Status of ORCHIDEE's routing scheme development

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1 Introduction

We discuss here the computation of the mean topographic index λ for each of the HTU (Hydrological transfer units) within the atmospheric grid. The semi-distributed approach from hydrology is used to define the sub-grid elements which have the correct hydrological connectivity. That is the river graph is as close as possible to the one given by the original hydrological data.

This geometric parameter of the routing scheme describes the speed of the water flow and is defined as :

$$\lambda = \sqrt{\frac{d^3}{dz}} \tag{1}$$

where d is the length of the river segment considered and dz the elevation change of that river segment. Both variables are given in meters and the resulting λ is converted to kilometres. λ can also be expressed in terms of river segment length and slope (Ducharne 2020 [3]). Multiplying the topographic index (λ) by a constant, which is in units of an inverse speed, will give the emptying time characteristic of the stores in the routing scheme.

2 Information from the hydrological file

The hydrological files (HydroSHEDS, MERIT or Fekete & Vörösmarty (FV)) do not only provide flow direction but also river length and hydrological corrected elevation changes (i.e. water cannot run up-hill) which will be exploited in order to compute the properties of the river at their resolution.

The hydrological files are always at higher resolution than the atmospheric grid for which we wish to compute river discharge. We thus need to aggregate the information to the level of the HTUs.

In the following discussion the information of the hydrological grid (called pixels here) will always be indexed with i and we will use the following variables :

- d_i : river length on the hydrological grid.
- dz_i : elevation change within the pixel.
- λ_i : computed with equation 1 applied to the pixels of the hydrological grid.

3 Construction of hydrological transfer units (HTU)

The concept of HTU is very close to what is used in other hydrological models such as Chaney et al. [1], Coxon et al. [2] and Fleischmann et al. [4]. This class of hydrological model is classified as semi-distributed.

The general idea is to generate within ORCHIDEE a sub-grid tiling which preserves the hydrological continuity.

For each HTU we define the mainstream river pixels by following the pixels with the largest flow accumulation going upstream from the outflow.

3.1 Area driven HTU decomposition

This method of decomposition is the one developed by Trung Nguyen [5] and aims to have about the same size for all the HTUs within an atmospheric grid. One important condition is that each outflow direction of the atmospheric grid has to be in a separate HTU in order to preserve as much as possible the diversity of hydrological flows out of the atmospheric grid.

Each HTU with an area larger than 2% of the atmospheric grid will be subdivided further. To perform this subdivision, we consider the local flow accumulation at the outflow of the HTU fac_loc_out. It is representative of the surface of the HTU. Then we follow the main stream river to find the pixels which is closer the to $fac_loc_out/2$. This allows to divide the current HTUs in 2 HTUs with a similar area. The methodology is illustrated for one outflow point of an atmospheric grid in Figure 1.

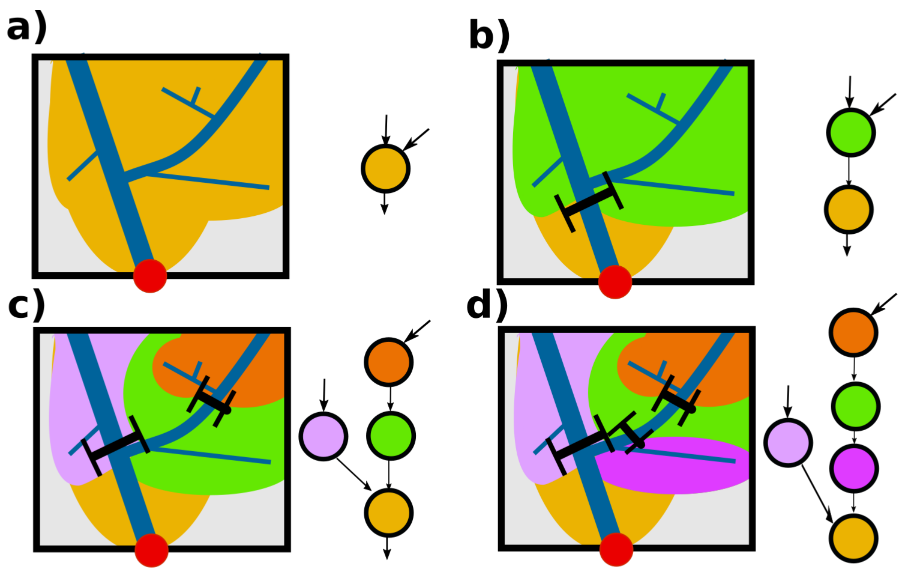

Figure 1: Schematic steps of the generation of HTUs with a area driven decomposition. It is illustrated here for one outflow point of an hypothetical atmospheric grid box.

The issue with this method is that, although it will optimise the generation of equal area HTUs, it will divide the major rivers in many segments as demonstrated in Figure 1. This may have consequences on the quality of representation of large rivers and the stability of the routing scheme.

3.2 River driven HTU decomposition

This methodology has been developed with the aim to preserve river segments flowing through the atmospheric grid would allow to better estimate their parameters (λ). It will also allow to control the impact of this rapid flow in the rivers on the time step of the routing scheme.

The first step is the same as the area driven HTU decomposition presented above. An initial HTU is constructed for each outflow of the grid point and contains all the pixels flowing to this outflow point (cf Fig. 2.a).

Then for each HTUs we have 2 level of decomposition :

- divide the HTUs to represent the large-scale structures : create new HTUs containing the tributaries of the mainstream river having the largest global flow accumulation (cf Fig. 2.b),
- if the next largest global flow accumulation is at the confluence, then the original river segment is divided (Fig. **??**.c)
- divide the HTUs to represent the local hydrological structures create new HTUs containing the tributaries of the mainstream river having the largest local flow accumulation - flow accumulation calculated over the grid point containing the HTU only - (Fig. 2.d).

