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Benchmarking different regridding libraries used in Earth System Modelling

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INFRASTRUCTURE FOR THE EUROPEAN NETWORK FOR EARTH SYSTEM MODELLING

Sophie Valcke, Andrea Piacentini, Gabriel Jonville

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Objectives and context

The OASIS3-MCT coupler

Preliminary analysis of regridding libraries

Regridding benchmark – grids, analytical functions, algorithms, metrics

Regridding benchmark – results DISTWGT, BILINEAR, 2nd ORDER, CONSERV 1st & 2nd O

Regridding benchmark – library performance and scalability

Conclusions

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Objective and context

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Evaluate the quality and the performance of different regridding libraries used in Earth System Modelling to complement the SCRIP library in the OASIS3-MCT coupler:

- ATLAS (ECMWF):
- MOAB-TempestRemap (DoE; USA)
- YAC (MPI-M; DE)
- ESMF (NASA, NOAA, DoD, NSF; USA)
- XIOS (IPSL/CEA, FR)

Funded by the IS-ENES3 EU project

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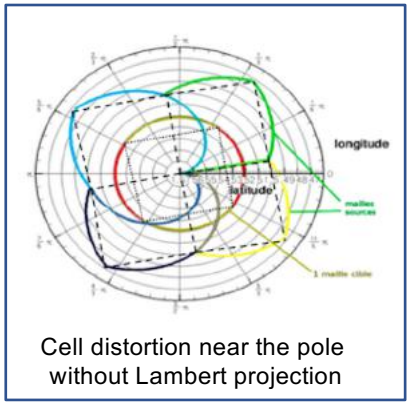
First step toward a “community” benchmark on regridding functionality of different coupling software? First discussed at the *5th Workshop on Coupling Technologies for Earth System Models* (Sept. 21-24, 2020, meeting summary submitted to BAMS)

Objective and context

SCRIP detailed quality analysis (2019)

SCRIP assumes borders are linear in (lat,lon) and uses Lambert equivalent azimuthal projection near the pole for intersection calculation



Cell distortion near the pole without Lambert projection

For longitude-latitude, logically-rectangular, icosahedral grids, SCRIP :

- with FRACAREA normalization OK with and without Lambert projection
- with DESTAREA normalization OK but
  - For logically-rectangular <-> longitude-latitude, only with Lambert projection
  - For icosahedral -> logically-rectangular, only without Lambert projection

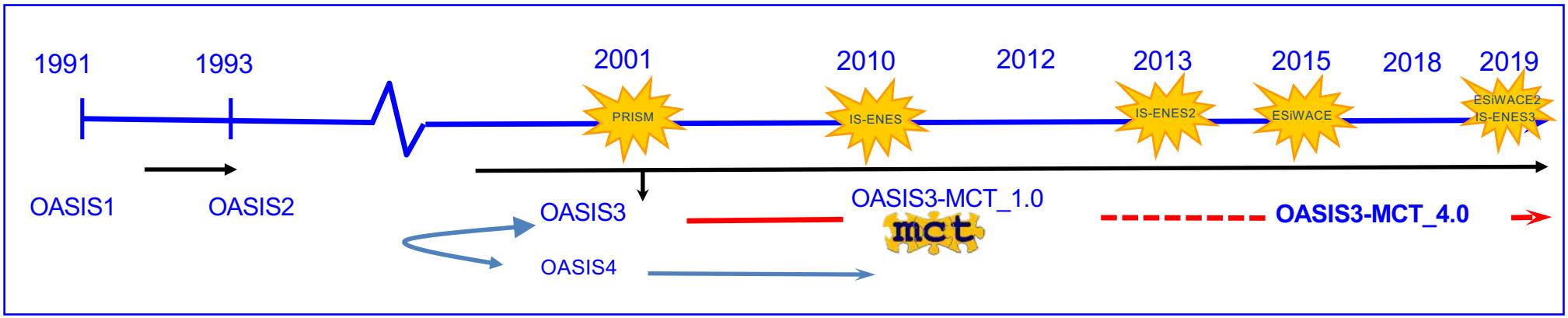
For Gaussian-reduced grids, SCRIP :

- with FRACAREA normalization OK without Lambert projection
- with **DESTAREA normalization not OK: error with & without Lambert projection**

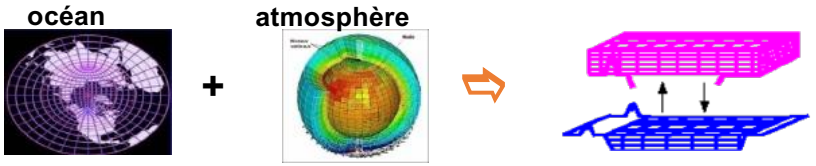
Jonville & Valcke 2019, Valcke & Piacentini 2019 (Cerfacs tech reports)

➢ **need to offer other regridding possibilities in OASIS3-MCT**

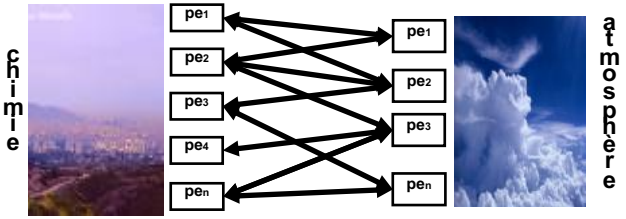
The OASIS3-MCT coupler



•OASIS1 -> OASIS2 -> OASIS3:
2D ocean-atmosphere coupling
low frequency, low resolution :
→ Flexibility, 2D interpolations



•OASIS4 / OASIS3-MCT:
2D/3D coupling of high-resolution parallel components
→Parallelism, performance



➢ F90 & C, LGPL licence, public domain libraries (MPI, NetCDF, SCRIP, MCT)

The OASIS3-MCT user community – 2019 survey

67 climate modelling groups around the world use OASIS3-MCT …

…. to assemble more than 80 coupled applications !!

OASIS3-MCT is used in 5 of the 7 European ESMs participating to CMIP6

Preliminary analysis of regridding libraries

ATLAS (ECMWF)

- no support for masks
- no conservative regridding
  - ➢ useful & portable toolkit for the best usage of heterogeneous architectures but can't be the choice on the short term (Piacentini 2020, CERFACS Tech Rep)

MOAB-TempestRemap (DoE; USA)

- conservative regridding only
- no support of masks (masked cells removed => grid with holes => problems for 2nd O)
  - ➢ not mature enough, analysis of 1st O conservative regridding only

YAC (MPI-M; DE)

- dynamic developer (OASIS experience !) but lack of official commitment for support on the long term

ESMF (NASA, NOAA, DoD, NSF; USA)

- large community, good long-term perspectives
- good and efficient user support

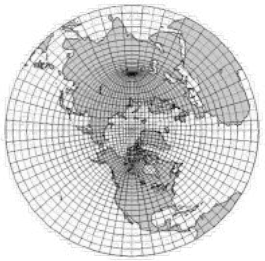
XIOS (IPSL/CEA, FR):

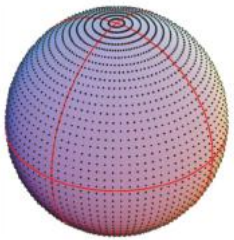
- conservative regridding only
- growing community, growing number of developers
- natural collaboration with CERFACS

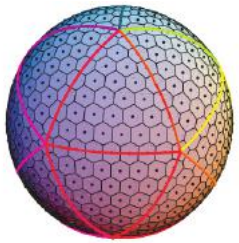
Regridding benchmark – grids

14 couples of grids involving 6 grids:

- torc: NEMO ORCA2 rotated-stretched logically-rectangular (182x149)
- nogt : NEMO ORCA1 rotated-stretched logically-rectangular (362x294)
- bggd: LMDz regular lat-lon (144x143)
- sse7: ARPEGE Gaussian reduced T127 (24572)
- icos: Dynamico icosahedral grid (15222)
- icoh: Dynamico icosahedral grid (2016012)

