MS2.4 “High quality interpolation weight and parallel coupling available to IPSL-CM and CNRM-CM”

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1. Introduction

The SCRIP 1.4 library [Jones 1999] is interfaced in the OASIS coupler for calculation of the weights and addresses needed to remap a coupling field provided by a source model on its grid to the target grid of the receiving model. It offers n-nearest-neighbour, first-order and second-order conservative remapping for all types of grids and bilinear and bicubic remapping for logically rectangular grids. Adaptations and complements were introduced in OASIS3-MCT, for example the "additional non-masked nearest neighbour" option for target grid points that would not receive any value with the original schemes, or the pre-processing allowing the detection of overlapping points due to periodical or polar closures. For Gaussian Reduced grids, the SCRIP is completed by an in-house bilinear and bicubic algorithms.

It is known for some time that the SCRIP presents some specific issues near the poles. As noted in the SCRIP User Guide[1] and in [Jones 1999], the SCRIP search and intersection

[1] http://dust.ess.uci.edu/ppr/ppr_Jon01.pdf

algorithms are based on linear parameterizations which is not valid near the pole[2]. To avoid these problems, a Lambert equivalent azimuthal projection can be used poleward of a given threshold latitude (called *north_tresh*).

We proceeded to a detailed analysis of the quality of the SCRIP library and the objective was also to compare it to other remapping libraries (ESMF[3], XIOS[4], OpenPalm[5]). This work led us to identify few SCRIP specific issues (section 2) and to propose bug fixes that are now included in the latest OASIS3-MCT_4.0 version [Valcke et al, 2018a] (section 3). The poor performance of the SCRIP sequential library was also addressed with a mixed MPI+OpenMP parallelisation (section 4). Thanks to a 4-month training period, we were also able to achieve important first steps in the evaluation of ESMF (section 5) but we were not able to go further in the comparison of different libraries, due to a lack of time.

2. Specific considerations on the SCRIP library

The work undertaken in CONVERGENCE on the quality of the SCRIP library led us to analyse and understand few specific issues of this library. The tests presented in this section and in section 3 are based on an analysis of the SCRIP remappings using the version of the coupler in use when the work started in CONVERGENCE, i.e. OASIS3-MCT_3.0. They were realised in a specific environment (programs and input files) managed under SVN (see https://oasis3mct.cerfacs.fr/svn/trunk/INTERPOL).

The subdirectories of this environment are:

- /SCRIP: sequential interpolation environment
- /PSCRIP: parallel interpolation environment (very close to test_interpolation environment delivered with OASIS3-MCT sources)
- /DATA/GRIDS: files (grids.nc, masks.nc, areas.nc) containing the definition of the grids used in the tests.
- /DATA/OASIS: OASIS3-MCT configuration files *namcouple* used in the tests

This environment allows the user to evaluate the quality of the remapping between the source grid of model1 and the target grid of model2 by calculating the remapping error on the target grid. Only one coupling exchange is performed at t=0 when model1 sends its coupling field that is received by model2. The field values on model1 grid are defined by an analytical cosine bell function with one maximum and one minimum over the globe. The remapping error is defined as the difference between the interpolated values of the received field and the values of the analytical function on the target grid points (divided by the interpolated field and multiplied by 100 to have it in %). The target model model2 writes out the field and the error after reception, slightly transformed so that: for masked points, the field = 10000 and the error = 0; for non-masked points which did not receive any value, the field = 1.e20 and the error = -1.e20.

The grids tested correspond to the grids used in the low-resolution coupled models at CNRM, CNRM-CM6-1, and IPSL, IPSL-CM6_LR, all with proper mask:

- bggd: LMDz regular latitude-longitude grid, 143x144 points
- ssea: ARPEGE T127 Gaussian Reduced, 24572 points

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[2] See for example Figure 3.5 of Kilicoglu & Valcke 2010 for an illustration of how this hypothesis distorts the cells located near the pole.
[3] https://www.earthsystemcog.org/projects/esmf/
[4] http://forge.ipsl.jussieu.fr/ioserver
[5] http://www.cerfacs.fr/globc/PALM_WEB/

- nogt: NEMO ORCA1 logically rectangular grid, 362x294 points; columns with i=1,2 overlap columns with i=361,362 and columns with i=1 and i=362 are masked; row with j=294 is masked as it overlaps row with j=293
- icos: DYNAMICO icosahedral grid, 15212 points.

The remappings tested are the SCRIP n-nearest-neighbour with either one (DISTWGT-1) or 4 (DISTWGT-4) neighbours, bilinear (BILINEAR), bicubic (BICUBIC), and conservative remapping CONSERV of first and second order for each couple of ocean and atmosphere grids, i.e. nogt to and from ssea (corresponding to CNRM-CM6-1), nogt to and from bggd (corresponding to IPSL-CM6), and nogt to and from icos.

2.1. Impact of the Lambert equivalent azimuthal projection for CONSERV

We tested the impact of the Lambert equivalent azimuthal projection on first-order CONSERV for our grids, comparing the error obtained with *north_thresh*=1.45 (projection above 83°N) and *north_thresh*=2.0 (i.e. no projection). The results are shown in 2D poleward of 75°N in section 3 of [Jonville et al, 2018]. Table 1 summarizes the mean and the maximum interpolation errors over that region for each couple of grids.

	A) max, 2.0 (%)	B) max, 1.45 (%)	C) mean, 2.0 (%)	D) mean, 1.45 (%)
nogt -> ssea	0.944	9.58	0.0357	0.175
ssea -> nogt	0.52	10.6	0.134	0.163
nogt -> bggd	0.646	0.646	0.0396	0.047
bggd -> nogt	0.307	0.306	0.103	0.103
nogt -> icos	0.745	0.745	0.0387	0.0358
icos -> nogt	0.838	0.838	0.212	0.212

Table 1 – Maximum and mean error for first-order CONSERV remapping poleward of 75°N for *north_thresh*=1.45 (B and D, projection above 83°N) and *north_thresh*=2.0 (A and C, no projection).

We see that the projection increases notably the value of the maximum error when the Gaussian Reduced grid ssea is involved, and does not improve the results for the other cases. For the nogt to bggd case, the 2D results even show that the projection slightly increases the error on the upper row of the target grid (even if the error maximum over the domain does not change).

A detailed analysis of the resulting remapping weights was also performed and is available in section 4 of [Jonville et al, 2018]. With north_thresh = 1.45, remapping weights can get very erroneous values well above 1 or below 0 when the Gaussian Reduced grid ssea is involved (e.g. -12.39 for link #19, see also Figures 1 and 2 there in). For all other couples of grids, weights are reasonable for both north_thresh = 1.45 and 2.0, even if they can be in few cases slightly above 1 or slightly below 0, always near the pole. The only couple of grids for which the weights are always strictly smaller than 1 and bigger than 0 is for the icos <-> nogt remappings.

We investigated more deeply the reason for the strong degradation for the ssea grid for north_thresh = 1.45. Figure 1 shows the cells of the ssea grid in the Lambert equivalent azimuthal projected space. We see that the corners of the cells on a specific latitude row do not coincide with the corners of the cells of the upper or lower latitude rows. The calculation of the cell border intersections between source and the target cells will therefore not work properly when the ssea grid is involved. This can be suspected by examining Figure 2, which shows two cells of the Gaussian Reduced ssea grid in red and two cells of the ORCA1 nogt grid in blue.

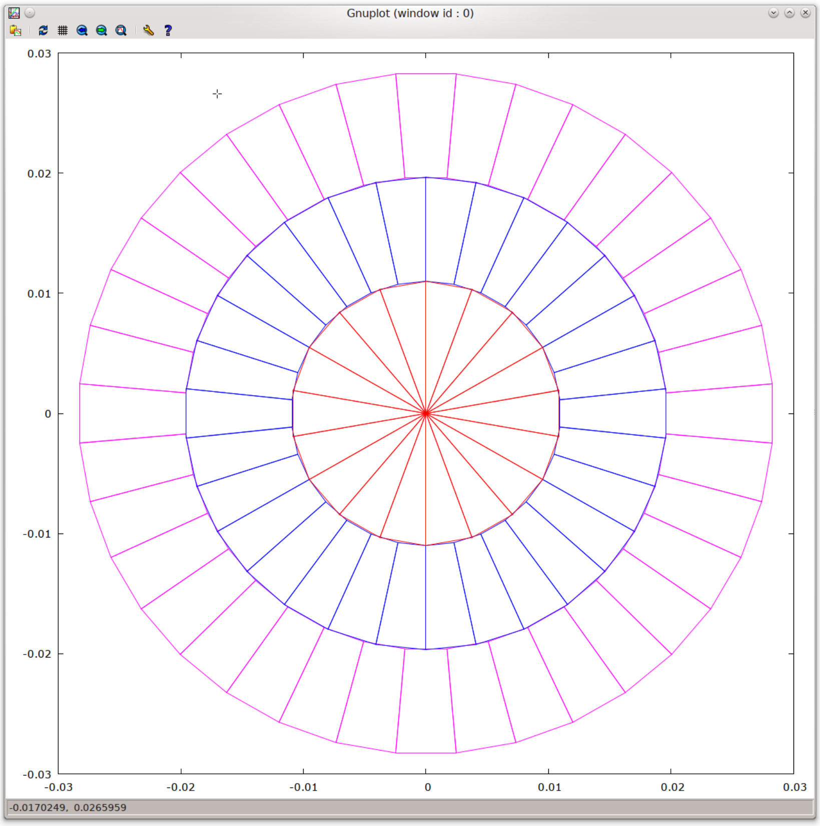

Figure 1 – Cell borders for the 3 latitude rows of the Gaussian Reduced ssea grid in the Lambert equivalent azimuthal projected space around the pole

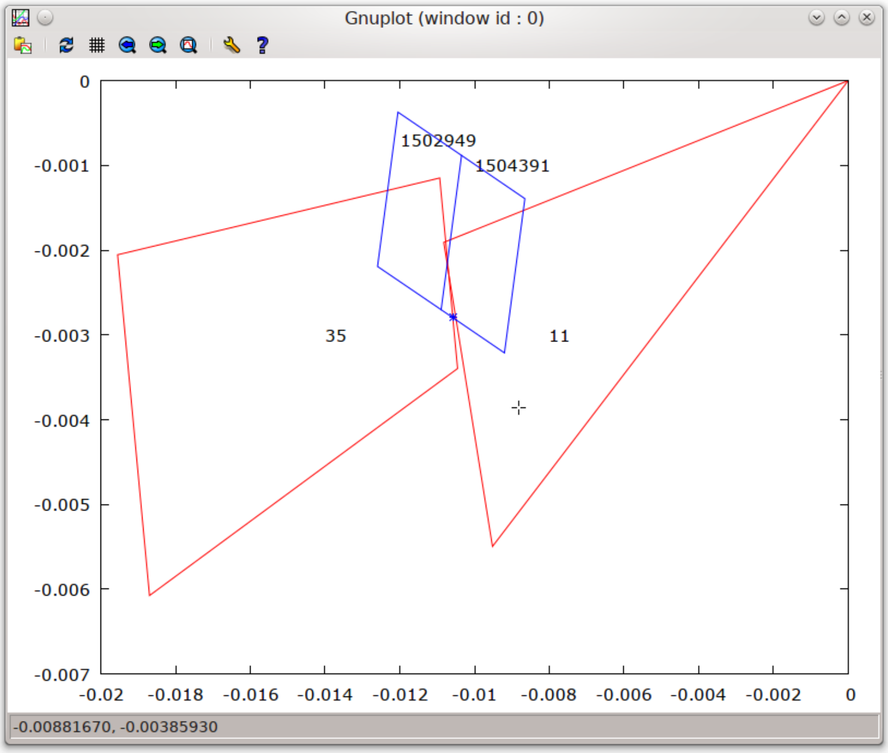

Figure 2 - Two cells of the Gaussian Reduced ssea grid (in red) and two cells of the ORCA1 nogt grid (in blue) in the Lambert equivalent azimuthal projected space

Therefore the Lambert projection cannot be activated for Gaussian Reduced grids. For other grids, it does not improve the results and even, in some cases, slightly degrades them. Given this analysis, we simply decided to not activate the projection (i.e. put *north_thresh*=2.0) in all our tests.

