Hydrological modelling on atmospheric grids; using graphs of sub-grid elements

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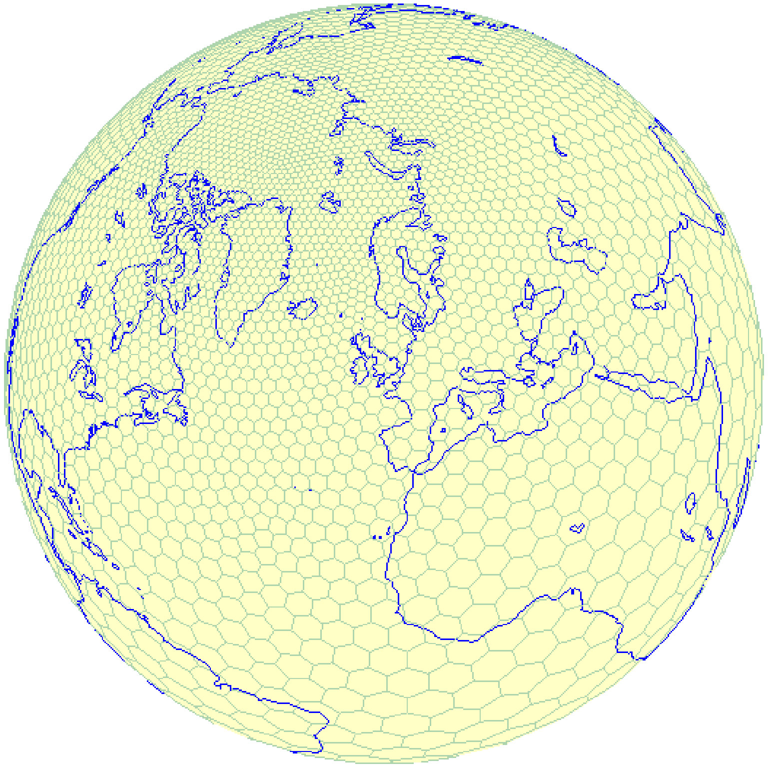
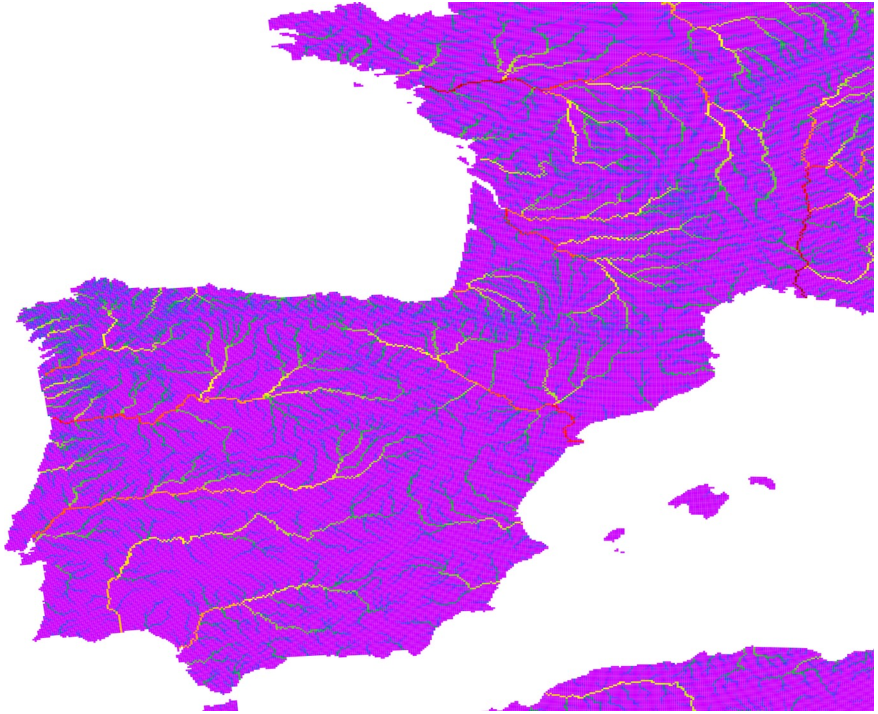
- The original ideas for the this river scheme in ORCHIDEE are over 20 years old.
- The implementation was poor and not very practical.
- The advancements in atmospheric models and hydrological information could not be exploited by the scheme.

Polcher et al., 2022, GMD

Later water transport for Earth System models





River routing is a different thing to different climate scientists :

- Close the global water cycle with stream flows,
- Feed water to regions of strong evaporation,
- Predict floods in km-scale climate and weather models
- Transport energy and biogeochemical elements to close their cycles.

The incompatibility of atmospheric and hydrological grids

The first order approach are interpolations :

- The water transport is computed on its own grid.
- Interpolations generate information and smooth gradients.
- If many variables are exchanges it becomes costly.

A more integrated approach - Hydrological Transfer Units :

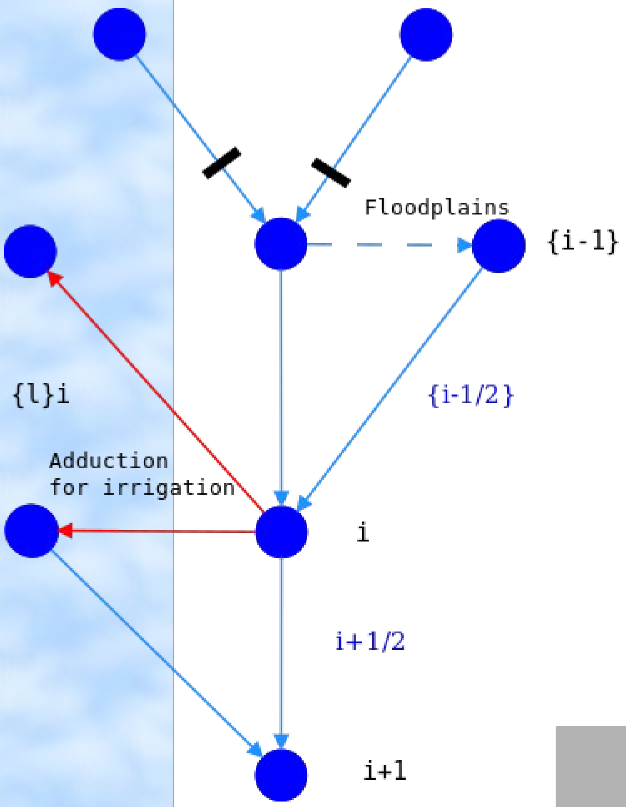
- It is just another tiling of the surface, but now with hydrological continuity as the main focus.
- Water transport can remain within the land system model and exchange with other components at any point.
- Other sub-grid elements can adapt to the hydrological tiling.

The proposed hybrid grid-vector transport scheme

This presentation will cover the following points :

- Building HTU graphs automatically for any atmospheric grid. Stations and other infrastructures can also be positioned.
- A truncation parameter allows to adapt the transport scheme to the needs of the Earth system model and its resolution.
- A criteria is proposed to ensure numerical convergence and remove the need for parameter adjustments.
- The scheme is used to demonstrate a stream temperature scheme which takes advantage of ORCHIDEE’s soil thermal model.