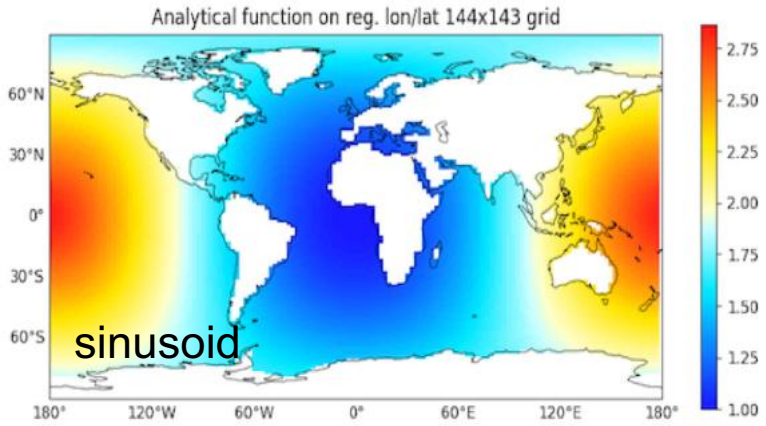


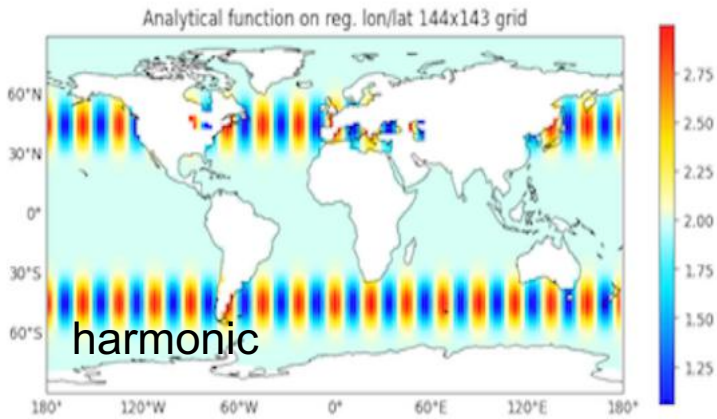


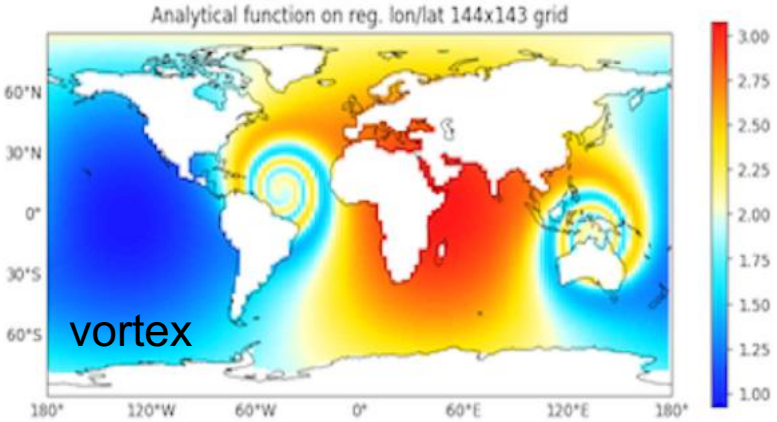


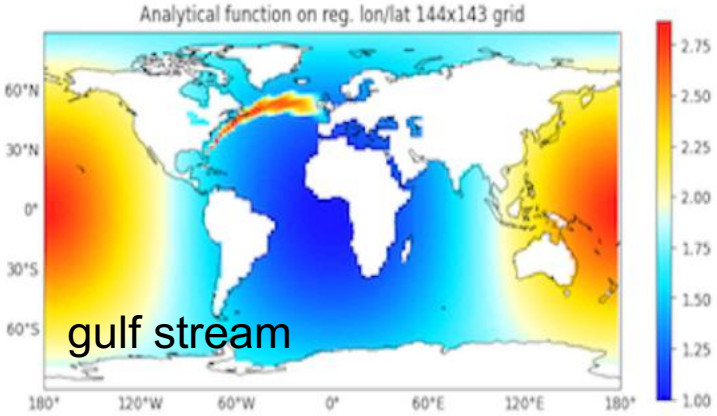
Regridding benchmark – test cases

4 functions:









4 algorithms: nearest-neighbour, bilinear, bicubic, 1st and 2nd order conservative

Regridding benchmark – criteria & metrics

From CANGA project (https://github.com/CANGA/Remapping-Intercomparison)

Ψ^s *Analytical function on source grid* Ψ^t *Analytical function on target grid* $\mathbf{R}\Psi^s$ *Source analytical function regridded on target grid*

- sensitivity : algorithmic invariance to underlying mesh topology
  - ✓ test cases with 14 couples of grids
- consistency: accuracy and preservation of discretization order
  - ✓ accuracy: misfit mean, max, rms

$$\text{mean}\frac{|\mathbf{R}\Psi^s - \Psi^t|}{|\Psi^t|} \qquad \max\frac{|\mathbf{R}\Psi^s - \Psi^t|}{|\Psi^t|} \qquad \sigma\frac{|\mathbf{R}\Psi^s - \Psi^t|}{|\Psi^t|}$$

- conservation:
  - ✓ conservation

$$\frac{|I_t(\mathbf{R}\Psi^s) - I_s(\Psi^s)|}{I_s(\Psi^s)}$$

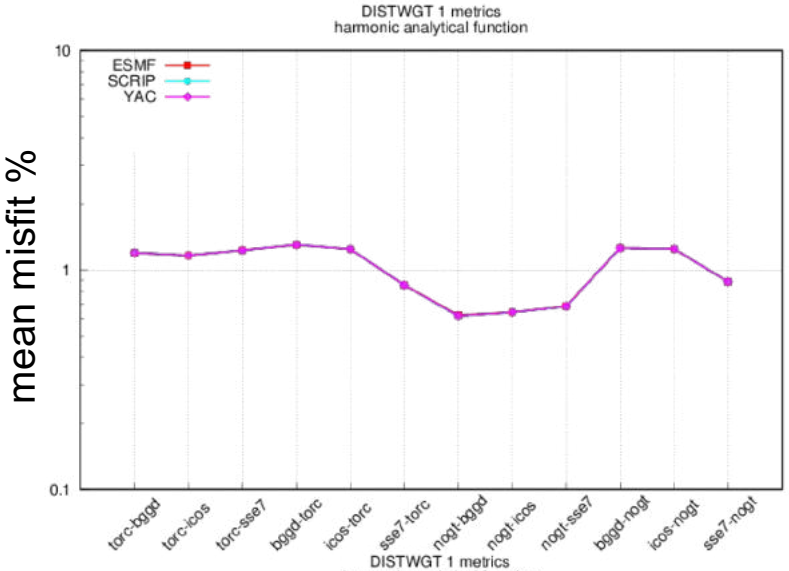
- monotonicity: preservation of global solution bounds
  - ✓ Lmin & Lmax

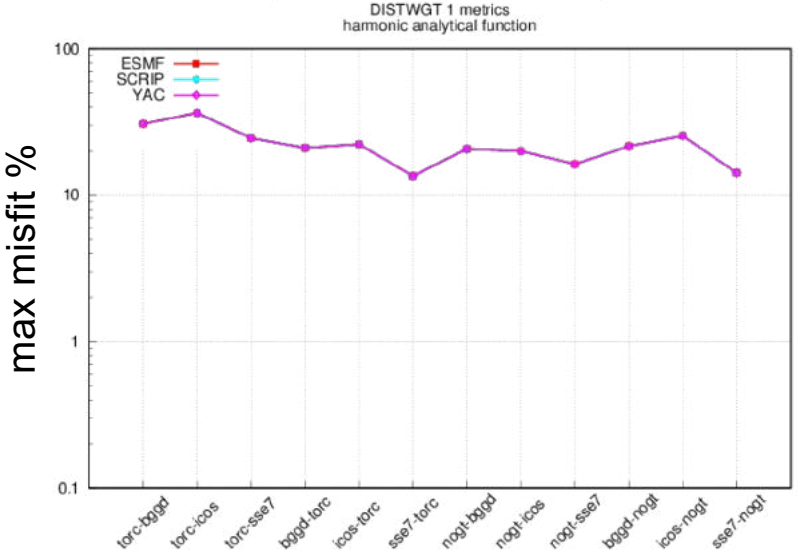
$$L_{\min} = \frac{\min\Psi^t - \min\mathbf{R}\Psi^s}{\max|\Psi^t|} \qquad L_{\max} = \frac{\max\mathbf{R}\Psi^s - \max\Psi^t}{\max|\Psi^t|}$$

Lmin/Lmax positive
➢ under/overshoots
Lmin/Lmax negative :
➢ smoothing (~dissipation?)

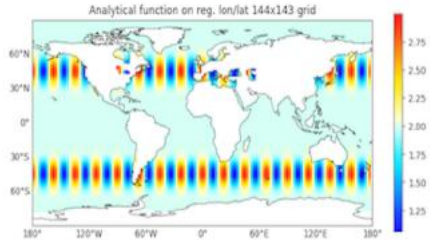
- performances
  - ✓ Scalability curves on kraken (Cerfacs Lenovo)
- dissipation (over a back-and-forth exchange)