2.2. Limitations of the binning strategy in the SCRIP library

An analysis of the SCRIP binning strategy, implemented to restrict the search loops over the grid cells in the interpolation weight computation, revealed some flaws and usage restrictions are presented here[6]. All details are available in Appendix 2 of [Piacentini et al 2018].

Bins are meant to associate index spans in both grids to latitude bands. The binning splits the global [-π/2,π/2] domain in NBINS of equal latitudinal extension, NBINS being prescribed by the user. The bins can therefore be used to target subsets of the grid before performing further matching tests or brute force searches. The association between grid cells and bins is based on their bounding boxes, which is defined as the rectangle in the longitude-latitude space that contains the cell or the bin cells. A cell will be associated to a bin if their bounding boxes intersect.

For CONSERV, the bounding box definition is based on the minimum and maximum value of the grid cell corners, which is a robust definition for all grids. But for the other interpolations, the bounding box is estimated by the relative position of the grid cell centres. First this means that the whole sphere is not covered if the most northern and most southern grid centres are not located at the poles. Second, the algorithm implicitly assumes that the grid is Cartesian and stored with longitude increasing first. This introduces an error for other grid types

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[6] Note that in the analysis of the SCRIP quality performed in the next sections, we have never activated the binning option so the usage restrictions have been respected *de facto*.

(except for the Gaussian-reduced grid for BILINEAR and BICUBIC, see below) that can lead to wrong or incomplete binning. Indeed, for grids with latitude increasing first, every bin would be associated with the entire index range (minus a few elements), annihilating any effect of the optimization.

In addition for DISTWGT, if the destination grid cell centre belongs to bin n, the search uses bins n-1, n, n+1 (on the source grid) for the neighbour computation; for a large number of bins (leading to bins with small latitudinal extension) or when searching for a large number of neighbours, use of only three bins may not be enough, and the search could fail.

For BILINEAR and BICUBIC, a distance weighted sum of the 4 nearest non masked neighbour values will be applied for a target grid point that has at least one neighbour from the original bilinear/bicubic stencil masked; but the corresponding 4 nearest neighbour search is restricted by the original binning, which may be not optimal. It may happen for example that a source point located at a similar latitude but relatively far in longitude will be chosen instead of a source point that would be closer in longitude and absolute distance but located in another southern or northern bin.

For BILINEAR and BICUBIC on Gaussian-reduced grids, a specific algorithm is implemented. In that case, the number of bins used to split the grid automatically coincides with the number of latitude circles in the grid. The bin definition algorithm works fine but only if the Gaussian-reduced grid is stored from North to South. If this convention is not respected, the bins definition will not fail but all target points will in the end use a 4-nearest-neighbour algorithm.

In conclusion, the only robust implementation of the SCRIP bin restriction, at least as implemented in OASIS3-MCT, is for CONSERV for all grid types and for BILINEAR and BICUBIC for Gaussian-reduced grid stored from North to South. These usage restrictions were clarified in OASIS3-MCT_4.0 User Guide.

2.3. Improvement of bounding box definition

An important effort was also devoted to analyse the algorithm used for the cell bounding box (i.e. the rectangle in the longitude-latitude space that contains the cell) definition, highlighting some strong drawbacks of the current method. In some cases, the current method results in too large bounding boxes leading to a drastic reduction of the restriction effectiveness. A new strategy for defining them and for calculating their intersection was proposed; see Appendix 1 of [Piacentini et al, 2018] for details.

A study of the impact of this new strategy for the quality of the different remappings for our couple of grids was realised. It led to the conclusion that the new strategy has no impact for CONSERV and DISTWGT but slightly changes the results of BILINEAR and BICUBIC for few points near the pole for nogt to bggd and for nogt to ssea, and for few points near the continent borders for nogt to/from bggd and for nogt to/from ssea. In all cases, the error stays in the range of the error obtained without the new strategy[7].

Regarding the performances, great gains were observed with this new strategy. For example, on an Intel(R) Core(TM) i7-4930MX with 3.0GHz clock, the generation of the interpolation weights from ORCA025 (1442x1050) to T359 (181724) with the old bounding box definition takes 851 seconds without binning and still 840 seconds with 500 latitude bins, while with the

[7] All analysis details are available on the wiki page https://inle.cerfacs.fr/projects/oasis3-mct/wiki/SCRIPESMFXIOS(YAC)_remapping_comparison , at dates16-17-24/04/2018.

new bounding box definition it takes 821 seconds without binning and the time drops to 40 seconds with 500 bins.

Because it greatly improves the performance of the remapping weight calculation and as it maintains the same level of overall quality, it was decided to include this new strategy in OASIS3-MCT_4.0.

3. Quality analysis for different SCRIP remappings

The tests presented in this section were performed to evaluate the quality of the SCRIP remappings as implemented in OASIS3-MCT_3.0. The details of this analysis are presented in section 1 of [Jonville et al, 2018].

In this document, one can find, for each couple of grids and each remapping, the mean and the maximum interpolation errors, which are also illustrated on Figure 3:

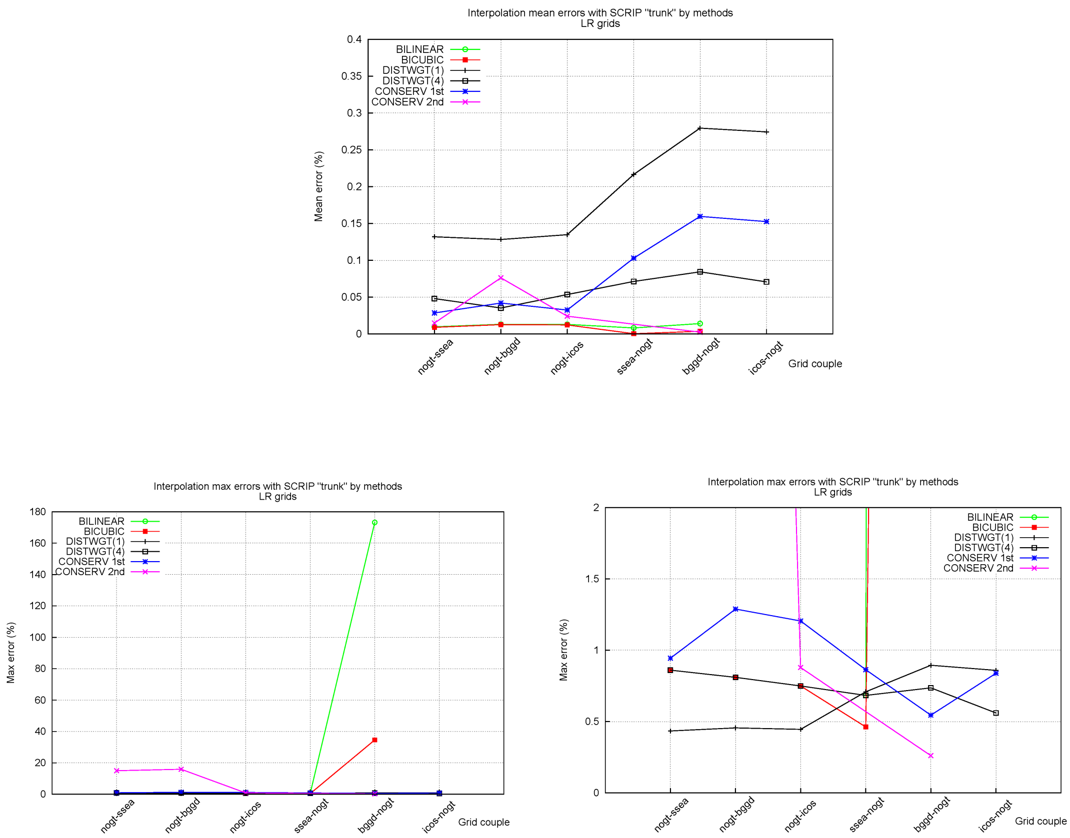

Figure 3 – Top: Mean interpolation error, bottom left: maximum interpolation error (between 0 and 180%), bottom right: maximum interpolation error (between 0 and 2%) for different couples of grids for SCRIP remappings as implemented in OASIS3-MCT_3.0

Then, on one page for each couple of grids, 3 columns of 2D figures illustrate the interpolation error plotted between 0 and 1, the interpolation error plotted between 0 and its maximum, and the target grid points that do not receive any interpolated values (i.e. for which the interpolation error is -1.e20, see section 1.1).

The following points are important to analyse and understand the results presented in this document.

- The BILINEAR and BICUBIC algorithms from SCRIP work only for logically rectangular grids, so these remapping could not be performed with icos as source grid. For the Gaussian Reduced ssea grid, an alternative in-house algorithm is available and was used.
- For DISTWGT, BILINEAR, BICUBIC, if some of the (N or 4 or 16) original[8] neighbours are masked, a distance weighted average with the remaining ones is done by default; if all (N or 4 or 16) original neighbours are masked, no value is calculated for that point (i.e. the "additional non-masked nearest neighbour" option is not activated corresponding to logical *ll_nnei=.false*. in the OASIS3-MCT sources.)
- For CONSERV, we used in all cases the FRACAREA normalization, which means that the weights are normalized by the intersected area (and not by the whole area of the target cell as with the DESTAREA option); this option ensures that the remapped field has reasonable values but does not ensure local conservation.

The analysis of the remappings presented in that document led us to identify specify issues that are detailed in the next subsections. Some issues were solved and the corresponding bug fixes are included in the latest OASIS3-MCT_4.0 version (see section 2 of [Jonville et al, 2018]); other issues were only analysed and should be corrected in future versions of the coupler.

3.1. BILINEAR and BICUBIC for bggd grid

As can be seen on Figure 3, BILINEAR and BICUBIC remappings from bggd to nogt show big and unreasonable errors with a maximum of respectively 173% and 34.6%. These error maxima are located on one point in the western Pacific on the equator, as illustrated on Figure 4 for BILINEAR.

[8] By "original" we mean the source grid points that would participate in the remapping of a target grid point, not considering, in a first step, whether or not they are masked.

