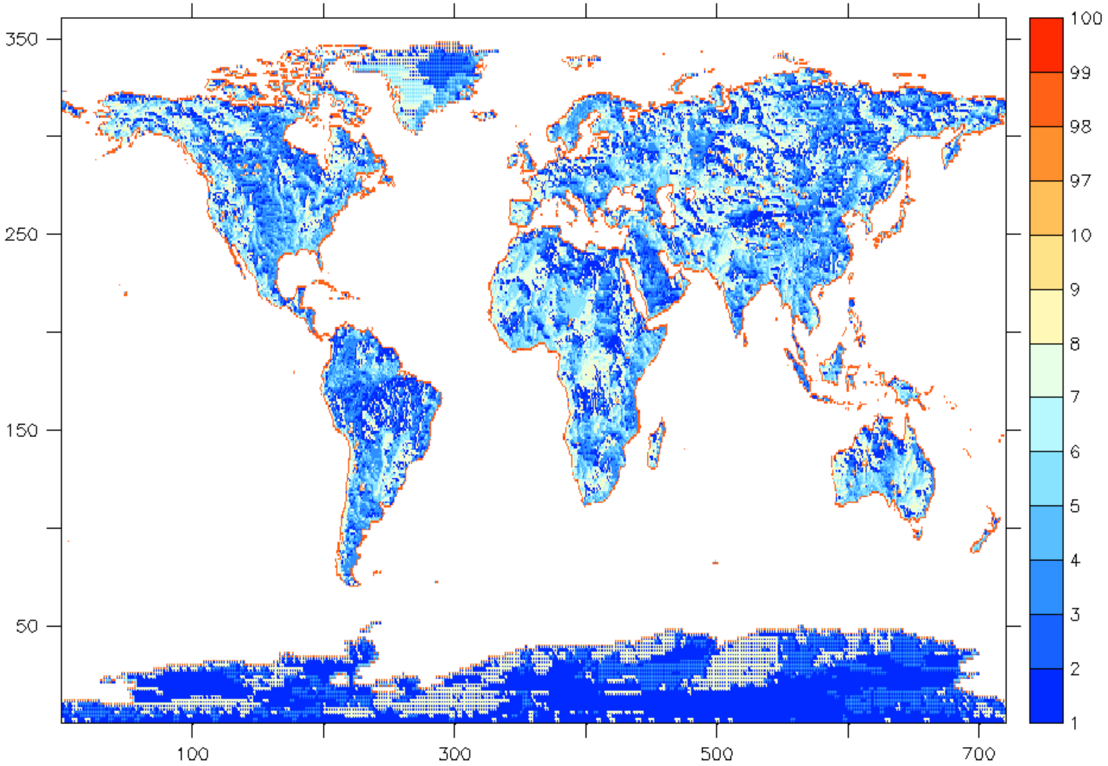
0.5° ORCHIDEE
river flow direction map

- **DEM**: **D**igital **E**levation **M**ap
- **DDM**: global **D**rainage **D**irection **M**ap
    - **STN-30p**: **S**imulated **T**opological **N**etwork
- **TRIP** (**T**otal **R**unoff **I**ntegrating **P**athways)

The river flow direction map

- For each grid cell, the map provides single flow direction among the 11 possibilities attributed by numbers in the code:
  - 8 directions (1→8) towards another grid cell
  - 3 other directions:
    - 97 → lake inflow
    - 98 → coastalflow (diffusive into the oceans)
    - 99 → riverflow (river discharge into the oceans)

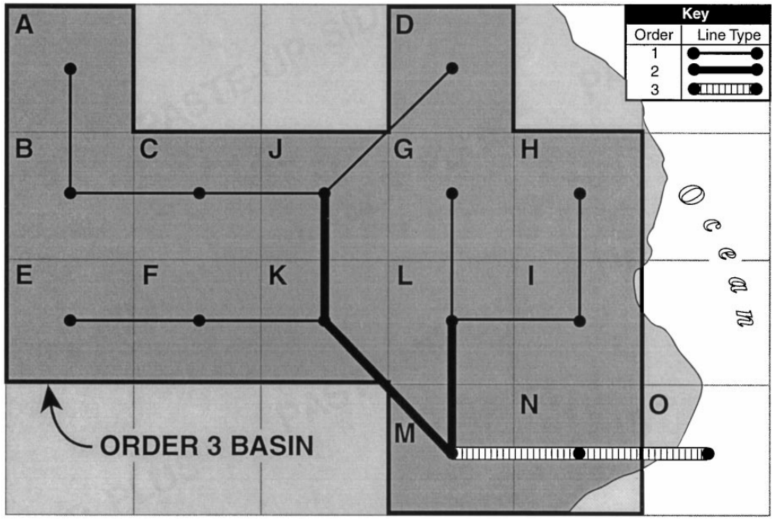
8	1	2
7		3
6	5	4



Numbers giving the flow directions between grid cells

The basin map

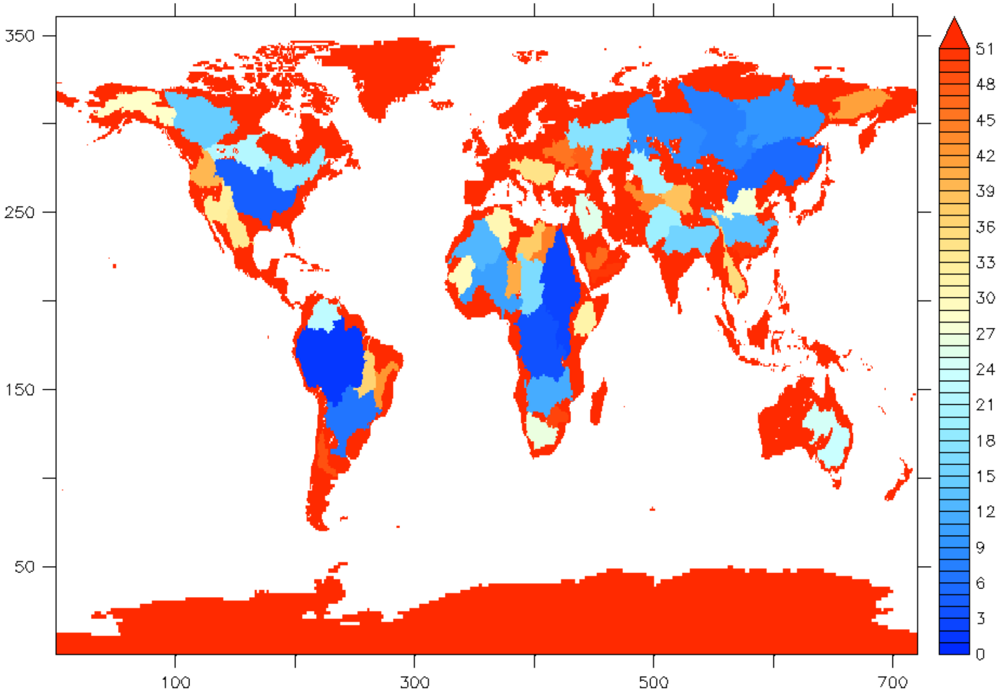
- Drainage basins are defined: collections of grid cells topologically connected by flow lines representing river links and segments
- Ordered river segment are defined: individual set of contiguous, linked grid cells having identical order. The stream order is based on Strahler (1957, 1964)'s classification system:
  - 1st order: channels that originate at a “source” (doesn’t have tributaries)
  - when two streams of order n join, a stream of order n+1 is created
  - when two streams of different order join, the channel segment immediately downstream has the higher order of the two combining streams



Vörösmarty et al. (2000)

The basin map

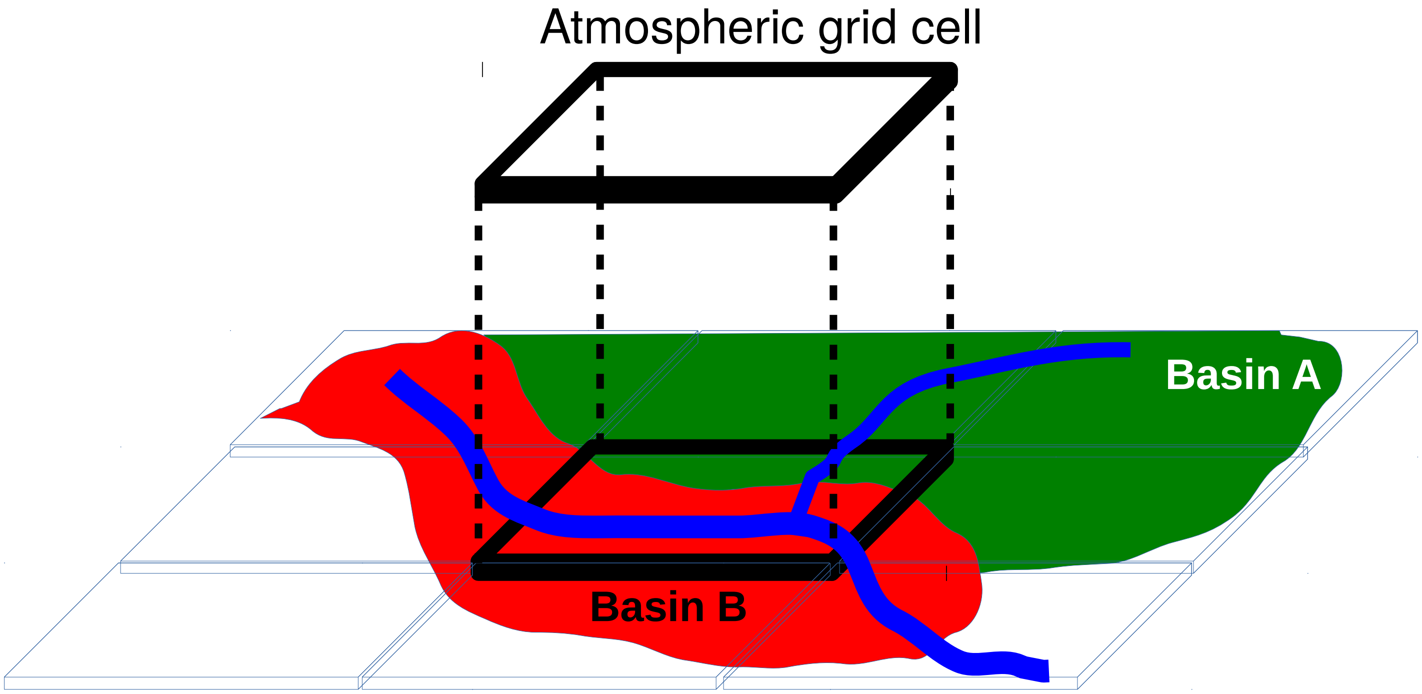
- 6930 basins available at 0.5°x0.5° spatial resolution
  - 6152: continental non-glacierized land area from STN-30p
    - sizes ranges from ~ 390 km² to ~ $5.8.10^6$ km² (Amazon basin)
  - 778: continental glacierized land area (Greenland and the poles) from TRIP
- By default in the code, the 50 largest basins of the running area are selected in the code (num_largest parameter)
- Attribution of a unique ID by the map