The equations to be implemented



- Each HTU has 3 reservoirs : Stream, fast & slow.
- Each HTU belongs to only one atmospheric grid. But each atmospheric polygon can contain many HTUs.
- The continuity equation is written on the river graph.

$$\lambda = \sqrt{\frac{d^3}{dz}}$$

Reservoir	Source	Outflow
Stream	Upstream HTUs	$Q_{stream} = \frac{W_{stream}}{\lambda_{stream} * g_{stream}}$
Fast	Surface runoff	$Q_{fat} = \frac{W_{fast}}{\lambda * g_{fast}}$
Slow	Deep drainage	$Q_{slow} = \frac{W_{slow}}{\lambda * g_{slow}}$

Stream temperature equation

$$\frac{\partial T_{i,stream}}{\partial t} = \frac{1}{W_{i,stream}} \sum_{j\in\{i-1\}} \left(Q_{j+\frac{1}{2},slow}T_{j,slow} + Q_{j+\frac{1}{2},fast}T_{j,fast} + Q_{j+\frac{1}{2},stream}T_{j,stream}\right)$$
$$- \frac{1}{W_{i,stream}} Q_{i+\frac{1}{2},stream}T_{i,stream} + K\left(T_{i,up} - T_{i,stream}\right)$$

- A simple advection equation for temperature.
- To avoid the singularity for empty streams a relaxation to top soil temperature is added.
- Initial conditions for reservoir temperatures :
  - $T_{fast\ :}$ *: Top soil temperature 0-0.3m*
  - T_{slow} *: Bottom soil temperature : 3-17m*
- K depends on the water height in the HTU and a scaling parameter.
- The equation is basic but allow to analyse the relative importance of the initial conditions and the exchange with the land scape along the river.

Hydrological information

- In order to build the HTUs we require a detailed digital elevation model, flow directions, flow accumulation and distance to the ocean = HDEM.
- Other information will be computed along the way.
- Three such data sets are available and were used.

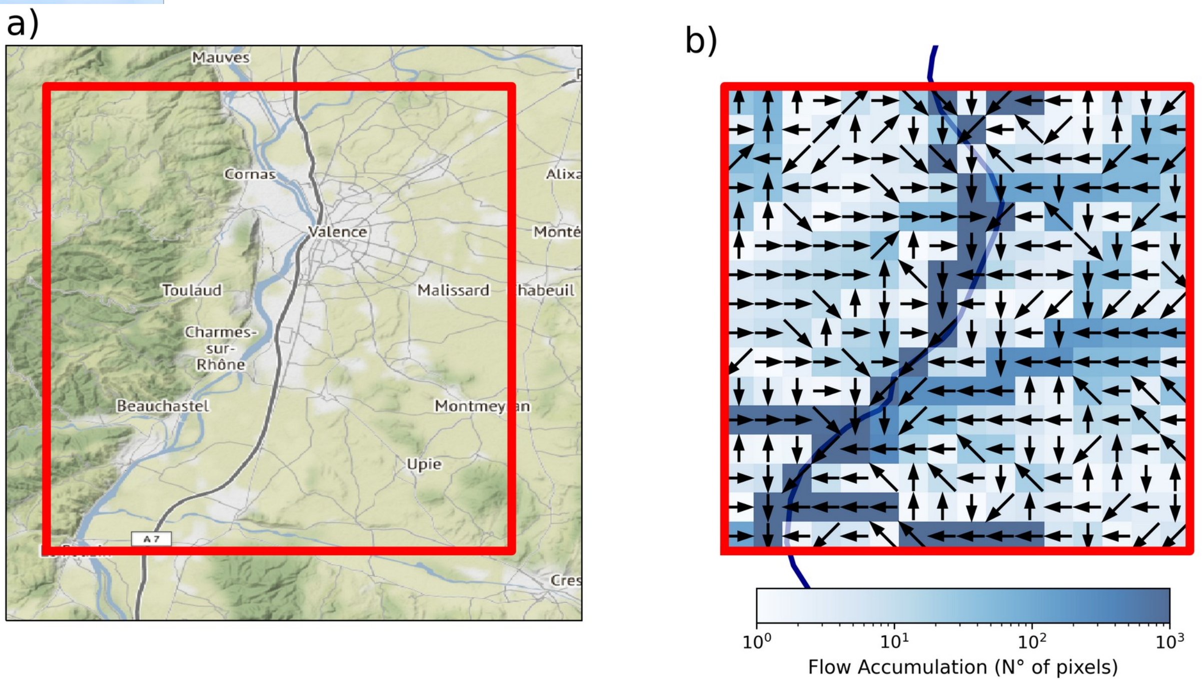
Data set	resolution	Domain	Choice of constants [s/km]: stream, fast, slow
Fekete & Vörösmarty (2000)	0.5°	Global	6, 80, 600
MERIT (Yamazaki et al. 2019)	2km	Global without Antarctica	6.3, 80, 600
HydroSHEDS (Lehner et al. 2013)	1km	Between -60° and +60°	6.3, 80, 600

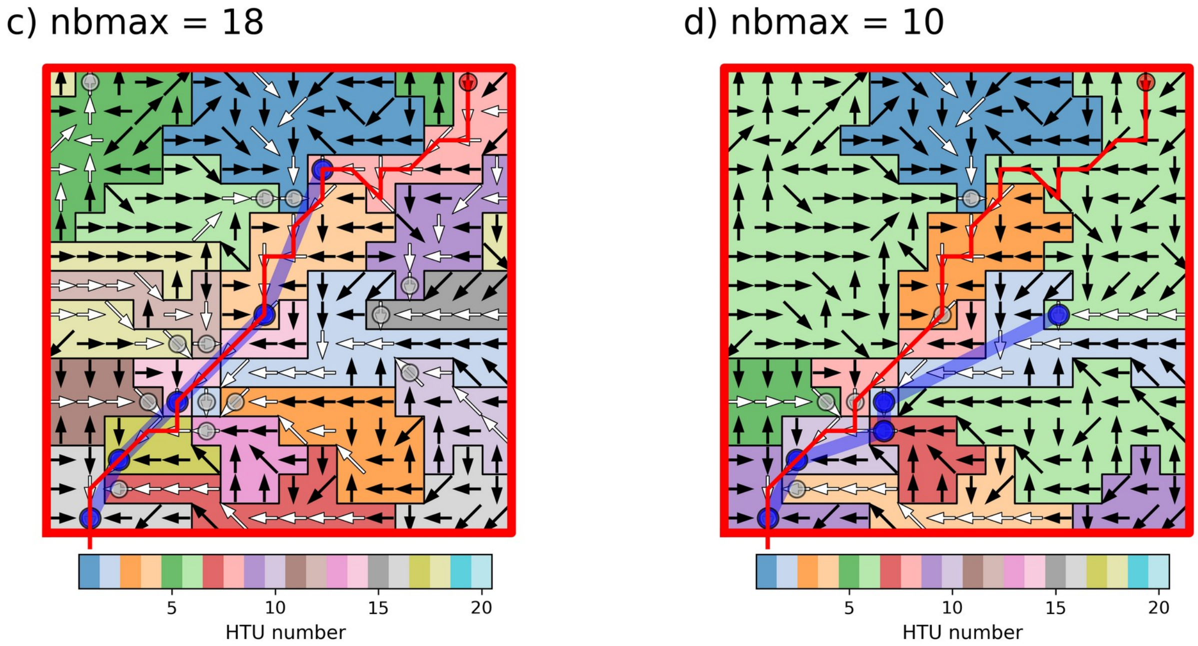
The atmospheric grids tested here

Grid name	Source	Resolution	Projection
WFDEI	WFDEI focing	0.5°	Regular lon/lat
E2OFD	E2OFD forcing	0.25°	Regular lon/lat
Med-CORDEX	RegIPSL	20km	Lambert conformal
EuroMED	RegIPSL	11km	Cassinin

- Euro-Mediterranean grids are used to demonstrate the methodology. Others have been used as well (no triangular grids yet !)
- The supermesh between the hydrological and atmospheric grids are built.
- Spherical geometry is used to ensure a wide validity of the methodology.
- The computations need to be done in parallel because of the volume of data to be handled.

