EGU21-13489

Two-way nesting ocean models with different vertical coordinates

J. Chanut[(1)], J. Harle[(2)], T. Graham[(3)] and L. Debreu[(4)]

1) Mercator Ocean International, Ramonville Saint-Agne, France
2) National Oceanography Centre, Liverpool, UK
3) UK Met Office, Exeter, UK
4) INRIA, Saint Martin d'Hères, France

mercator-ocean.eu/marine.copernicus.eu

1. Background
2. Methodology
3. Test cases

Background: AGRIF

- NEMO has an online versatile block refinement capability, but in the horizontal directions only. This has proven to be quite useful in numerous numerical studies using NEMO (see Schwarzkopf et al 2019 for a recent application with AGRIF).

- Grid exchange is “two-way”: it enables upscaling the embedded solution outside the refined area.

- Implementation is based on the AGRIF software (Debreu et al, 2008) which enables sharing in memory space different levels of logically refined (coarsened) grids.
  - ⇒ Little code modification is required.
  - ⇒ Deals with the time sub-stepping
  - ⇒ Provides interpolation/restriction operators that ensure basic conservation properties (e.g. volume)

Background: Vertical nesting

- "Vertical nesting" is not a new concept per se but:
  => It has been restricted so far to "one-way" (Daniels et al, 2016)
  => if "two-way", it assumes vertical grids are logically defined from each other (i.e. an integer refinement, see Fox and Maskell, 1995)

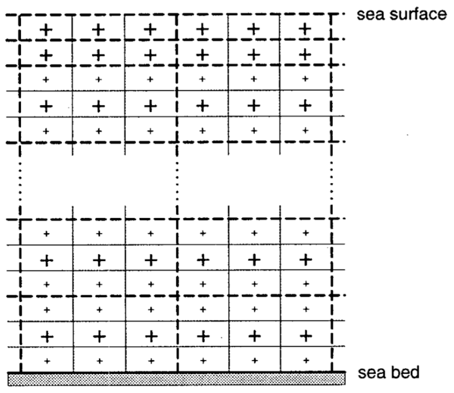
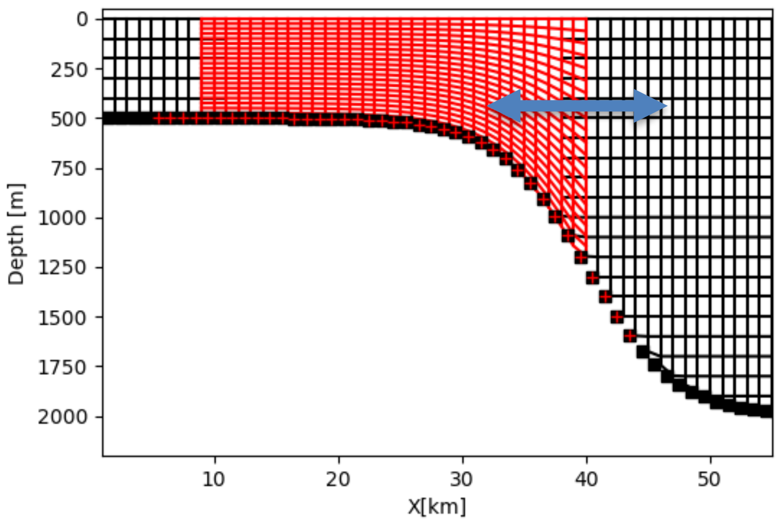


FIG. 7. Vertical nesting: interpolation of FG boundary values: + horizontally interpolated points and + vertically interpolated points.

- We propose here a methodology to nest any vertical grid, (i.e. possibly a terrain following s-grid into a z-grid, even ALE)

- Expected outcome for overflow regions, nesting shelf models, …



Methodology: Vertical remapping

- Split grid exchanges into horizontal and vertical directions.
- Two-way vertical nesting is based on two sequences of “Parent to Child” and “Child to Parent” vertical remapping.
- Vertical remapping operators must be conservative and monotone.
- We use here high order polynomial reconstruction schemes inherited from MOM6 ALE framework (Engwirda and Kelley 2016, White et al 2009). https://github.com/dengwirda/PPR