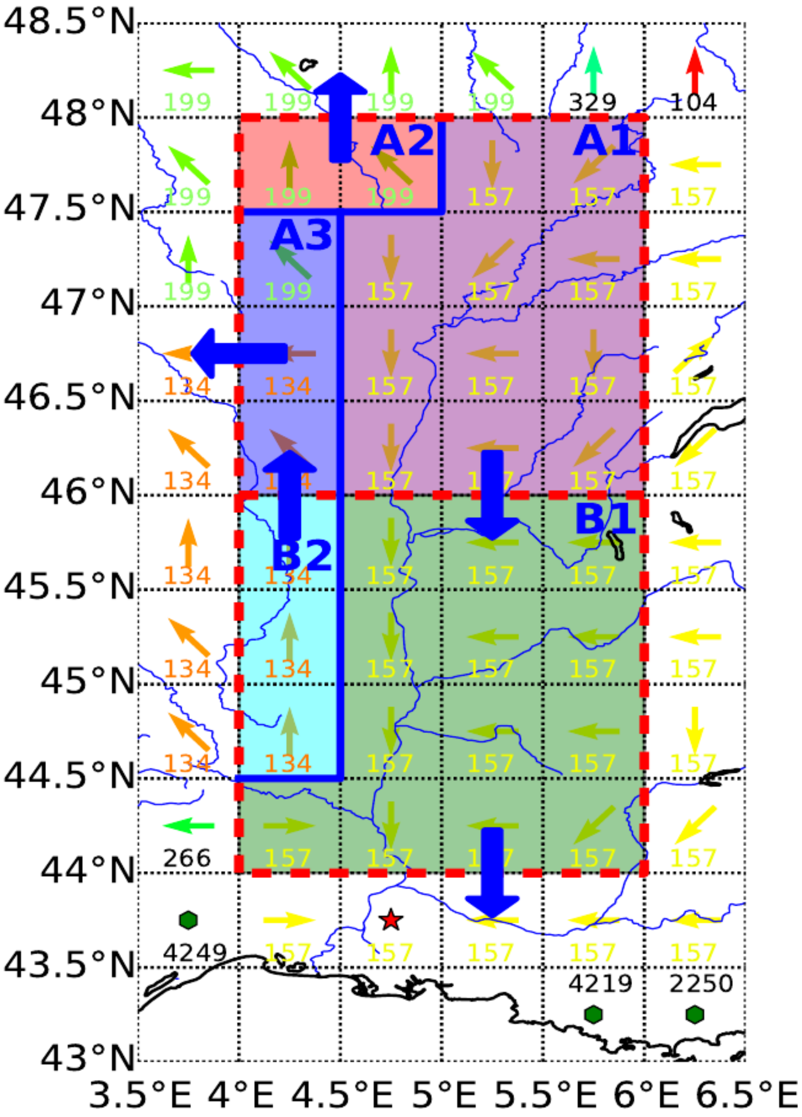
IDs of the 50 largest basins

The truncation procedure in routing.f90

- The spatial resolution of the atmospheric grid cell is coarser (>0.5°) than that of the routing → more than one basins can be included in the grid-cell
- <u>Truncation</u>: by default in the code, no more than 7 basins can be included in a grid cell (nbasmax parameter)



The basins (and grid cells) are now connected



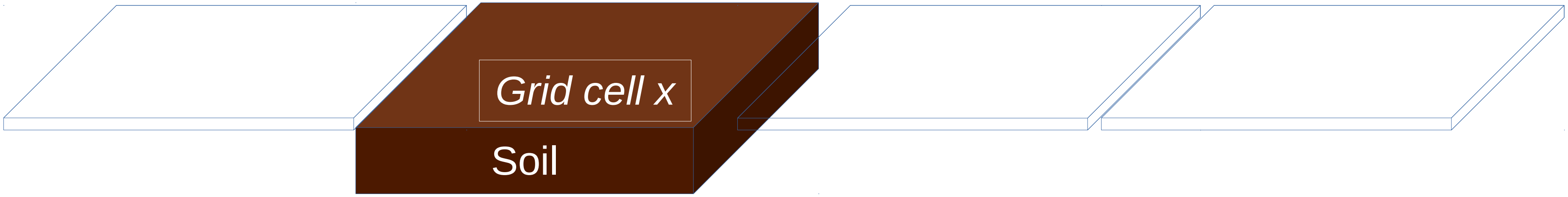
Courtesy of Trung Nguyen Quang and Jan Polcher

2.3

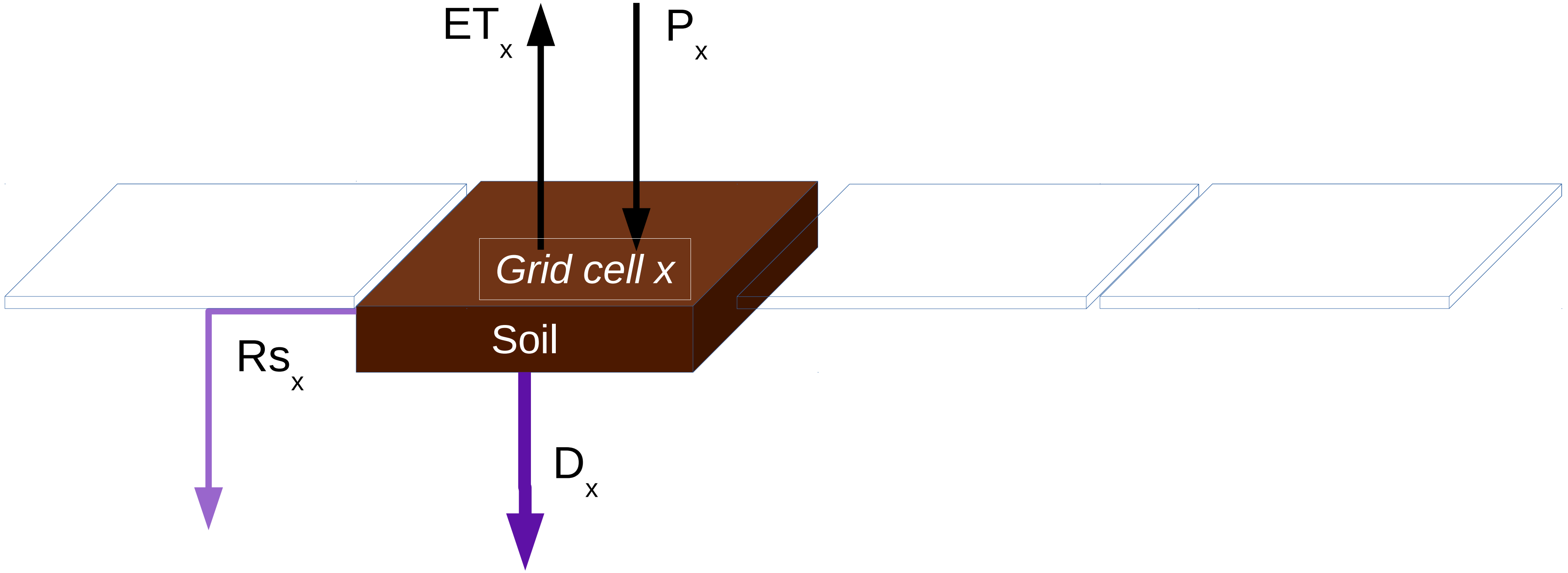
The routing scheme in ORCHIDEE

- Overview
- River network
- **Transfer between reservoirs**

Transfer of runoff into the reservoirs



Transfer of runoff into the reservoirs



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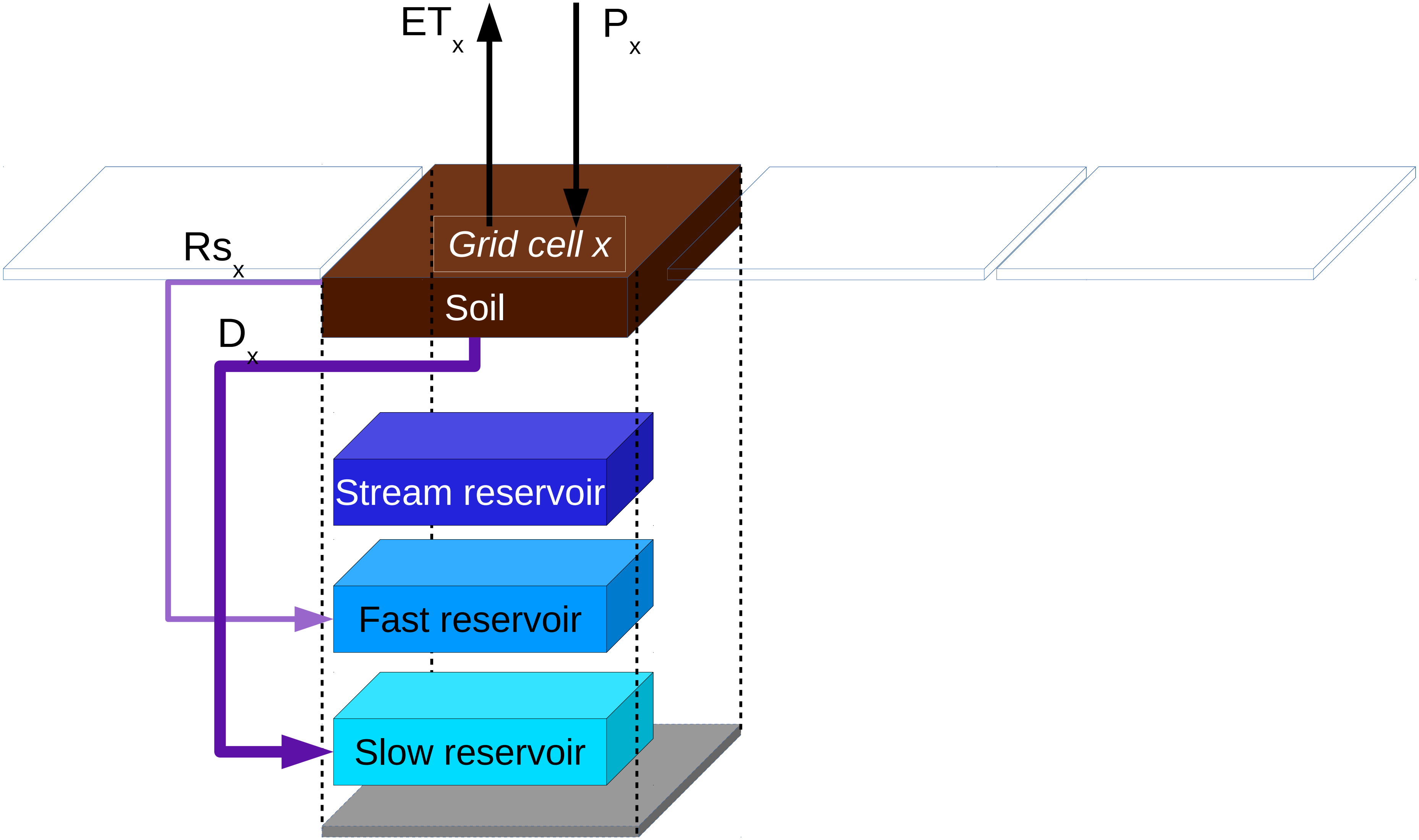