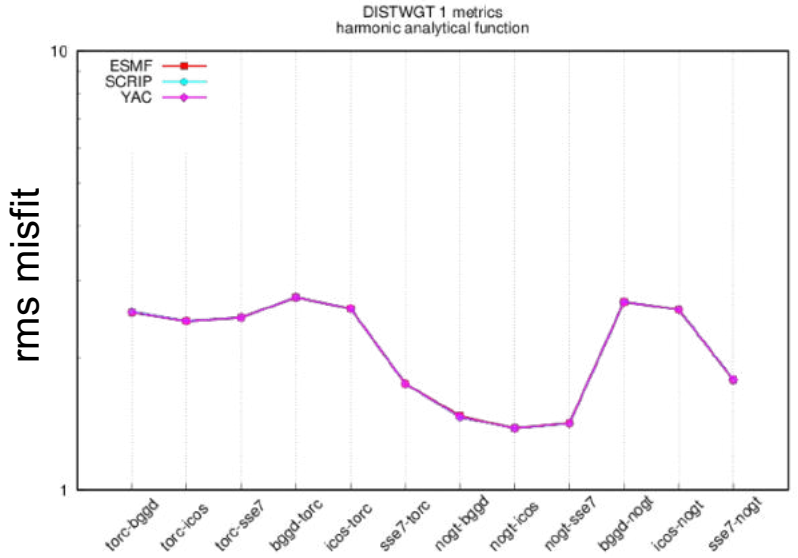
Regridding benchmark – results DISTWGT





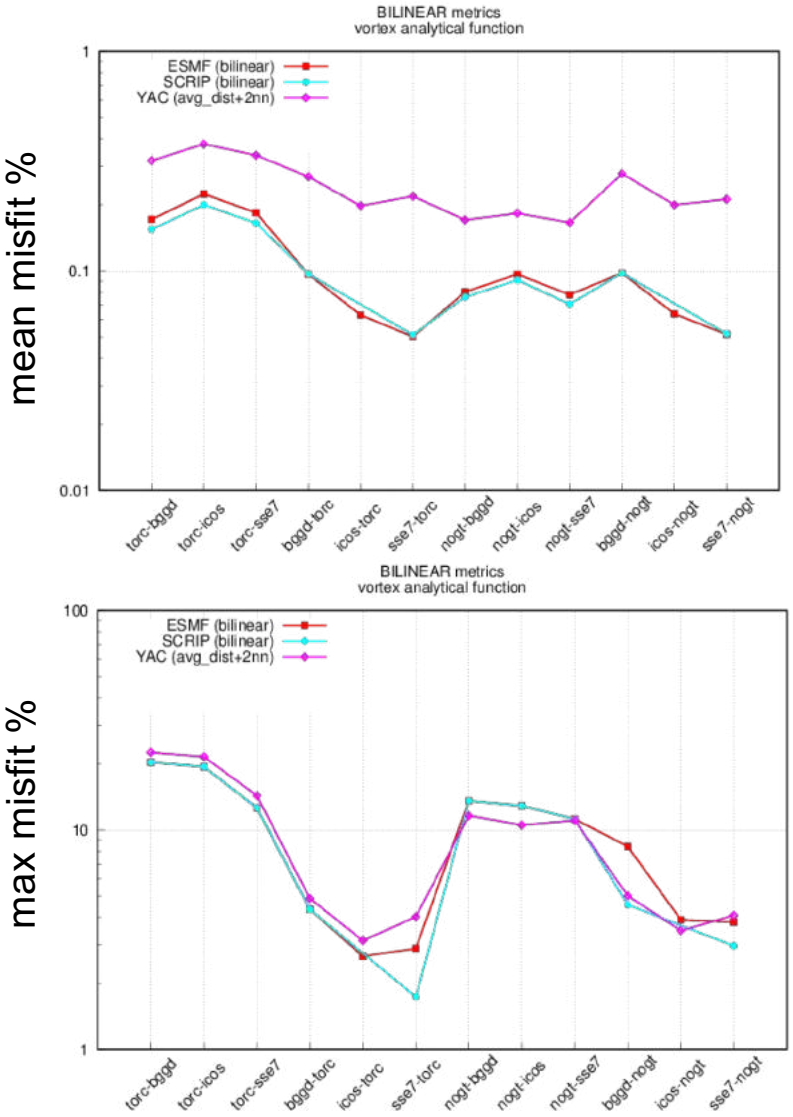
DISTWGT (nearest-neighbour)
harmonic
SCRIP, ESMF, YAC
not implemented in XIOS or MTR

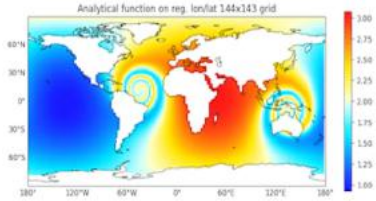




- SCRIP, ESMF & YAC produce same and reasonable results

Regridding benchmark – results BILINEAR





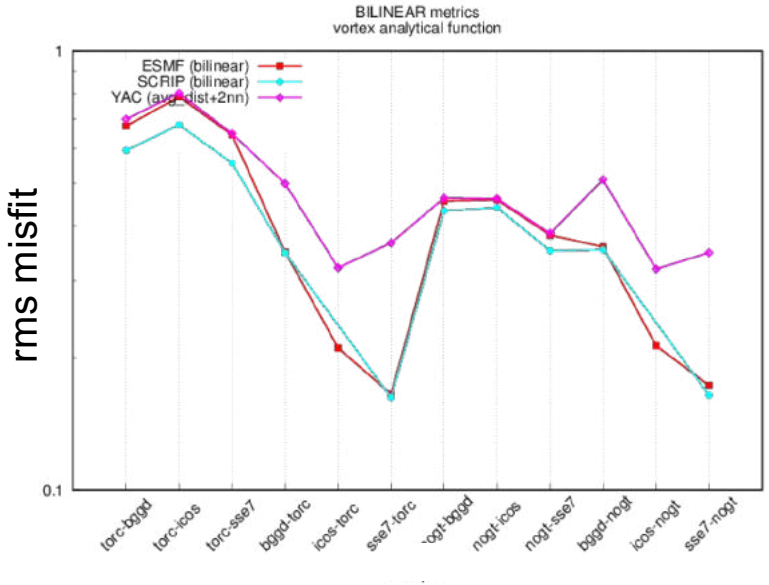
BILINEAR

vortex

SCRIP, ESMF

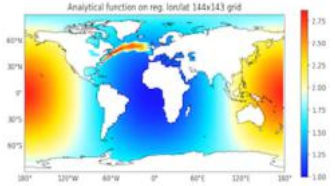
YAC (inverse distance weighting of enclosing neighbours)

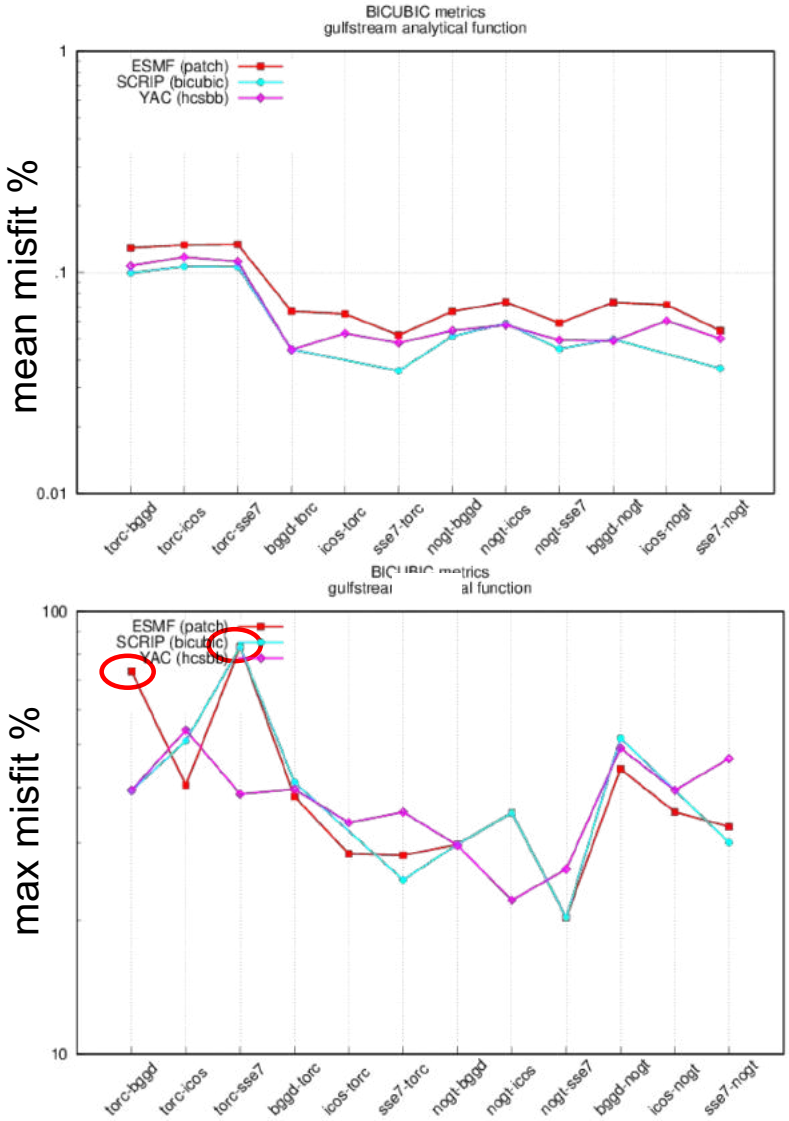
not implemented in XIOS or MTR



➢YAC less accurate on average

Regridding benchmark – results 2nd ORDER





BICUBIC, PATCH, HCSBB

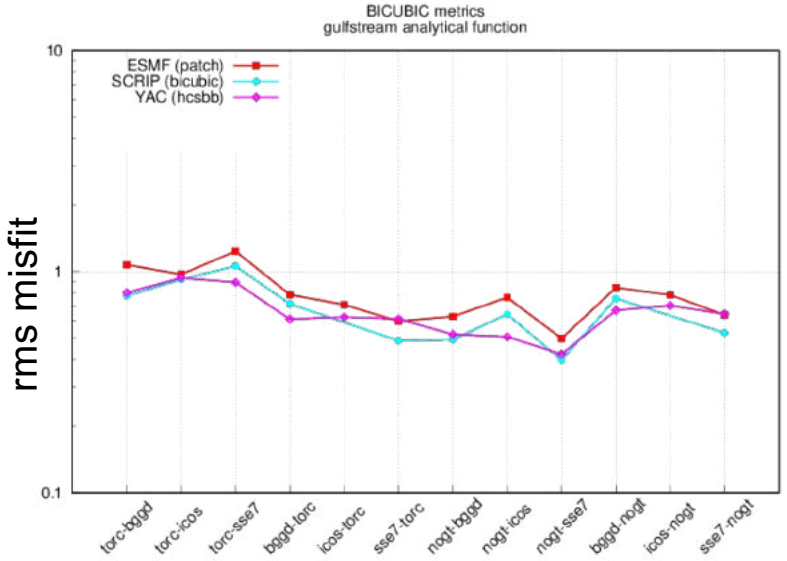
gulfstream

SCRIP (local-coordinate system bicubic approx, Jones 1999)

ESMF (multiple 2nd deg 2D polynomial source patches)