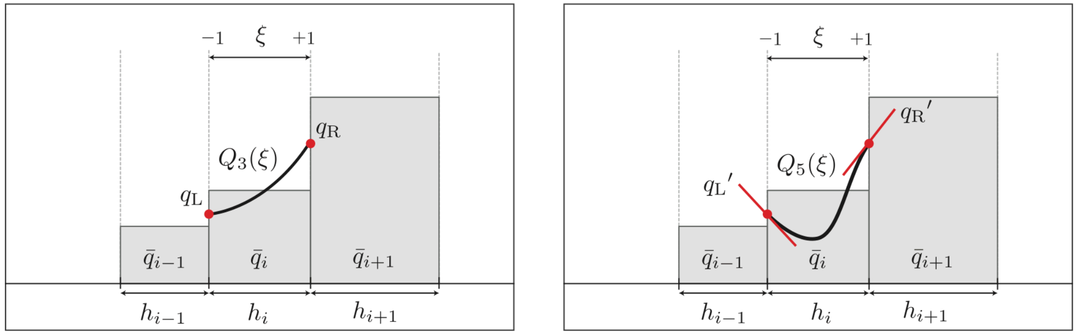
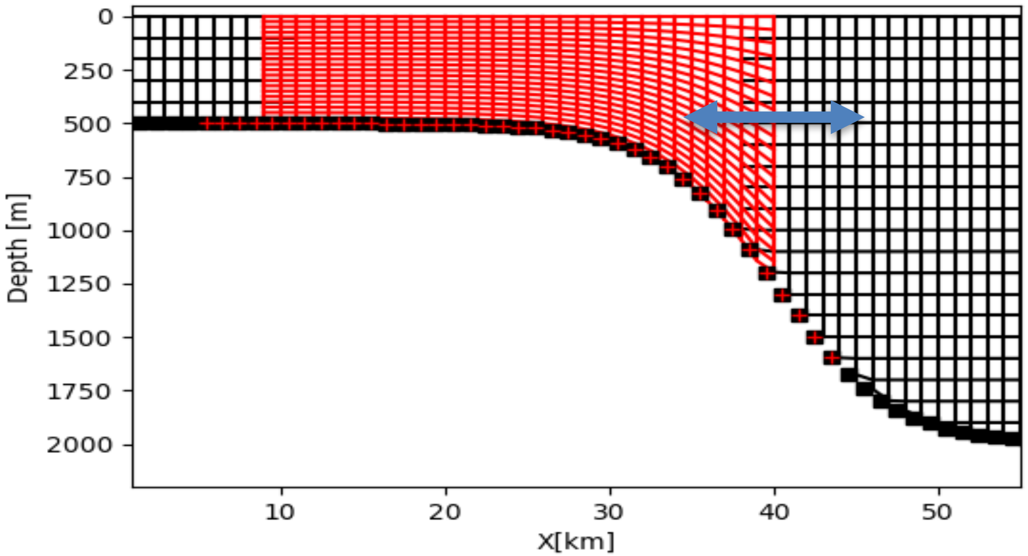
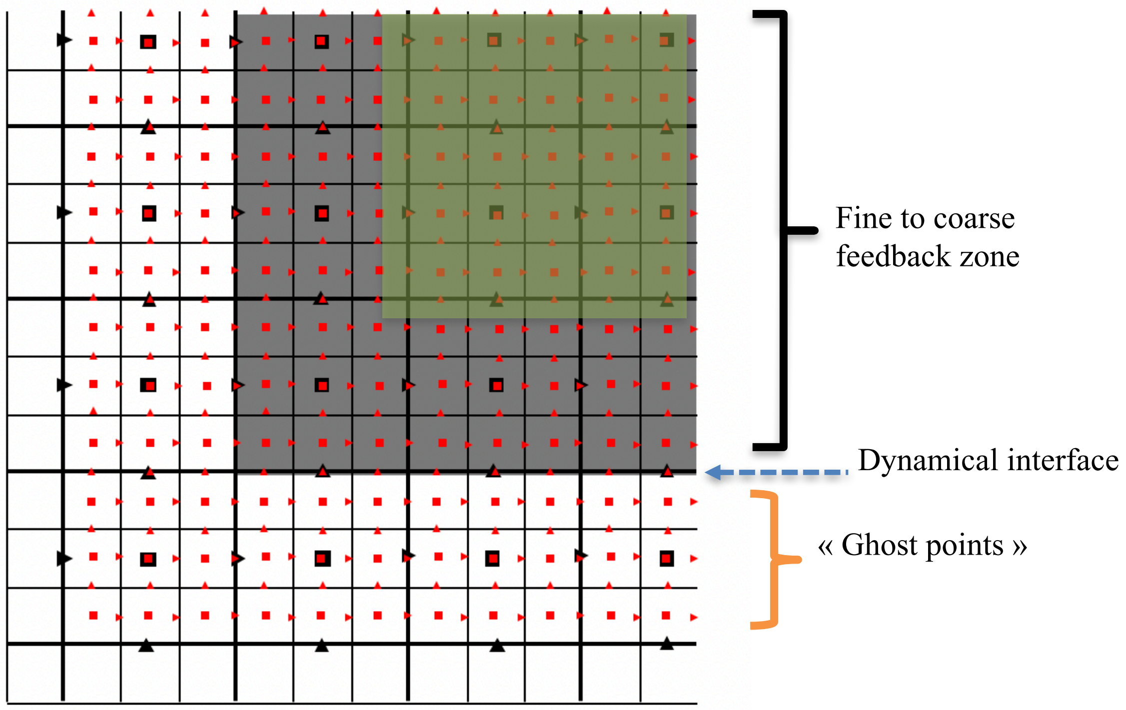


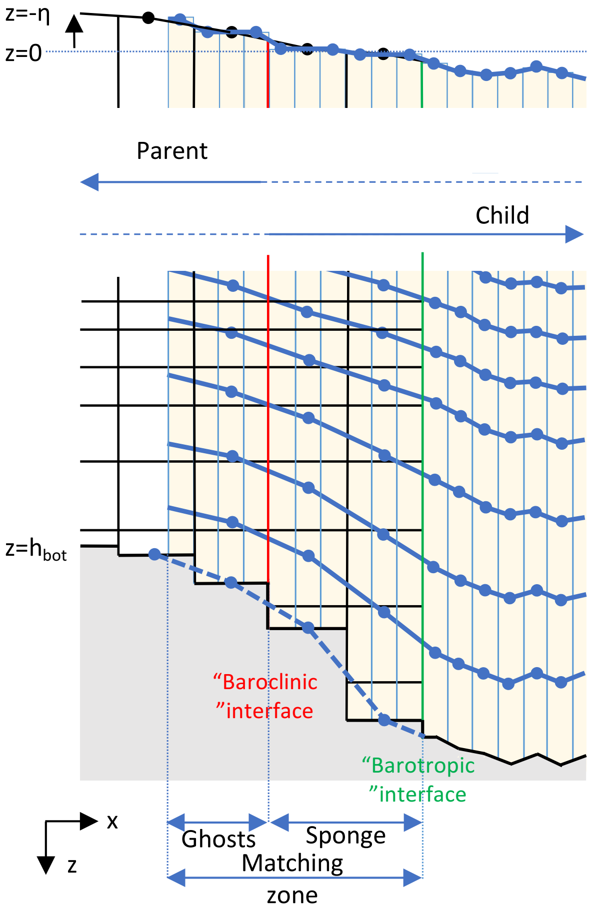
Figure 1: Reconstruction of grid-cell polynomial $Q(\xi)$ from local data, showing (i) the piecewise parabolic method (PPM), and (ii) the piecewise quartic method (PQM).