The HTU graph produced from the HDEM




c) nbmax = 18

d) nbmax = 10

The algorithm is based on :

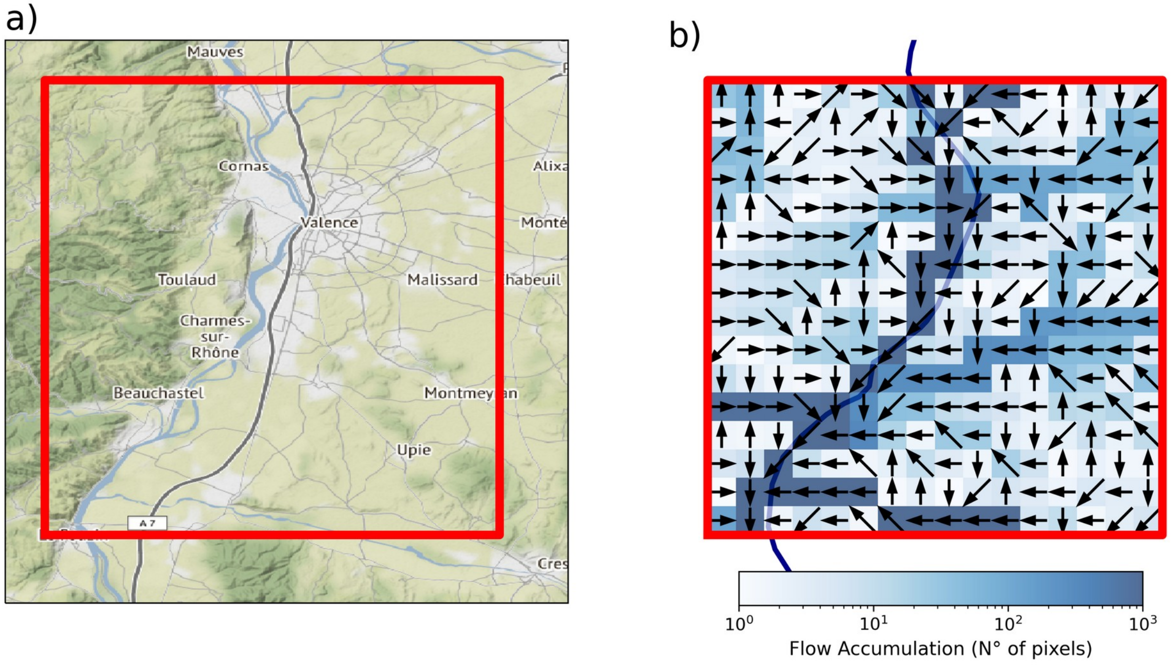
- Flow directions
- Flow accumulation
- Distance to ocean
- Topography

It produces for a selected number of HTU :

- A graph of HTU.
- Identifies main river in each HTU (white arrows).
- Topographic properties of each HTU.

Gauging stations, lakes, irrigated areas, dams and reservoirs are also placed on the HTU graph.

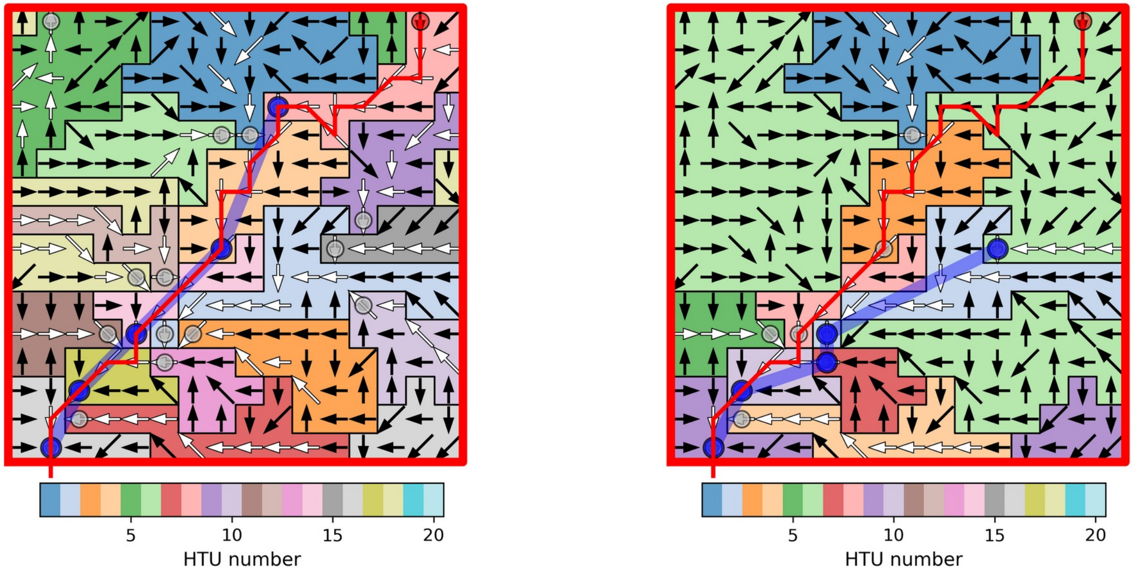
Validating the HTU graph


a)

b)