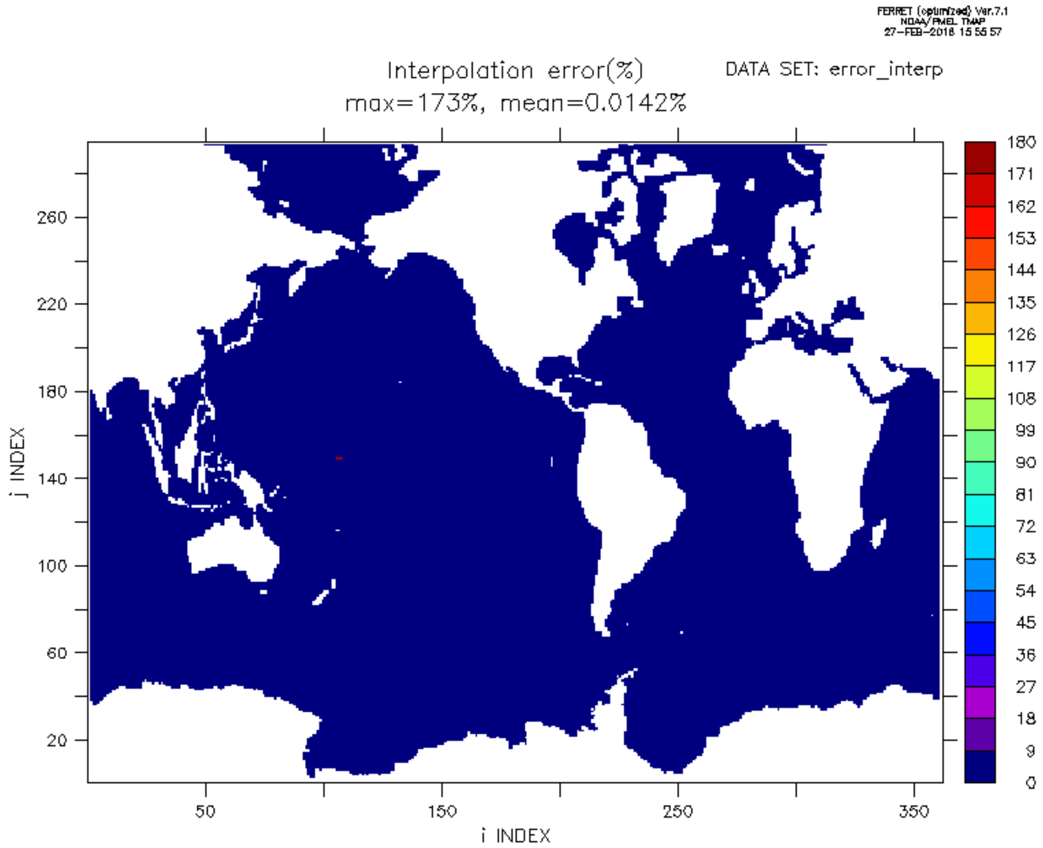

Figure 4 – Interpolation error (%) for BILINEAR from bggd to nogt showing one point in the western Pacific on the equator (very small red point) with an error of 173%

This problem is studied in detail Appendix 3 of [Piacentini et al, 2018]. In that case, the multiple cross product test implemented to check if a target grid point falls into a source grid cell has a flaw. The cross product criterion aims to assess if the destination point lays always to the right or always to the left of all the sides of the cell. It translates mathematically by checking that the cross product between the vector corresponding to a cell side and the vector extending from the beginning of the cell side to the destination point has the same sign for all cell sides. In OASIS3-MCT_3.0, the sign comparison is wrongly implemented: it tests if the product of the last and the current evaluation of the cross-product is not strictly < 0. If the two first cross products have the same sign and the third one 0, then, regardless of the sign of the fourth cross-product, the product of the third and fourth results is 0, therefore not strictly < 0 and the cell is accepted. This situation arises if the target point is aligned with the north side of the cell; this is the case for the nogt target grid points with longitudes 177.5°, 178.5°, 179.5° and latitude 0° o that are all wrongly found to fall into the bggd cell with longitude between 357.5° and 0° and latitude between -1.268° and 0°.

The test was corrected simply by checking that one of the cross product is not equal to zero. This correction solves the issue for the BILINEAR and BICUBIC remappings from bggd to nogt, which now show a very reasonable maximum of less than 1% (see Figure 4 of section 2 of [Jonville et al, 2018], which presents the interpolation error mean and maximum values obtained for the different remappings with OASIS3-MCT_4.0).

3.2. Source grid overlap for DISTWGT, BILINEAR and BICUBIC

DISTWGT, BILINEAR and BICUBIC remappings with nogt as source grid show a specific problem around nogt periodicity located around 73° W. This is illustrated of Figure 5, which shows the interpolation error for BILINEAR from nogt to ssea. Even if the maximum of the error is located near the coasts, which is expected given the non-matching sea-land masks in the two coupled component models[9], we see a distinct local maximum in the interpolation error around 73° W.

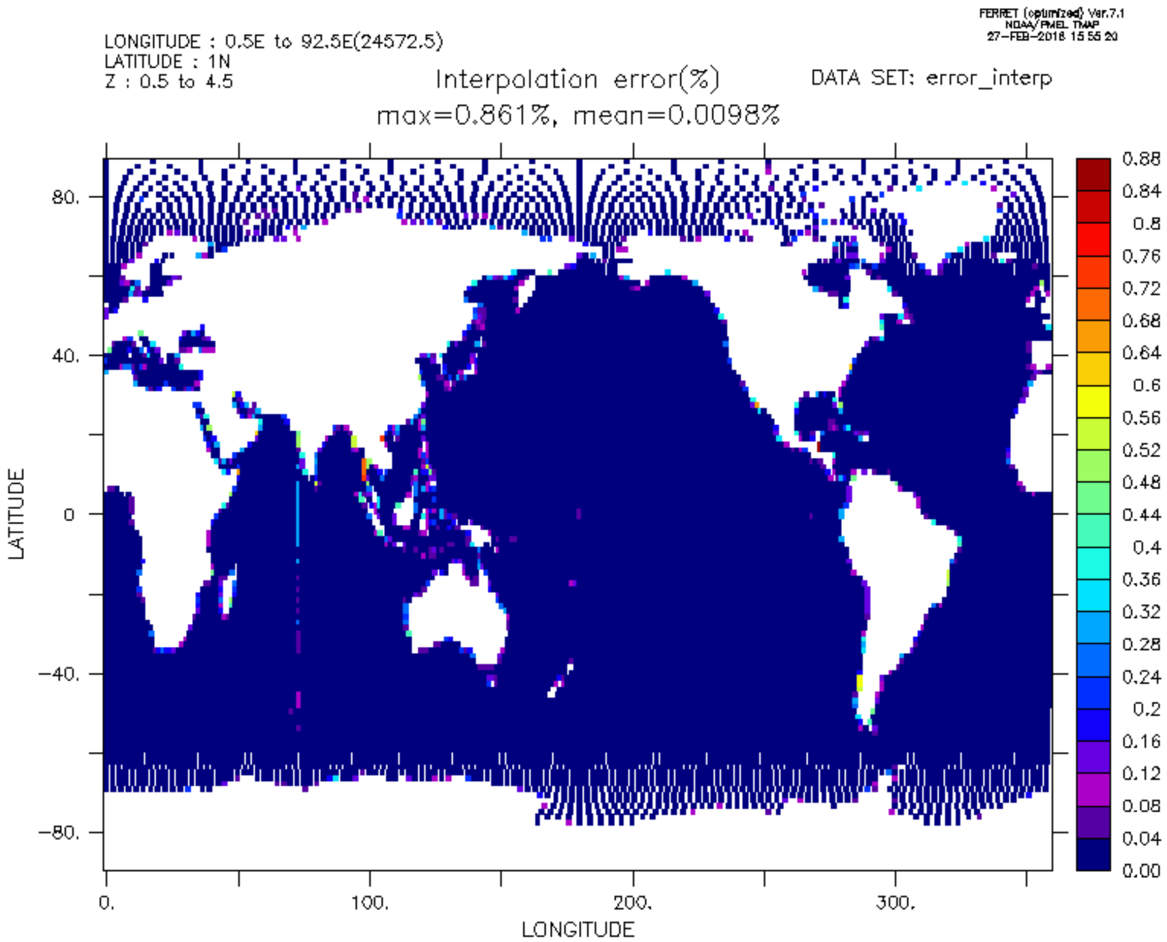

Figure 5 – Interpolation error for BILINEAR from nogt to ssea

Another example is shown on Figure 6, which illustrates the grid points that do not receive any interpolated value for DISTWGT from nogt to bggd. Again we see that because of the non-matching sea-land masks, some target grid points near the coast do not receive any value as their original nearest neighbour is masked. But this also happens for grid points located near nogt periodicity.

[9] Because of non-matching sea-land masks, some target grid points will have some of their original neighbours masked; the original scheme cannot be applied and a distance weighted average with the remaining non masked original neighbours is done which leads to less precise results than with the original scheme.

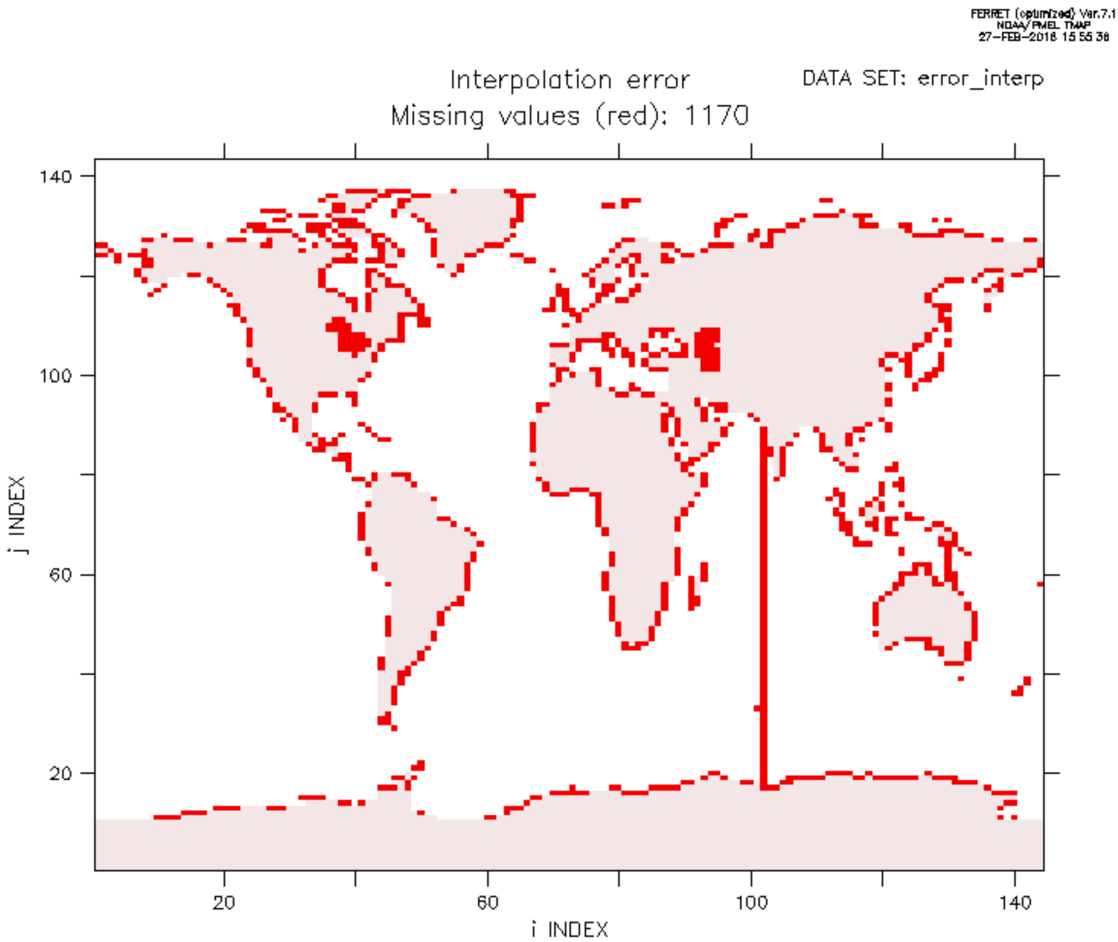

Figure 6 - Grid points that do not receive any interpolated value for DISTWGT from nogt to bggd.