This type of decomposition allows to keep various important features of the river network : (1) keep the major river pathway undivided so we limit the instability related to the too frequent divisions of the major river; (2) better represent the large scale feature by generating separated HTUs for the most important tributaries (important in terms of upstream area); (3) improve the representation of the local features HTUs with a small upstream area but occupying more space on the grid point. It sacrifices the objective of having HTUs of similar areas.

3.3 Achieving the truncation requested by the user

In both methods for decomposing the HTUs presented above, we will generate in a first phase more HTUs than the user has selected with the *nbasmax* parameter. Thus we need a process in which we assemble HTUs with as little impact as possible on the river graph as possible.

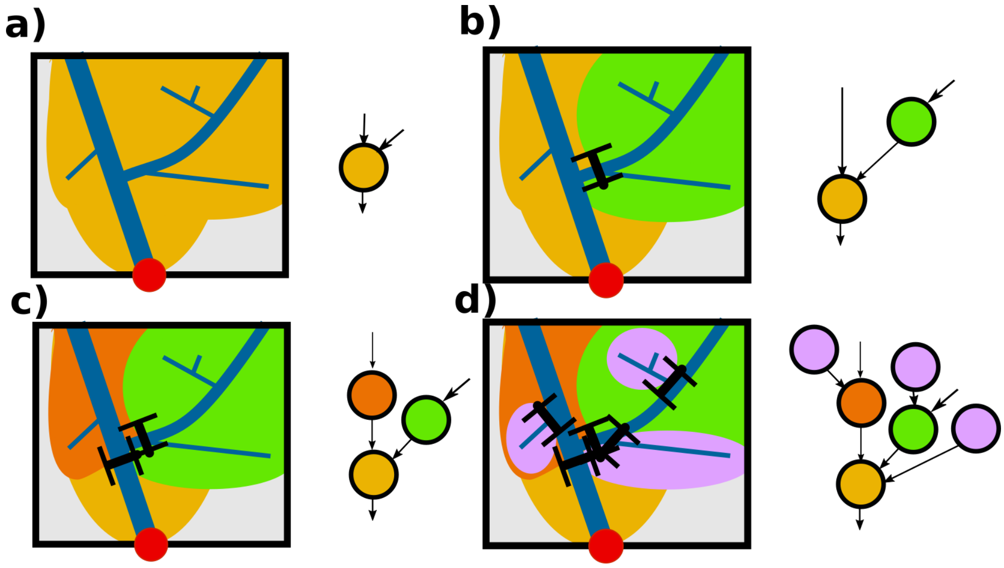

Figure 2: Schematic steps of the generation of HTUs with a river driven decomposition on the same case as in figure 1.

The HTUs with the smallest flow accumulation area are merged first and we only merge HTUs flowing into the same neighbouring atmospheric grid. This will allow to reach the *nbasmax* HTUs requested with a minimal impact.

This procedure is used less often for the "river driven decomposition" as the number of HTU achieved is closer to the truncation selected by the user.

4 Properties of HTUs

A number of options have been implemented to compute mean topoindex for each HTU using the original information from the hydrological file at the pixel level. The methods are taken from Ducharne 2020 [3] and some further tests were added to test the system.

At this stage each HTU still includes more than one river segment. All these rivers only have one outflow point, the one of the HTU. Each of these river segments has a different source or inflow points but they are converging to only one outflow.

This can be written as r rivers segments of length $n_j$with$j \in \{0, r\}$ which connect the information of the hydrological grid within the HTU. The weight of each river segment j within the HTU is given by $\alpha_j = n_j / \sum_{i=0,r} n_i$. As the rivers can converge before the outflow of the HTU, $\sum_{i=0,r} n_i$ is not the area of the HTU. It is larger or equal as some points can be counted more then once.

The problem at hand is to estimate the mean topographic index for this HTU. Two options are available.

4.1 Averaging topoindex

An idea implemented here is to sum topoindex over the river segment and then average between all segments. The original topoindex (λ_i) has been computed on the pixels of the hydrological grid.

The topoindex for river segment j is given by :

$$\Lambda_j = \sum_{i=0,n_j} \lambda_i \tag{2}$$

A weighted average of all river segments yields a representative topographic index for the HTU $\overline{\Lambda}$:

$$\overline{\Lambda} = \sum_{j=0,r} \alpha_j \lambda_j \tag{3}$$

An alternative to this method, which is closer to the proposal in Ducharne 2020 [3], is to sum topoindex from each grid point within the HTU to the ouflow point. This could be written as follows :

$$\Lambda'_i = \sum_{i=0,n_i} \lambda_i \tag{4}$$

where n_i is the river segment from point i to the outlow. The HTU average would be same as in equation 3 but now obviously over all points within the HTU. This method provides more weight to the most downstream points of the HTU as they are counted more often.

4.2 Averaging river length and slope

Another approach is to compute the geometric parameters of each of the r river segments, average them over the HTU and only then compute the topoindex.

The river segment length and elevation changes are given by :

$$D_j = \sum_{i=0,n_j} d_i \tag{5}$$

$$dZ_j = \sum_{i=0,n_j} dz_i \tag{6}$$

$$\tag{7}$$

Using the same approach a representative river length and elevation change can be computed for the HTU :

$$\overline{D} = \frac{1}{r} \sum_{j=0,r} D_j \tag{8}$$

$$\overline{dZ} = \frac{1}{r} \sum_{j=0,r} dZ_j \tag{9}$$

$$\tag{10}$$

Using these representative geometrical properties of the HTU applied to equation 1 we obtain the following formula for the topographic index :

$$\overline{\Lambda} = \sqrt{\frac{\overline{D}^3}{\overline{dZ}}} \tag{11}$$

4.3 Topoindex for river driven HTUs

As in this decomposition of the atmospheric grid the HTU is driven by a river segment and most of the areas are sloping towards the river, we have chosen to introduce a topoindex specific for the river : Λ_s.