c) nbmax = 18

d) nbmax = 10



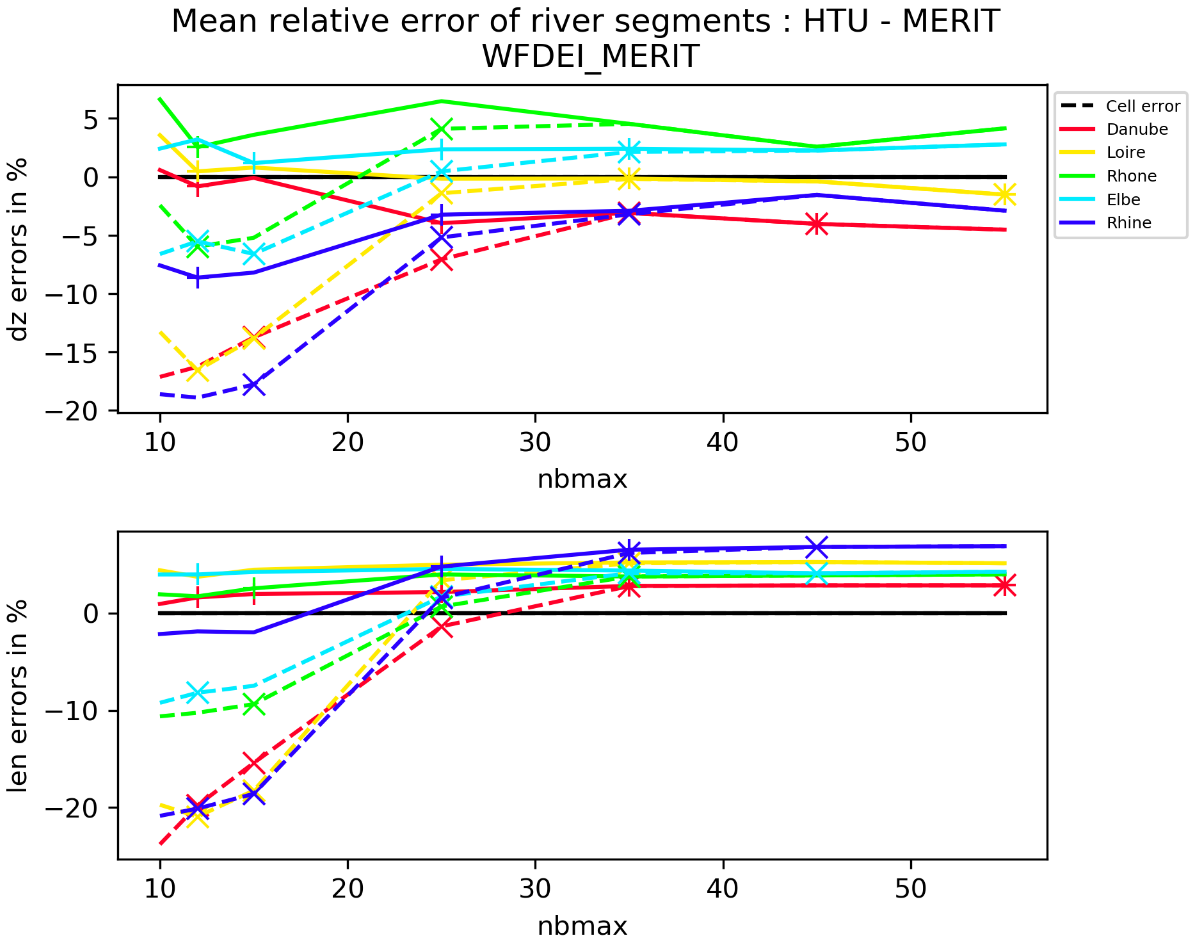
A large sample of river segments are randomly generated to validate the graph.
Their properties in the HDEM (red line) and HTU spaces (blue line) are then compared.

The pictures for nbmax 18 and 10 allow already to identify two types of errors :

- Cellular errors
- Topological errors

- Nbmax=18 : only a small cellular error in HTU=8
- Nbmax=10 : cellular and topological error in HTU=6.

Evolution of quality with number of HTU



Statistical evaluation with a large sample of segments :

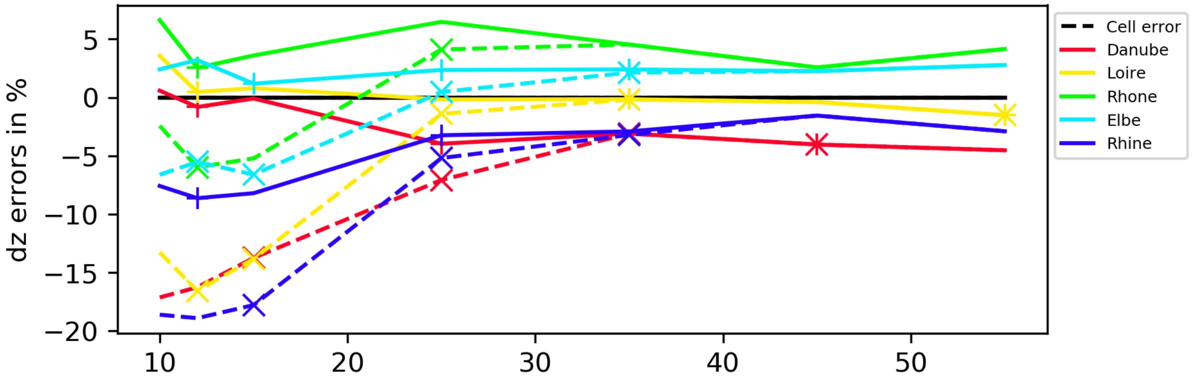
The total error (full line) and cellular errors (dashed) in length and elevation change of segments are compared for a range of nbmax.

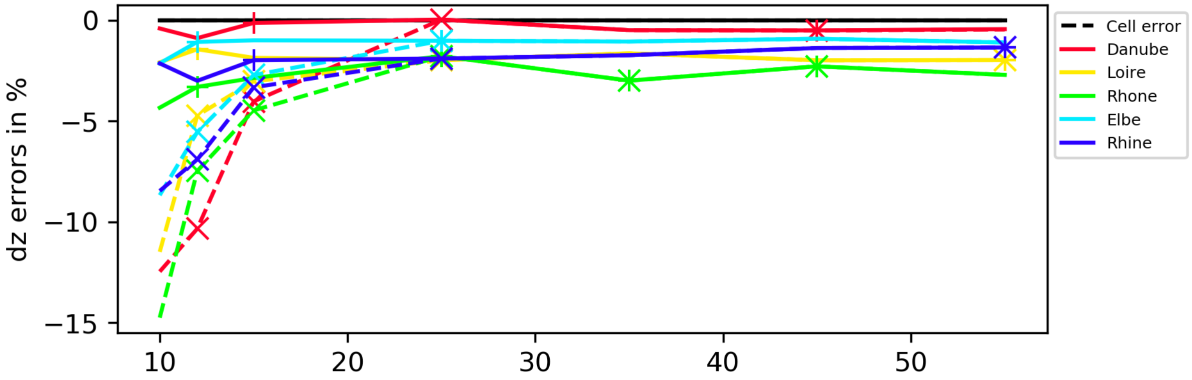
Crosses indicate that the change of error with nbmax is significant.

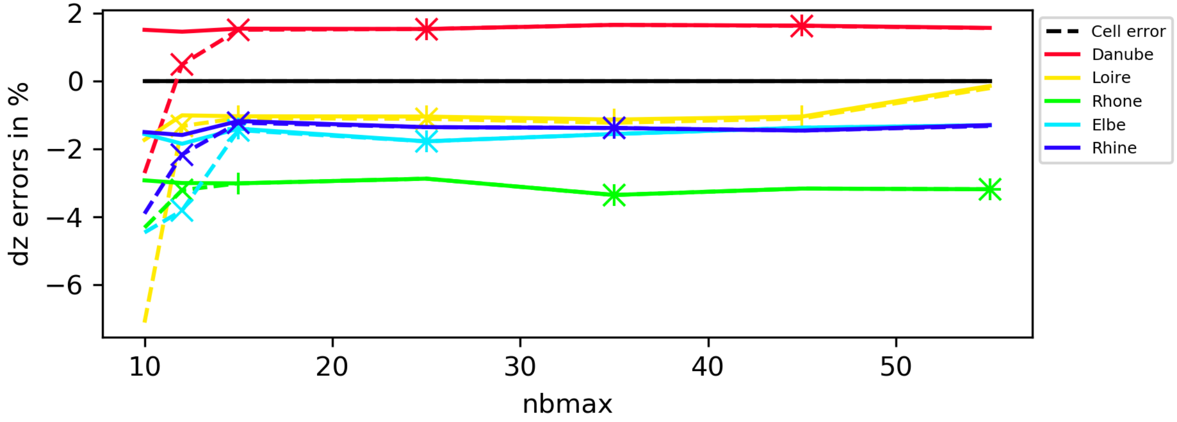
- Cellular errors are partly compensated by the topological errors.
- There is a small residual error remaining.