Methodology: Volume matching



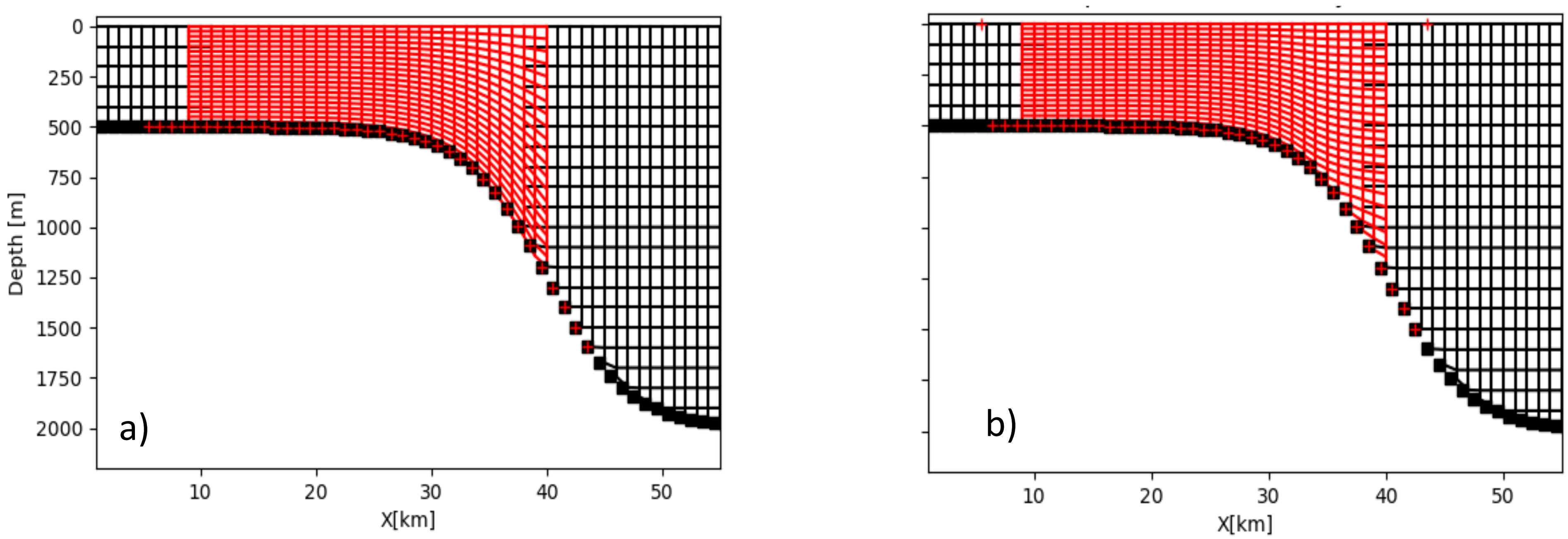
Grid nesting positioning in a 3:1 refinement case. Child grid points are in red, parent grid points in black. Grey frame is the inner child grid domain. Child to parent feedback area overlaps the child grid domain except in the case of "interface separation" (green frame). Squares refer to the position of "T-points" (tracers, pressure, vertical velocity,…) while staggered triangles refer to each velocity component.



2d x-z sketch illustrating the volume matching in the case of a 3:1 s-coordinates child grid nested in a z-coordinate grid. Lines refers to cell interfaces for parent (black) and child (blue) grids. Top: detail of the free surface matching. Bottom: piecewise bottom topography matching. Divergence conserving interpolation within the ghosts and nudging zones ensure piecewise constant sea level anomaly matching parent.

- Vertical remapping scheme requires exact volume matching within exchange zone.
- In the non-linear free surface case, use divergence conserving horizontal interpolators (Balsara 2001).

Methodology: Additional grid matching procedures

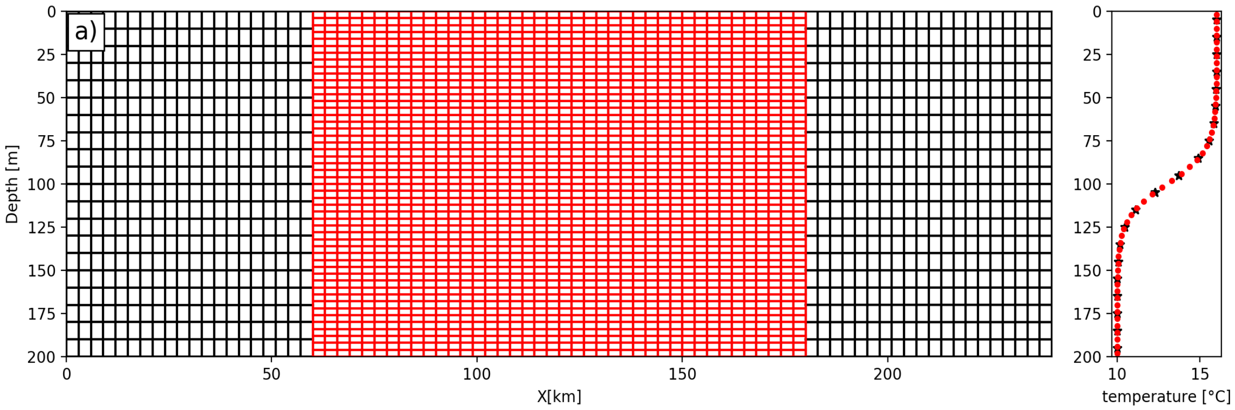


The 2d overflow test case with a child s-coordinate grid nested in a z-coordinate grid. a) without any smoothing. b) With interfaces Laplacian smoothing in the cross interface direction and additional bottom layers.

- Nesting s into z requires layer interfaces iterative smoothing (see OVERFLOW test case)
- Other methods to connect grids with continuous into piecewise constant representation of topography should be foreseen (penalization methods ?)

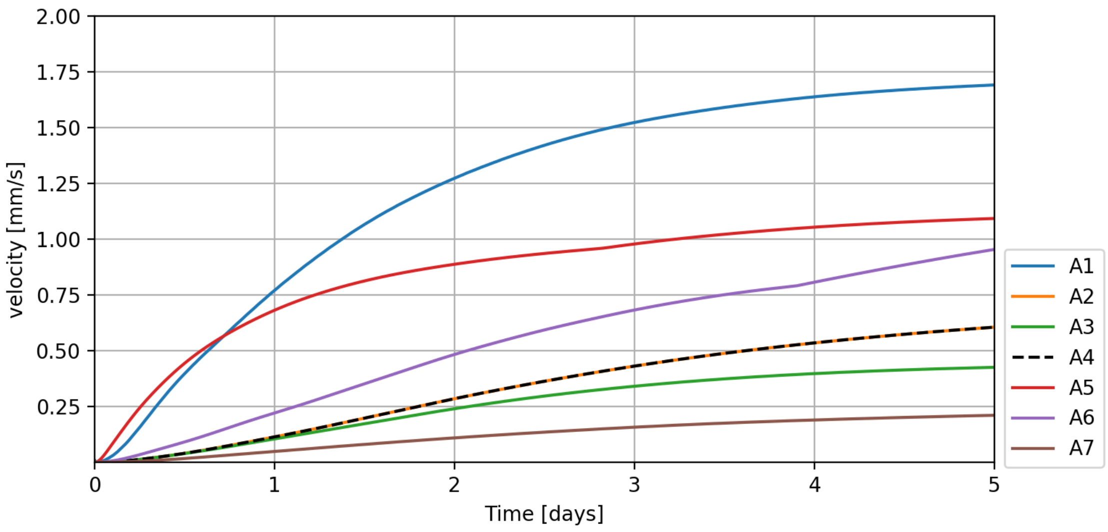
Test case #1: 2DV set up with constant stratification