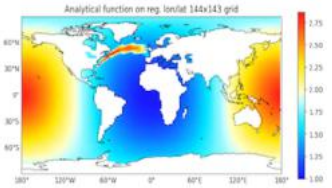
YAC (spherical Bernstein-Bézier polynomials, Hanke & Redler, 2019)

not implemented in XIOS nor MTR



- ESMF patch slightly less accurate on average
- High max misfit for torc-sse7 (ESMF, SCRIP) and torc-bggd (ESMF), linked to strong gradient (not visible for harmonic)

Regridding benchmark – results 2nd ORDER



$$L_{\min} = \frac{\min \Psi^t - \min \mathbf{R}\Psi^s}{\max |\Psi^t|}$$

$$L_{\max} = \frac{\max \mathbf{R}\Psi^s - \max \Psi^t}{\max |\Psi^t|}$$

BICUBIC, PATCH, HCSBB

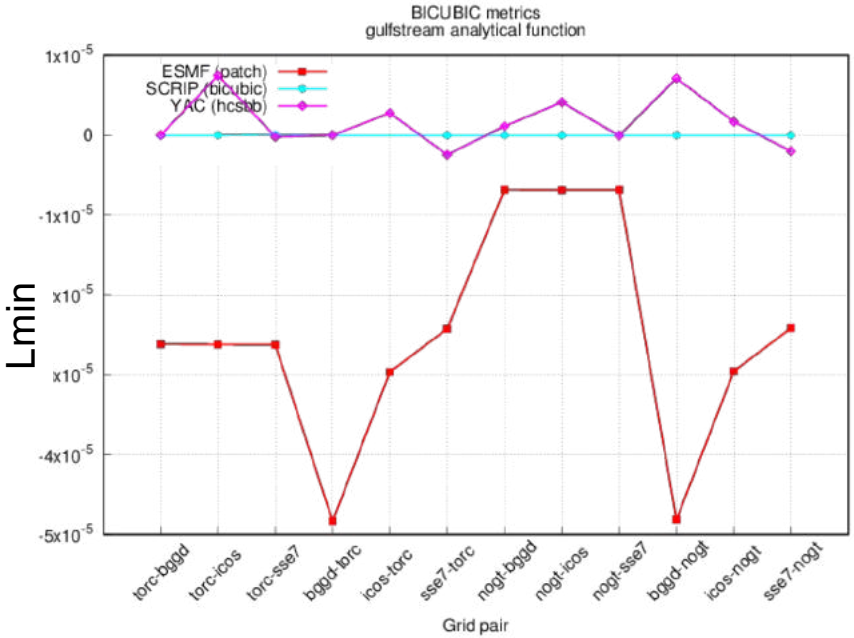
gulfstream

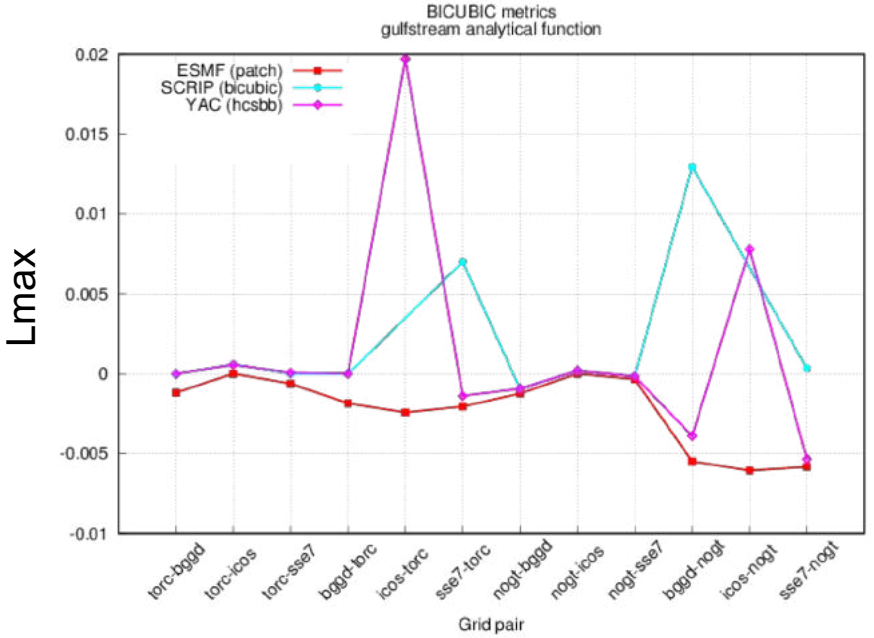
SCRIP (local-coordinate system bicubic approx, Jones 1999)

ESMF (multiple 2nd deg 2D polynomial source patches)

YAC (spherical Bernstein-Bézier polynomials, Liu & Schumaker 1996)

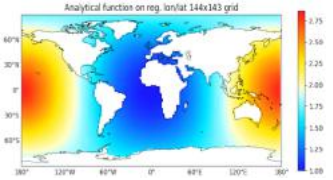
not implemented in XIOS nor MTR





- ESMF smooths function minimum
- YAC overshoots when source grid is icosahedral (icos-torc & icos-nogt) (??)

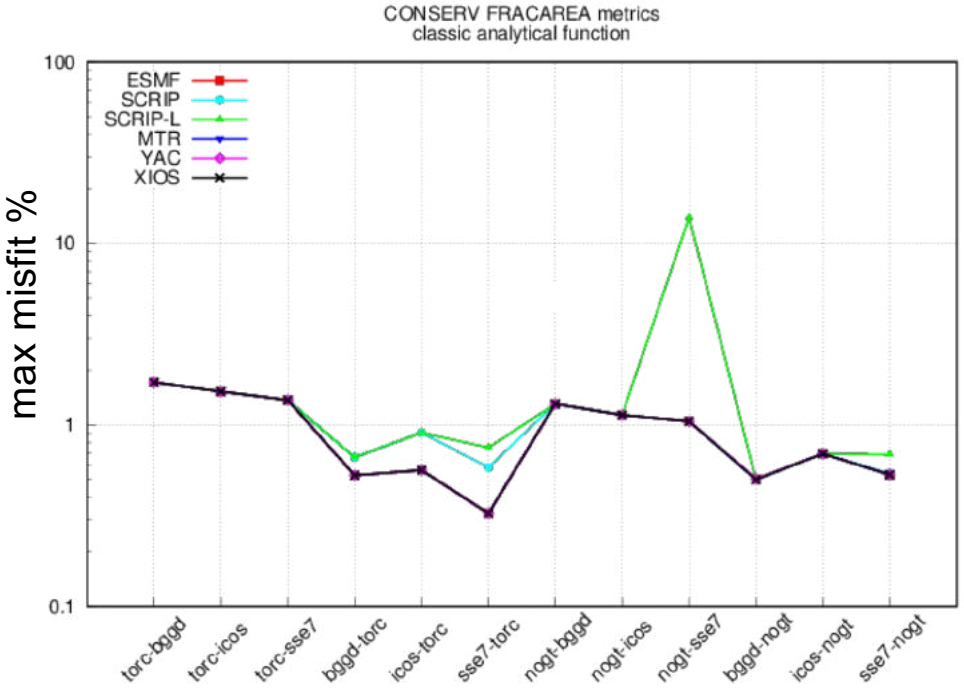
Regridding benchmark – results CONSERV 1st O

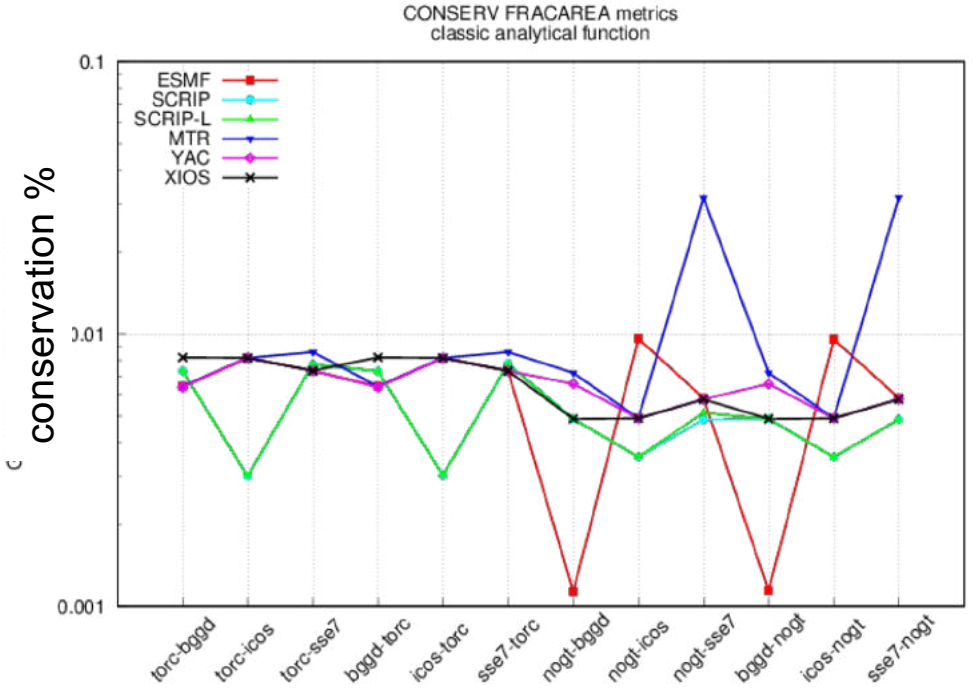


FRACAREA: if non-matching sea-land masks, normalisation with **intersected area** (sometimes cancels error)

CONSERV 1st O (FRACAREA)

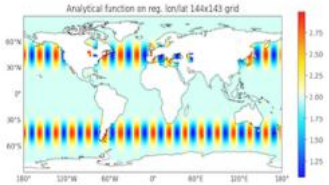
sinusoid
SCRIP, SCRIP-L (with Lambert proj. above 83 N)
ESMF, YAC, XIOS, MTR