During the decomposition the length of the river segment (D_s) and the elevation change (dZ_s) are computed explicitly. In order to avoid the accumulation of small errors in the original hydrological data, the elevation change of the river segment is computed between the most upstream and most downstream points. As for the hydrological files we have to impose a minimum dZ_s. It is set to $0.1\,m$ here. We can then write :

$$\Lambda_s = \sqrt{\frac{D_s^3}{dZ_s}} \tag{12}$$

For the slow and fast reservoirs (which are assumed to represent the flow of the slopes into the river segment) the topoindex are computed as presented in equation 3. The sum is performed over the various small tributaries to the main river of the HTU and which are then averaged.

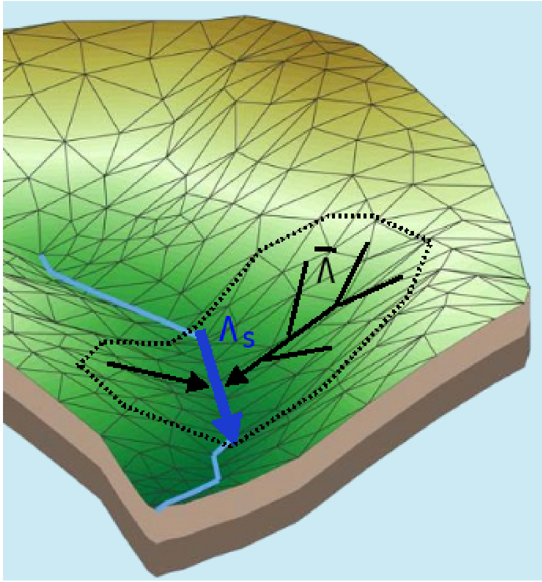

Figure 3: Illustration of an HTU obtained y a river driven decomposition. It shows the distinction between the segment of the river and the small tributaries.

5 Preserving properties when merging HTUs

In the routing pre-processor the user chooses the truncation of the routing schemes by selecting the number of HTUs per atmospheric grid box needed. This is the nbasmax parameter.

In a second phase the original HTUs discussed above are merged in order to reduce the resolution of the routing scheme in terms of HTUs (truncation). Thus a method needs to be devised in order to be able to provide representatives properties for the merged units.

Two methods are possible here as well :

- In all cases a weighted average of the HTU properties are computed for the merged unit. The weight being the area of the HTUs.
- If one of the HTU flows into the other and their mean elevation difference is larger than the average elevation change ($\overline{dZ}$) of both units, then the properties are summed.

The second method could be refined as we have at our disposal also the maximum and minimum elevation of the HTUs.

6 Analysis of the resulting topographic indices

The analysis will be presented for three cases : nbasmax=10, 35 and 55. Obviously in the first case the merger of HTU will play an important role. In the second and third cases the merger will be less used in the code.

The focus will be on the probability distribution of the resulting topoindex for the HTUs obtained for South America on the 0.5° grid of WFDEI. For reference the distribution of λ_i for the 2km MERIT grid and 0.5° FV grid will also be presented. To avoid the issues with the resolution of elevation in MERIT (which causes a strong peak above values of 200km), the representation of its histogram is limited to values of λ_i below 200km.

Within MERIT each topoindex value represents about the same area as it is a regular longitude/latitude grid. On the atmospheric grid (WFDEI here) we have to be more careful as the HTU can be of very different areas. Thus the graphics provide in the top panel the simple distribution of $\overline{\Lambda}$ while in the lower panel the values of the topoindex are weighted by the size of the HTU.

The configurations compared are provided in table 1.

Experiment	Option for initial HTUs	Option for HTU merger
Asum	Sum topoindex along river segments and weighted average of river segments.	Area weighted average of HTU topoindex.
Xsum	Sum topoindex along river segments from all points of the HTU and weighted average of river segments.	As in Asum.
Bsum	Average river length and elevation changes are use to compute a representative topoindex	As in Asum
Csum	As Bsum	Sums of topoindex are used if one HTU is clearly above the other, else as above.

Table 1: The configurations tested to evaluate the impact on the distribution of topoindex.