Indeed the nogt grid is defined with two overlapping columns, i.e. i=1,2 overlapping i=361,362. To be coherent with the way the nemo model completes masked columns of input coupling fields, the columns with i=1 & i=362 are masked (i.e. nemo will duplicate on i=1 the values received for i=361 and on i=362 the values received for i=2). In the DISTWGT, BILINEAR and BICUBIC operations, the periodicity of the source grid should be considered and unmasked values of overlapping columns should be used to activate the more precise original schemes. This problem is now identified but was not fixed in OASIS3-MCT_4.0 because of lack of time. We consider that this problem is serious but not crucial as, contrary what was chosen in the current tests, in real coupled models we always activate the "additional non-masked nearest neighbour" option (i.e. set the parameter ll_nnei to .true. in OASIS3-MCT sources which is the default), which means that at least the non-masked closest neighbour is used to provide a value to all non-masked target grid points.

3.3. CONSERV for grid cells on the pole

Another specific problem of the SCRIP CONSERV is linked to grid cells covering the pole or extending to the pole. This is illustrated on Figure 7 for a first-order CONSERV from nogt to bggd and on Figure 8 for a second-order CONSERV from nogt to ssea.

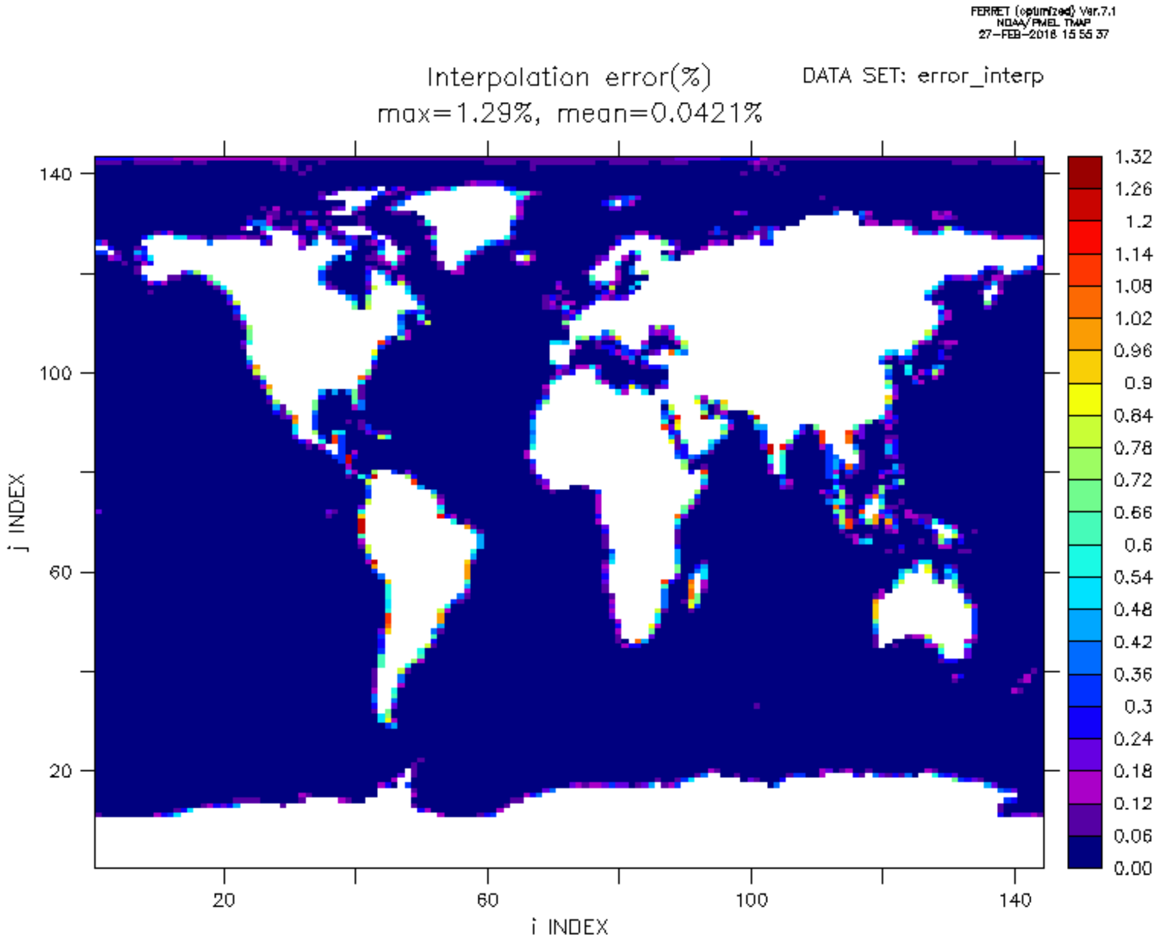

Figure 7 – Interpolation error for first-order CONSERV from nogt to bggd

On Figure 7, we see again that the interpolation error is important near the coast due to the sea-land mask mismatch in the two grids but we also see a local maximum of error on the upper part of the figure. We note here that, as observed in section 2.1, the Lambert equivalent azimuthal projection would not solve this problem as it even increases the error on the upper bggd row.

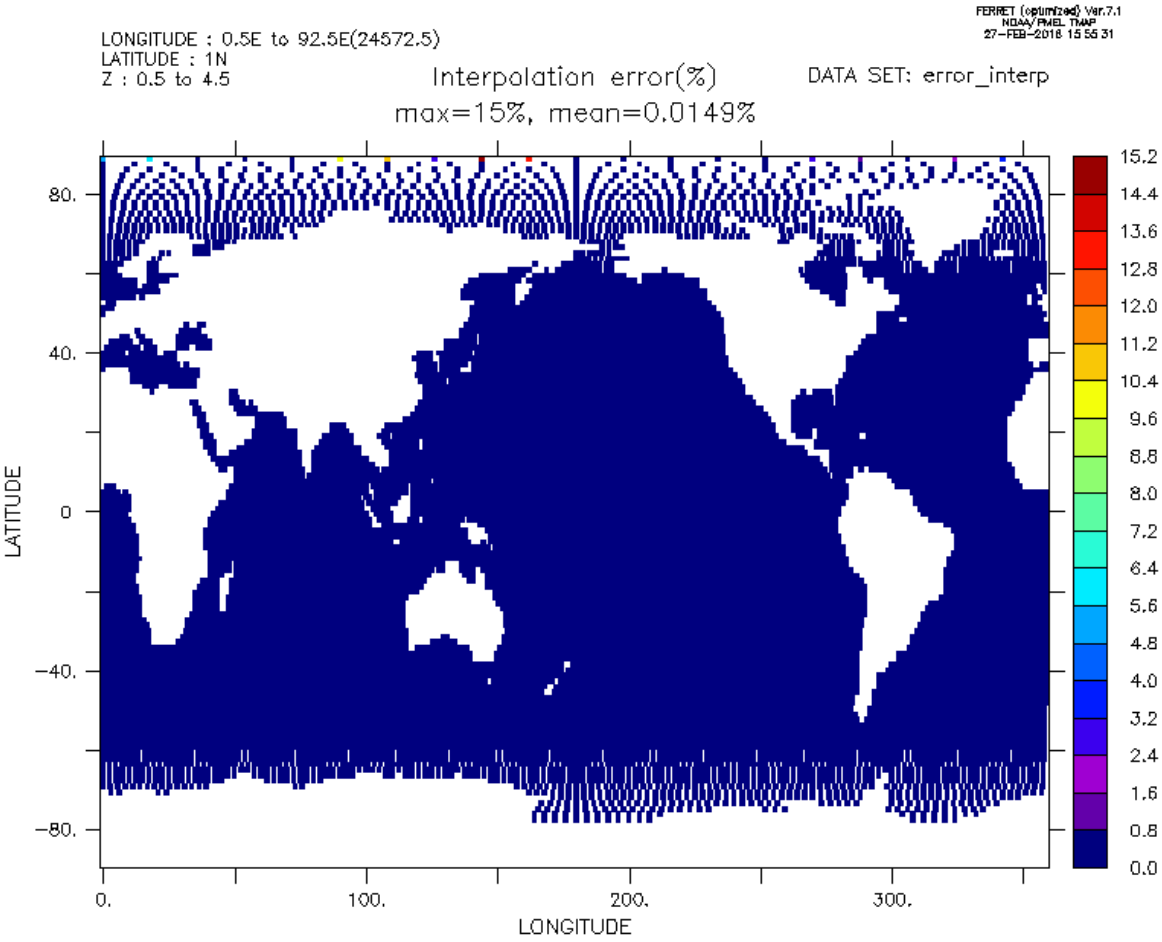

Figure 8 – Interpolation error for second-order CONSERV remapping from nogt to ssea

It is obvious on Figure 8 that the second-order CONSERV from nogt to ssea shows specific problems near the pole with an error going as high as 15% for some cells. Here also, the Lambert equivalent azimuthal projection would not help as we have seen in section 2.1 that it is not a valid solution for Gaussian Reduced grids

In both cases, the target grids have cells extending to the pole: for the bggd and ssea grids, cells of the northern-most row are in fact triangles with their upper two corners exactly at 90° N. And in both cases, the source grid nogt has two cells (97,293) and (266,293) with one border theoretically crossing the pole. For those cells, the SCRIP library using an algorithm supposing that the cell borders are linear in latitude and longitude necessarily gives inexact results.

In conclusion, the impact of the incorrect behaviour of the SCRIP library for cells crossing the pole has to be evaluated for each coupled model individually. In our case, the first-order CONSERV still gives reasonable results for all our grids, with a maximum error between 0.5% and 1.3% (as shown on Figure 3 bottom right) always located near the coast due to the sea-land mask mismatch and with an error near the pole smaller than that. However, the second-order CONSERV gives wrong results near the pole for nogt to ssea and for nogt to bggd and should not be used for these couple of grids.

3.4. Additional non-masked nearest neighbour option for Gaussian Reduced grids

Additional tests with BICUBIC remapping from the higher resolution T359 Gaussian Reduced (181724 points) grid to the ORCA025 grid (1442 x 1050 points), used in the high-resolution version of CNRM-CM6, revealed another issue. In that case, and contrary to the tests described above, the "additional non-masked nearest neighbour" option was activated which means that all target grid points, even the ones falling "outside" the source domain, should get a value. But this option did not properly working for a series of non-masked target grid points located at the very South of the domain, which did not get any value.

For those grid points, an inspection of the code revealed that the "additional non-masked nearest neighbour" was effectively activated but considering only the source grid points in the original restriction bin which, in that specific case, contained only masked points. This bug is corrected in OASIS3-MCT_4.0, extending the search to the whole grid for cases where the source restriction bin contains only masked points. This problem did not show up for our low-resolution grids because the masks were coinciding better and the case where a non-masked target grid point would fall into a source bin with all masked points did not happen.