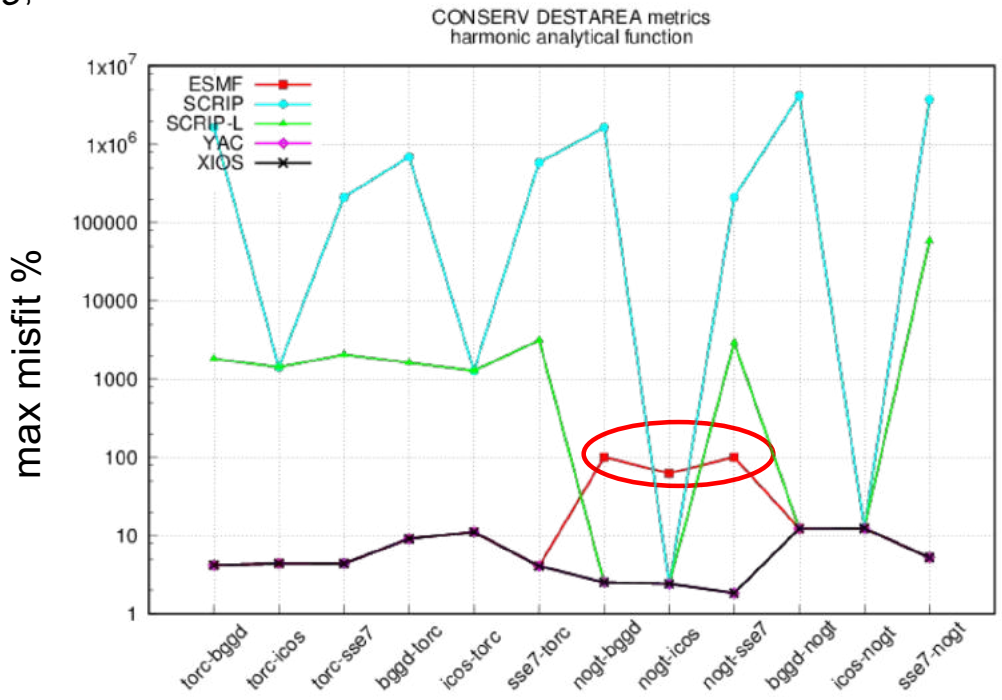
➢ Good conservation for ESMF, YAC & XIOS, problems for SCRIP-L & MTR (nogt<->sse7)

Regridding benchmark – results CONSERV 1st O



DESTAREA: if non-matching sea-land masks, normalisation with full target cell area (reveals errors, no cancellation)

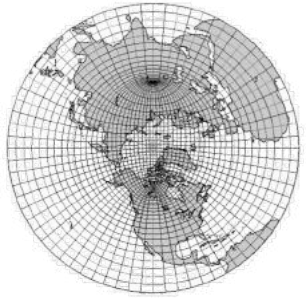
CONSERV 1st O (DESTAREA)
harmonic
SCRIP, SCRIP-L (with Lambert proj. above 83 N)
ESMF, YAC, XIOS



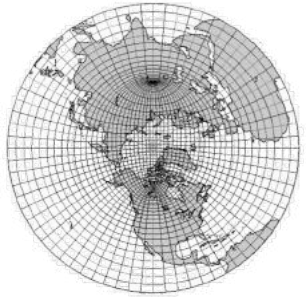
- Good and similar results for XIOS, ESMF and YAC (Kritsikis et al 2017)
- Problems with NEMO North fold for ESMF when nogt **structured** is source

Regridding benchmark – results CONSERV 1st O

CONSERV 1st O (DESTAREA) – harmonic – nogt->bggd

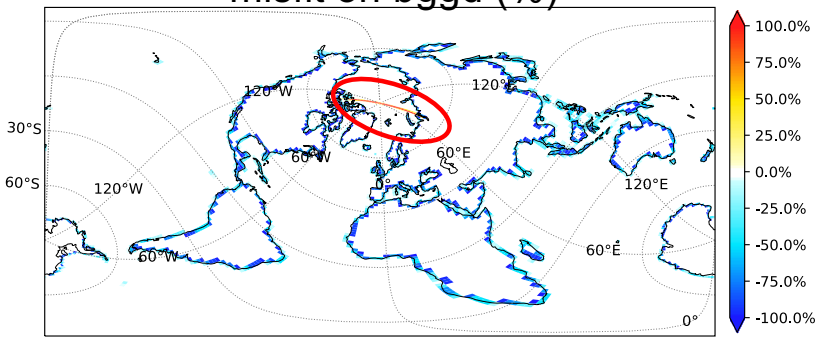


Regridding benchmark – results CONSERV 1st O



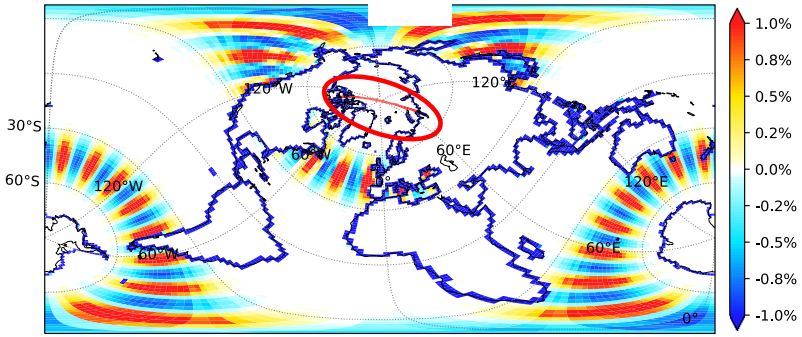
CONSERV 1st O (DESTAREA) – harmonic – nogt->bggd

misfit on bggd (%)

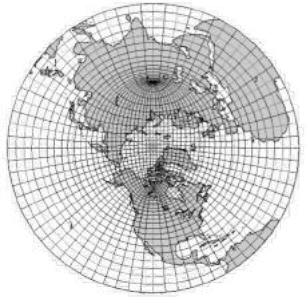


nogt NEMO ORCA1 ***structured***

misfit on bggd (%)

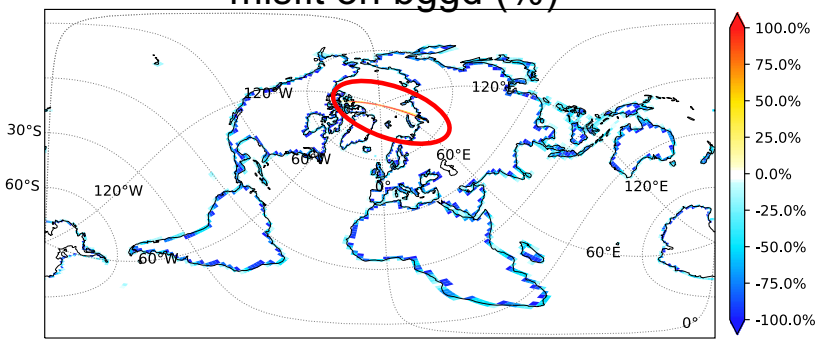


Regridding benchmark – results CONSERV 1st O

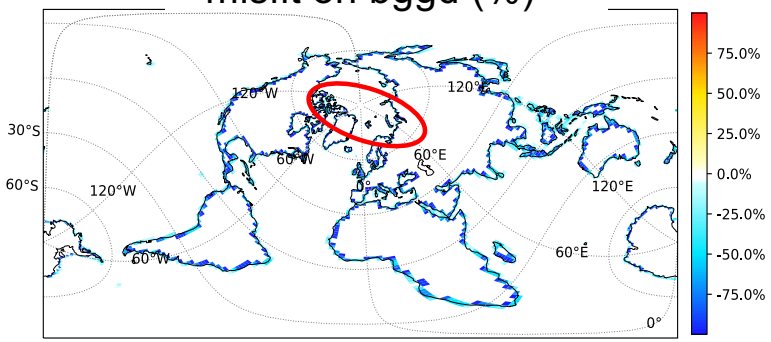


CONSERV 1st O (DESTAREA) – harmonic – nogt->bggd

misfit on bggd (%)

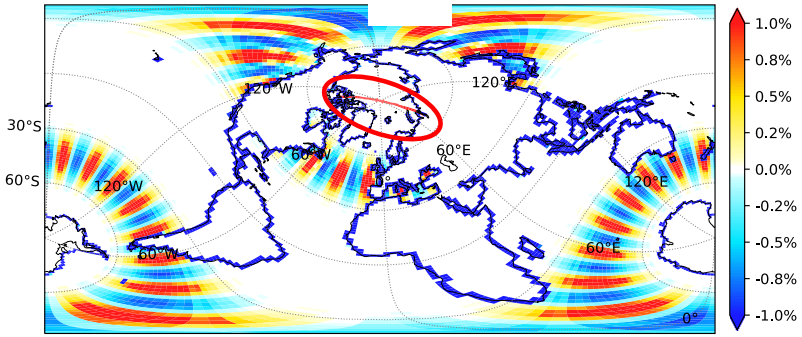


misfit on bggd (%)



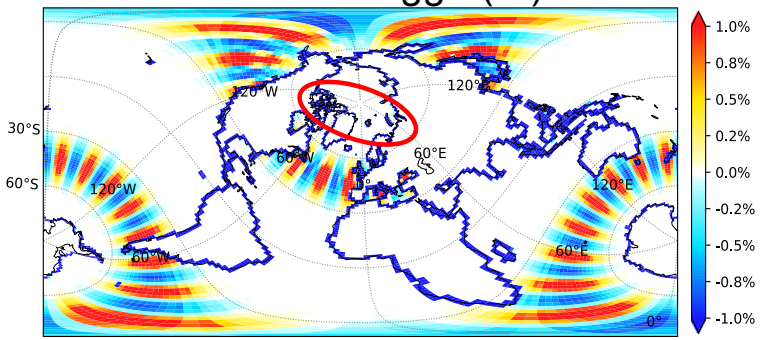
nogt NEMO ORCA1 ***structured***

misfit on bggd (%)