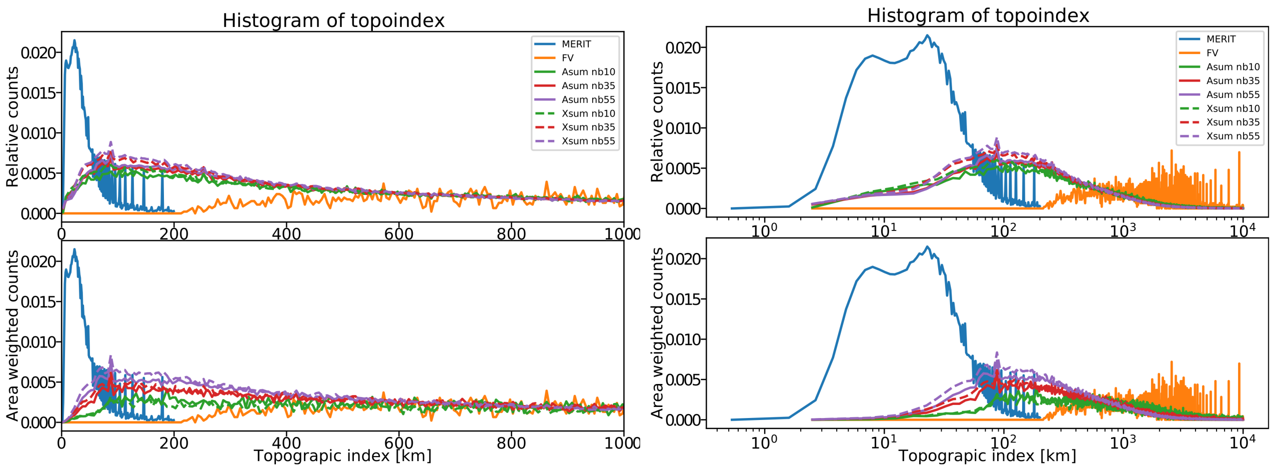

Figure 4: Comparing the Asum and Xsum methods for computing the first stage HTU properties. Figures for three truncations : nbasmax=10, 35 and 55. The top row shows the distribution of the topoindex while the lower row where topoindex are weighted by the area of the HTU. The left column provides the results on a linear X axis while the right column displays the distributions on a logarithmic axis. The linear X axis is limited to the 0 to 1000km.

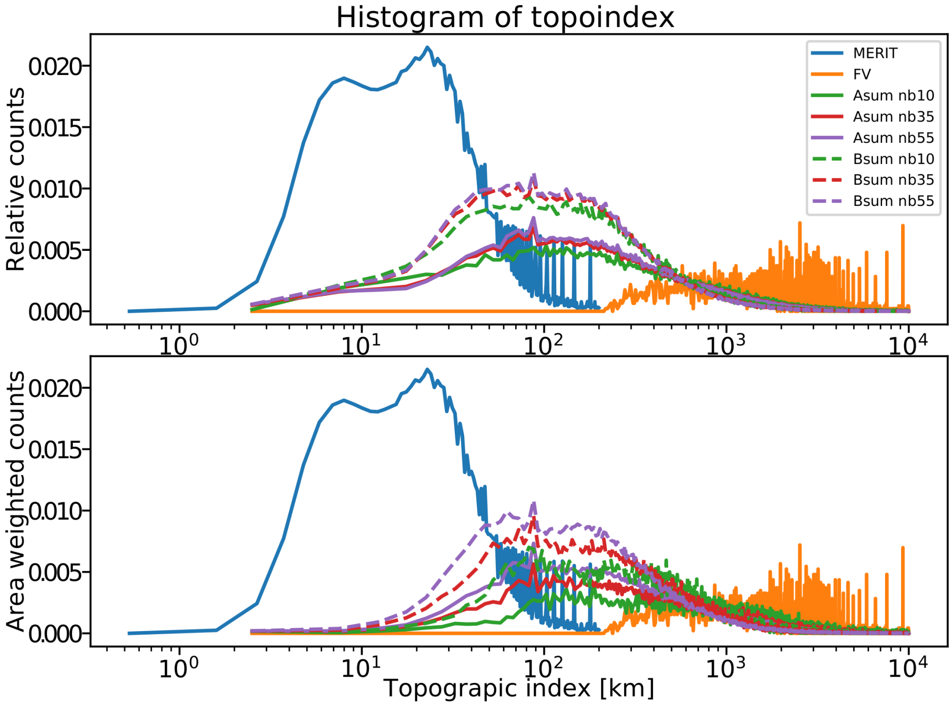

Figure 5: Comparing the two methods for computing the first stage HTU properties (Asum and Bsum). Figures for three truncations : nbasmax=10, 35 and 55. In the top graph shows the distribution of the topoindex while in the lower one each topoindex value is weighted by the area of the HTU.

Comparing Asum and Xsum : The various methods to compute representative properties of the HTUs are compared using the probability distribution of values over the entire South American domain. In figure 4 we show the properties it allows to illustrate based on the comparison of Λ computed either equation 3 or 4.

The first column of figure 4 shows that in particular for coarse resolution (FV in particular) the distribution tails-off quite slowly. The most relevant information is for smaller values of the topographic index where we count the largest number of HTUs (for ORCHIDEE) or pixels for MERIT. FV does not show any peak at smaller values and this is probably because of its low resolution and the important simplification of the routing graph it contains.

Looking at the distribution plotted with a logarithmic abscissa allows to focus on peak of the distribution and better see the differences between the various assumptions. As the area under the distribution is by definition one, a change in the peak will be compensated by an opposite change in the tail fo the distribution.

When we compare the two methods to compute Λ (Asum vs Xsum) we note a rather small change. Xsum keeps a higher peak but the differences with Asum are smaller than when changing nbasmax.

Comparing Asum and Bsum : With this comparison we compare the averaging of λ to computing Λ with average geometrical properties for the HTU (river length and slope).

Figure 5 shows that both methods for computing the topoindex provide a peak between 40 and 200km. This is larger than for MERIT (peaks between 6 and 20km) but lower than the distribution of FV (MERIT is provided on a 2km resolution grid while FV is on a 0.5° grid). The HTU decomposition allows to preserve some of the details of the hydrological network of MERIT. In the case where $\overline{\Lambda}$ is computed by averaging λ_i ("Asum") the distribution is flatter and less HTUs with smaller scales than in the "Bsum" case are preserved.