- Horizontally constant temperature profile
- Test different vertical horizontal grids, initialization methods and remapping order
- Should stay at rest, hence monitor “spurious velocities”



Expts	Hor. Res. (km)		Vert. Res. (m)		Vert. remapping order	Coupling	Initialization
	Parent	Child	Parent	Child			
A1	3	3	10	4	3^{rd}	2 way	Straightforward
A2	3	3	10	4	3^{rd}	2 way	Vol. av.
A3	3	3	10	4	3^{rd}	1 way	Vol. av.
A4	3	3	4	10	3^{rd}	2 way	Vol. av.
A5	3	0.75	10	4	3^{rd}	2 way	Vol. av.
A6	3	3	10	4	1^{st}	2 way	Vol. av.
A7	3	3	10	4	5^{th}	2 way	Vol. av.

Test case #1: 2DV set up with constant stratification



Maximum absolute velocity recorded in Case A

- Initialization matters: a grid cell/face contains a volume/section averaged property !
- Remapping order (and limiter) matters.

3rd order (PPM)

one way

1st order (PLM)

5th order (PQM)

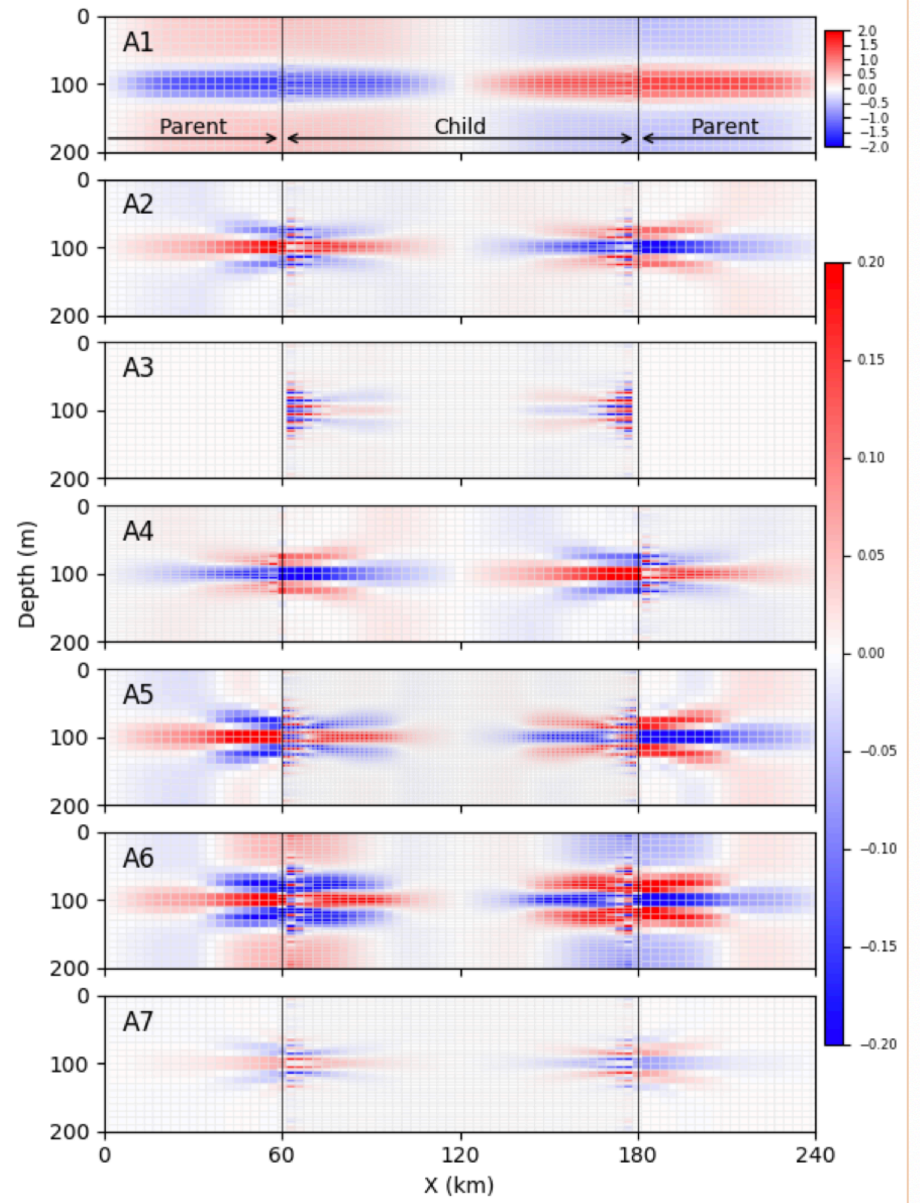
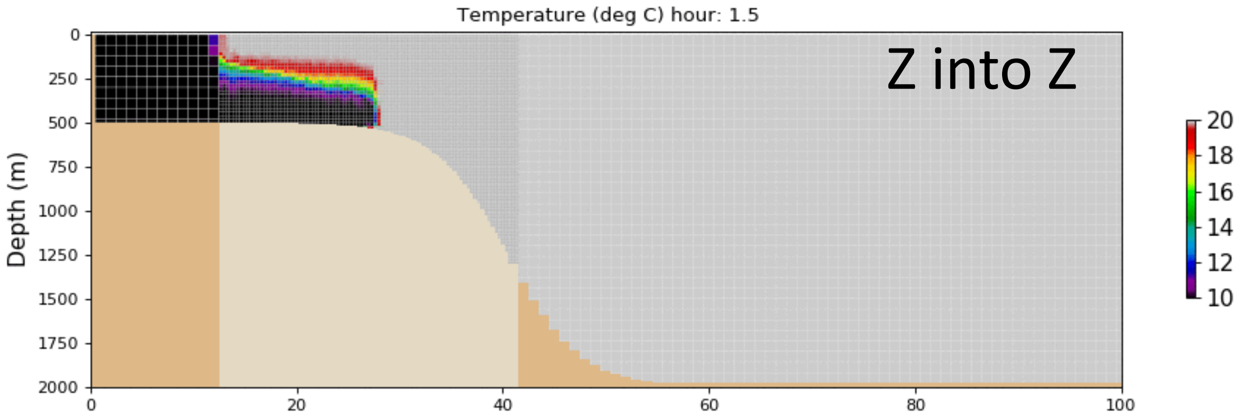
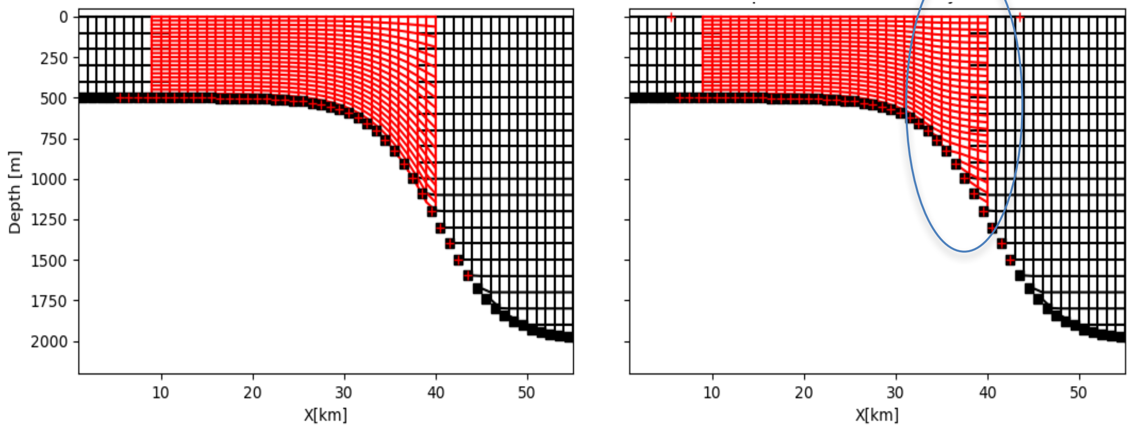