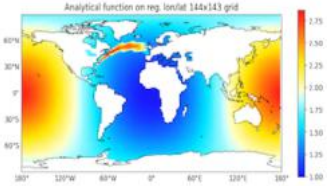
nogt NEMO ORCA1 ***unstructured***

misfit on bggd (%)



➢ Good results for ORCA grid North fold with ESMF if nogt is declared **unstructured**

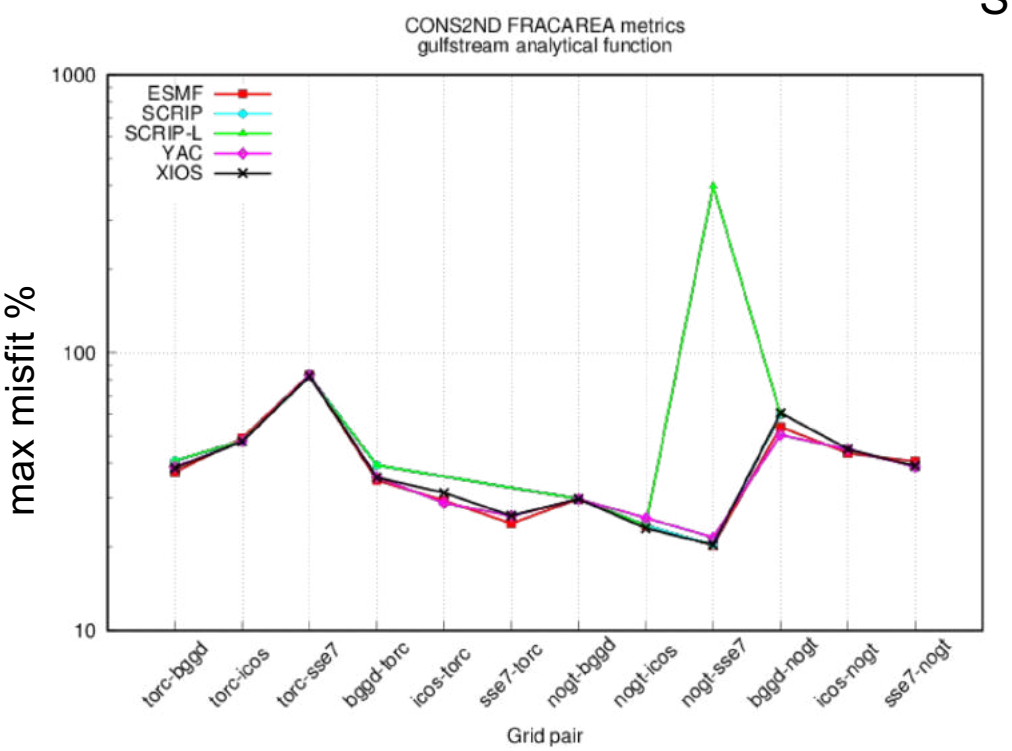
Regridding benchmark –results CONSERV 2nd O

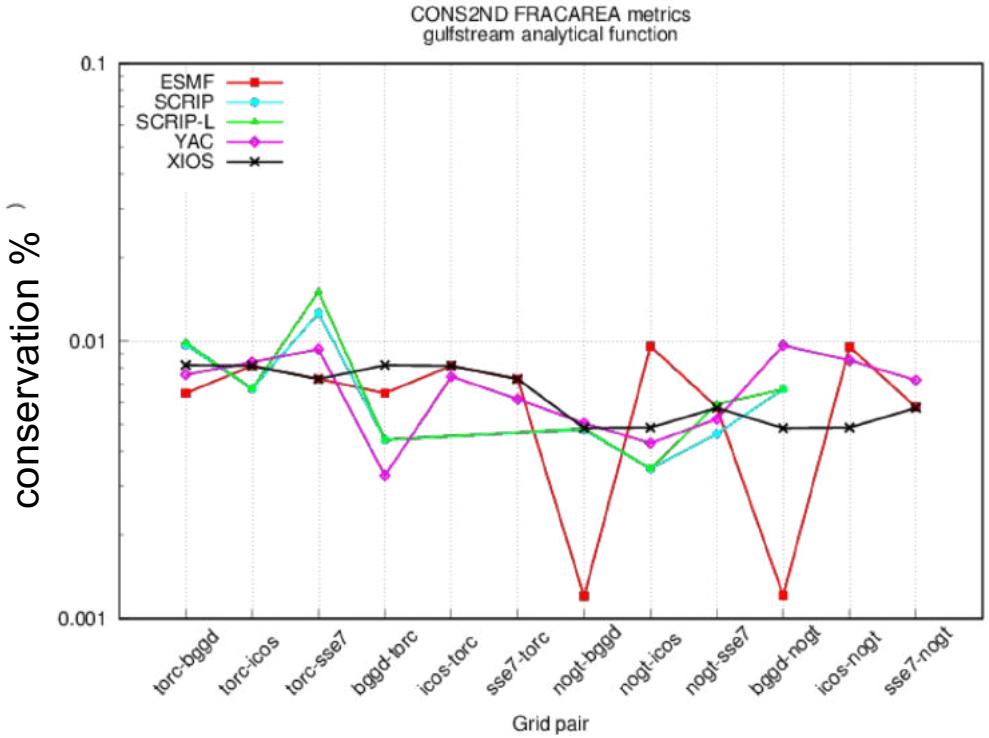


CONSERV 2nd O FRACAREA

gulfstream

SCRIP, SCRIP-L, ESMF, YAC, XIOS



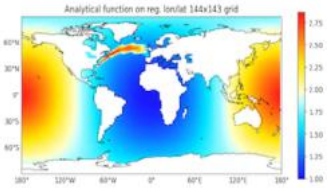


- Good and similar results for XIOS, ESMF and YAC (Kritsikis et al 2017)
- Problems for SCRIP & SCRIP-L (in OASIS3-MCT) for nogt-sse7

Regridding benchmark –results CONSERV 2nd O

$$L_{\min} = \frac{\min \Psi^t - \min \mathbf{R}\Psi^s}{\max |\Psi^t|}$$

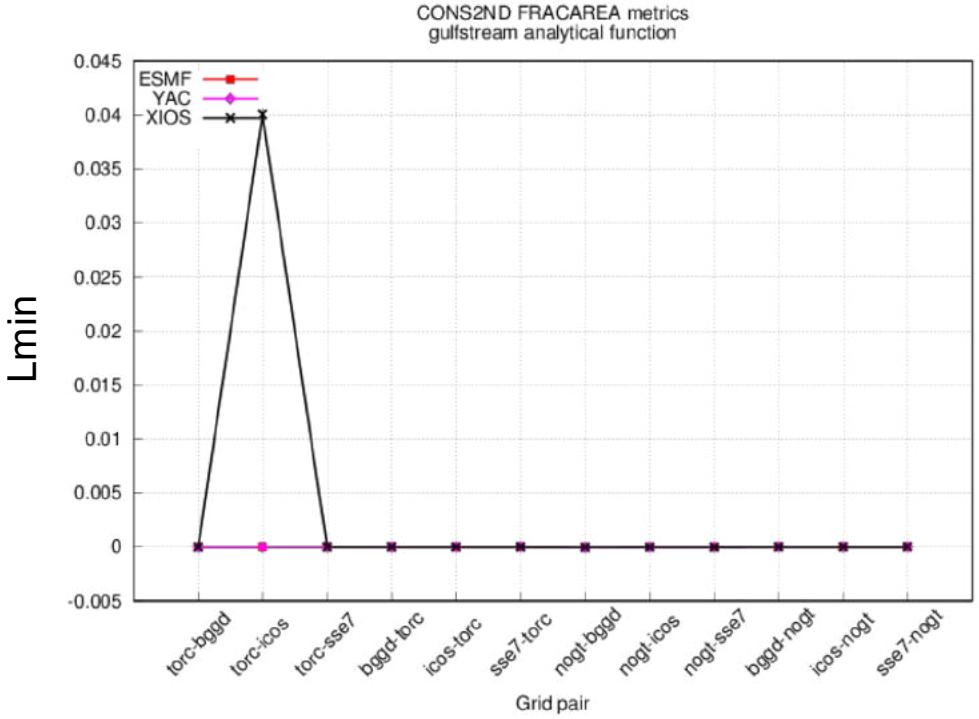
$$L_{\max} = \frac{\max \mathbf{R}\Psi^s - \max \Psi^t}{\max |\Psi^t|}$$