The information preserved for low topoindex values is within small HTUs as can be seen by comparing the upper and lower panels of figure 5. The area weighting brings large difference between nbasmax values. The distribution of "Bsum" at nbasmax=10 is now equivalent to "Asum" at nbasmax=55. This shows that "Bsum" better preserves the properties of the routing network for small

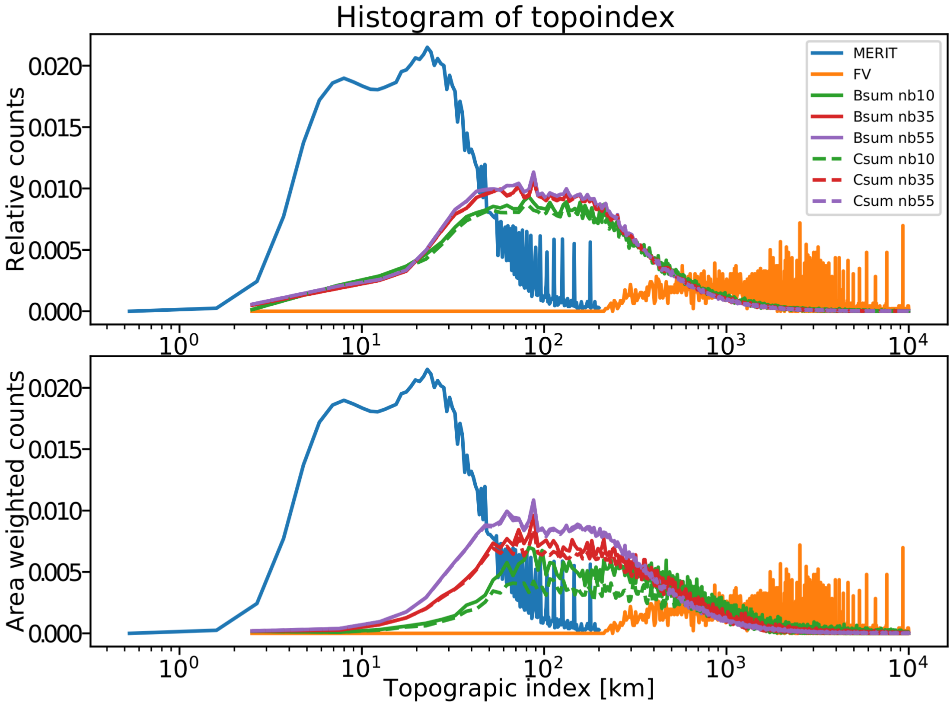

Figure 6: As above but comparing the two methods for merging HTU properties in the second phase : Bsum and Csum.

HTUs.

In none of the cases the double peak of the MERIT distribution over this regions is preserved.

The fact that the histogram for ORCHIDEE is shifted to larger values of topoindex is logical as the effective resolution on the atmospheric grid is lower than for MERIT.

One can expect that the "Bsum" method will better preserve regional characteristics within the domain. If this is only the case for small HTUs then it will be of little consequence on the simulated discharge. This is to be verified with simulations of the river discharge.

Comparing Bsum and Csum : Figure 6 illustrates the impact of adding the option to sum the topoindex when cascading HTU are merged. One sees that the impact is smaller than the assumption in the first phase of the HTU construction. The cascading option will only reduce the number of HTUs when lower values of nbasmax are chosen. This can be seen in Figure 6 as the impact is larger for nbasmax=10 than for nbasmax=55.

As expected, when the topoindex are added at the merger of HTUs displaces the entire distribution shifts to larger values. This becomes visible for nbasmax=10.

Comparing Csum to results of the river driven HTU decomposition : The new subdivision of HTU which favours the river segments produces a distribution of topoindex not dissimilar to the one of the Csum case. There are a few item worth noting :

- The difference between the distribution of topoindex with or without are weighting is much larger for the river driven HTU decomposition. An expected result as a broader range of areas of the HTUs will be obtained.
- The general shape of the distributions for Csum and the new subdivision are quite similar.
- The distribution of the stream topoindex will be slightly displaced toward larger values but also narrower. There are fewer HTUs with stream topoindex larger than 500km.
- The distribution in the river driven decomposition is more sensitive to truncation than for the area driven decomposition.

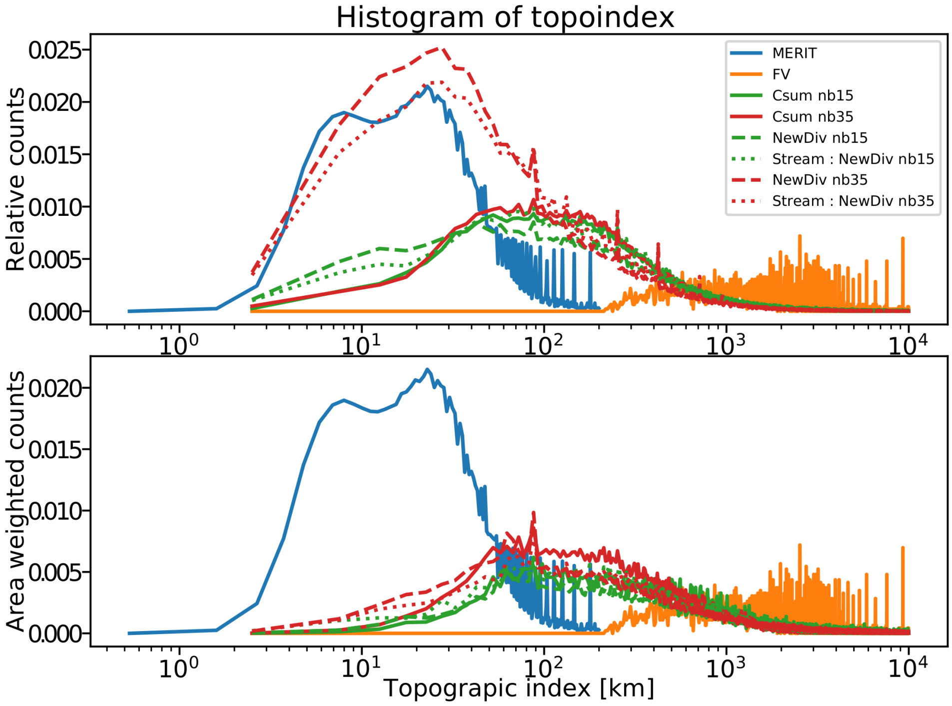

Figure 7: Comparing the topoindex distribution of Csum and the one obtained with the river driven HTU decomposition. In the latter case we also show the distribution of the topoindex for the stream reservoirs.

