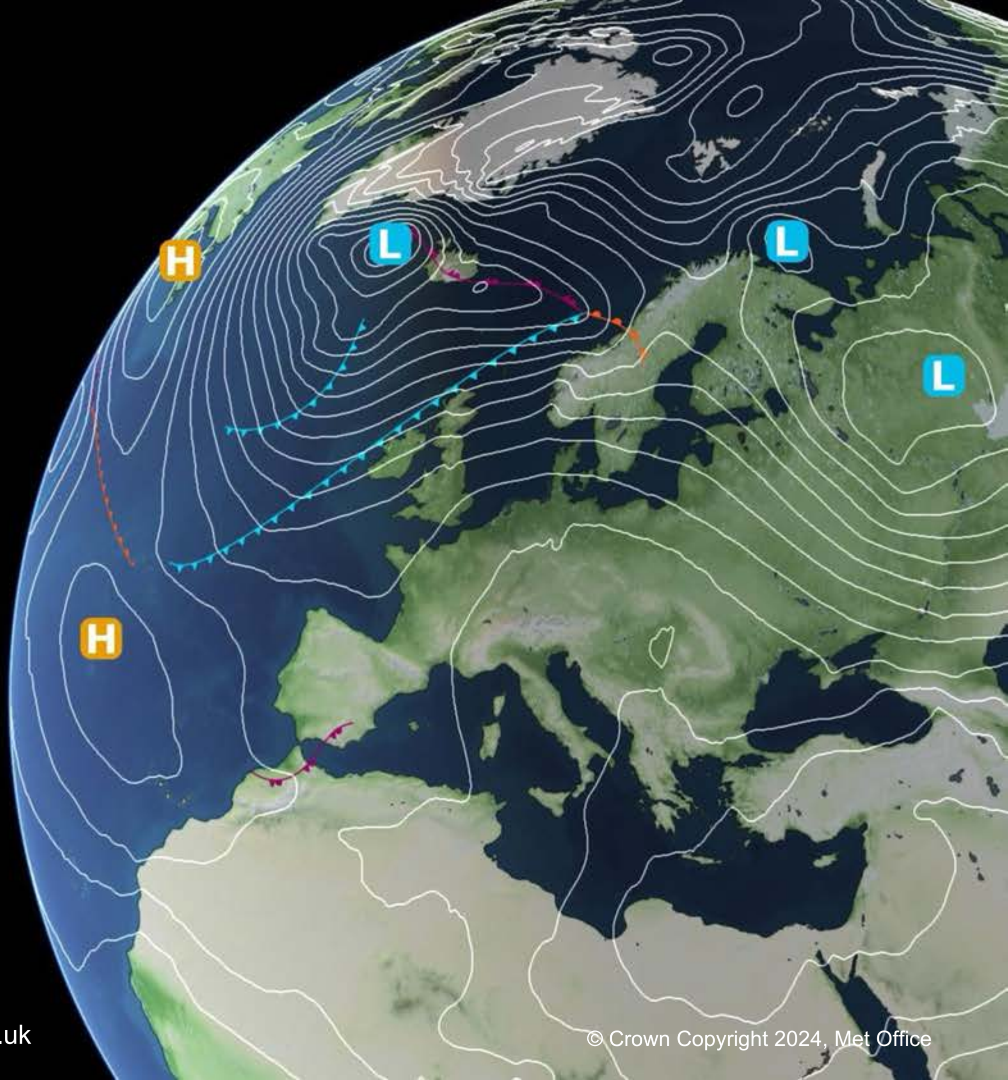
Met Office
Hadley Centre

Two-way nesting and localized multi-envelope vertical coordinates to improve flow-topography interactions in ocean models

D. Bruciaferri(1), J. Harle(2), J. Chanut(3), L. Debreu(4)

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

Ocean Model Development, Data-driven Parameterizations,
and Machine Learning in Ocean Models of the Earth System
A Joint CLIVAR, OMDP and COMMODORE Workshop
Sep. 9-12, 2024, NSF NCAR Mesa Lab, Boulder, Colorado



www.metoffice.gov.uk

diego.bruciaferri@metoffice.gov.uk

Met Office Hadley Centre

What are the issues with flow-topography interactions in models?

Lateral resolution

Increasing the horizontal resolution can be beneficial *(see Hewitt et al. 2017 for a review)* **BUT**

finite computational resources limit how much we can **uniformly increase the horizontal resolution** of our models, especially in the case of global coupled systems.

Vertical coordinates

The type of vertical coordinates significantly impacts the way an ocean model represents flow-topography interactions (e.g., *Griffies et al. 2000, Legg et al. 2006*). For example, **in the case of quasi-Eulerian (QE) vertical coordinates**:

- Terrain-following levels **are better suited to represent flow-bathymetry interactions** than z-coordinates, even when using partial steps (e.g., *Bruciaferri et al. 2020, Wise et al. 2021*)
- The vast **majority of OGCMs** participating **in CMIP6 DECK** used geopotential vertical coordinates (IPCC, 2023)
- Classical terrain-following coordinates introduce **errors in the computation of the pressure-gradient force**, making their **use in configurations for climate studies challenging** (e.g., *Lemarié et al. 2012*).