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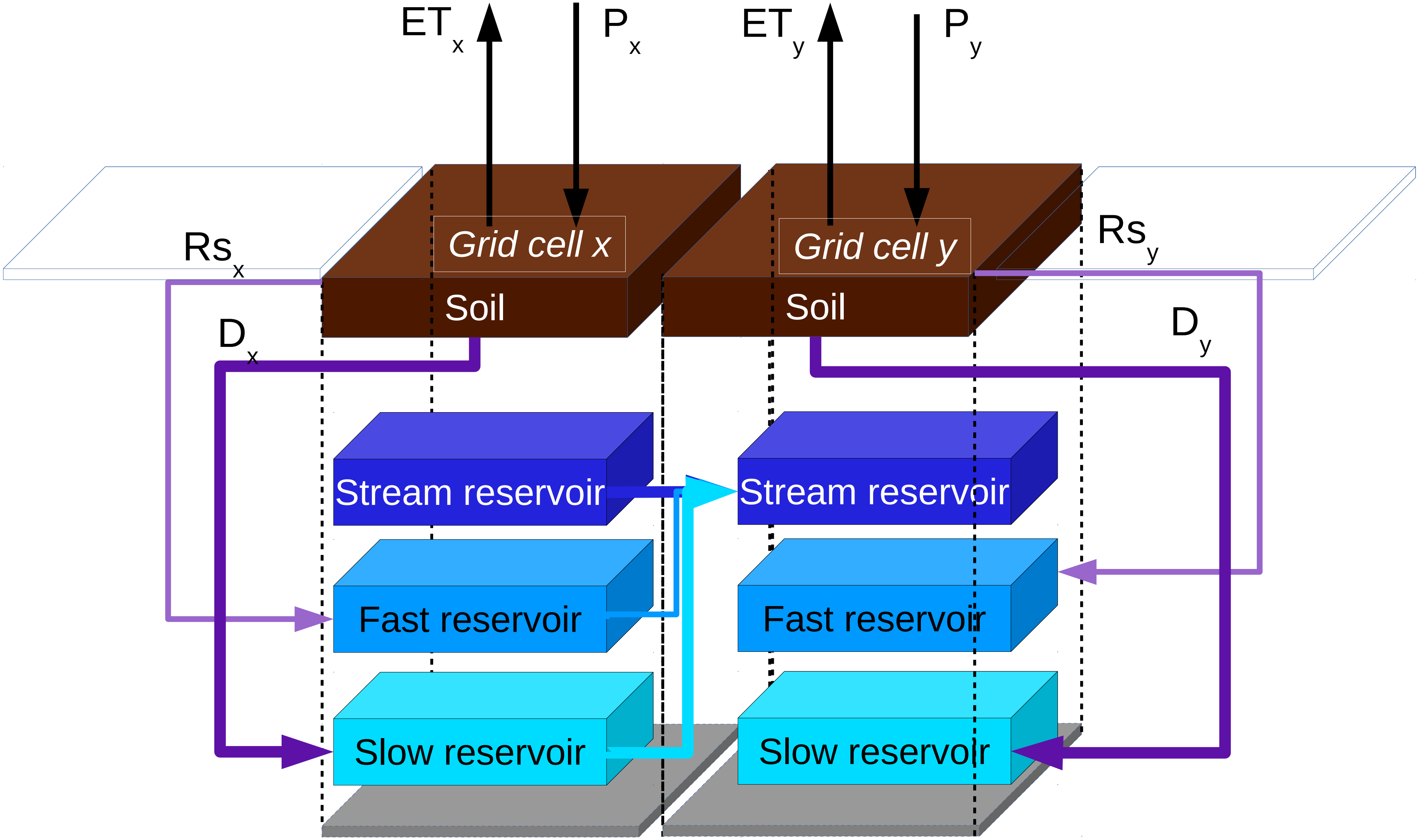
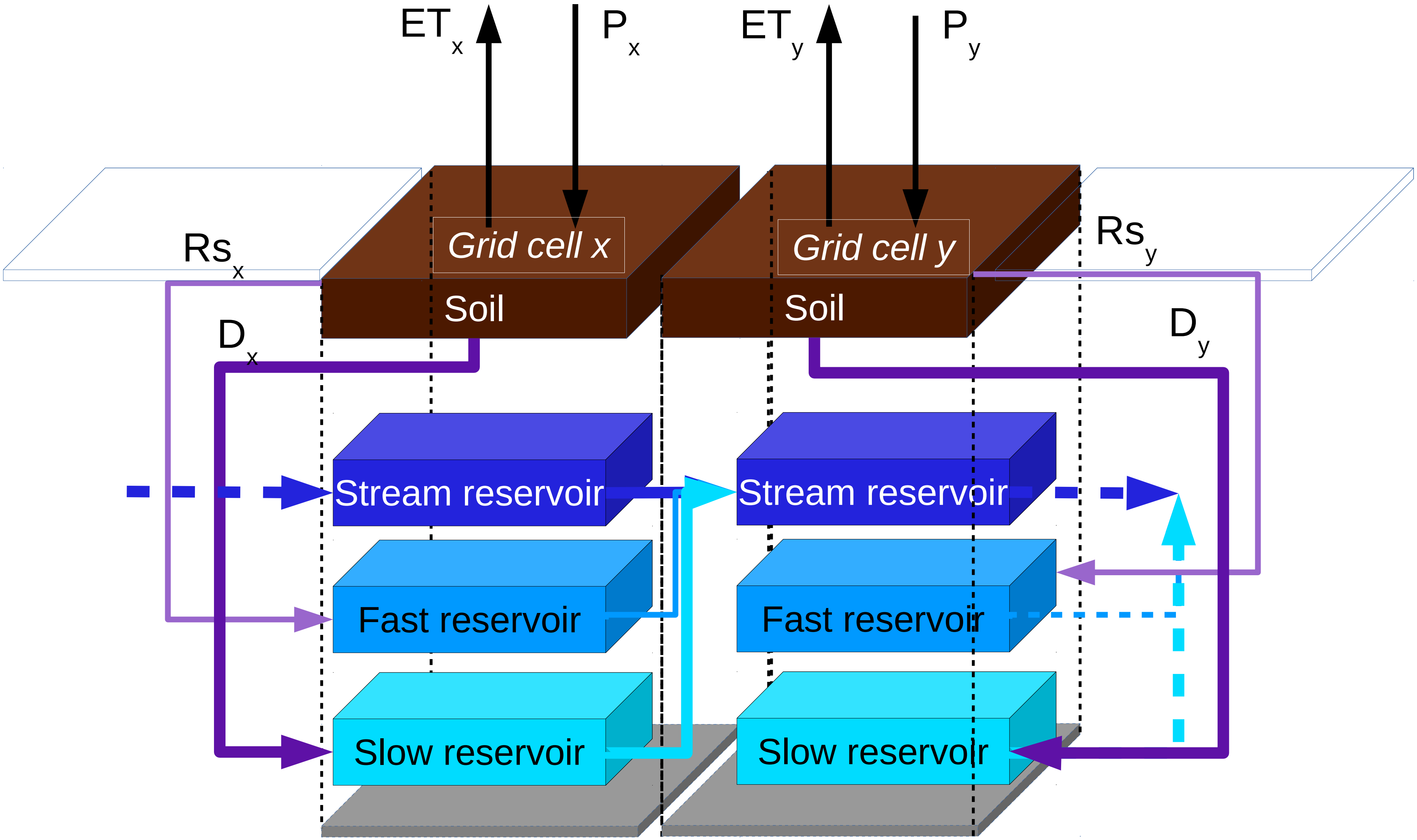


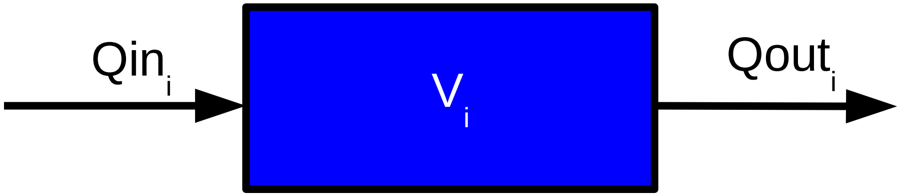
Transfer of runoff into the reservoirs

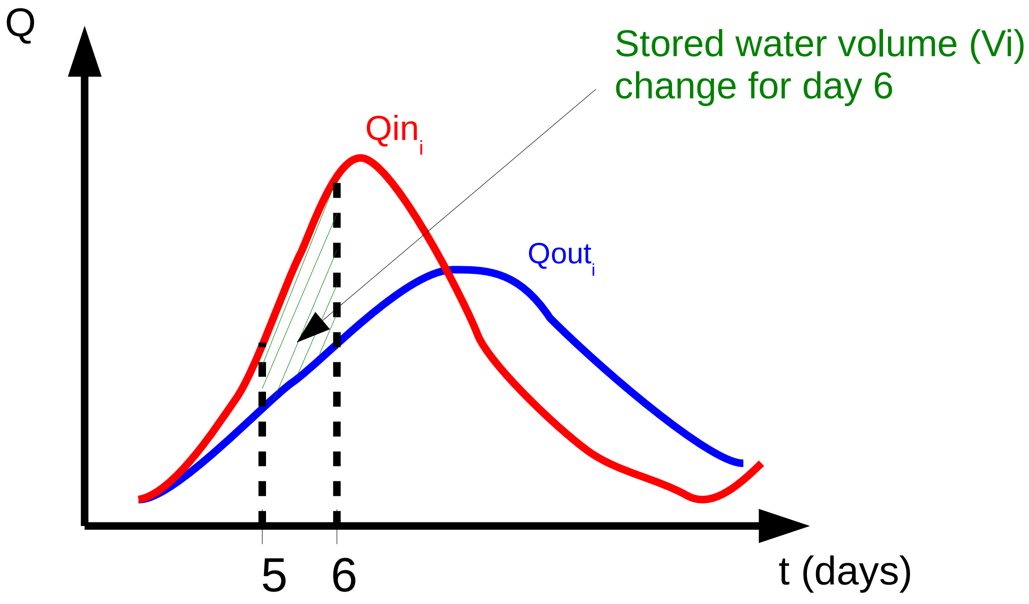


General equation of mass conservation (continuity equation)

$$\boxed{\frac{dV_i(t)}{dt} = Qin_i(t) - Qout_i(t)}$$

- $V_i(t)$ $[L^3]$, volume of water stored in the reservoir i
- Qin_i $[L^3.T^{-1}]$, rate of inflow of the reservoir i
- $Qout_i$ $[L^3.T^{-1}]$, rate of outflow of the reservoir i