Afterwards, the mask of the ARPEGE T359 Gaussian Reduced grid was modified so to fit to the sea-land coastline defined by the NEMO ORCA025 mask. The ORCA025 mask was remapped to the T359 grid and the value of the land and sea proportion in each T359 grid cell was adapted so to fit the remapped mask. For the mask considered by the coupler, a T359 cell is declared unmasked as soon as it gets some proportion of sea. This implies that the "additional non-masked nearest neighbour" option is not required anymore as all ORCA025 grid cells now get a value from at least one ARPEGE T359 cell.

4. MPI+OpenMP parallelisation of the SCRIP library

This subsection summarizes the developments introduced in OASIS3-MCT SCRIP library to enhance its computing performance both in sequential and hybrid MPI+OpenMP modes. All these developments are available in OASIS3-MCT_4.0 and are presented in [Piacentini et al, 2018]. This work was mainly supported by the European Centre of Excellence ESiWACE (https://www.esiwace.eu) and is reported in the corresponding deliverable [Valcke et al, 2018b]; it is also summarized here as it is fully relevant for CONVERGENCE task 2.4.

4.1. Rationale

Since its first implementation in OASIS, the SCRIP library performs the calculation of the remapping weights only on the MPI master process of each coupled component model. As OASIS3-MCT-based coupled systems are usually exploited on supercomputers and are, for most of them, parallelised with MPI or even in hybrid MPI+OpenMP mode, we decided to implement a hybrid MPI+OpenMP parallelisation of the SCRIP library. It relies on the MPI parallel layout of the calling model but only enrols one MPI process per node. The number of OpenMP threads per node is set by a dedicated environment variable

OASIS_OMP_NUM_THREADS, and for optimum performance, it is recommended to set this variable to the number of cores of the node.

Bilinear, bicubic, and nearest-neighbour remappings mainly follow the same procedure. For each unmasked target grid point, a distance is calculated with all (or, when a bin restriction is applied, with a subset of) source grid points to determine which ones are the closest and could participate to the weight calculation. These calculations, independent for each target point, can be scattered to different nodes of the machine without major communication overhead. On this outer loop, a MPI parallelisation is done on every first core of each node. In addition, to avoid memory duplication of source grid point arrays, OpenMP threads also parallelise the outer loop on target grid points and share the source grid point related variables. After the remapping weight calculation by the different threads, results are copied in shared variables and gathered on the master process of the model.

The weight calculation procedure is slightly different for conservative interpolations. Mesh contour intersections are calculated for both source and target grid cells. Consequently, the MPI+OpenMP hybrid parallelisation is done on two outer loops (over source and target grid cells). The search of neighbour cells potentially intersected can be restricted using the so-called "bin" technique. In a second step, a complementary nearest-neighbour search can be launched (if the user chooses the FRACNNEI option[10]) and this step is now also parallelised with OpenMP.

The performance improvement obtained with the SCRIP hybrid MPI+OpenMP parallelisation is presented in the next paragraphs after a short description of optimisations that were introduced in the sequential code.

4.2. Code optimisation in sequential mode

A pre-processing key -DTREAT_OVERLAY allows the detection of overlapping points due to periodical or polar closures. This was added in the OASIS version of the SCRIP. When activated, only the point with lowest index is active and the replicas are masked out. The original version used to scan the whole grid for every point to be checked (complexity $O(n^2)$). The new version sorts the grid coordinates calling a modified version of the standard heapsort (complexity of $O(n \log(n))$. This greatly improves the efficiency of this overlap check, e.g. reducing its cost from 731 seconds to 0.4 in the orca025 to t359 remapping. Since the parallelisation would require extra storage to avoid conflicts while modifying the grid mask, it was decided to keep this improved treatment sequential.

The part of the code associating a complementary non-masked nearest neighbour to non-masked target cells that are not involved in any conservative link (FRACNNEI option) was also optimised. These modifications significantly enhance the performance of OASIS. For example, the computing time of this whole complementary non-masked neighbour treatment for the T359 to ORCA025 coupling goes down from 293 to 5.9 seconds. As noted above, this part of the code was also parallelised with OpenMP.

4.3. Parallelisation tests and results

The SCRIP parallelisation was tested with a toy coupled system using typical high-resolution grids (HR, NEMO ORCA025 and Gaussian-reduced T359) or ultra-high-resolution grids

[10] FRACNNEI works as FRACAREA (see section 3) except that an "additional non-masked nearest neighbour" is activated for target grid cells that would not get any remapped value.

(UHR): NEMO ORCA12 (4322x3147 points) and Gaussian-reduced T799 (843490 grid points).

The performance of the weight calculation was tested on Météo-France Bullx beaufix (Intel 5.1.2.150 compiler and MPI library) for the following 4 interpolations in both directions: DISTWGT-4, BILINEAR, BICUBIC and first-order CONSERV(with FRACNNEI normalisation). For the ORCA grid, a restriction of neighbouring search with 500 bins is used with CONSERV, while the number of bins is automatically given by the truncation number for the Gaussian-reduced grid for BILINEAR and BICUBIC (see section 2.2). Reproducibility of the parallelisation (due to different operation orders) was validated at the machine precision.

Results are shown on Figure 9 for ORCA025 to T359 (HR) and on Figure 10 for ORCA12 to T799 (UHR), for 1, 2, 4, 8, 20 and 40 OpenMP threads and 1, 2, 4, 8, 16, 32, 64, 128 and possibly 256 MPI tasks, i.e. a total of 1, 2, 4, 8, 20, 40, 80, 160, 320, 640, 1280, 2560 and 5120 OpenMP threads (40 threads correspond to the number of physical cores per node on beaufix).

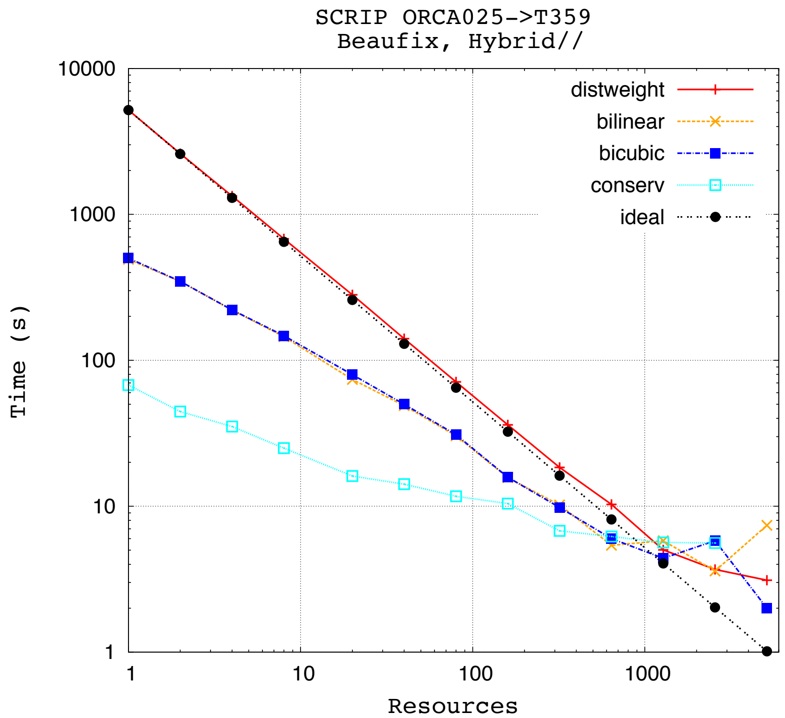

Figure 9: Time for the remapping weight calculation as a function of the total number of OpenMP tasks for different remapping with the parallel version of the SCRIP library for the HR ORCA025 (1442x1050) to T359 (181724) case.

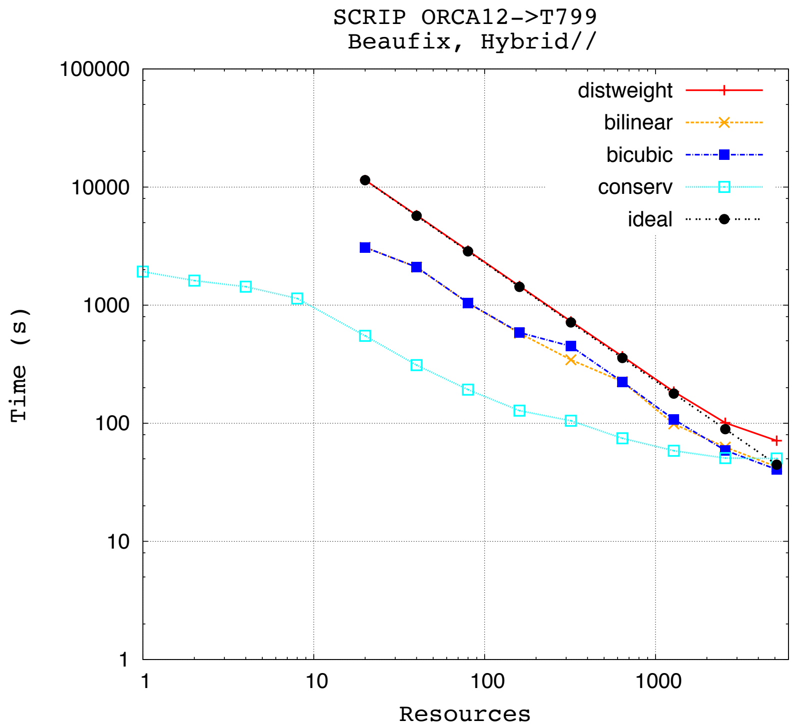

Figure 10: Same as Figure 9 but for the UHR case: ORCA12 (4322x3147) to T799 (843490) coupling.

For distweight, bilinear, bicubic, the large number of source points considered in the search (no bin restriction is applied as explained above) slows down the calculation at low resources but favours the good scaling for up to 1280 threads for HR and up to 2560 tasks for UHR. A higher scalability would be achieved with a better load balancing, which is made difficult by the heterogeneity of the operations per target grid point (complementary neighbour search, iterative loops, ...).

For the conservative interpolation (conserv), the hybrid parallelisation gains are also very significant but the less-scalable behaviour can be explained by better performance at low resources due to the bin restriction and a large load imbalance between the different threads due to the variable number of possible neighbours to check.

In conclusion, the performance of the SCRIP library is greatly improved by its parallelisation, showing a reduction in the weight calculation time of 2 or 3 orders of magnitude for high-resolution grids at high number of cores even if it does not reach ideal scalability. Further improvements would require a thorough rewriting of the grid search algorithms and potential solutions are discussed in Piacentini at al 2018 but this was beyond the scope of the present work.

5. ESMF Evaluation

During CONVERGENCE, we also started using and evaluating ESMF library version 6.3.0rp1 remappings. The work is not completed but first steps have been achieved and are described here. One motivation was that the ESMF library was at the time, i.e. before SCRIP parallelisation described in section 4, much faster than SCRIP. The schemes supported by ESMF were, when we tested it, nearest-neighbour, bilinear, higher-order patch[11], first-order

[11] ESMF version of a technique called "patch recovery" commonly used in finite element modelling; it typically results in better approximations of values and derivatives when compared to bilinear interpolation.

conservative; in the last version of ESMF v7.1.0r released in March 2018, the second-order conservative remapping and the option to use the additional non-masked nearest neighbour for grid points that would not receive any value were added but we did not tested them.