7 Geometric characteristics used

As we now follow the representative length of the river (D_i) and elevation change (dZ_i) per HTU, we can evaluate their realism against MERIT and HydroSHEDS between selected gauging stations.

This has been done between Obidos and three upstream stations : Serrinha, Manacapura and Porto Velho. See the map in figure 8 for the geographic details.

The distance and elevation change can be estimate from HydroSHEDs and MERIT on their respective grid. For this discussion only Obidos-Serrinha is considered :

Obidos-Serrinha	HydroSHEDS	MERIT
riverlen	1389 km	1750 km
riverdz (sum with minimal step of 0.1 m)	1668 m	121 m
delta orography (max-min)	35 m	24.4 m

The same statistics are given for various configurations of the routing graph. Figure 9 shows the results corresponding to the Obidos-Serrinha segment.

The representative geometrical characteristics computed for the cascade of HTUs between the two stations is quite different from the number in the original data.

Two issues are identified :

- The construction of the HTU does not give priority to the main rivers but is rather oriented towards sub-dividing the area atmospheric grid. Thus HTU properties are not driven by the main course of the river but are result from the combination of any number of tributaries to the main river.
- There are also problems with the elevation changes within MERIT and HydroSHEDS. The sum of dz_i is biased by the fact the minimum value is set to 0.1m even though the elevation change is smaller. When averaging topoindex or computing topoindex with average properties (section 4.2) we accumulate the errors in MERIT.

As the river driven HTUs are based on the mainstream river. We have been able to extract some extra information about the distance and difference of altitude among the mainstream river. The

Figure 8: Map of the stations considered along the Amazon.

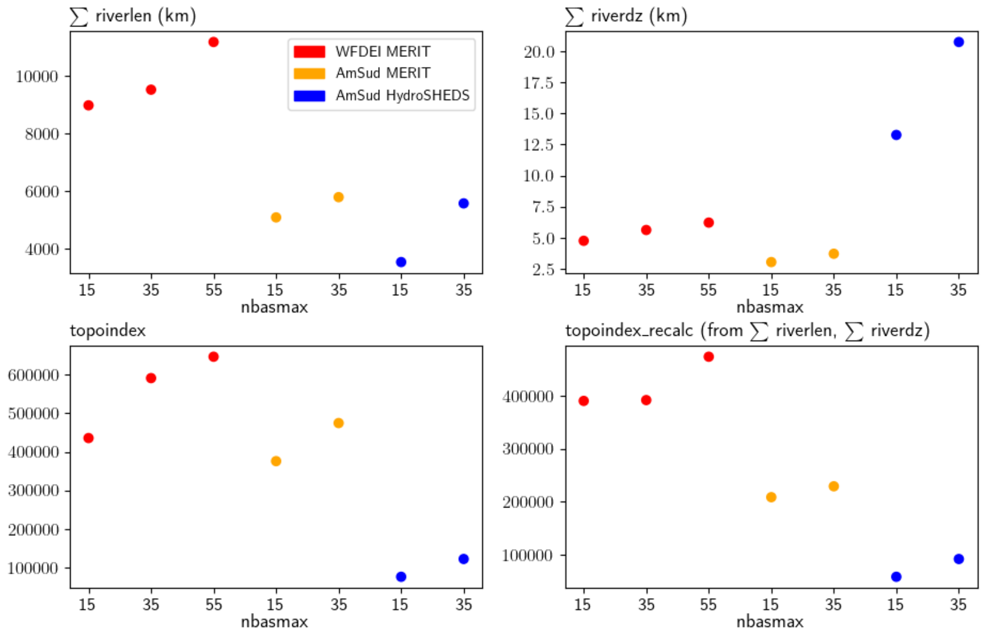

Figure 9: The statistics of the routing graph on the segment of the Amazon between Obidos and Serrinha. River segment length, elevation change and sum of topoindex for difference choices of nbasmax and grids.

River length (km)				
	MERIT	nbasmax = 15	nbasmax = 35	nbasmax = 55
Porto Velho	1747	995	1093	1270
Serrinha	1531	1054	1134	1318
Elevation change (m)				
	MERIT	nbasmax = 15	nbasmax = 35	nbasmax = 55
Porto Velho	52	319	169	53
Serrinha	24	223	112	42

Table 2: River length and elevation changes between Obidos and two upstream stations along the Amazon. The quantities are estimated from the MERIT data set and computed in the model for the river driven HTU decomposition at different truncation.

River length (km)				
	MERIT	nbasmax = 15	nbasmax = 35	nbasmax = 55
Posadas	394	410	410	479
Porto Murtinho	1095	609	677	943
Salto del Guaira	985	764	778	970
Elevation change (m)				
	MERIT	nbasmax = 15	nbasmax = 35	nbasmax = 55
Posadas	31	96	96	71
Porto Murtinho	28	108	119	104
Salto del Guaira	173	372	486	485

Table 3: As table 2 but for station Corrientes and upstream stations along the Parana.

distance is set to 0.1 m when the difference of altitude is smaller. From this information we have been able to calculate the difference of altitude and the distance between the different station which can be localised in the river routing scheme. Table2 presents the distance and difference of altitude between Obidos and Porto Velho or Serrinha along the Amazon while table 3 shows the same properties between Corrientes and three upstream stations along the Parana.