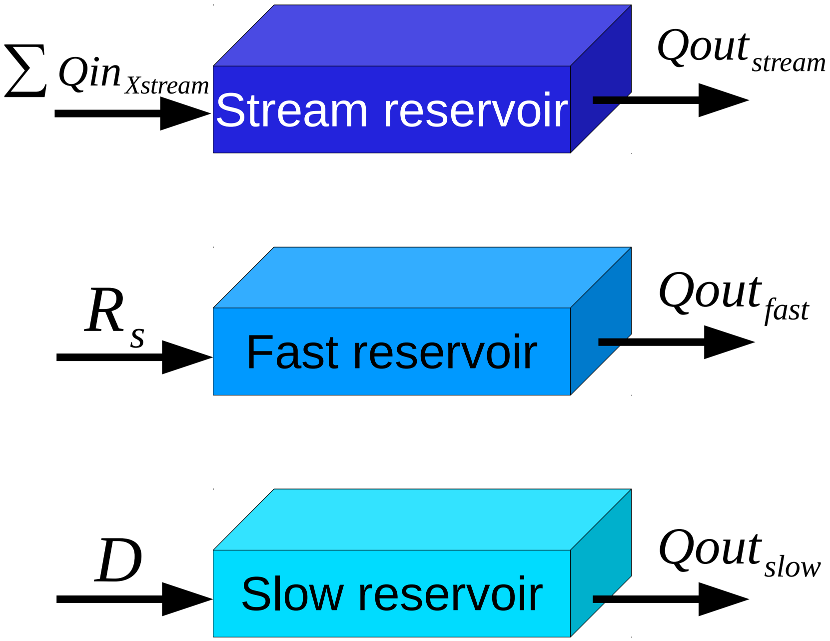
$$\frac{V_{i_{t+1}} - V_{i_t}}{\Delta t} = Qin_{i_t} - Qout_{i_t}$$

- **Δt = 1 day, time step** for the routing procedure in ORCHIDEE

General equation of mass conservation (continuity equation)

Equation of mass conservation applied for each reservoir of the grid cell:

$$\left\{\begin{aligned}
\frac{dV_{stream}(t)}{dt} &= \sum Qin_{Xstream}(t) - Qout_{stream}(t) \\
\frac{dV_{fast}(t)}{dt} &= Rs(t) - Qout_{fast}(t) \\
\frac{dV_{slow}(t)}{dt} &= D(t) - Qout_{slow}(t)
\end{aligned}\right.$$



- Qin_{stream} [kg/day], sum of all inflow from the stream reservoirs of neighbor cells ($Qin_{Xstream}$) that flow into that cell direction
- V_i [kg], Qin_i [kg/day], $Qout_i$ [kg/day]
- Rs [kg/day], surface runoff
- D [kg/day], drainage

Outflow-storage relation

$$\boxed{Qout_i(t) = \frac{1}{T_i} . V_i(t)}$$

T_i [day], the time of a water waves to travel through a reach

(also called “time constant”, “residence time”)

Outflow-storage relation

$$\boxed{Qout_i(t) = \frac{1}{T_i} . V_i(t)}$$

T_i [day], the time of a water waves to travel through a reach

(also called “time constant”, “residence time”)

with: $T_i = g_i . k$

The residence time in the reservoir i depends on 2 parameters:

- g_i [10^{-3} day/km], the property of the reservoir i
- k [km], the water retention index of the corresponding grid cell

Outflow-storage relation: property of the reservoir (g_i)

- g_i is constant for all grid cells and is unique for each reservoir:
  - g_{stream} = 0.24 10^{-3} day/km
  - g_{fast} = 3.00 10^{-3} days/km
  - g_{slow} = 25.0 10^{-3} days/km
- The values were obtained during a calibration of river discharge over the Senegal basin and then generalized to all the worldwide basins (Ngo-Duc et al., 2007)

Outflow-storage relation:
the water retention index (k)

- k varies spatially and does not depend on the reservoir
- Its formulation is a simplification of Manning's formula (from Ducharne et al., J. Hydrol, 2003)

Outflow-storage relation: the water retention index (k)

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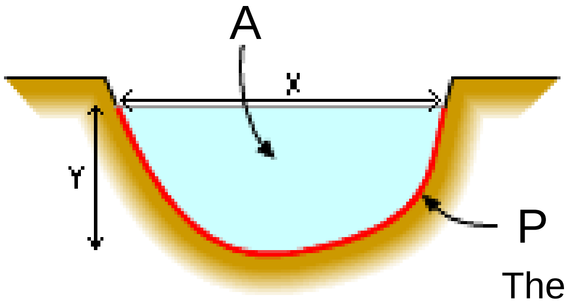
Manning equation: computes the velocity of open-channel flows

$$U = \left(\frac{u_m}{n}\right) . R_h^{2/3} . \sqrt{\tan\beta}$$

- U [m/s], open-channel flow velocity
- u_m [$m^{1/3}$/s], unit-conversion factor
- n, Manning coefficient which characterizes channel resistance
- R_h [m], hydraulic radius
- tanβ, water-surface slope

Hydraulic radius: measures the channel flow efficiency



$$R_h \equiv \frac{A}{P}$$

- A [m²], cross-sectional area of the flow
- P [m], length of the wetted portion of the flow boundary (“wetted perimeter”)

The greater R_h, the greater the efficiency of the channel and the more volume it can carry.

For channels of a given width (x), R_h is greater for the deeper channels (y is high).

Outflow-storage relation: the water retention index (k)

$$\boxed{U=\left(\frac{u_m}{n}\right).R_h^{2/3}.\sqrt{\tan\beta}}$$

Manning equation

$$\downarrow$$

$$\frac{1}{U}=\left(\frac{n}{u_m.R_h^{2/3}}\right)\cdot\left(\frac{1}{\sqrt{\tan\beta}}\right)$$

$$\downarrow$$

$$\frac{d}{U}=\left(\frac{n}{u_m.R_h^{2/3}}\right)\cdot\left(\frac{d}{\sqrt{\tan\beta}}\right)$$

$$\downarrow$$

$$t_{adj}=\alpha.\left(\frac{d}{\sqrt{\tan\beta}}\right)$$

- $t_{adj}=d/U$ [s], transfer time between two adjacent grid cells. Equivalent to T_i.
- d [m], distance between two adjacent grid cells.
- α [s/m], a scaling parameter, including the influence of roughness of the river bed (influence of the water stage being neglected). Equivalent to g_i.

$$\downarrow$$

$$k=\frac{d}{\sqrt{\tan\beta}}$$

- $k=t_{adj}/\alpha$ [m], water retention index

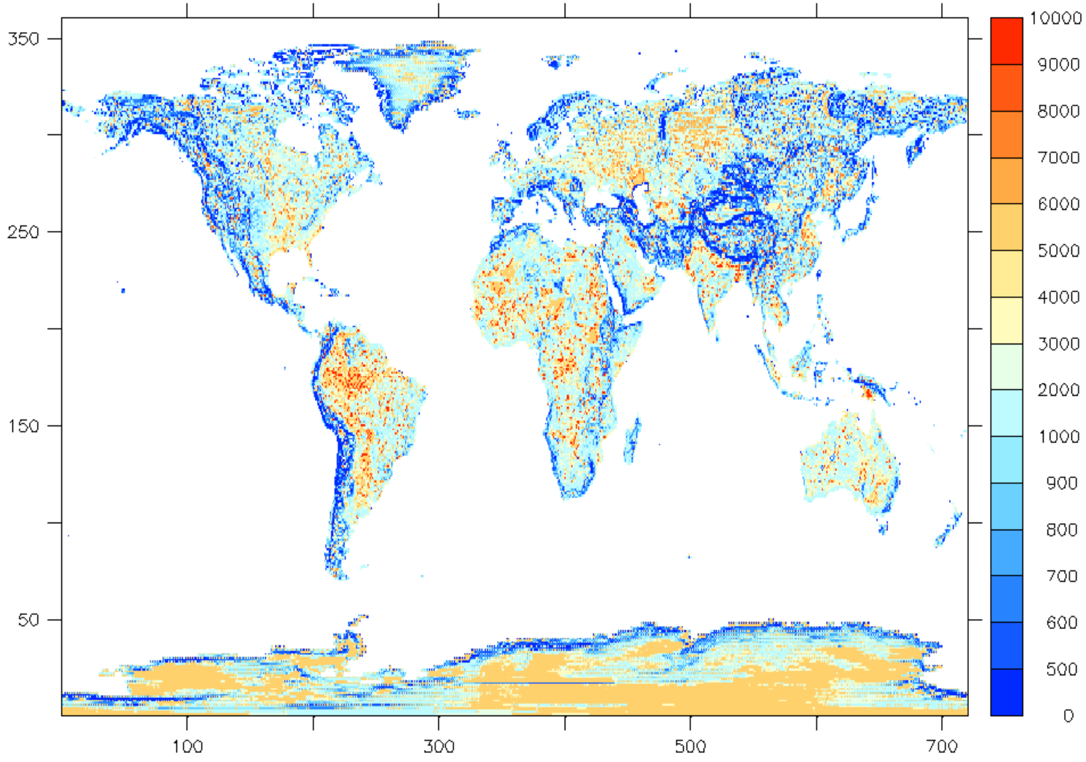
$$\downarrow$$

Water retention index in ORCHIDEE

$$k=\sqrt{\frac{d^2}{\tan\beta}}\longrightarrow k=\sqrt{\frac{d^2}{\frac{\Delta z}{d}}}\longrightarrow k=\sqrt{\frac{d^3}{\Delta z}}$$

then: $\boxed{k=\sqrt{\frac{d^3}{\Delta z.10^6}}}$ to put k in km

The water retention index map



Water retention index [km]