- As nbmax increases the errors reduce.
- The optimal nbmax for this grid (WFDEI at 0.5°) is 35.

Evolution with atmospheric grid


Mean relative error of river segments : HTU - MERIT
WFDEI_MERIT


Mean relative error of river segments : HTU - MERIT
MEDCORDEX_MERIT


Mean relative error of river segments : HTU - MERIT
EuroMERIT

3 grids are compared using the MERIT (2km) HDEM :

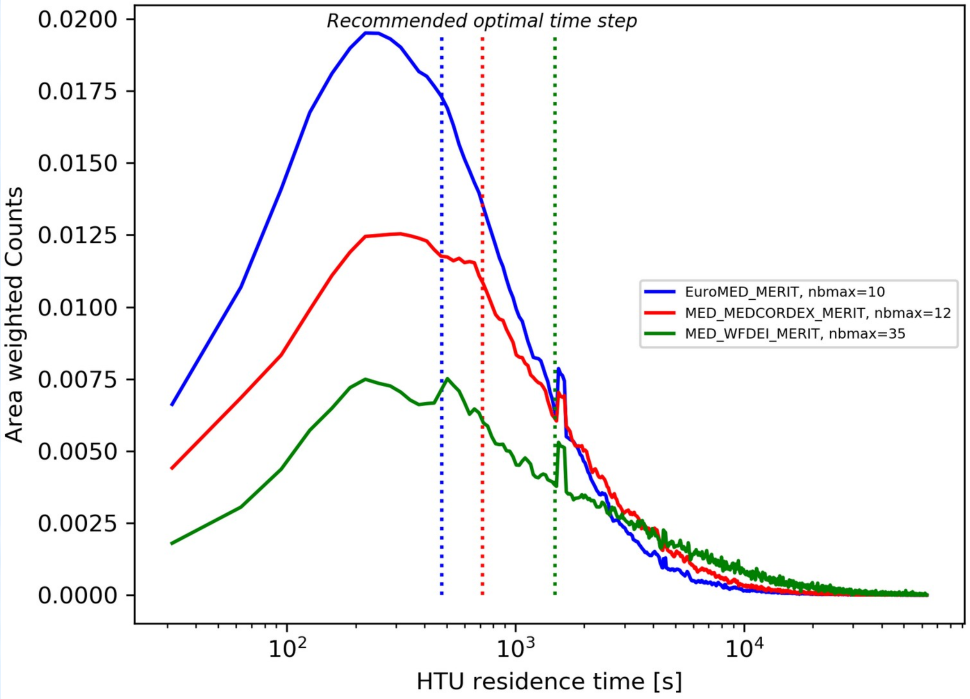
- WFDEI at 0.5°
- MEDCORDEX at 20km
- EuroMED at 11km

As the atmospheric grid is refined the HTU graphs become better :

- The residual error are different.
- Fewer HTUs are needed to obtain the same quality of graphs.

Comparisons between MERIT and HydroSHEDS graphs were also done.

Which time step is to be used ?

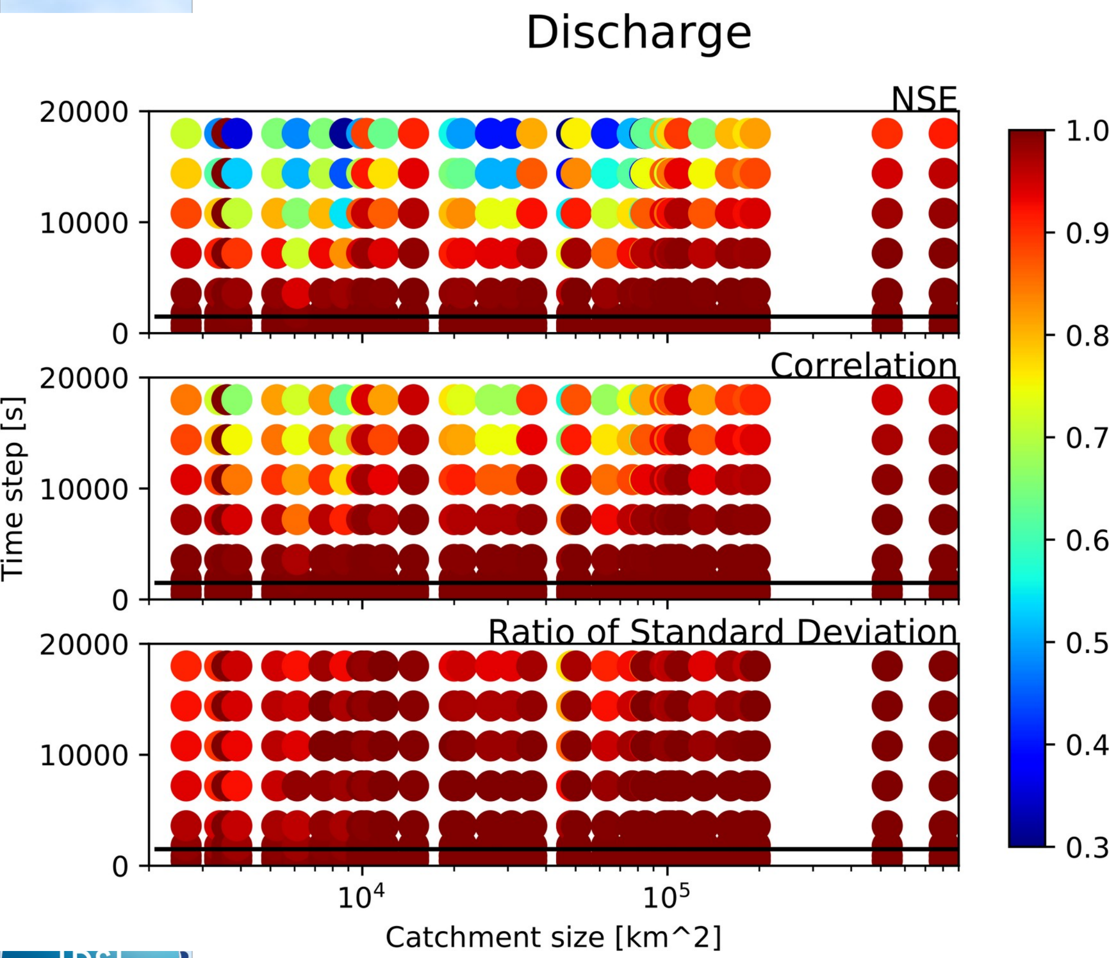


- To satisfy the CFL criteria the time step has to be smaller than the residence time.
- With our HTU decomposition we have a large range of residence times.

- The proposal is to use the 25% quantile of the area weighted distribution.
- A flux limiter is needed for the fastest HTUs.
- To test this hypothesis a forcing data set was extracted from a WFDEI simulation. Runoff and drainage are interpolated to the various resolutions.