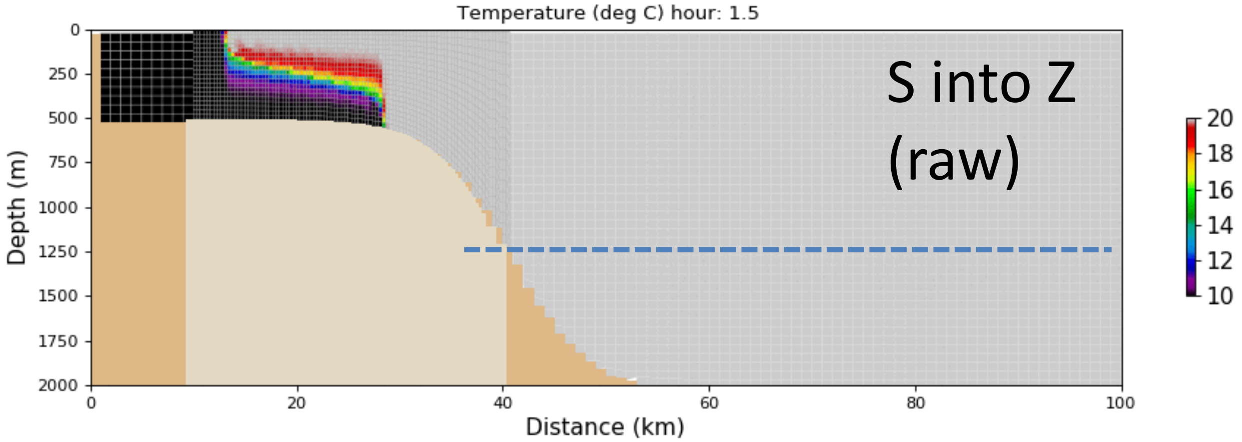
Figure 3: Uniform stratification test (Case A): Spurious velocities in mm/s after 5 days. Note the different color scale for case A1. The thin grey lines display cell interfaces. A3 is the "one-way" case.

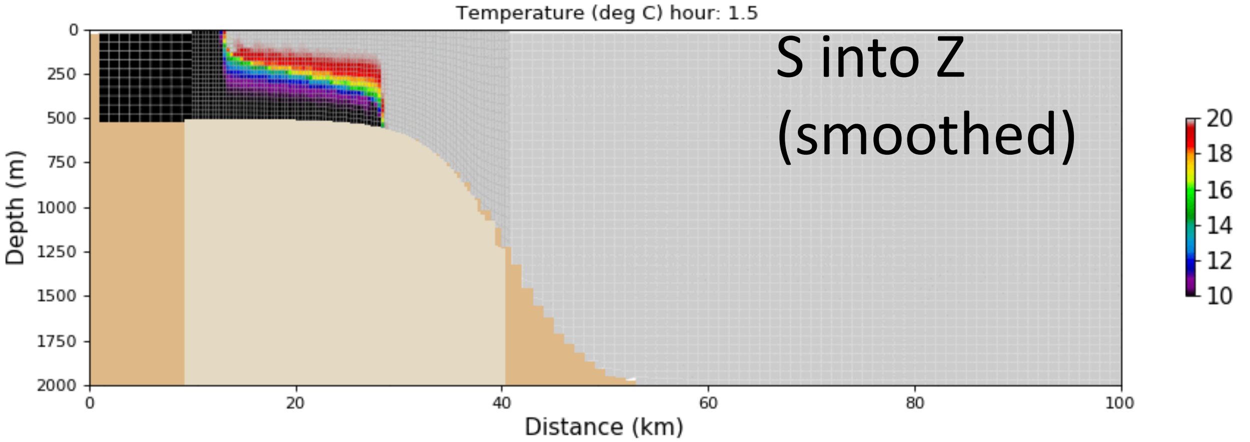
Test case #2: 2DV OVERFLOW (Ilicak et al 2012)

- Animations available at: https://github.com/jeromechanut/IMMERSE/blob/master/DEMO/overflow_demo.md