- 0.5°x0.5° spatial resolution

$$T_i = g_i . k$$

$$12.5\,days < T_{slow} < 250\,days$$

Groundwater residence time estimated in the literature: 10-300 days

3

Inland and man-made wetlands

- Irrigated lands
- Floodplains
- Swamps
- Ponds

ORCHIDEE
LAND SURFACE MODEL

Inland and man-made wetlands in ORCHIDEE

Irrigation

Swamps

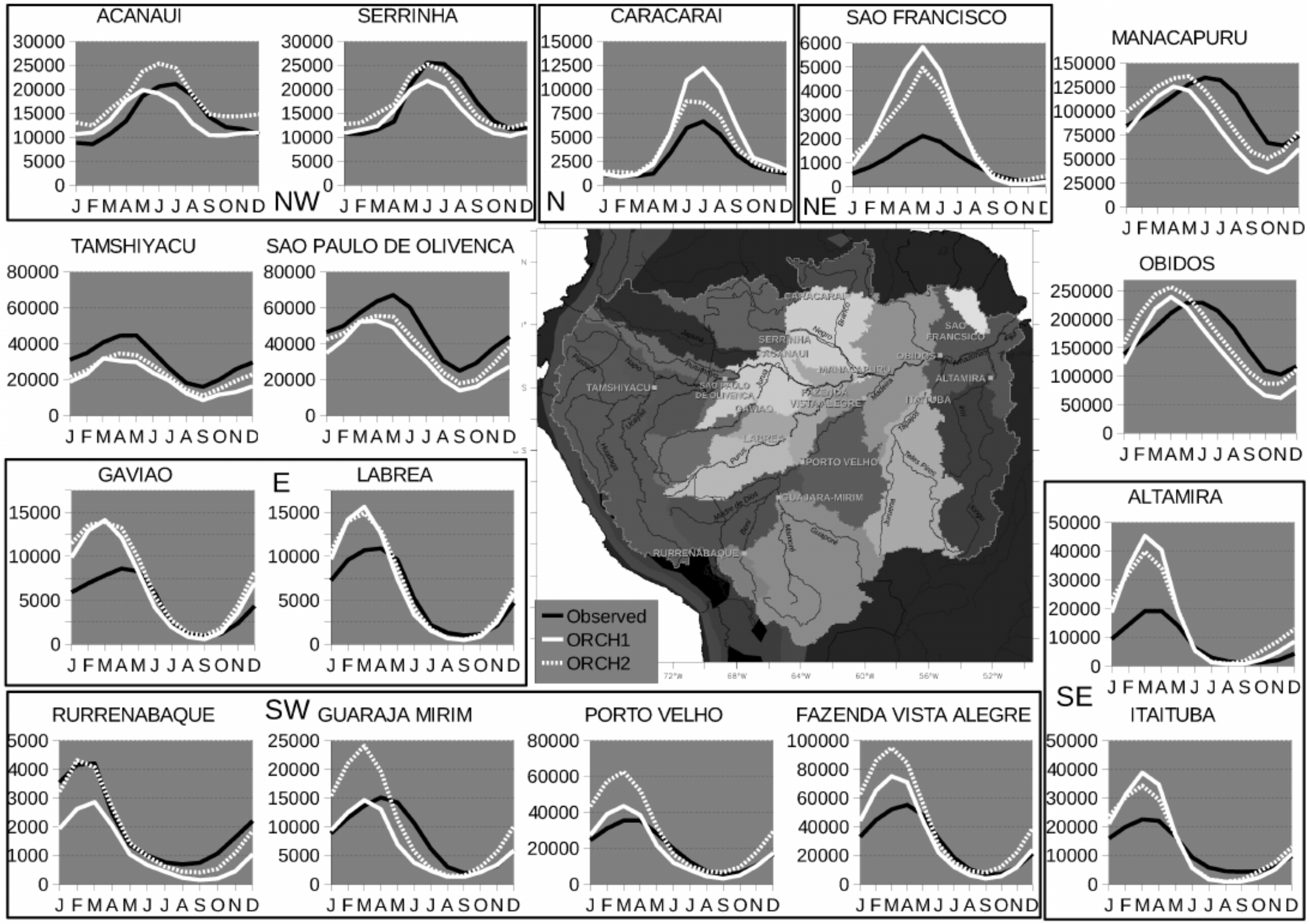
Ponds

Floodplains

4

Applications

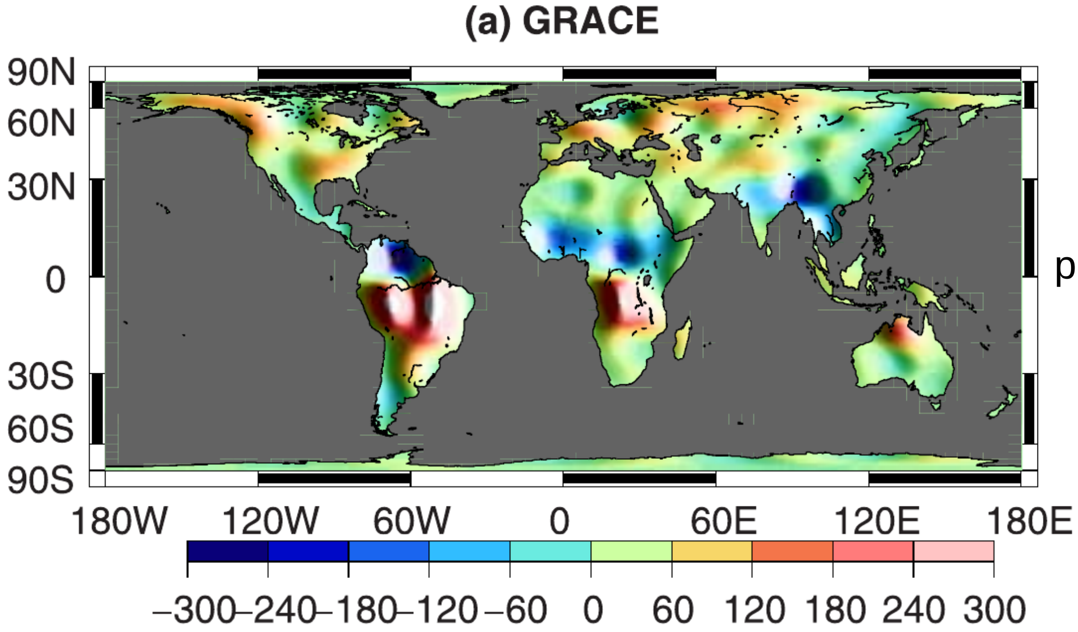
River discharge (Q)



Mean seasonal discharges (m^3/s) over the sub-basins of the Amazon basin (white: ORCHIDEE simulations; black: observations from the ORE-HYBAM database) *Guimberteau et al. (HESS, 2012)*

Simulated river discharge can be compared with data from gaging stations

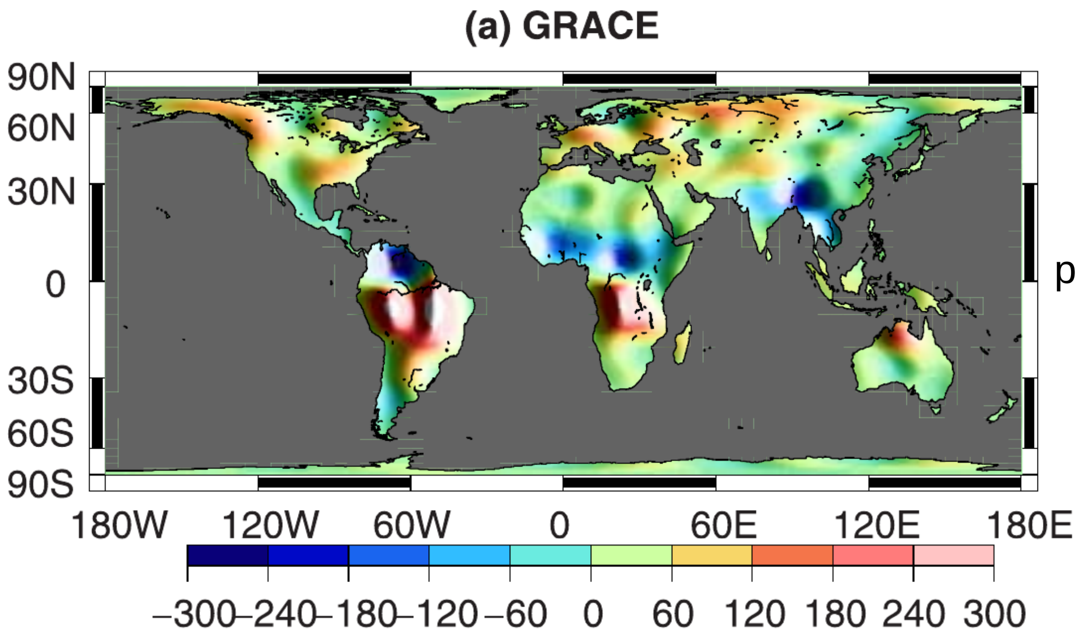
Total water storage variation (TWS): comparison with GRACE



TWS (in mm) for the time period FMA minus ASO 2003

Ngo-Duc et al. (2007, WRR)

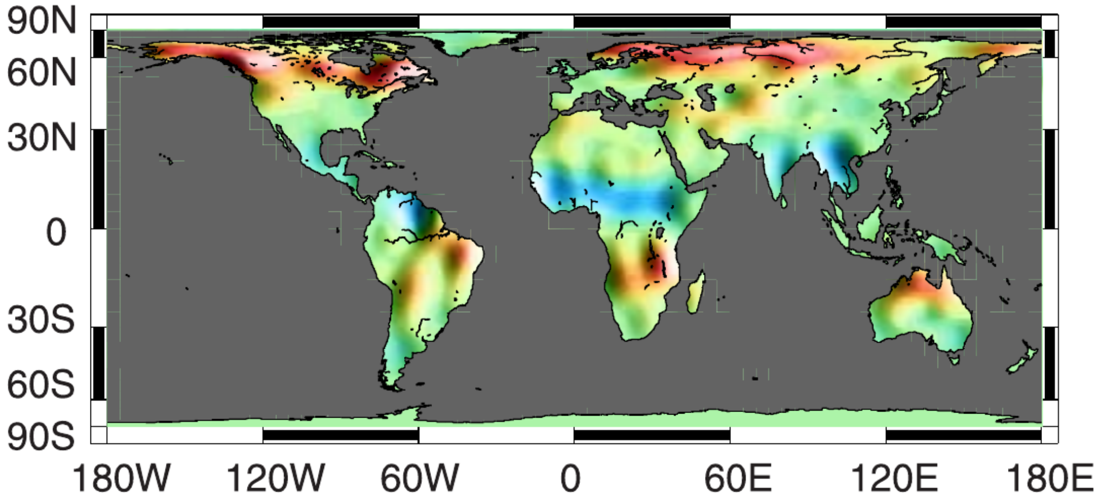
Total water storage variation (TWS): comparison with GRACE