Numerical solution on WFDEI grid

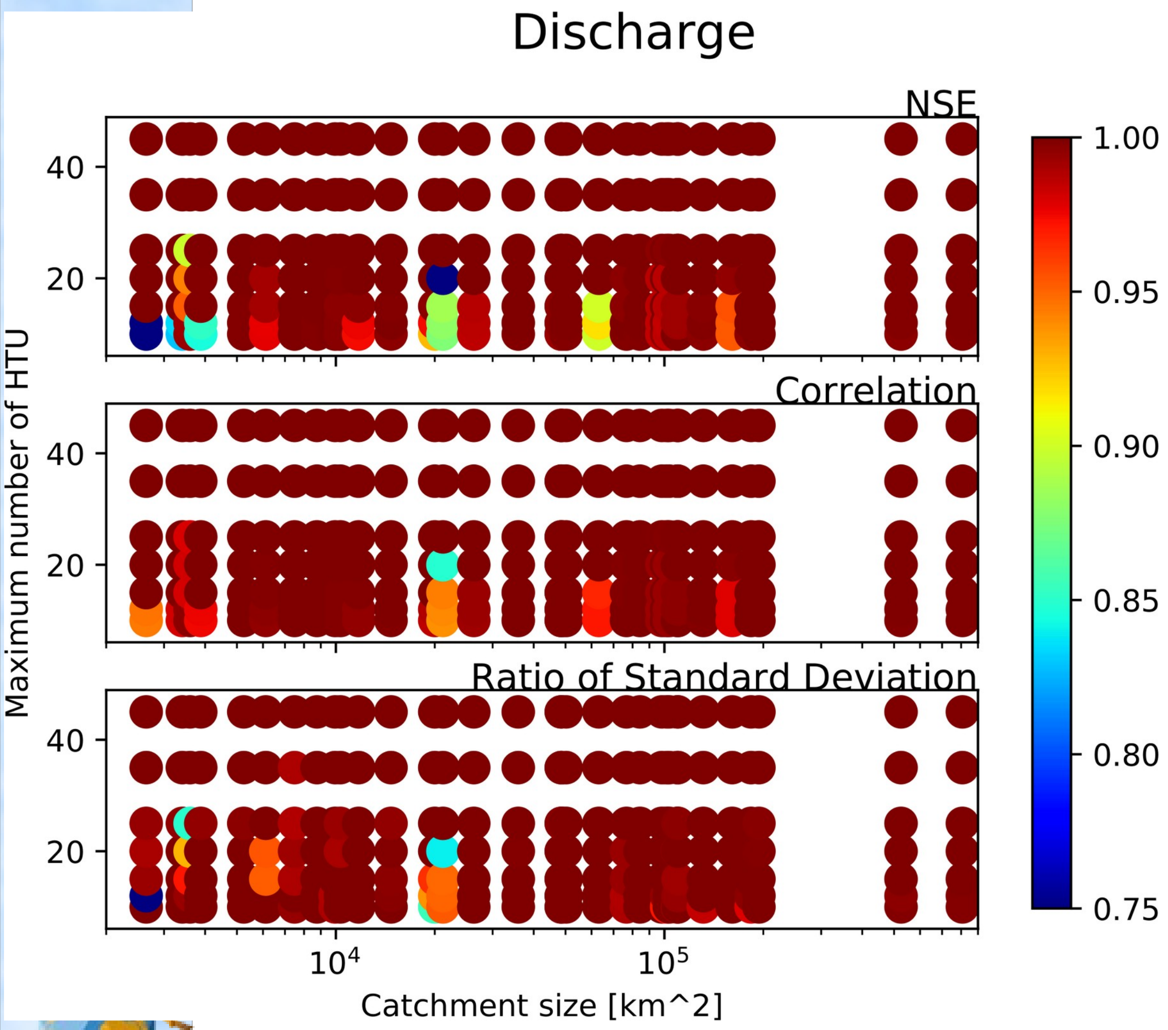
- The evaluation is done for 35 stations on European river.
- They are plotted sorted by catchment area (The smallest is about the area of the WFDEI grid).



- Three metrics are used : NSE, correlation and ratio of STD.
- The solution converges at the recommended time step.
- This is also true at the 3 other resolutions tested.
- Temperature is less sensitive to the time step.

WFDEI at 0.5° resolution

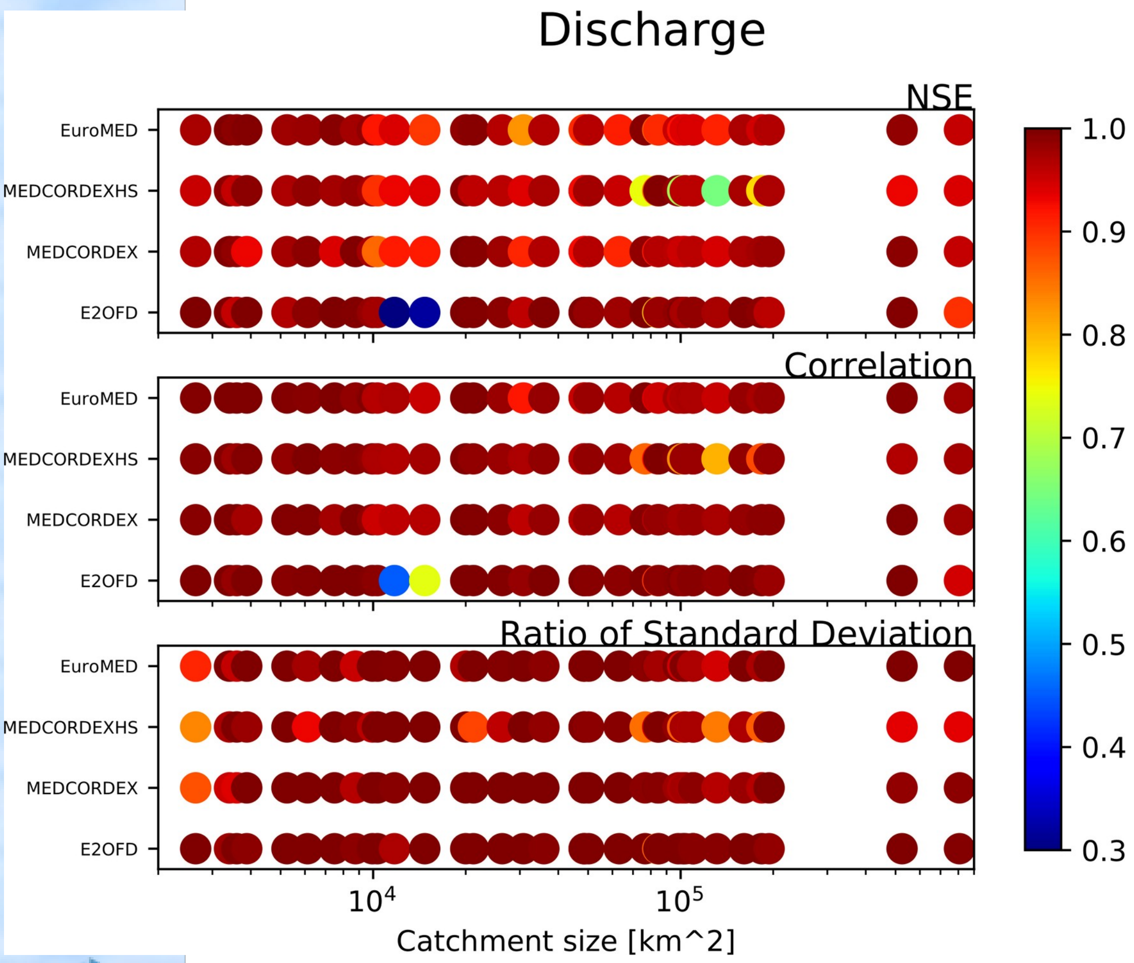
How sensitive are the solutions to nbmax ?