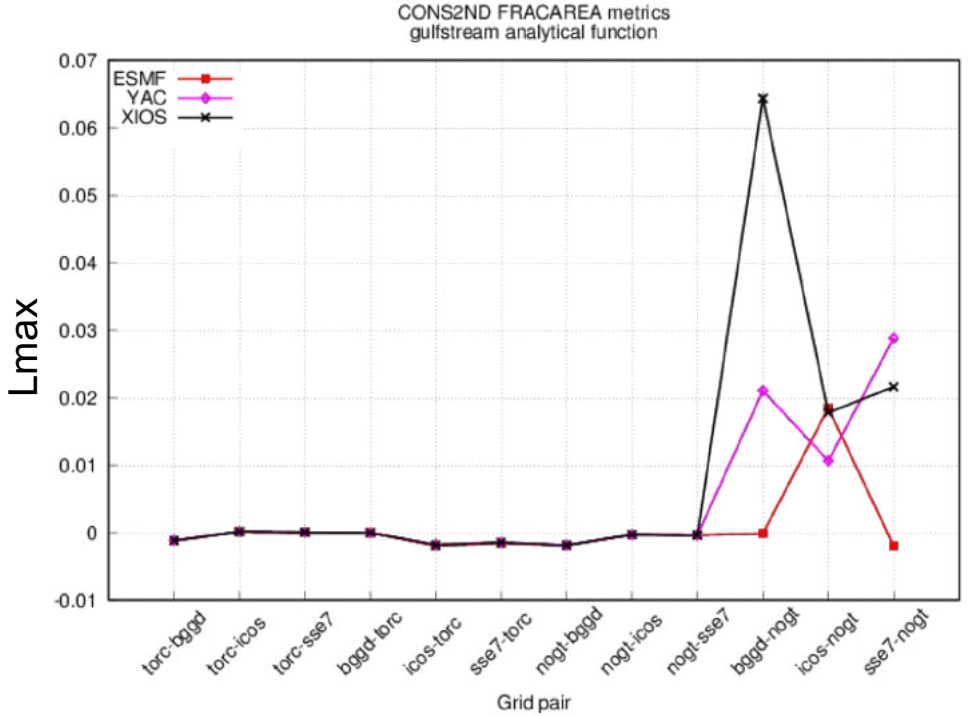


CONSERV 2nd O FRACAREA

gulfstream

ESMF, YAC, XIOS

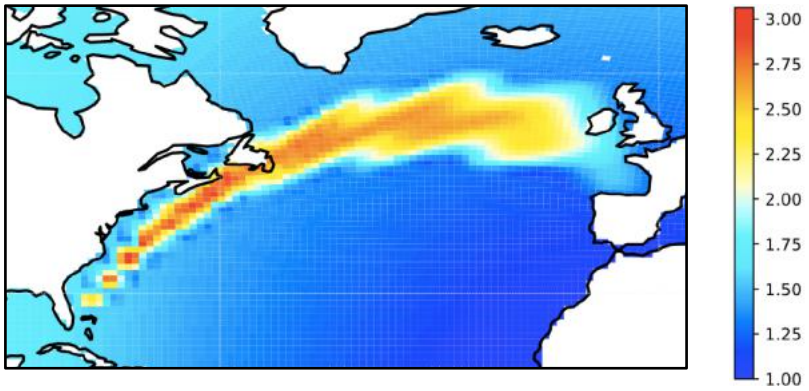




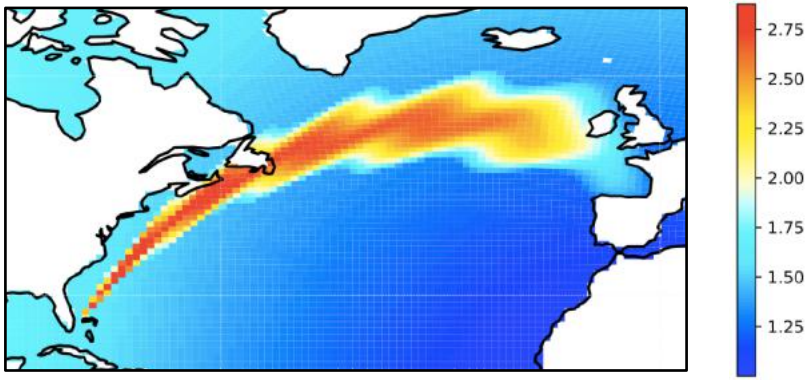
- XIOS undershoots for torc-icos and overshoots for bggd-nogt (??)

Regridding benchmark – results CONSERV 2nd O

regridded function on nogt



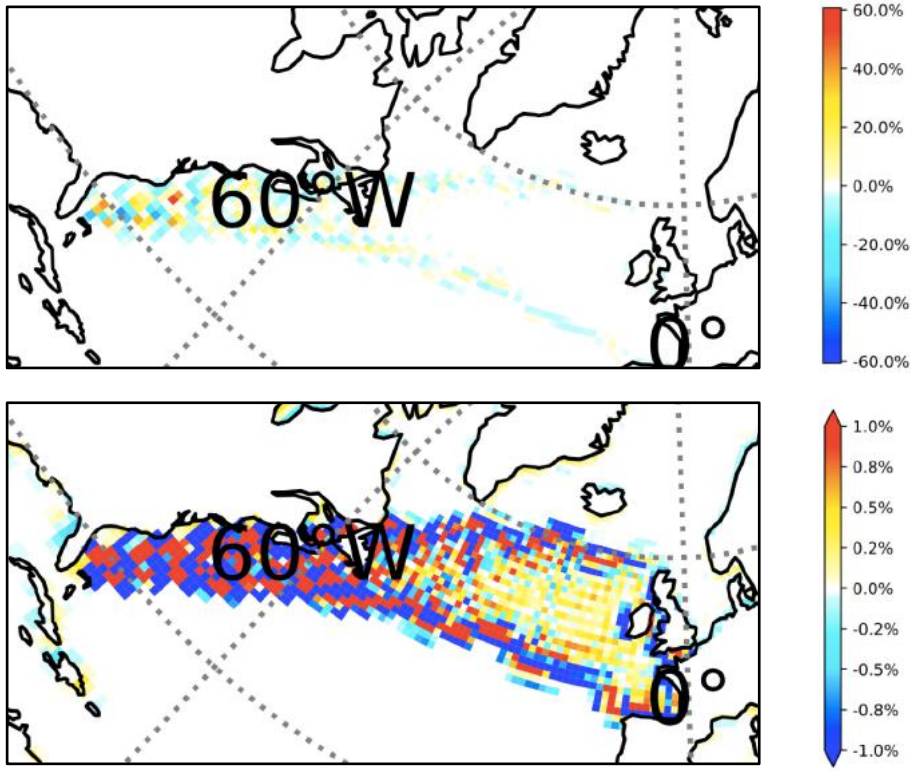
gulfstream function on nogt



CONSERV 2nd O FRACAREA

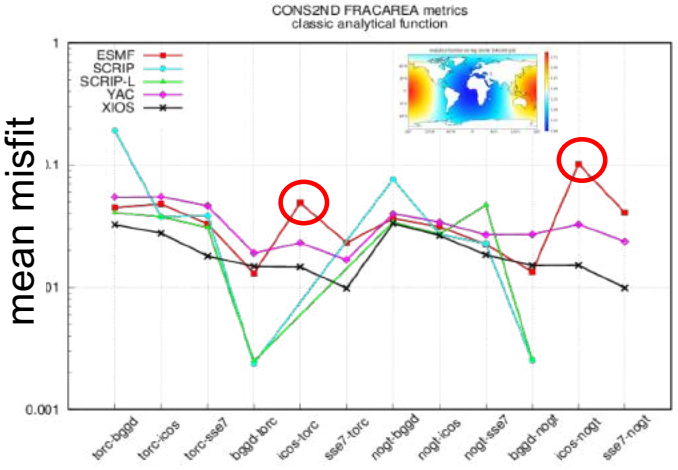
gulfstream lon-lat (bggd) -> NEMO ORCA1 (nogt)
XIOS, ESMF, YAC

misfit of regridded function on nogt



➢ CONSERV 2nd O shows oscillations near strong gradients (XIOS, ESMF, YAC)