TWS (in mm) for the time period FMA minus ASO 2003

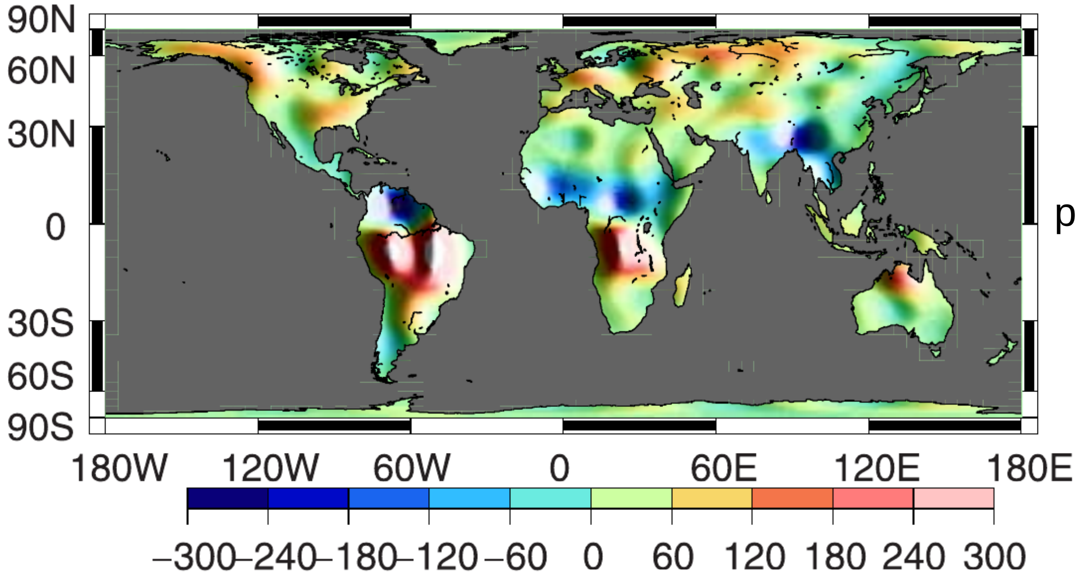
Ngo-Duc et al. (2007, WRR)

ORCHIDEE (without routing module)



Total water storage variation (TWS): comparison with GRACE

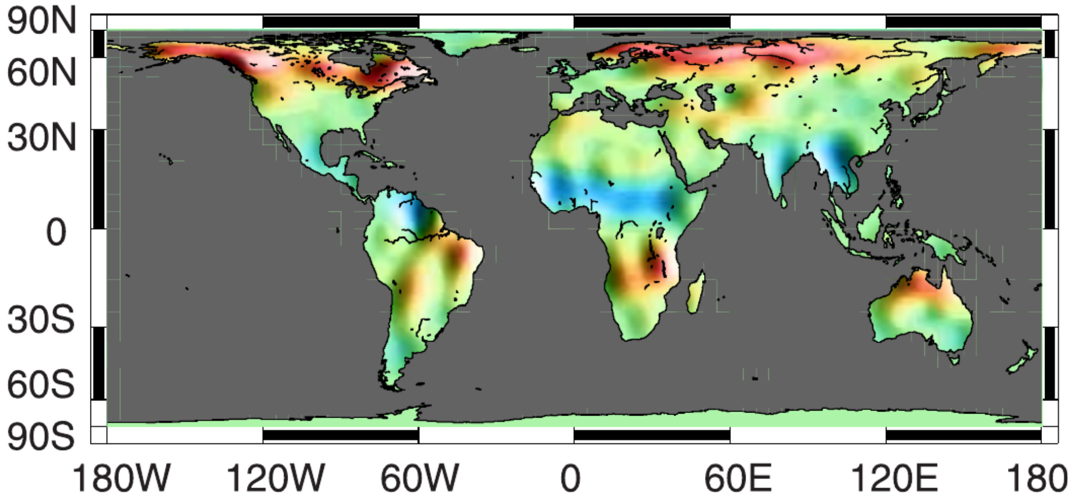
(a) GRACE



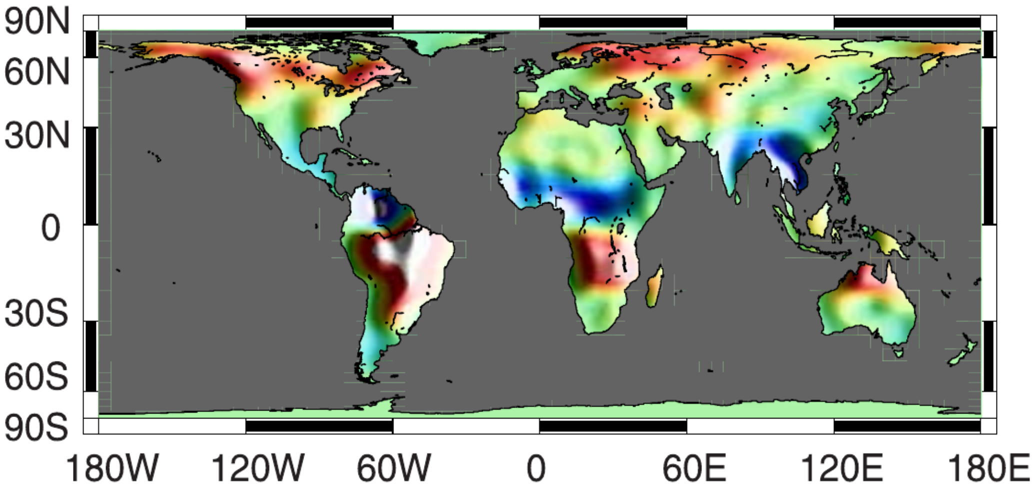
TWS (in mm) for the time period FMA minus ASO 2003

Ngo-Duc et al. (2007, WRR)

ORCHIDEE (without routing module)



ORCHIDEE (with routing module)



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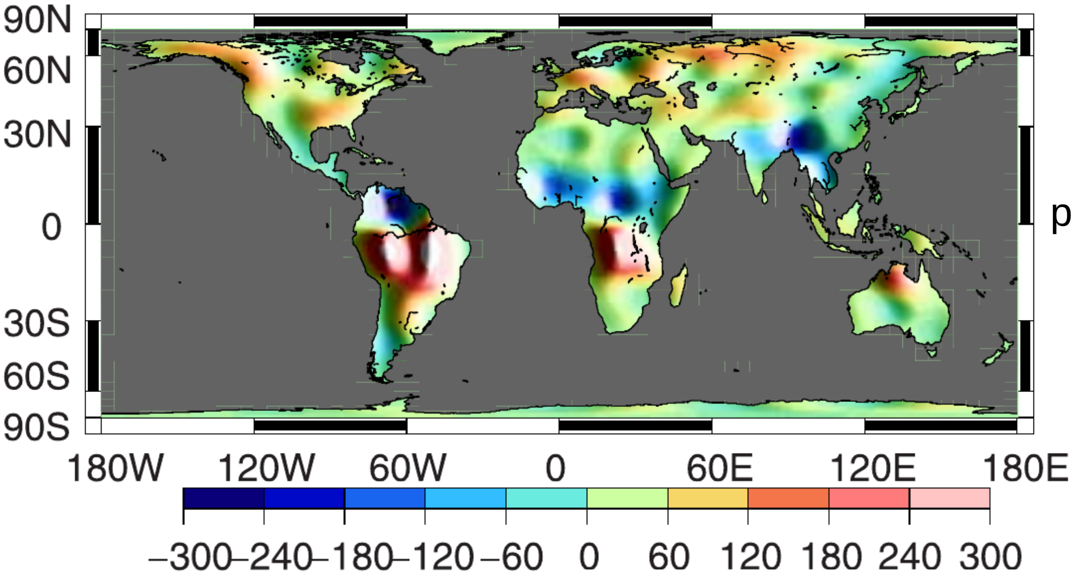
(a) GRACE



TWS (in mm) for the time period FMA minus ASO 2003

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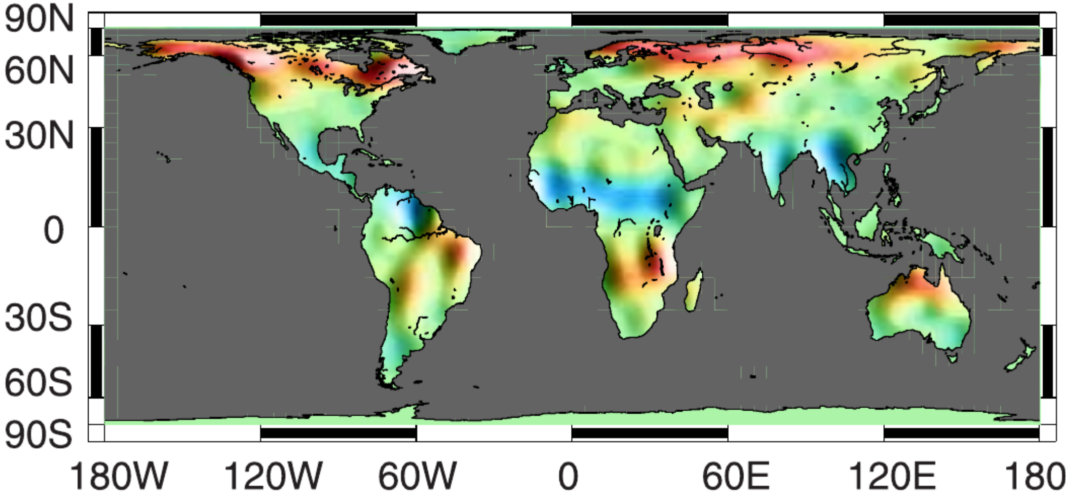