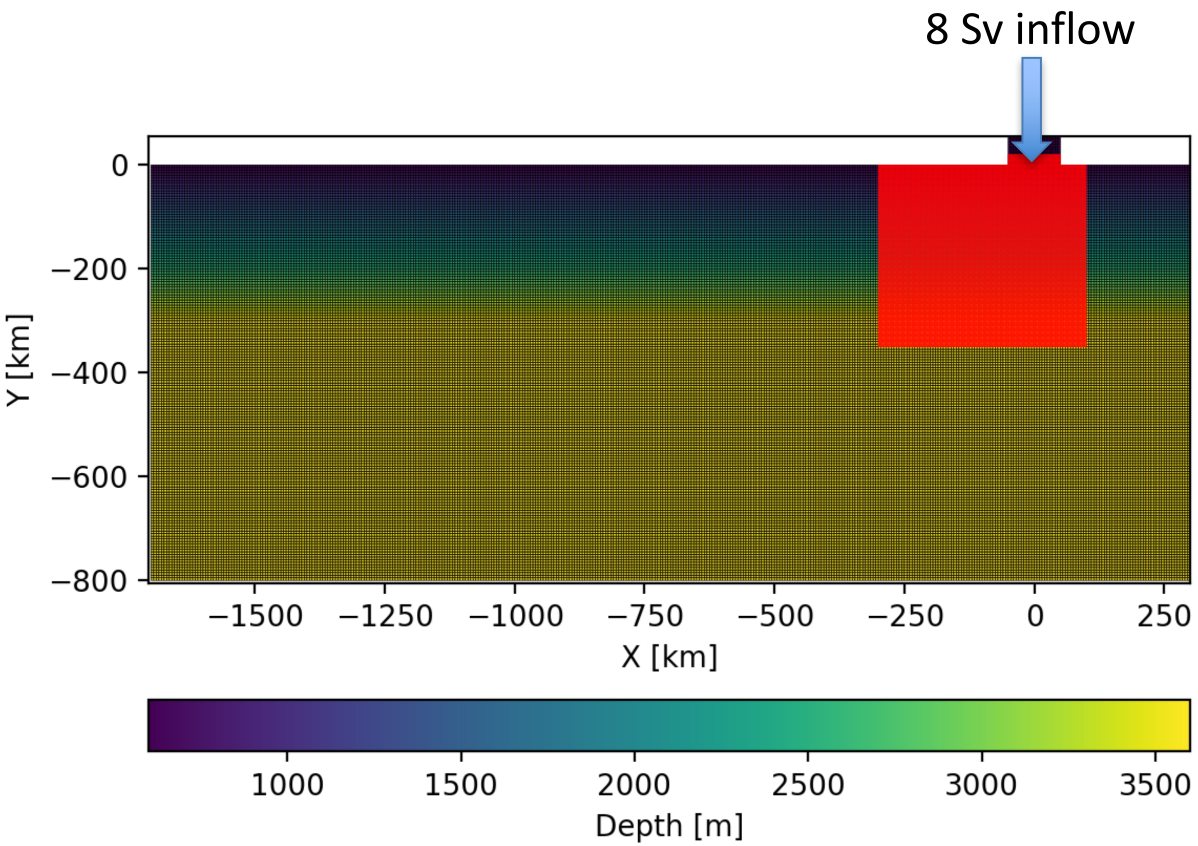






- Upscaling benefit of local s depends on grid transition. Smoothing of interfaces in that (stringent) test is necessary.

Test case #3: DOME



The DOME setup showing the 2:1 child grid in red spanning the initial descent of the buoyant plume.

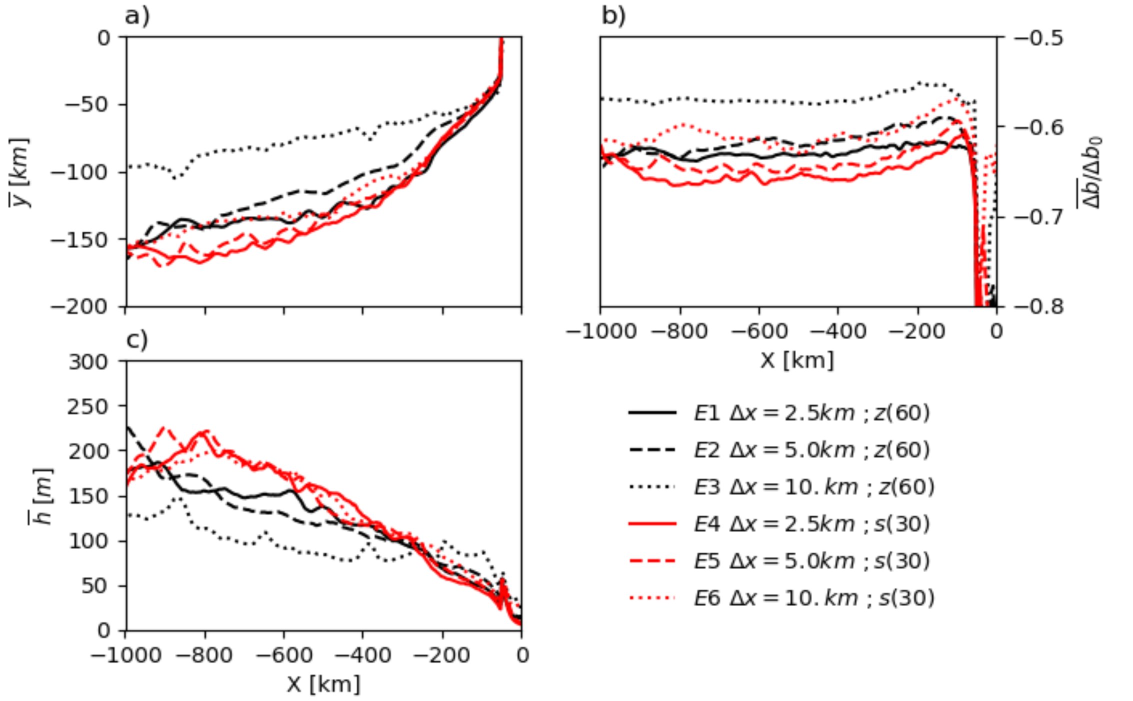
Experiments	Hor. Res. (km)		Vertical Coordinate type (number of levels)	
	Parent	Child	Parent	Child
E1	2.5	-	z (60)	-
E2	5.0	-	z (60)	-
E3	10.0	-	z (60)	-
E4	2.5	-	s (30)	-
E5	5.0	-	s (30)	-
E6	10.0	-	s (30)	-
E7	10.0	5.0	z (60)	z (60)
E8	10.0	2.5	z (60)	z (60)
E9	10.0	2.5	z (60)	z (240)
E10	10.0	5.0	z (60)	s (30)
E11	10.0	2.5	z (60)	s (30)
E12	5.0	2.5	z (60)	s (30)

DOME experiments. The first 6 experiments do not have any nested grid. Vertical grids, whether z or s, have uniform vertical resolution.