Regridding benchmark – results CONSERV 2nd O

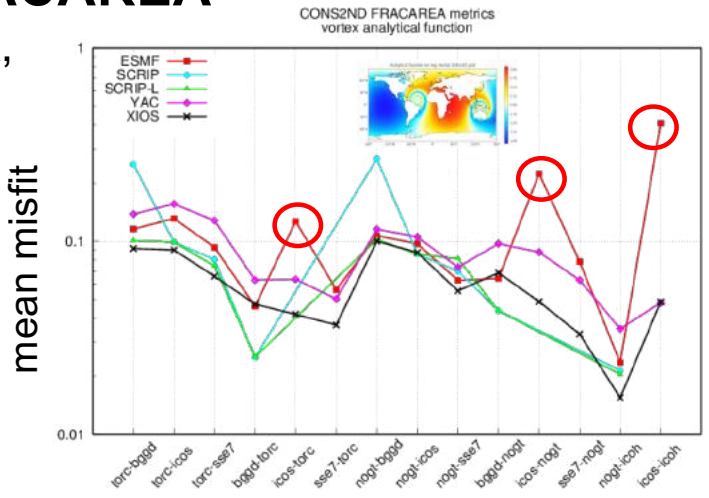


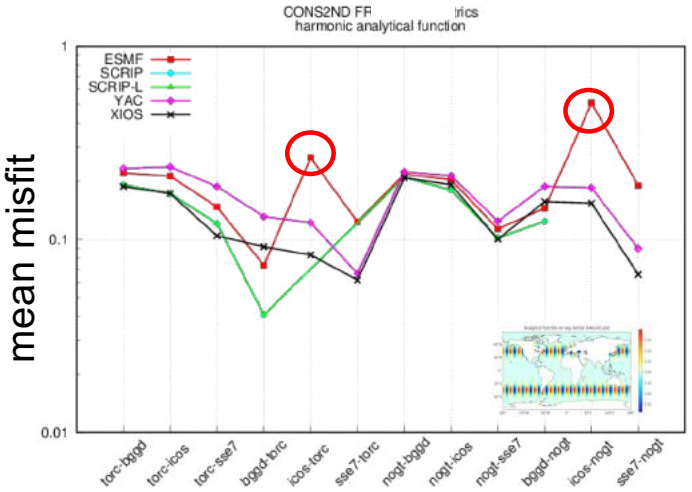
CONSERV 2nd O FRACAREA

sinusoid, harmonic, vortex, gulfstream

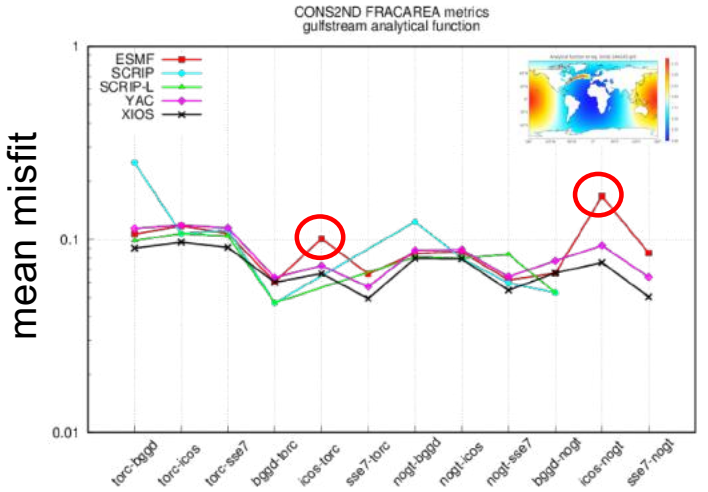
SCRIP, SCRIP-L, ESMF, YAC, XIOS

mean misfit





- high mean misfit with ESMF when icosahedral is source.
- working on it with ESMF support!



Regridding benchmark – results CONSERV 2nd O

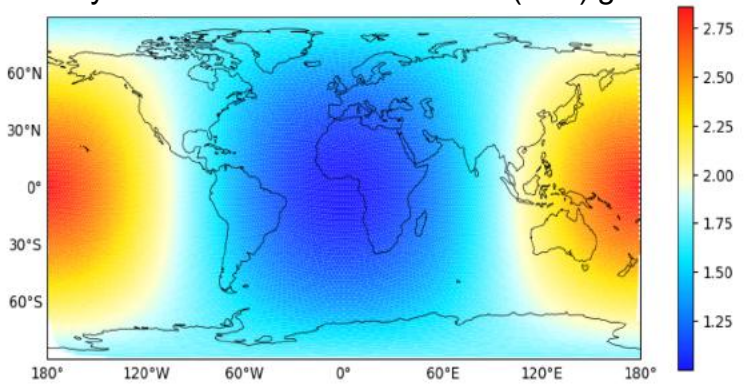
CONSERV 2nd O FRACAREA

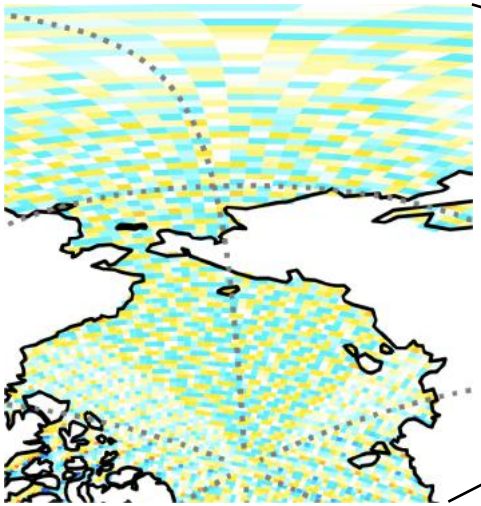
sinusoid

icos->nogt (icosahedral -> NEMO ORCA2)

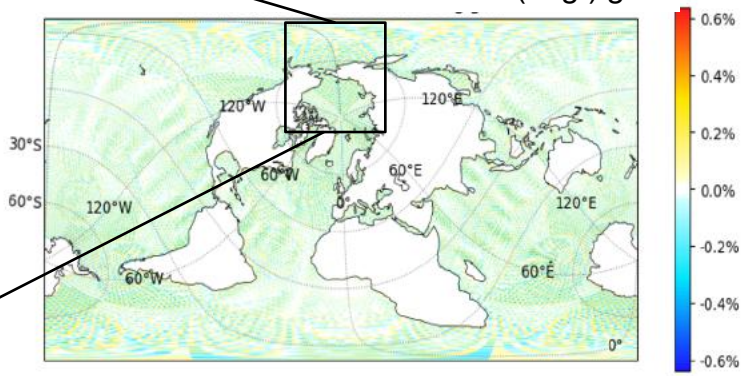
ESMF

Analytical sinusoid on icosahedral (icos) grid



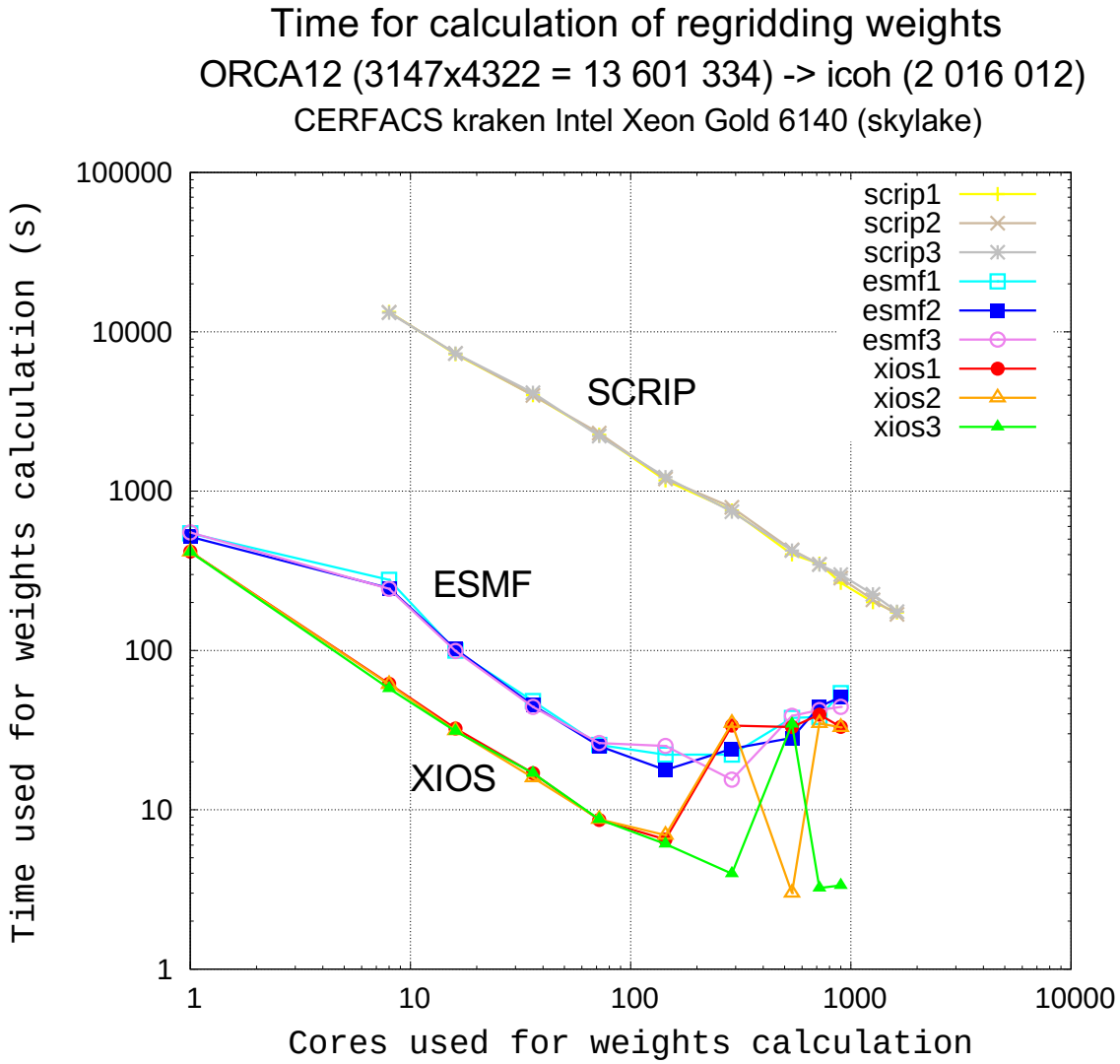


Relative misfit on NEMO ORCA2 (nogt) grid



➢ alternating + and – pattern with ESMF; working on it with ESMF support!

Regridding benchmark – library performance and scalability



- ESMF and XIOS show good performances (much more than the SCRIP)
- XIOS is more performant than ESMF but shows unstable behaviour for more than ~200 cores (to be investigated)

Regridding benchmark - conclusions

Technically

- Preliminary analysis : ATLAS (ECMWF) and MOAB-TempestRemap (DoE; USA) are not mature enough to be considered on the short term
- More detailed analysis of benchmark results : ESMF, YAC and XIOS are good candidate
  - YAC : lack of official commitment for support on the long term
  - ESMF : large community, good long-term perspectives, good and efficient user support
  - XIOS : conservative regridding only, growing community and number of developers, natural collaboration with CERFACS
- Good performance for ESMF and XIOS (much faster than the SCRIP)

➢ provide a unified environment to pre-calculate regridding weights with SCRIP, ESMF & XIOS in OASIS3-MCT_5.0 (12/2021)

Philosophically

Benchmarks help not so much to compare libraries but more to identify specific problems and solve them through interactions with developers!

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Oasis

Benchmarking different regridding libraries used in Earth System Modelling

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the end

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Kritsikis, E., 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

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