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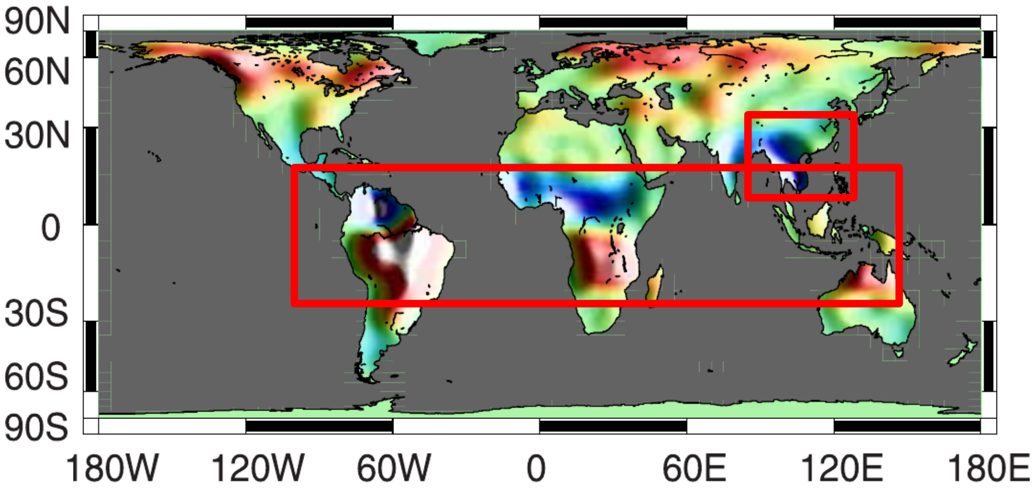
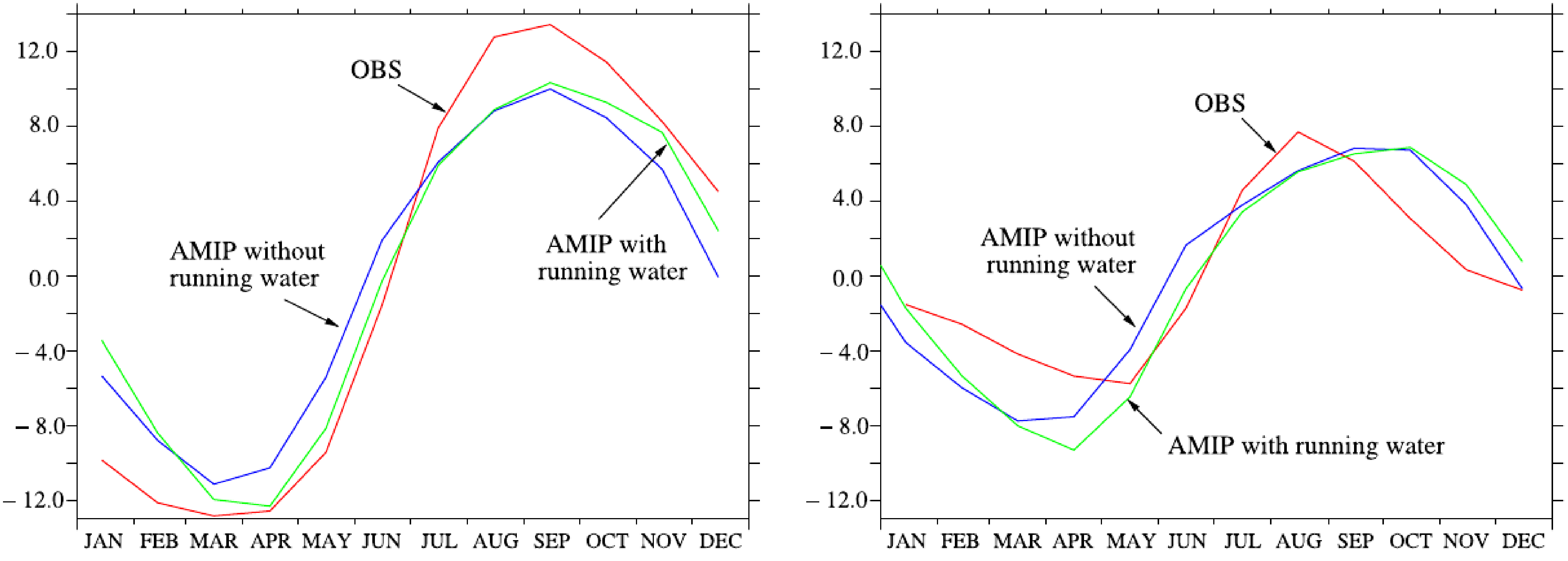


Contribution of continental water to sea level variations: comparison with TOPEX/POSEIDON



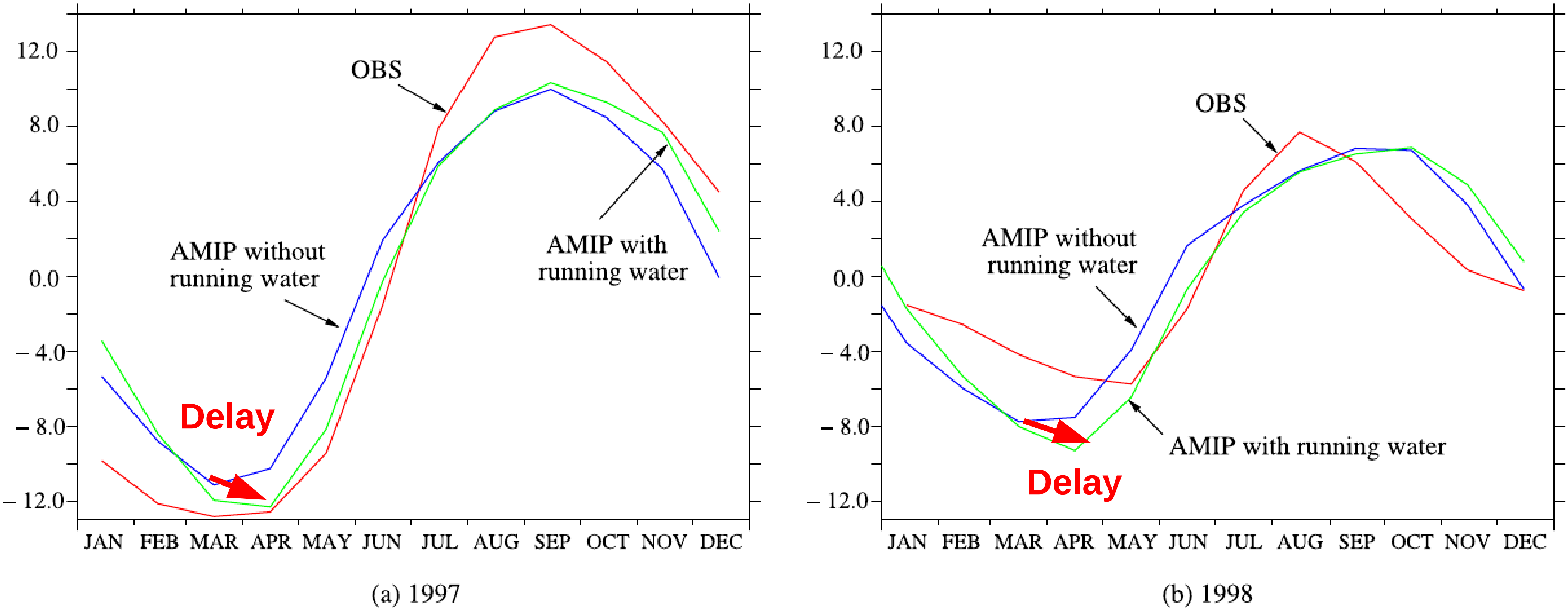
(a) 1997

(b) 1998

Contribution of continental water to sea level variations (mm)
Obs = T/P sea level - steric effect - vapor contribution (from NCEP/NCAR reanalysis)

Ngo-Duc et al. (2005, JGR)

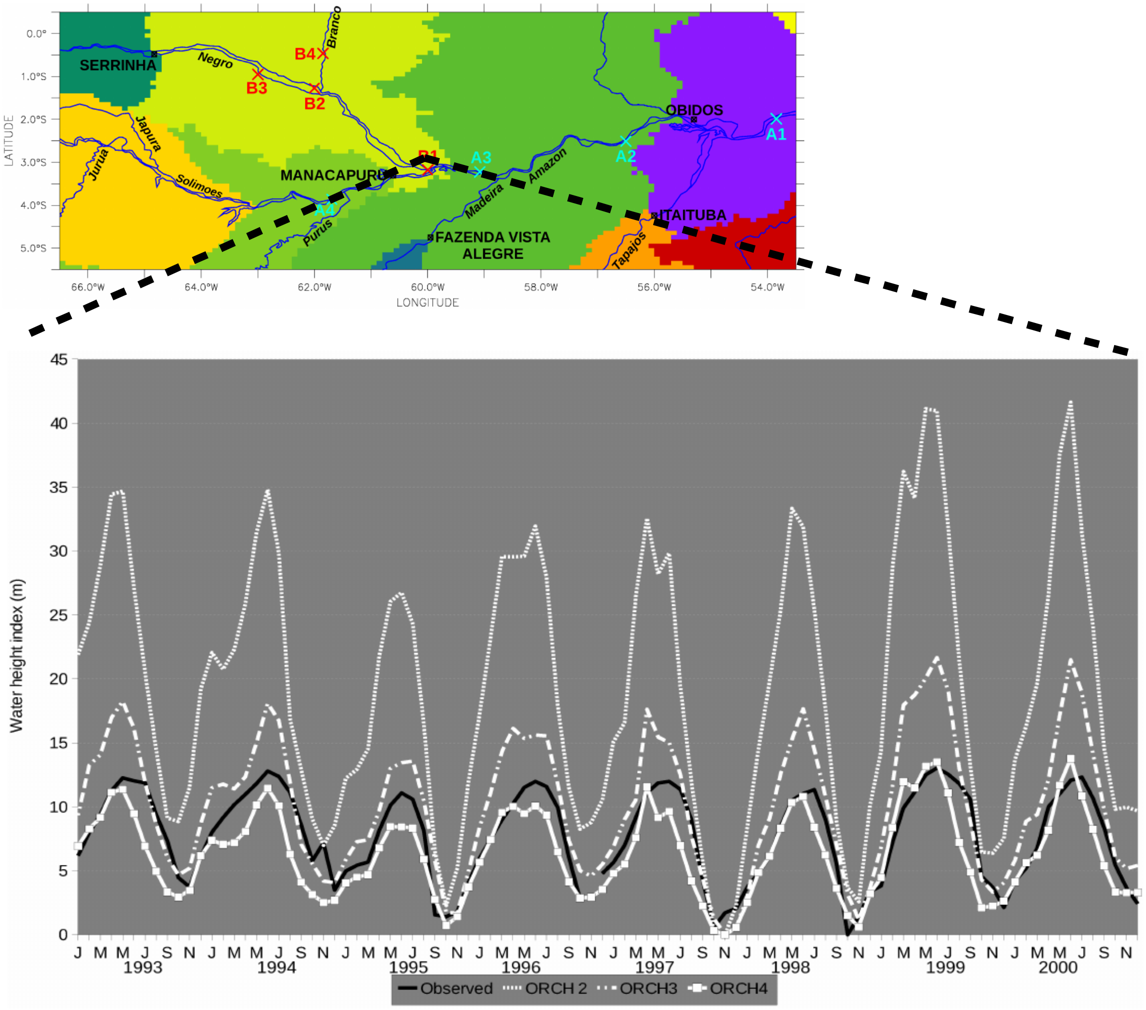
Contribution of continental water to sea level variations: comparison with TOPEX/POSEIDON



Contribution of continental water to sea level variations (mm)
Obs = T/P sea level - steric effect - vapor contribution (from NCEP/NCAR reanalysis)

Ngo-Duc et al. (2005, JGR)