We first constructed an environment similar to the one developed with SCRIP to test the quality of ESMF remappings. The programs are coded in NCL (http://www.ncl.ucar.edu/) that is interfaced with ESMF[12] and use OASIS3-MCT grids.nc and masks.nc files to get the grid definition.

5.1. Structured grids

A preliminary analysis showed that ESMF nearest-neighbour, bilinear, patch and first-order conservative remapping works fine for structured (or logically-rectangular) grids with a correct consideration of the source and target grid masks. A first comparison of the results obtained with SCRIP and with ESMF is done in [Senhaji, 2016] and the main conclusions of this study are described here.

5.1.1. Nearest-neighbour and bilinear

For bilinear, the two libraries provide very similar results[13], except that ESMF is more "strict" in the sense that when at least one of the original neighbours of a target grid point is masked, the original scheme cannot be applied and by default ESMF does not provide any value for that target point; this results in more target points not receiving any value for ESMF than for SCRIP[14]. See for example, [Senhaji 2016] Figures c) and d) on p.15 for bggd to nogt[15] and Figures c) and d) on p.24 for nogt[8] to bggd.

For the nearest-neighbour, the libraries give equivalent results. See the figures at the bottom of p.31 illustrating the differences between ESMF and SCRIP results for a) bggd to nogt[8] and b) nogt[8] to bggd.

5.1.2. Patch/bicubic

The ESMF patch algorithm is compared to SCRIP bicubic algorithm. The results for nogt to bggd are reproduced here on Figures 11 for SCRIP and 12 for ESMF. Again, it can be observed here that ESMF is more "strict" in the sense that when at least one of the original neighbours of a target grid point is masked, ESMF does not provide any value for that target point. But besides this aspect, SCRIP shows a slightly bigger error then ESMF over the whole domain. For an illustration of bggd to nogt[15] results, please refer to [Senhaji 2016] p.27, figures c) for SCRIP and d) for ESMF.

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[12] ESMF is included in NCL since version 6.2.0

[13] Aside from the SCRIP major problem on the equator in the western Pacific (see section 3.1), which is also observed in [Senhaji, 2016] and was solved later.

[14] We recall that the SCRIP library will instead use the remaining non-masked neighbours to perform a n-nearest neighbour remapping.

[15] In [Senhaji, 2016], "teo1" is used instead of "nogt".

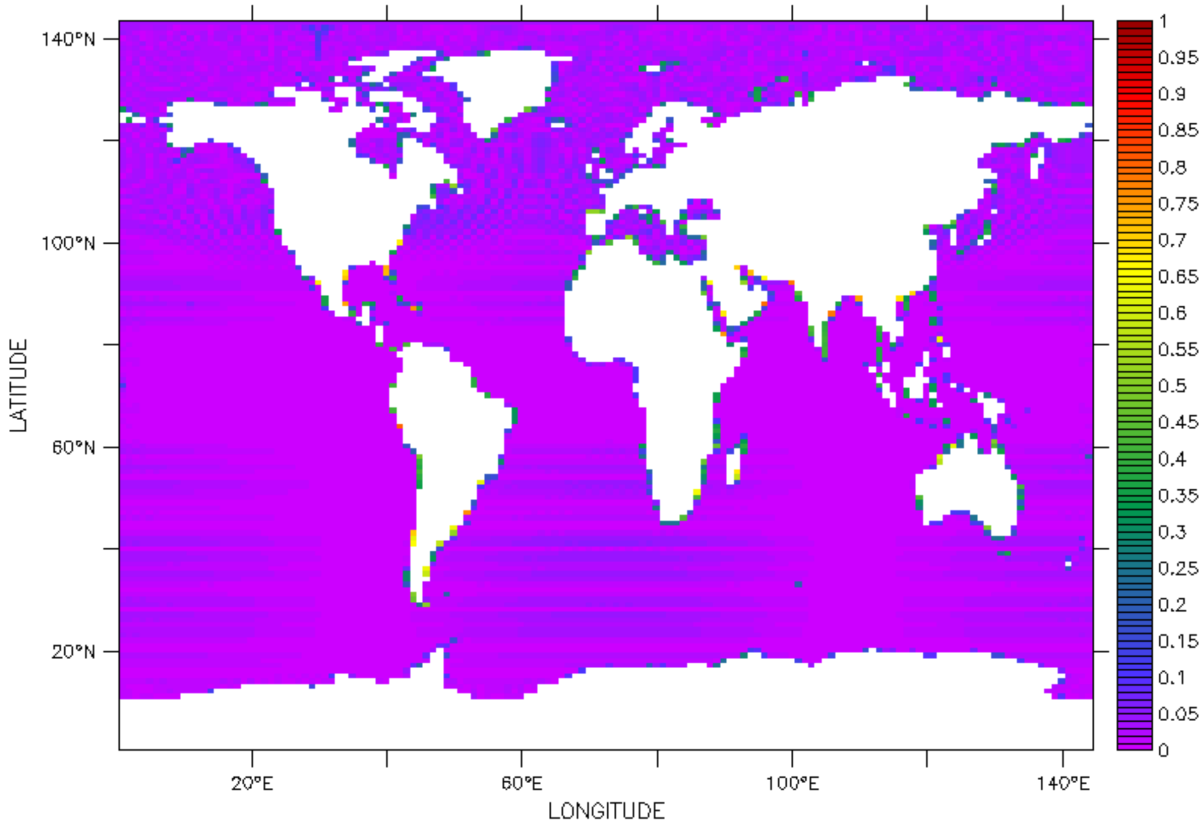

Figure 11 – Interpolation error for the SCRIP bicubic remapping from nogt to bggd

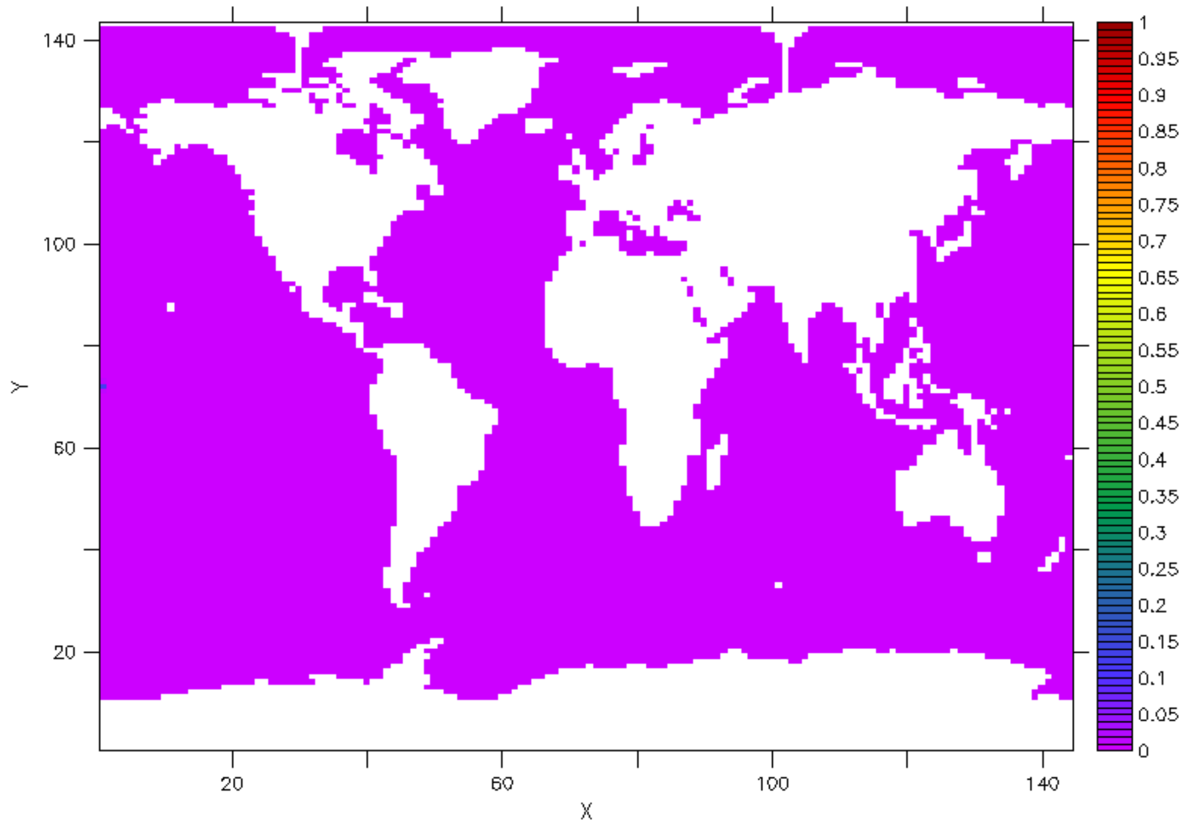

Figure 12 – Interpolation error for the ESMF patch remapping from nogt to bggd

5.1.3. Conservative

For the conservative remapping, the results are also very close. Figure 13 shows the error for the conservative remapping with SCRIP for the nogt to bggd grids; the results are the same than on Figure 7 but the colour scale is different. ESMF reproduces the local maximum of error near the pole, i.e. on the upper row of the bggd source, but also in the region corresponding to the north fold of the ORCA1 (nogt) grid, as can be seen on Figure 14. The reasons for this local maximum still have to be clarified.

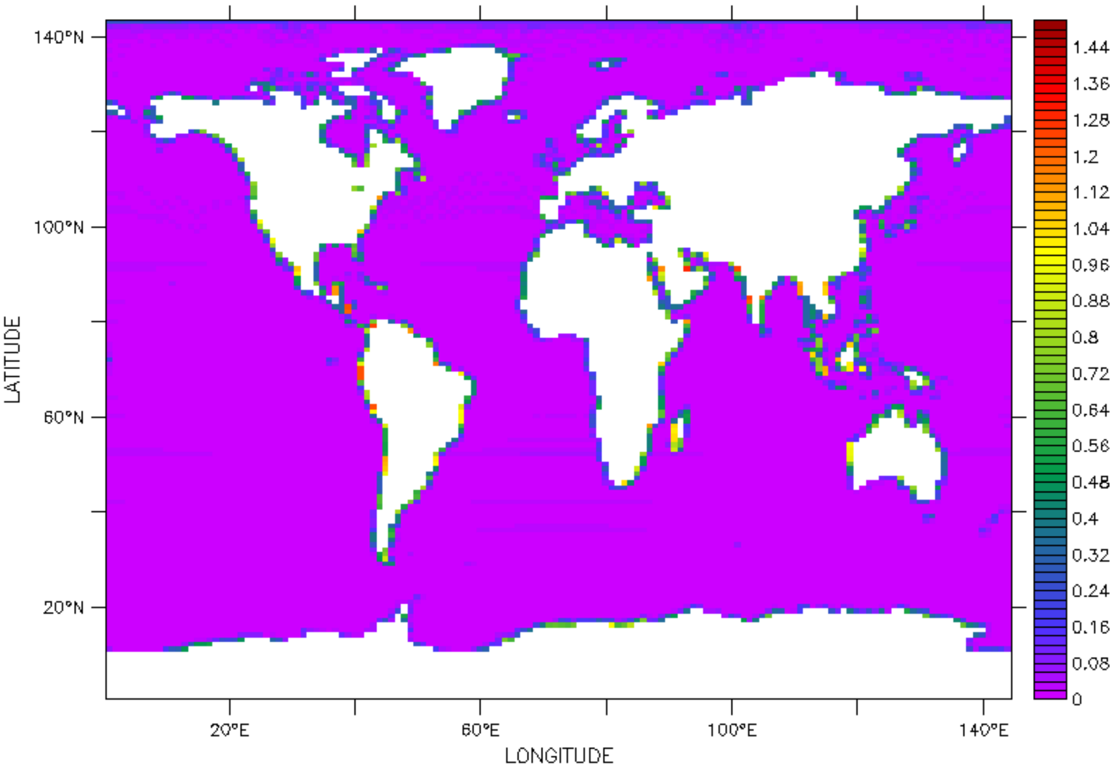

Figure 13 – Interpolation error for the SCRIP conservative remapping from nogt to bggd as in [Senhaji, 2016]