- The degradation starts below nbmax=35 for the 0.5° grid.
- This confirms our analysis of the graphs.

When comparing simulations with different grids or nbmax, the position of the station can also change. Both effects are thus validated.

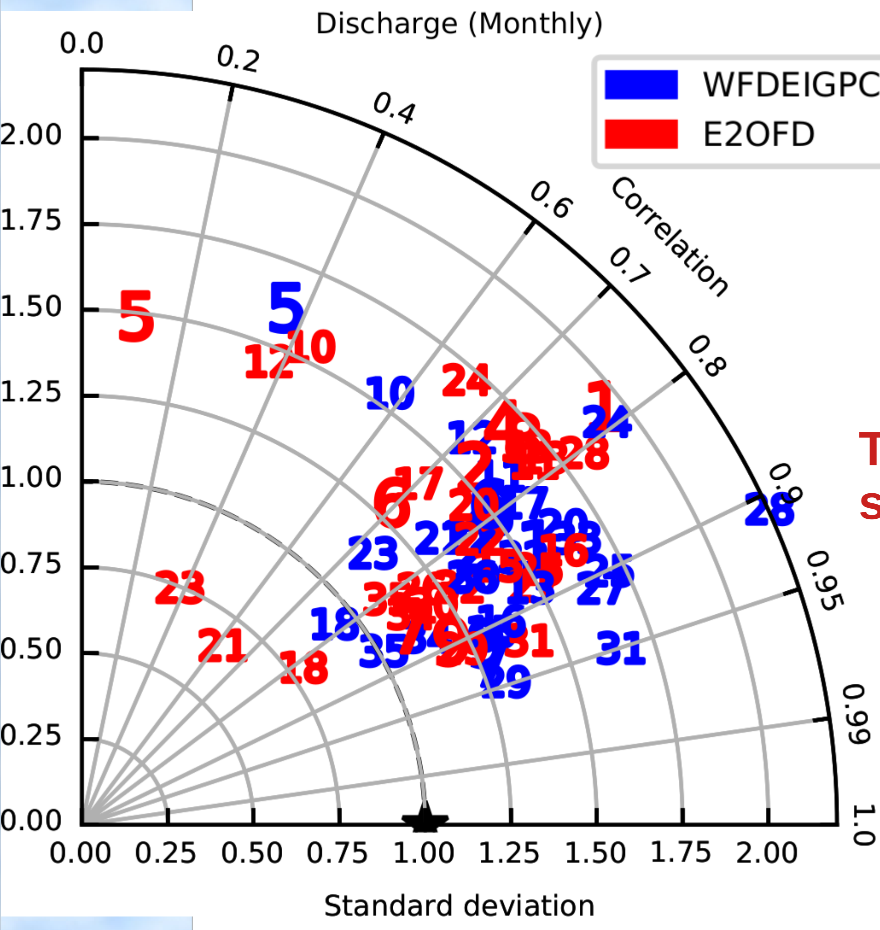
How sensitive are the numerics to atmospheric resolution ?

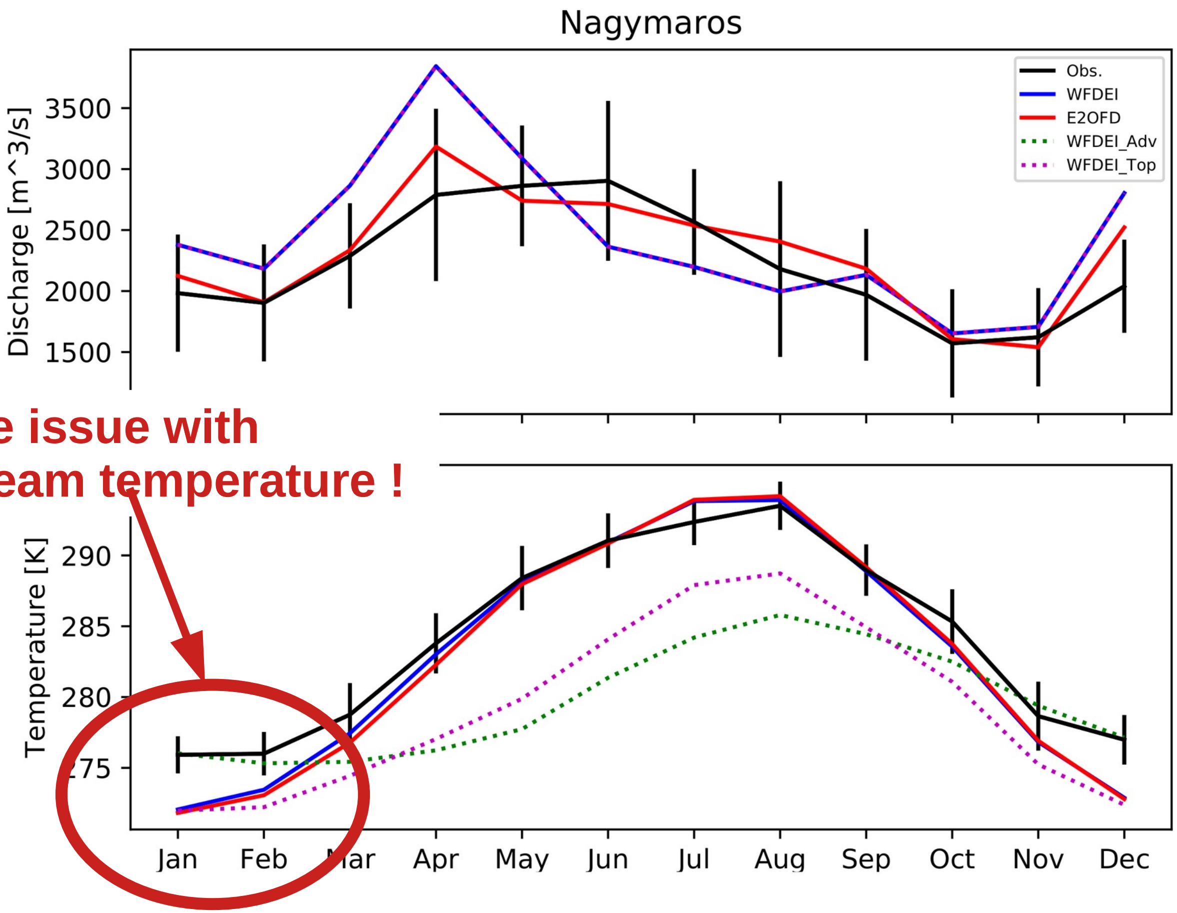


- The result are not changing strongly with the atmospheric grid.
- MEDCORDEXHS differs from MEDCORDEX only by its HDEM (HydroSHEDS vs. MERIT).
- A few stations are outliers. These are probably placement issues.