Floodplain water height



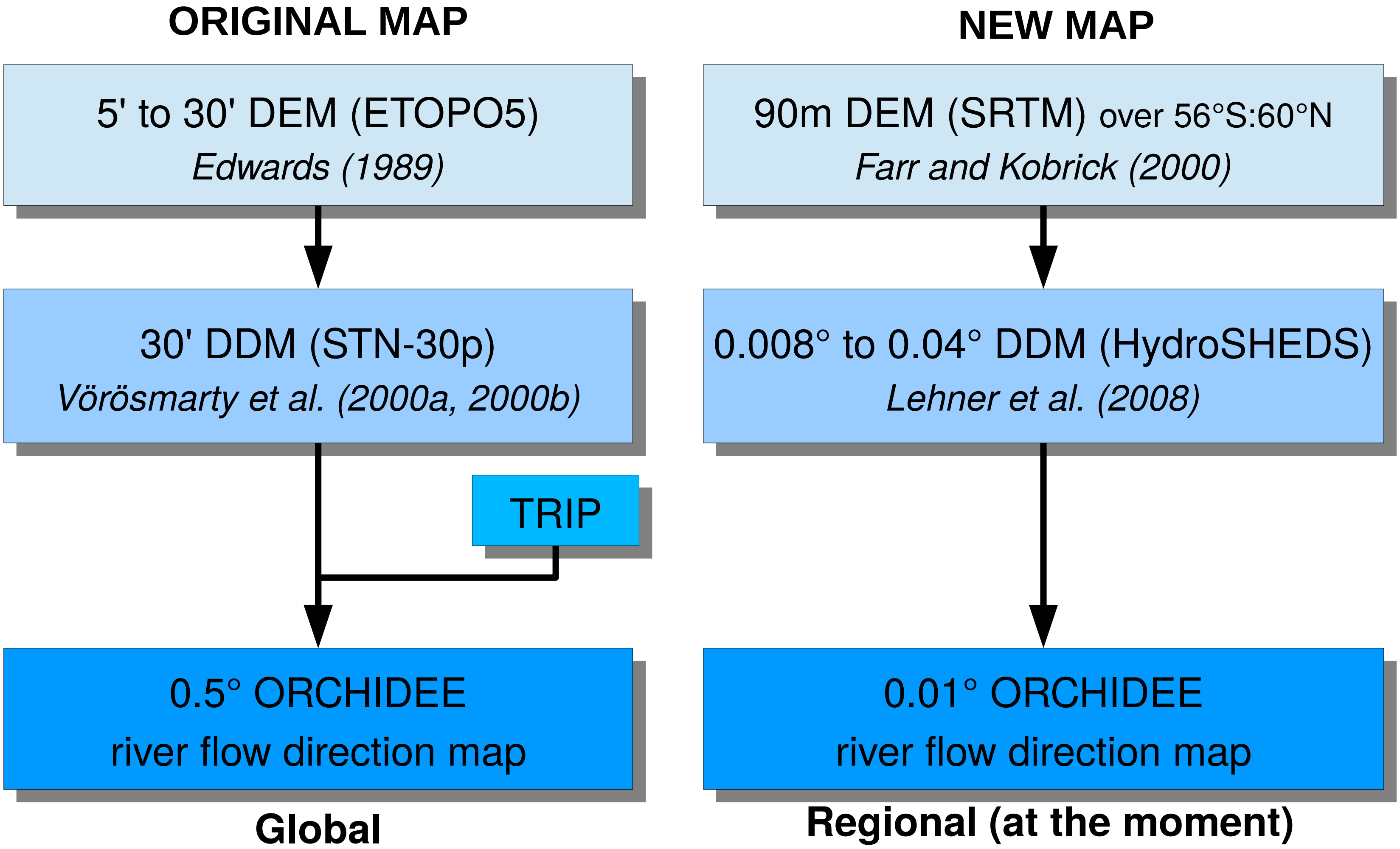
Interannual variation of monthly water height index (m) simulated with ORCHIDEE on the Rio Negro. Comparison with Topex/Poseidon observations. *Guimberteau et al. (HESS, 2012)*

5

Ongoing developments: the high resolution routing scheme (developed by Trung Nguyen Quang (LMD), Phd student of Jan Polcher)

ORCHIDEE
LAND SURFACE MODEL

A new river flow direction maps



ORIGINAL MAP

5' to 30' DEM (ETOPO5)
Edwards (1989)

30' DDM (STN-30p)
Vörösmarty et al. (2000a, 2000b)

TRIP

0.5° ORCHIDEE
river flow direction map

Global

NEW MAP

90m DEM (SRTM) over 56°S:60°N
Farr and Kobrick (2000)

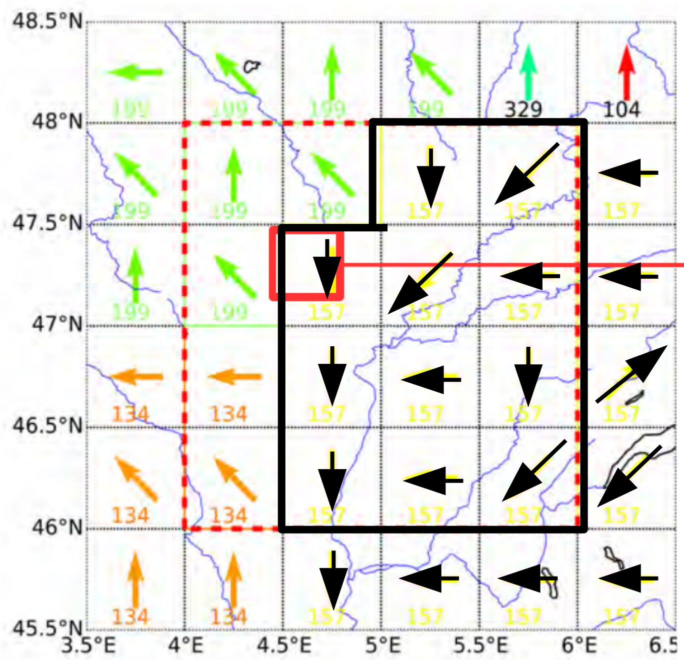
0.008° to 0.04° DDM (HydroSHEDS)
Lehner et al. (2008)

0.01° ORCHIDEE
river flow direction map

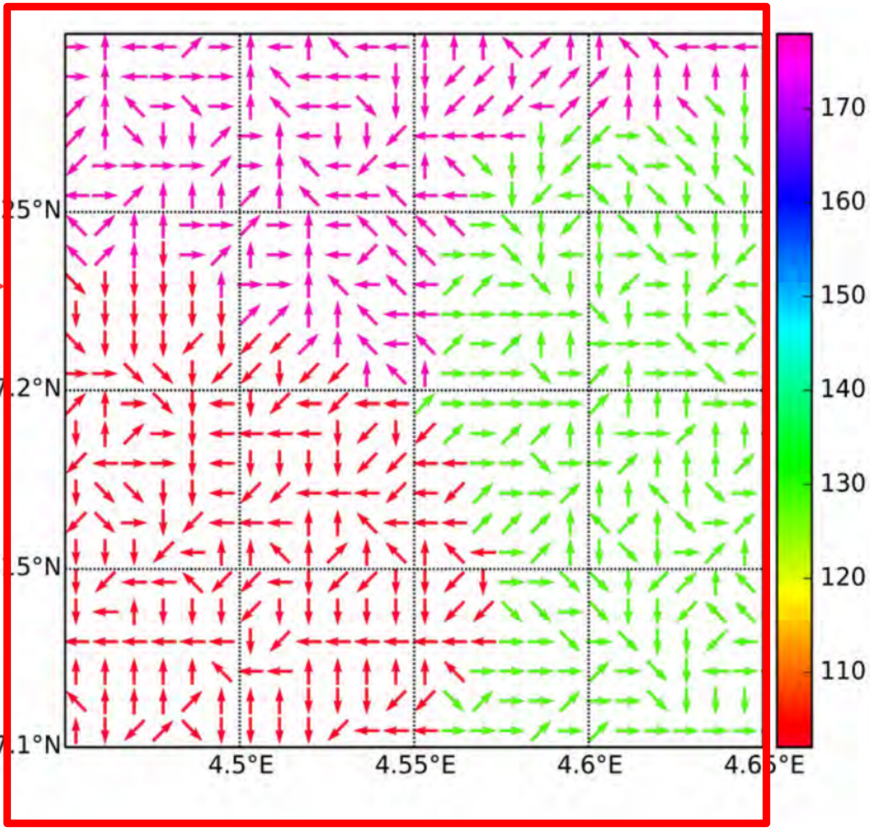
Regional (at the moment)

- **SRTM**: **S**huttle **R**adar **T**opography **M**ission
- **HydroSHEDS**: **Hydro**logical data and maps based on **SH**uttle **E**levation **D**erivatives at multiple **S**cales

A new river flow direction maps



STN-30p (Vörösmarty 2000)



HydroSHEDS

Courtesy of Trung Nguyen Quang and Jan Polcher

High resolution routing scheme

- New **river flow direction map** + new **basin map** (using the Pfafstetter coding system for watershed identification) + re-computation of the **water retention index map** + re-calibration of the **truncation parameter** and the **time constants of the reservoirs** in routing.f90.
- Allow us to define more sub-basins per grid cell
- Provide a more precise description of river network within the sub-grid basins and more details about the river structures
- The detailed water retention index allows the water flow movement be closer to the reality
- Short residence time in small grid cell allows **routing in a short span** (up to 1h), and benefits to **evaluate the model at a daily scale**
- **Modest improvement** compared with the former scheme over large basins
- Now, we can consider **adduction infrastructures** (reservoirs, man-made channels): in development (Jan Polcher and his Phd student Xudong Zhou (LMD), Patrice Dumas (CIRED))

6

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Parameters used in routing.f90

Name	Value	Unit	Description
General			
diagunit	87	*unitless*	Diagnostic file unit
dt_routing	one_day	s	Routing time step
nbasmax	5	*unitless*	Maximum number of basins per grid cell
nbvmax	440	*unitless*	
num_largest	50	*unitless*	Number of largest basins
fast_tcst	3.0	10^{-3} day/km	Fast reservoir property
slow_tcst	25.0	10^{-3} day/km	Slow reservoir property
stream_tcst	0.24	10^{-3} day/km	Stream reservoir property
Swamp subroutine			
swamp_cst	0.2	*unitless*	Swamp constant
Floodplain subroutine			
beta	2.0	*unitless*	Fix the shape of the floodplain
floodcri	2000	mm	Potential height for which all the basin is flooded
flood_tcst	4.0	10^{-3} day/km	Flood reservoir property
Pond subroutine			
betap	0.5	*unitless (0-1)*	Ratio of the basin surface intercepted by ponds and the maximum surface of ponds
pondcri	2000	mm	Potential height for which all the basin is a pond
Endoheric lake subroutine			
maxevap_lake	7.5/86400	mm/s	Maximum evaporation rate from lakes

Thank you

ORCHIDEE
LAND SURFACE MODEL