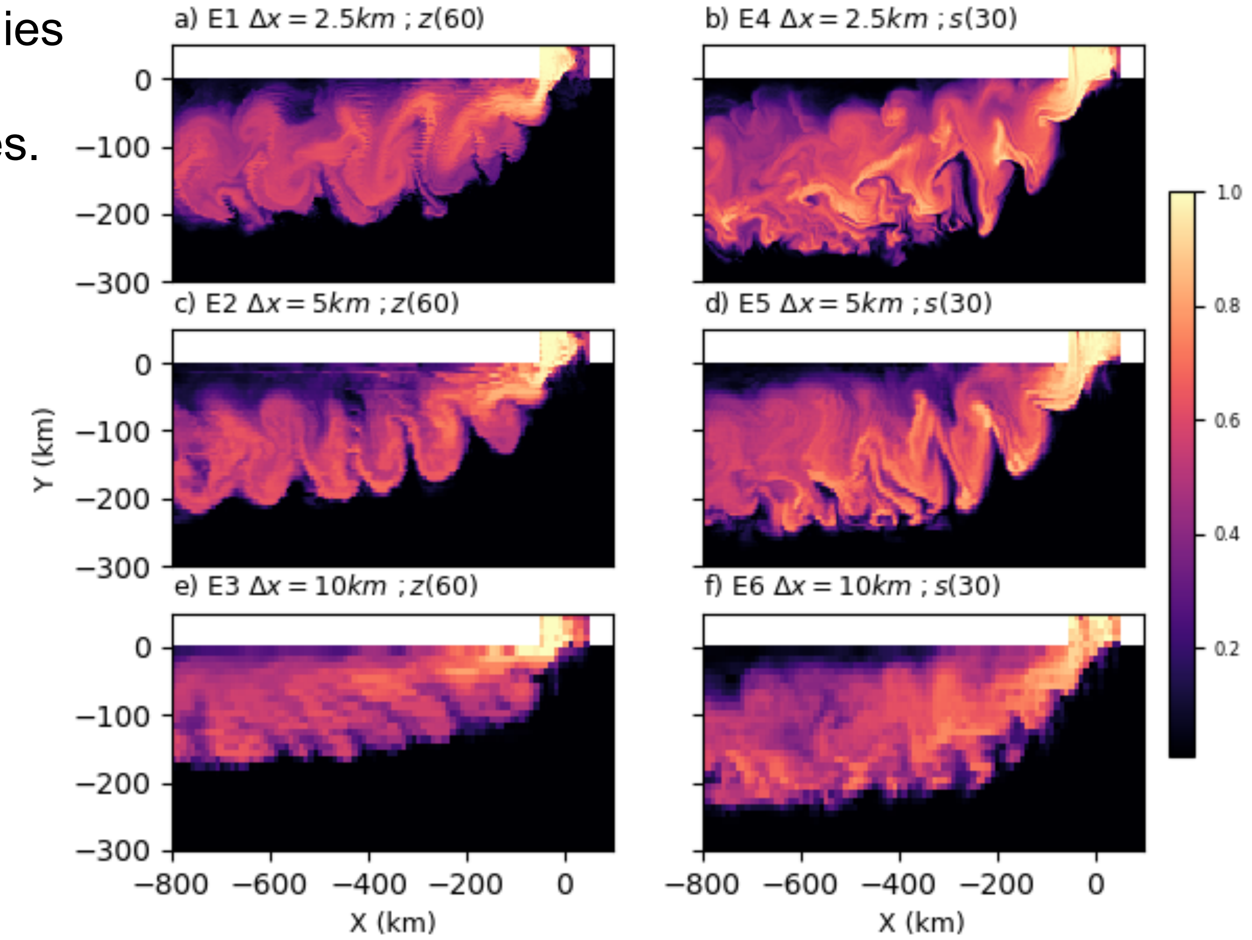
- DOME: “Dynamics of Overflow Mixing and Entrainment”, Legg et al (2006)

Test case #3: DOME

- No zoom experiments: less diluted plume and more eddies as horizontal resolution increases.
- Steeper descent and even less mixing with s-coordinates.
- Consistent with results obtained in other models !



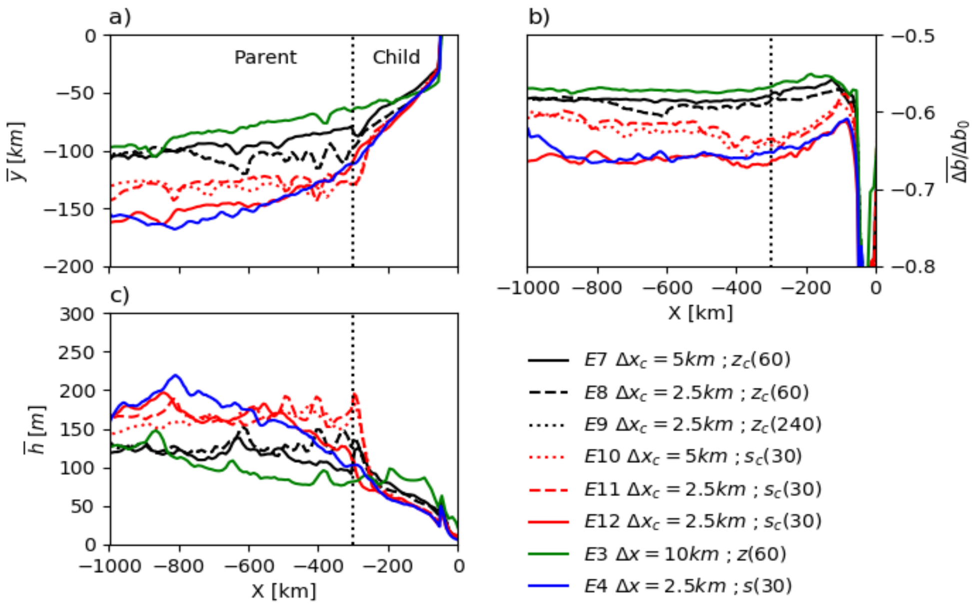
a) Mean path of overflow water; b) Normalized buoyancy anomaly of overflow ; c) Mean overflow thickness. Time averages are performed between day 40 and day 60. No embedded grid in these results.