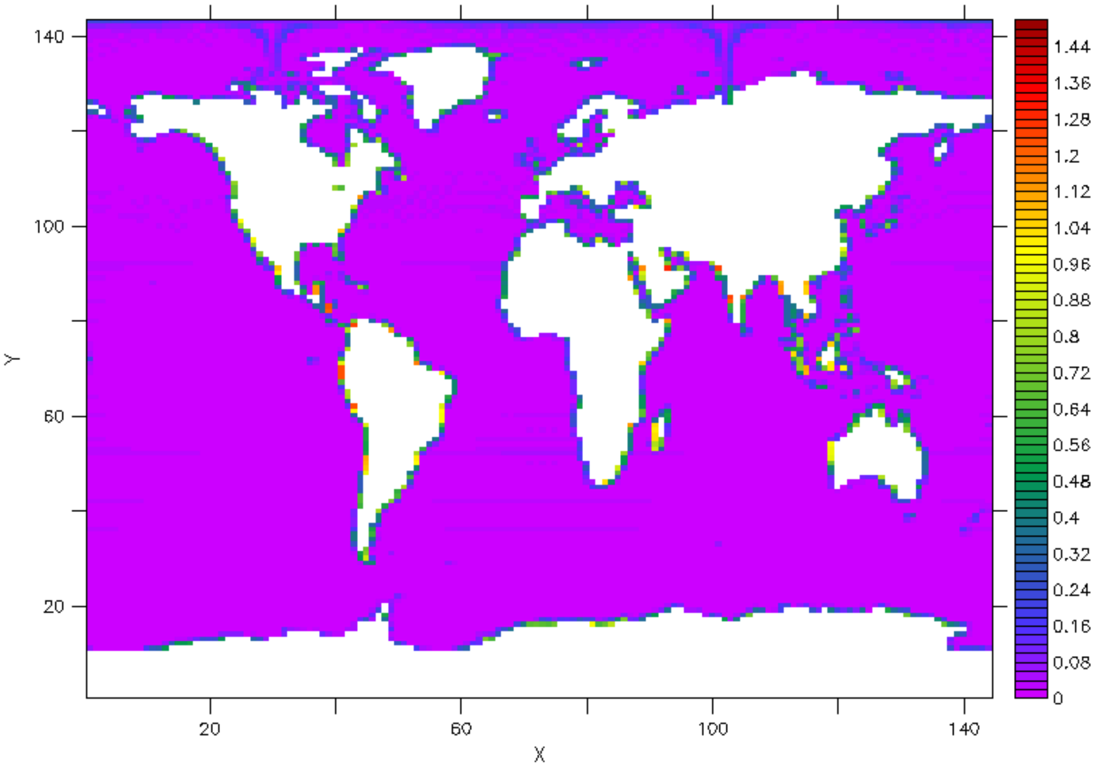

Figure 14 – Interpolation error for the ESMF conservative remapping from nogt to bggd as in [Senhaji, 2016]

Figure 15 illustrates the error difference between ESMF and SCRIP for the conservative remappings from bggd to nogt. The conclusion at this point is that it is not possible to state if one library is better than the other, as the results are very similar except for the last row of points for which ESMF is better than SCRIP for few points and vice-versa for other points.

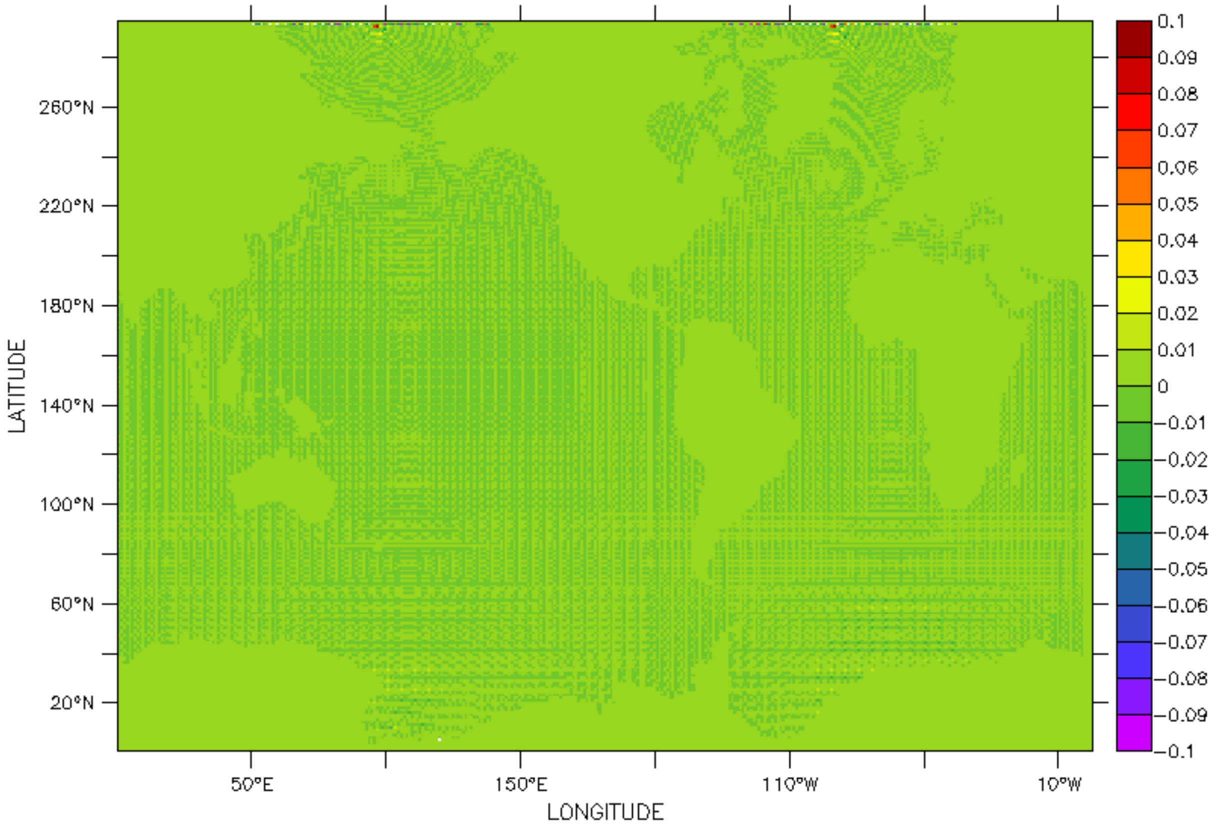

Figure 15 – Difference in interpolation error for the ESMF-SCRIP conservative remapping from bggd to nogt[8] (as in [Senhaji, 2016] p.30[16])

5.2. Unstructured grids

For unstructured grids, the preliminary analysis revealed important problems with ESMF and we did not get to a point where we could more precisely compare ESMF and SCRIP. In fact, with ESMF, a triangulation of the source unstructured grid is first done and the values at the nodes are used to evaluate the value of a remapped target point (which would be appropriate for the nearest-neighbour, bilinear, and patch schemes) but it seems that the definition of the mask is lost in the triangulation, at least in the ESMF version we tested.

For the conservative remapping, the tests we did involved the Gaussian Reduced grid ssea and we did not manage to have a proper conservative remapping to work. Details are provided in [Senhaji, 2016] .We note here that the situation would probably be different for other type of unstructured grids, such as the icosahedral one. Again the problem for the Gaussian Reduced grid comes from the fact that the corners of the cells on a specific latitude row do not coincide with the corners of the cells of the upper or lower latitude rows (see also section 2.1). To have a proper conservative remapping, the vertices of a cell should be defined by its corners but also by the corners of the cells of the lower or higher latitude bands located on the edge of the cell. This is illustrated on figure 16.

[16] Note that there is a typo in captions of figures a) and b) of [Senhaji, 2016] p.30 as the figures illustrate bggd to teo1 (and not teo1 to bggd) conservative remapping.

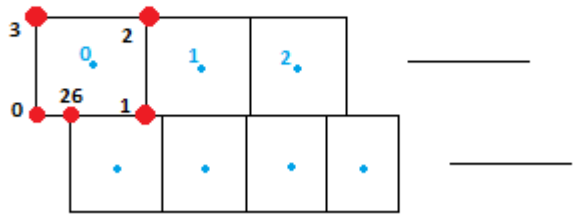

Figure 16 – Vertices that should be associated to a Gaussian Reduced grid cell for a proper conservative remapping.

To define proper vertices for the Gaussian Reduced grid cells, we first tried to use the *csvoro* from NCL. Figure 17 on the left illustrates the first results we obtained. We then added two points at the North Pole and redefine the longitudes of all the points at the pole, which were all 0 originally, so to fit the longitude of the expected cell borders and obtained what is illustrated on Figure 17 on the right.

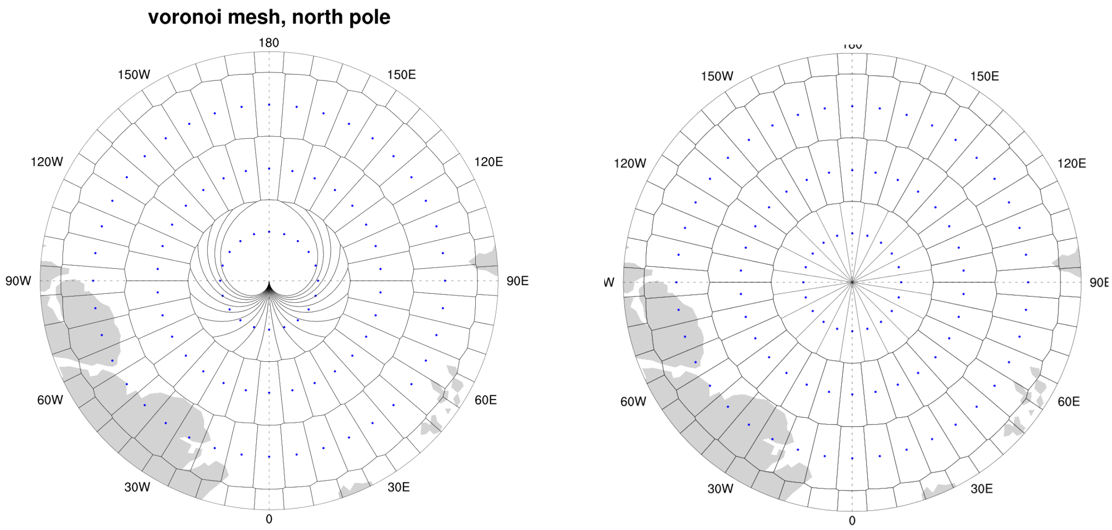

Figure 17 – Definition of vertices for Gaussian Reduced cells using the NCL csvoro function: left) originally with longitudes of all points at the North Pole defined as 0^o ; right) after adding two points at the pole and redefining the longitudes of the points at the pole so to fit the longitude of the expected cell borders.