The numerical solution is stable and one set of parameters (g) is sufficient for the transport equation.

Validating the scheme with observations





The issue with stream temperature !

- Comparing simulated river discharge in ORCHIDEE to observations remains challenging !
- The human intervention on the river systems are larger than atmospheric uncertainties … which are themselves larger than numerical issues !
- The differences between both forcing are independent of the routing.

Possible sources of errors for stream temperature

Two factors determine the stream temperature :

1) Temperature at which water leaves the soil,

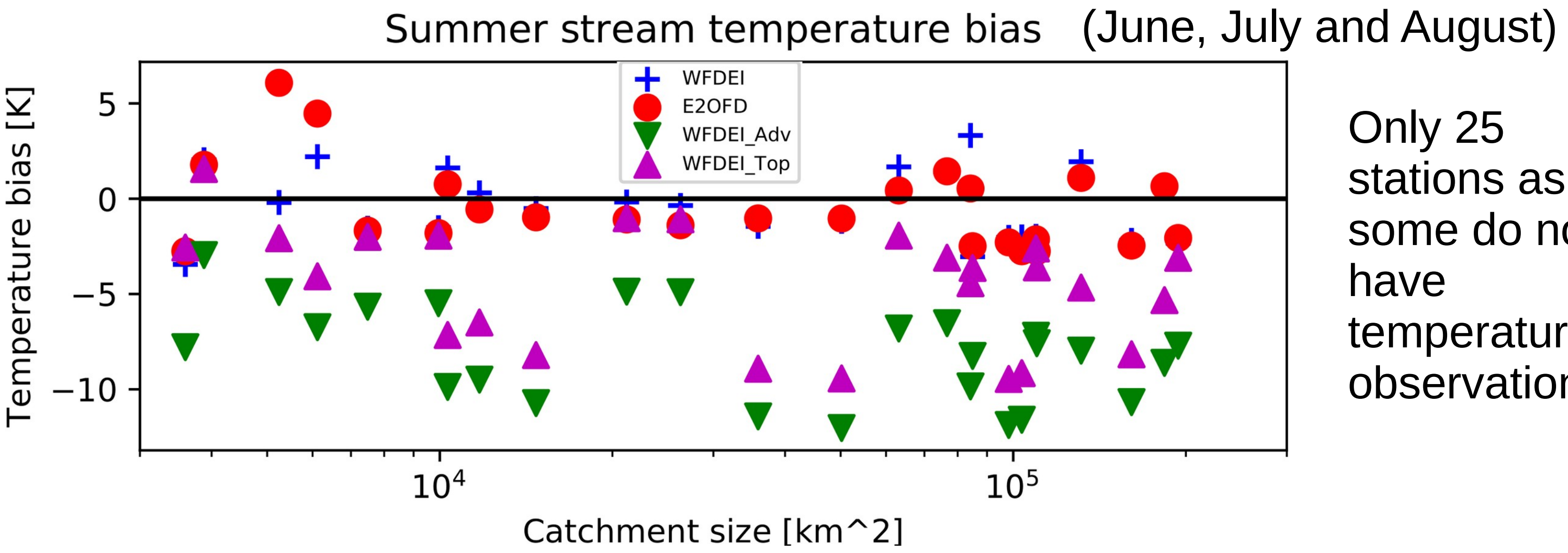
2) Interactions of the open water with the landscape and atmosphere.

How can we ascertain that by adding processes to 2) we do not compensate errors in 1) and vice-versa ?

In our simple set-up we can de-activate 2) (set relaxation to zero) to test some hypothesis. Two sensitivity experiments are proposed :

- **Adv** : runoff and drainage have different initial temperatures but no atmospheric interactions.
- **Top** : As above but both fluxes have the top soil temperature.

Impact on summer stream temperature

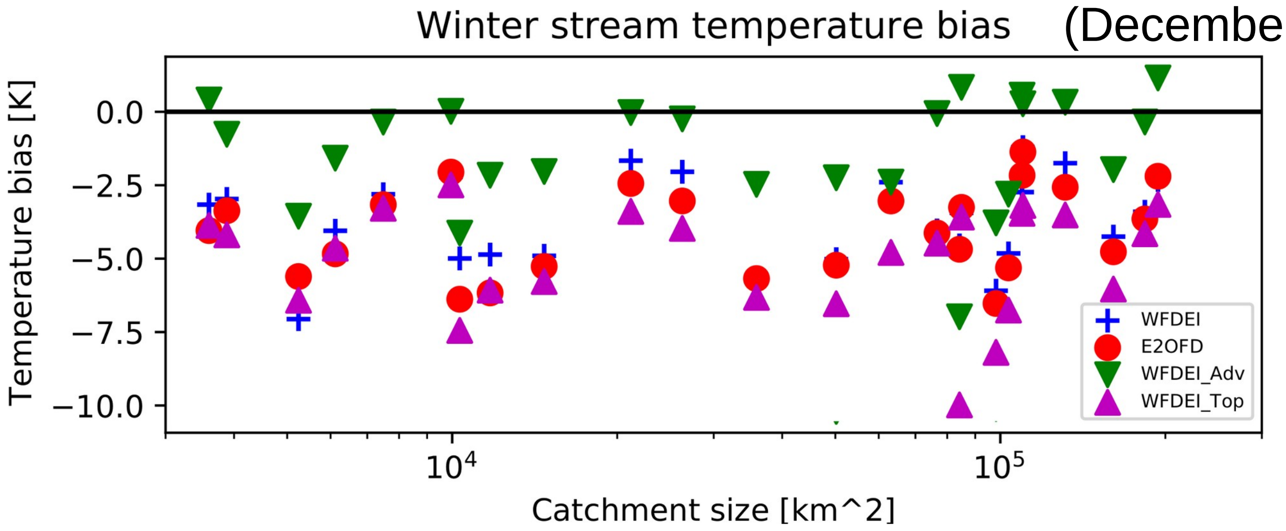


Summer stream temperature bias (June, July and August)

Only 25 stations as some do not have temperature observations.

- The reference simulations (+,●) are quite realistic given the challenge of simulating land surface temperature
- Without energy input from the landscape or atmosphere (▲ , ▼) stream temperatures are too low in summer.
- The initial temperatures still plays a role : ▲ vs ▼ .
- Realistic energy balance over streams and lakes will help here.

Impact on winter temperatures



(December, January and February)

- In this regions winter is the low flow season. Thus a more important role of groundwater.
- The rivers lose energy to the atmosphere in this seasons as they are warmer (compare ● and ▼).
- Without relaxation and using deep soil temperature for drainage the result is quite realistic (▼).
- We can conclude that we would need warmer groundwater temperatures to allow for the cooling to the atmosphere. This is particularly true in the Alps.

Conclusion

- The construction of the HTU is available here : https://gitlab.in2p3.fr/ipsl/lmd/intro/routingpp
- Surface water transport is a stable system on which we can now build more complex processes.
- Anthony showed that floodplains can be simulated and easily coupled to the atmosphere.
- Temperature is another application. It shows that groundwater needs to be better addressed in the scheme.
- Laure is now adding hydropower plants and irrigation (based on Xudong’s work).
- Marylin is adding lakes for the SWOT mission.