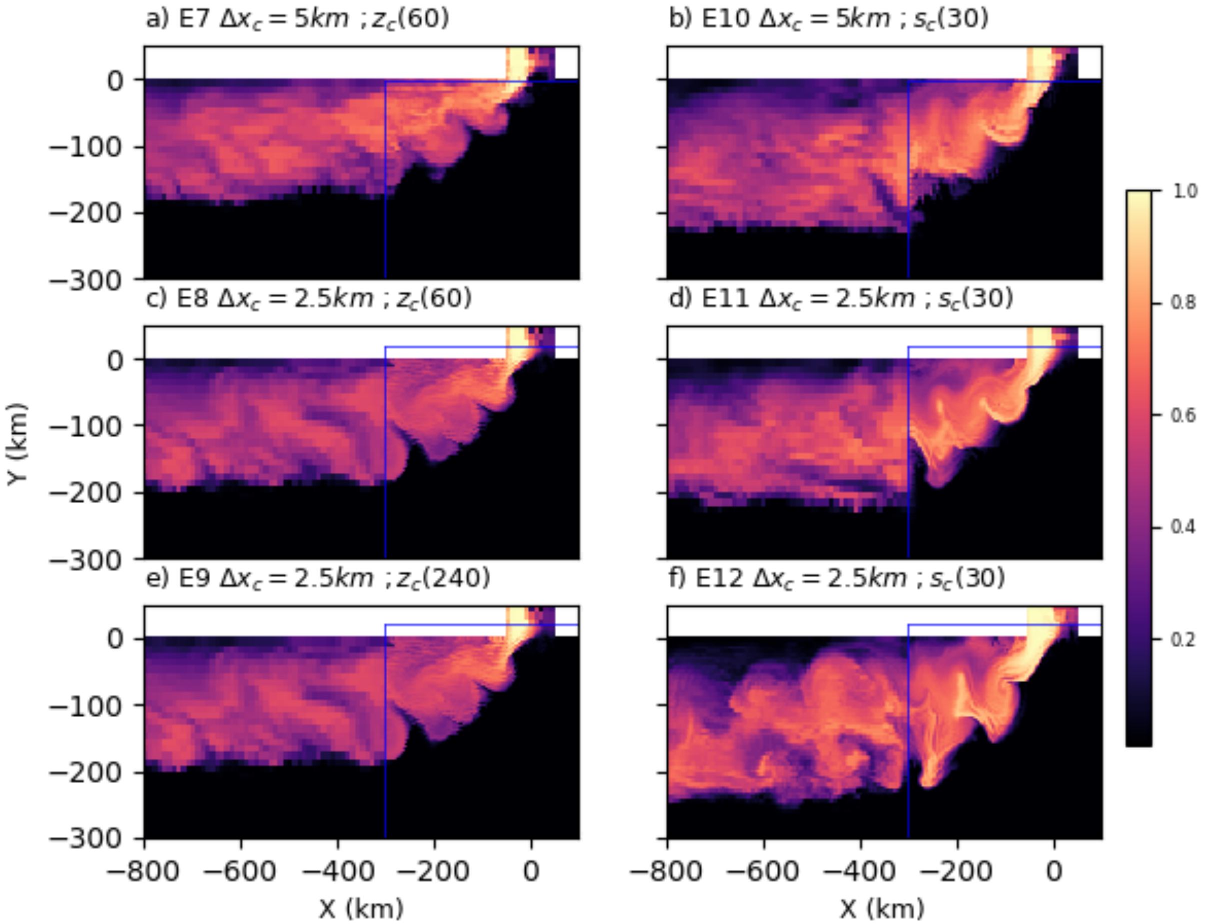
Bottom tracer concentration in the DOME experiments after 50 days and without nesting. a), c) and e) have 60 z-levels with respectively 2.5, 5 and 10 km horizontal resolution. b), d), e) are the same as left figures but with 30 evenly spaced s levels.

Test case #3: DOME

- Nesting a s-coordinate zoom in a z-coordinate grid can indeed improve the final plume properties (denser and deeper).
- Some mixing near the grid interface however occurs. This can be seen in the plume thickness when the z-coordinate poorly resolves the topographic slope (e.g. with Δx=10km)



Same figure as in the previous slide but with a nested grid and various horizontal resolutions and vertical grid types. All parent grids but E12 have 10km resolution and z coordinates. E3 and E4 are reported as the most extreme solutions without nesting.



Bottom tracer concentration in the DOME experiments after 50 days and with nesting. The blue frame indicates the nested grid position.

Conclusion

- An online, two-way, vertical nesting capability has been implemented into NEMO. It will be available in the upcoming mid-year (4.2) release.
- The method is generic enough to deal with any kind of vertical coordinates.
- As demonstrated in DOME experiments, it has the potential to improve overflows by getting rid of z-coordinates or increasing the number of levels over critical sills. This awaits for being tested in realistic setups (Denmark strait and Faroe regions) within IMMERSE project.
- Some additional work to further improve grid transitioning in the case of s-grids nested into z-grids should be foreseen. The ability of the method to properly transfer (upscale) the inner zoom solution is indeed the key here.

- Watch out videos at: https://github.com/jeromechanut/IMMERSE/blob/master/DEMO/overflow_demo.md

References

Balsara, D., 2001: Divergence-Free Adaptive Mesh Refinement for Magnetohydrodynamics. J. Comp. Phys, 174-2, 614-648.

Daniels, M. H., K. A. Lundquist, J. D. Mirocha, D. J. Wiersema, and F. K. Chow, 2016: A New Vertical Grid Nesting Capability in the Weather Research and Forecasting (WRF) Model. Mon. Wea. Rev., 144, 3725–3747.

Debreu, L., C. Vouland, and E. Blayo, 2008: AGRIF: Adaptive Grid Refinement in Fortran. Computers and Geosciences, 34-1, 8-13.

Engwirda, D. and M. Kelley, 2016: A WENO-type slope-limiter for a family of piecewise polynomial methods. ArXiv preprint https://arxiv.org/abs/1606.08188

Fox, A. and S. J. Maskell, 1995: Two-Way interactive nesting of Primitive Equation Ocean Models with topography. J. Phys. Ocean, 25-12, 2977-2996.

Ilicak, M., A. J. Adcroft, S. M. Griffies, and R. W. Hallberg, 2012: Spurious dianeutral mixing and the role of momentum closure. Ocean Modelling, 45-46, 37-58.

Legg, S., Hallberg, R. W. and J. B. Girton, 2006: Comparison of entrainment in overflows simulated by z-coordinate, isopycnal and non-hydrostatic models. Ocean Modelling, 11, 69-97.

White et al., 2009: High-order regridding–remapping schemes for continuous isopycnal and generalized coordinates in ocean models. Journal of Computational Physics, 228(23).