Both tables demonstrate that using the river driven HTU decomposition fewer errors are accumulated and the main geometric characteristics of the large rivers are better preserved. It also demonstrates that as truncation increases the estimation of these quantities in the river graph generally improves.

8 Evaluating the numerical stability of the area driven HTU decomposition (Csum case)

Using the runoff and drainage of a WFDEI simulation with ORCHIDEE, we simulate the discharge using the routing network and HTU properties described above and the testrouting.f90 code. The time constants of the model were adjusted for the "Csum" case of the area based HTU decomposition. The following values were determined :

- $stream\_tcst = 2.6 s/km$
- $fast\_tcst = 550.0 s/km$
- $slow\_tcst = 7500.0 s/km$

Figure 10 shows three main metrics comparing the simulated discharge to observations over the 1993-1999 period. Some of the stations are small (La Angostura has an upstream area of $400 km^2$) and thus the poor correlation is not very representative.

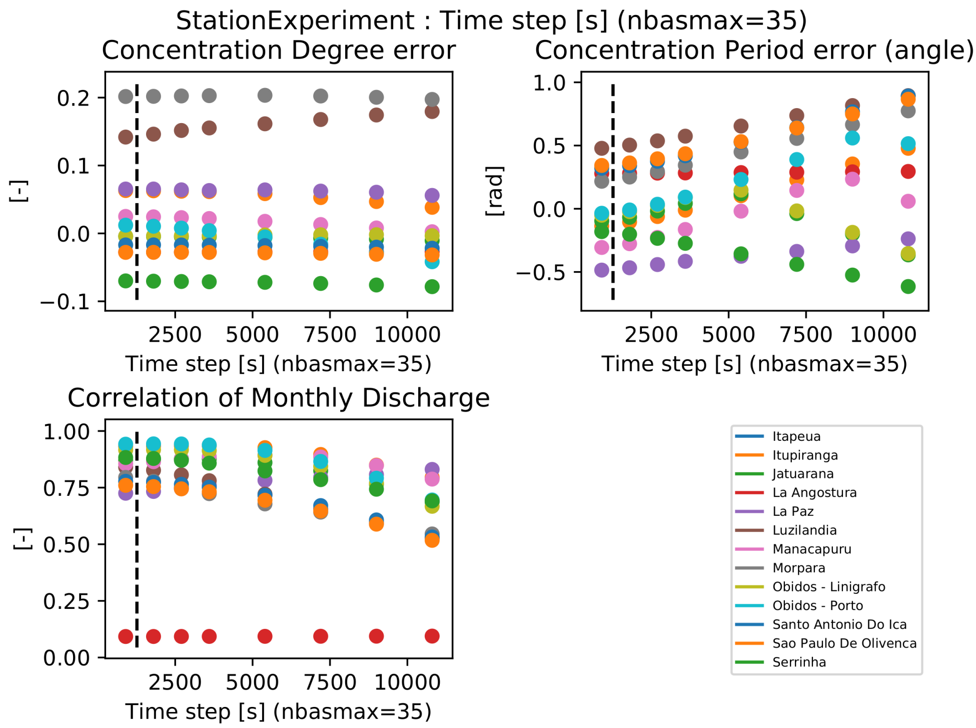

Figure 10: Three metrics comparing the discharge at 13 stations with observations for the period 1993-1999. The routing ran with time steps ranging from 30 minutes to 3 hours on the "Csum" routing properties. The vertical bar gives the predicted maximum time step.

Generally the correlation is quite good. The timing has been mainly adjusted at the Obidos station and thus its error in the concentration period is the smallest. The errors in phasing for some stations can also be explained by dams within the catchments.

The vertical line gives the predicted optimal time step for the scheme. It is computed with the area weighted median topoindex value over the region and the selected time constant of the stream reservoir (i.e. median of area weighted distribution of $\overline{\Lambda}.stream\_tcst$).

Simulation were also performed with the HTU properties obtained with the "Asum" method (only combining topoindex values). For this case the time constants of the reservoir was not adjusted again. The results are displayed in figure 11. As expected the general quality of the simulation is lower than in the "Csum" case. As shown by the concentration period the discharge is delayed relative to observations. Thus the time constants of the reservoirs for "Asum" should be lower than for "Csum".

Such a change would reduce the predicted optimal time step and improve the comparison with observations. Thus the higher optimal time step proposed for the "Asum" case would not remain once this version of the HTU properties is adjusted. It is safe to assume to we would obtain an optimal time step similar to the one of the "Csum" case.

The same tests were also executed for a routing graph constructed with the Fekete & Vörösmarty (FV) hydrological file. In this case the time constant of the reservoir were adjusted. During that process the impression was gained that the adjustment is more difficult than for the MERIT HTU graph. The discharge at Obidos could not be made to adjust as well to the observations as for MERIT.

The properties of the FV based HTUs was computed with the "Csum" method. We verified that this produces the same result as for "Asum". As the resolution of FV and the WFDEI atmospheric grid are very close, thus there are no averages of topoindex or geometrical properties computed.