However, it turned out that we never succeeded in performing an ESMF conservative remapping with the file generated as we always got errors like “clockwise polygons” or “entries are lower than 1”. It maybe that the only way forward would be to define manually the vertices of the cells ourselves by writing a program reading the original corners and detecting for each cell which corners should in fact be considered as an additional vertex of a cell in a lower or higher latitude bands. First steps were achieved in that directions and are described in section 4.3.3 of [Senhaji, 2016] but were not finalised because of lack of time.

6. Summary of the results

A detailed analysis of the SCRIP remapping quality was performed and led to the following conclusions and improvements that are now in the latest version of the coupler OASIS3-MCT_4.0[17]:

- The impact of the Lambert equivalent azimuthal projection, that can be activated for first-order CONSERV above a certain latitude threshold to bypass issues with the SCRIP around the pole, was examined in detail (section 2.1). It leads to the conclusion that this projection is inappropriate for Gaussian Reduced grids as the corners of some cells do not necessarily coincide with the corners of their neighbouring cells for these grids. Furthermore, the projection does not necessarily improve the results for other grids and even, in some cases, slightly degrades them. We therefore decided to not activate the projection in all our tests.
- The SCRIP binning strategy, implemented to restrict the search loops over the grid cells, was analysed (section 2.2). It revealed that its only robust implementation is for CONSERV for all grid types and for BILINEAR and BICUBIC for Gaussian-reduced grid stored from North to South. These usage restrictions were clarified in OASIS3-MCT_4.0 User Guide. In our tests, we never activated the binning option so these usage restrictions have been respected *de facto*.
- An important effort was also devoted to analyse and improve the algorithm used for the cell bounding box definition (section 2.3). A new strategy was implemented that greatly improves the performance of the remapping weight calculation while maintaining the same level of overall quality; this strategy is now used by default in OASIS3-MCT_4.0.
- An important bug for BILINEAR and BICUBIC remappings from the LMDz regular latitude-longitude grid (bggd) to the ORCA1 logically-rectangular stretched grid (nogt), linked to a problem in the multiple cross-product used to check if a target grid point falls into a source grid cell, was solved (section 3.1); the corresponding bugfix is available in OASIS3-MCT_4.0.
- A problem was identified for DISTWGT, BILINEAR and BICUBIC algorithms that do not take into account the periodicity of the source grid (section 3.2); unmasked values of overlapping columns should be used to activate the more precise original schemes but they are not. This issue should be fixed in a future version of OASIS3-MCT.
- The incorrect behaviour of the SCRIP library for cells crossing the pole was evaluated for our grids (section 3.3). In our case, the first-order CONSERV still gives very reasonable results. However, the second-order CONSERV gives wrong results near the pole when the ORCA1 logically-rectangular stretched grid (nogt) is the source grid. The CONSERV SCRIP library has to be used with cautions for grids covering or extending to the pole and the remapping quality has to be evaluated for each coupled model individually before using it in a coupled model.

These conclusions are based on an exhaustive series of tests performed with the grids used in the low-resolution version of IPSL-CM6 and CNRM-CM6 coupled models. A similar systematic analysis should have been achieved for the grids of the high-resolution coupled models but was not because of lack of time. However a detailed evaluation of the quality of the specific remappings involved in CNRM-CM6-1-HR was done and a bug was fixed in the

[17] The exhaustive list of plots done for the analysis of OASIS3_MCT_3.0 was repeated for OASIS3-MCT_4.0 and are available in section 2 of [Jonville et al, 2018].

search of the "additional non-masked nearest neighbour" for Gaussian Reduced grids (section 3.4). With this bugfix and other adjustments all remappings involved in CNRM-CM6-1-HR now provide satisfactory results[18].

An important effort, mainly supported by the European Centre of Excellence ESiWACE, was also devoted to the mixed MPI+OpenMP parallelisation of the SCRIP library. The results are reported here in section 4, as they are fully relevant for CONVERGENCE task 2.4. Important performance improvements, i.e. speedup of the calculations by 2 to 3 orders of magnitude, were obtained for DISTWGT, BILINEAR, BICUBIC and CONSERV. This mixed MPI+OpenMP parallel version of SCRIP is of course available in OASIS3-MCT_4.0.

Finally, first steps toward a systematic analysis of ESMF remappings and comparison with the SCRIP were achieved for structured grids:

- SCRIP and ESMF nearest-neighbour remappings provide very similar results.
- This is also the case for bilinear, except that ESMF is more "strict" in the sense that when at least one of the original neighbours is masked, ESMF does not provide any value for that target point.
- ESMF patch algorithm provides slightly more accurate results than the SCRIP bicubic.
- For the conservative remapping, the results are also very close and ESMF also reproduces the local maximum of error near the pole, although the reasons for this have not been analysed in detail.

For unstructured grid, the analysis of ESMF remappings revealed some specific issues, at least in the ESMF version we tested, that prevented us from a deeper comparison with the SCRIP:

- For nearest-neighbour, bilinear, and patch schemes, the definition of the source grid mask seems to be lost in the grid triangulation done in a preliminary step.
- For the conservative remapping, we tested only Gaussian Reduced grids, but did not manage to have a proper result for that grid due to its specific structure. To have a proper conservative remapping, the vertices of a cell should be defined by its corners but also by the corners of the cells of the lower or higher latitude bands located on the edge of the cell; we followed different paths to try to define appropriately the cell vertices but this task was not finalised because of lack of time.

7. Conclusions and perspectives

The objective of this milestone was to achieve a detailed analysis of the SCRIP library currently implemented in OASIS3-MCT, evaluate and improve its quality and performance, and to compare it with other remapping libraries (ESMF, XIOS, OpenPALM).

The work turned out to be much more difficult and to take much more time than expected. Indeed, covering the space of possibilities, when one considers different algorithms and many different grids, is very laborious. Identifying and understanding the many different issues that arise is extremely painstaking and time-consuming as they involve not only the library algorithm itself but also the way the grids are defined (cell definition, mask, ovelap, etc.).

Nevertheless, few bug were identified in the SCRIP library and are now fixed in the last version of the coupler, OASIS3-MCT_4.0. Even if the SCRIP is not full satisfactory, it still

[18] The details of this work can be found at https://inle.cerfacs.fr/projects/cnrm-cm6/wiki/Qualité_des_interpolations_CNRM-CM6_HR

provides appropriate results in many cases and it was judge useful to parallelise it with MPI+OpenMP, which improves its performances by 2 to 3 orders of magnitude.

However, the analysis leads us to conclude that the SCRIP library presents some structural drawbacks for the conservative remapping for cell extending to or covering the poles. A Lambert azimuthal projection is proposed in SCRIP to bypass this problem but it cannot be applied for the Gaussian Reduced grid and does not necessarily improve, if not degrade, the results for other grids. Implementation of a global rotation for the cells near the pole seemed to be a promising path [Kilicoglu & Valcke 2010] but turned out to be too complex to be implemented. Therefore it seems that the only real way forward is to consider alternative conservative schemes. First steps in that direction were taken with ESMF but revealed specific issues, at least with the ESMF version we tested (6.3.0rp1). We now have to push this effort further with the latest ESMF version, using in particular an appropriate definition of the Gaussian Reduced grid cells and analysing in more detail the results near the pole. Other libraries like XIOS or YAC, using other types of conservative schemes, also have to be evaluated, so to be able to propose the best state-of-the-art remapping library for use in OASIS3-MCT. This work will be addressed in the EU project IS-ENES3, recently funded in the framework or the H2020 program.

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- ESiWACE H2020 European Centre of Excellence, grant agreement no. 675191 (www.esiwace.eu).

9. References (Bibliography)

[Craig et al, 2017]
A. Craig, S. Valcke, L. Coquart, 2017: Development and performance of a new version of the OASIS coupler, OASIS3-MCT_3.0, Geosci. Model Dev., 10, 3297-3308, https://doi.org/10.5194/gmd-10-3297-2017.

[Hanke et al, 2016]
M. Hanke, R. Redler, T. Holfeld, M. Yastremsky, 2016. YAC 1.2.0: new aspects for coupling software in Earth system modelling. Geosci. Model Dev., 9, 2755–2769, www.geosci-model-dev.net/9/2755/2016/, doi:10.5194/gmd-9-2755-2016 .

[Jones 1999]
P.W. Jones, 1999. Conservative remapping: First- and second-order conservative remapping, Mon. Weather Rev., 127, 2204–2210.

[Jonville et al, 2018]
G. Jonville, S. Valcke, L. Coquart, E. Maisonnave and A. Piacentini, 2018. Specific analyses of the SCRIP interpolation library for OASIS coupler, CECI, Université de Toulouse, CNRS, CERFACS - WN-CMGC-18-93, Toulouse, France. https://cerfacs.fr/wp-content/uploads/2018/09/GLOBC-WN-Jonville_Specific_analyses_SCRIP_21092018.pdf

[Kilicoglu et Valcke, 2010]
E. Kilicoglu, and S. Valcke, 2010. Développement de la librairie d'interpolation du coupleur OASIS, URA SUC 1875, CERFACS/CNRS, TR-CMGC-10-22066, Toulouse, France. http://cerfacs.fr/wp-content/uploads/2017/08/GLOBC_TR_Kilicoglu_dvlpt_SCRIP_OASIS_2010.pdf

[Kritsikis et al, 2017]
E. Kritsikis, M. Aechtner, Y. Meurdesoif, and T Dubos, 2017. Conservative interpolation between general spherical meshes, Geosci. Model Dev., 10, 425-431, https://doi.org/10.5194/gmd-10-425-2017

[Piacentini et al, 2018]
A. Piacentini, E. Maisonnave, G. Jonville, L. Coquart, S. Valcke, 2018. A parallel SCRIP interpolation library for OASIS, Technical Report TR/CMGC/18-34, Cerfacs, France. https://cerfacs.fr/wp-content/uploads/2018/03/GLOBC-TR-PIANCENTINI-cmgc_18_34.pdf

[Senhaji 2016]
H. Senhaji, 2016. Evaluation et comparaison des interpolations numériques des librairies SCRIP et ESMF, Working Notes Cerfacs WN-CMGC-16-227, Cerfacs, France. http://cerfacs.fr/wp-content/uploads/2016/09/GLOBC-SHENAJI-Rapport_stage_2016.pdf

[Valcke et al, 2018a]
S. Valcke, T. Craig and L. Coquart, 2018. OASIS3-MCT User Guide, OASIS3-MCT_4.0, CECI, Université de Toulouse, CNRS, CERFACS - TR-CMGC-18-77, Toulouse, France. https://cerfacs.fr/wp-content/uploads/2018/07/GLOBC-TR-oasis3mct_UserGuide4.0_30062018.pdf

[Valcke et al, 2018b]
S. Valcke, L. Coquart, A. Craig, G. Jonville, E. Maisonnave and A. Piacentini, 2018. Multithreaded or thread safe OASIS version including performance optimizations to adapt to many-core architectures, Deliverable D2.3, ESiWACE project, CECI, Université de Toulouse, CNRS, CERFACS - TR-CMGC-18-74, Toulouse, France. https://cerfacs.fr/wp-content/uploads/2018/06/GLOBC_Valcke_TR_D2.3-OASIS_final_25062018.pdf