This is only a subjective result which would need to be verified with objective optimisation methods. The following values for the reservoir time constants were selected :

- $stream\_tcst = 6.0s/km$
- $fast\_tcst = 78.0s/km$

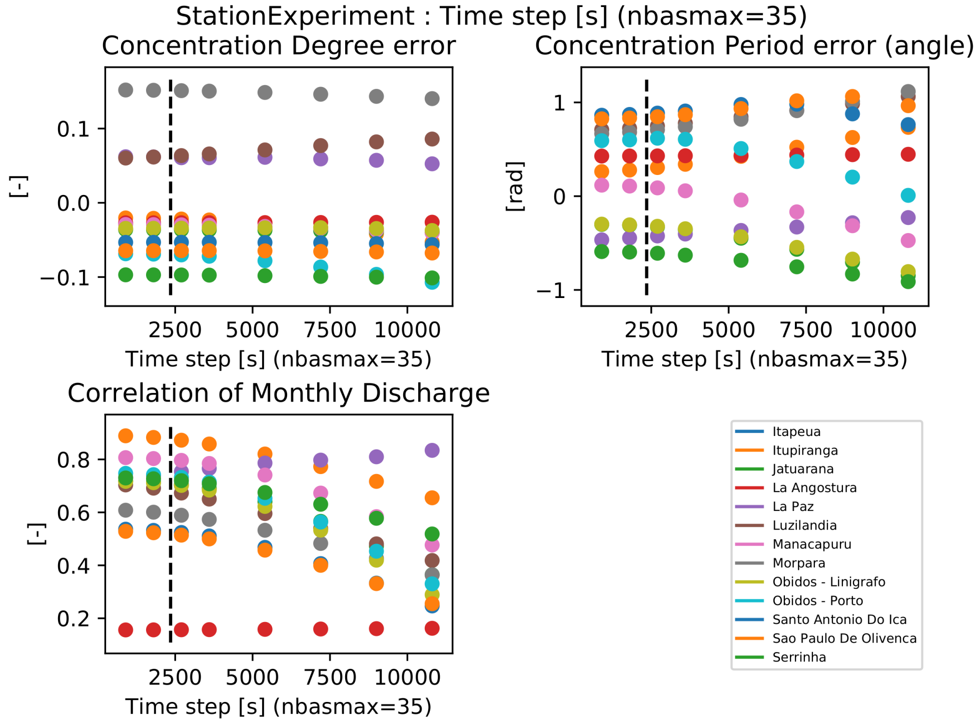

Figure 11: As figure 10 but for the routing graph constructed with the MERIT files and the "Asum" method to determine HTU properties. The same reservoir time constants were used as for the "Csum" case.

- $slow\_tcst = 600.0s/km$

The simulated discharge was compared to the 11 stations which could also be placed in this graph. At this stage the comparison between the MERIT and FV based discharge simulations is not very conclusive. A more detailed analysis would be needed to establish where the gains are by going to a higher resolution description of the rivers. One can note that the estimated optimal time step is larger for the FV case and generally the discharge is less sensitive to the time steps tested (30 minutes to 18 hours).

9 Evaluating the numerical stability of the river driven HTU decomposition

Still needs to be done !!

10 Tentative conclusions

- At this stage it is difficult to determine if combining the topoindex or computing it from representative dimensions of the HTU is better.
- The representative dimensions are not physical. But the delineation of HTUs can be improved in order to obtain HTU dimensions which are in better agreement with observations.
- Given the description of the hydrological network and after adjusting the time constants of the reservoir, we can determine an optimal time step to be used for the routing in ORCHIDEE.
- The FV based routing graph is less detailed than the one based on MERIT and fewer stations can be placed.

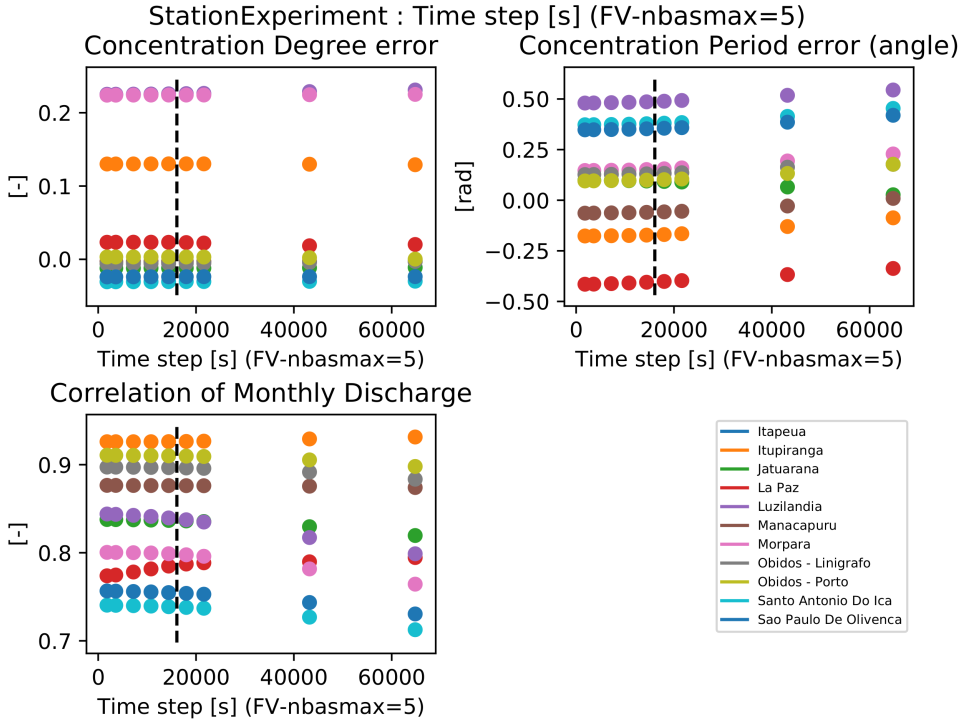

Figure 12: As figure 10 but for the Fekete & Vörösmarty (FV) hydrological network. The time steps tested range from 30 minutes to 18 hours. Fewer stations can be positioned on the routing graph produced with the FV file.

- It seems that the reservoir time constants for a FV based network cannot be as well adjusted as for MERIT. But this needs to be established with a objective optimization method.
- A more detailed comparison of the simulated discharge between the various configurations would be interesting. This raises the questions as to how far the adjustment of the time constants of the reservoirs should be carried out before the comparison can be considered fair.

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