Hewitt et al 2017 – OM, 120 | **Griffies et al 2000** – OM, 2 | **Legg et al 2006** – OM, 11 | **Bruciaferri et al 2020** – OM, 146 | **Wise et al 2022** – OM, 170 | **Lemarié et al 2012** – OM, 24 | **IPCC 2023 –** Annex II, Models

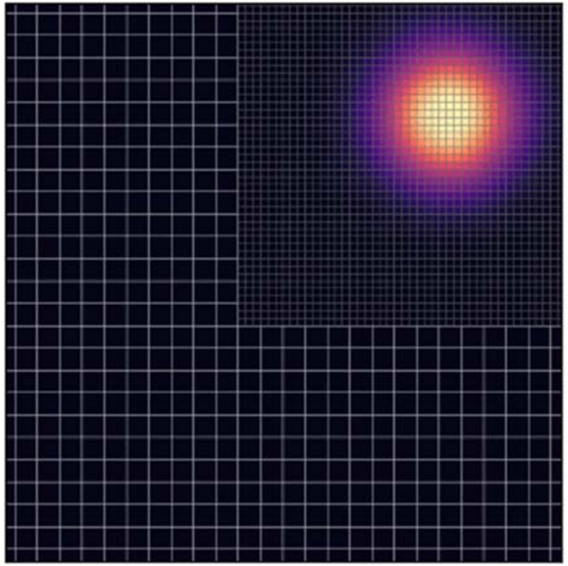
Met Office Hadley Centre

Two-way nesting techniques may be the via …

What if we use "two-way" horizontal/vertical nesting methods to ***locally improve the solution of the coarse parent model?***

Benefits

- different space/time refinement and physics in different areas of the domain
- high lateral/vertical resolution only where we want/need it
  ⇒ multi-scale capability for structured models
- zooms with different types of vertical coordinates wrt parent model ⇒ target the local physical processes
- no overhead from very large outputs
- coupling strategies can largely remain the same

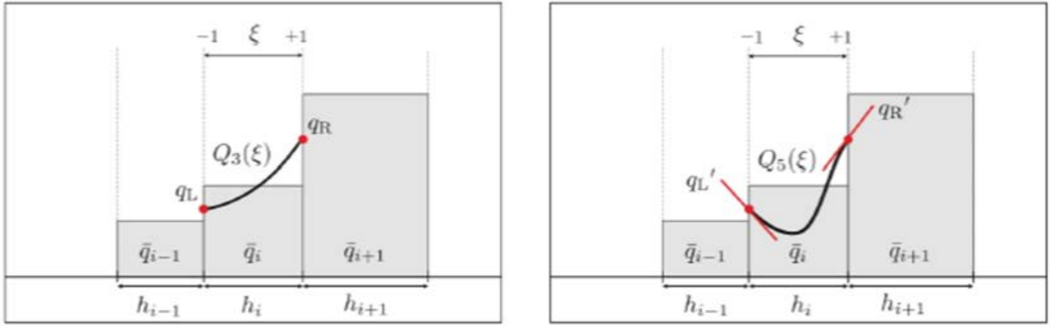


The Spall and Holland (1991) baroclinic vortex test-case (SST) replicated with NEMO-AGRIF (the zoom uses a refinement factor of 3; from https://sites.nemo-ocean.io/user-guide/zooms.html).

Two-way nesting with NEMO-AGRIF

- NEMO has an online versatile **block refinement capability** based on the **AGRIF** software (*Debreu et al, 2008*) **conservative interpolation/restriction operators** for “two-way” horizontal nesting
- *Chanut et al. 2023* introduces in NEMO-AGRIF **generic vertical conservative remapping operators** inherited from MOM6 ALE framework (*Engwirda and Kelley 2016*, *White et al 2009*) to allow vertical nesting

Reconstruction of grid-cell polynomial $Q(\xi)$ (from *Engwirda and Kelley 2016*):
(a) the piecewise parabolic method (PPM)
(b) the piecewise quartic method (PQM)



Debreu et al 2008 – ODYN, 58
Chanut et al. 2023 – EGU21-13489
Engwirda & Kelley 2016 – arXiv:1606.08188
White et al. 2009 – J Comp. Phy. 228

Met Office Hadley Centre

Two-way nesting with NEMO-AGRIF

- NEMO has an online versatile **block refinement capability** based on the **AGRIF** software (*Debreu et al, 2008*) ⃞ **conservative interpolation/restriction operators** for “two-way” horizontal nesting

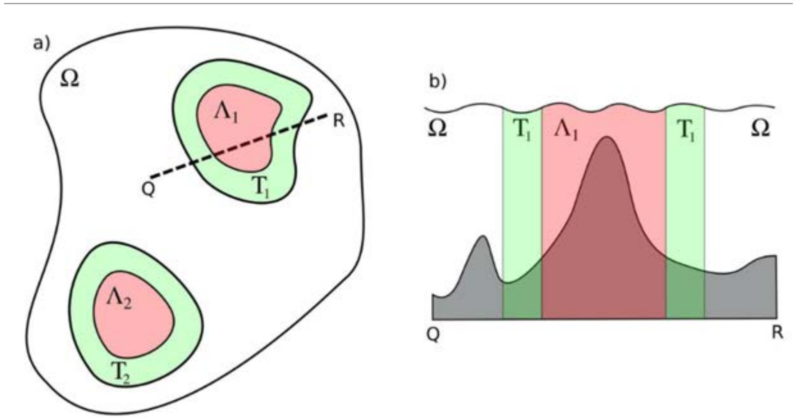
- *Chanut et al. 2023* introduces in NEMO-AGRIF **generic vertical conservative remapping operators** inherited from MOM6 ALE framework (*Engwirda and Kelley 2016*, *White et al 2009*) to allow vertical nesting

- Vertical remapping schemes require **exact volume matching** within exchanging zone: because of **land-sea mask mismatches at the boundaries**, this condition could be **hard** to satisfy **when changing type of vertical coordinates in realistic applications**

Debreu et al 2008 – ODYN, 58
Chanut et al. 2023 – EGU21-13489
Engwirda & Kelley 2016 – arXiv:1606.08188
White et al. 2009 – J Comp. Phy. 228

One possible solution could be …

Localization method: a general methodology to embed distinct types of vertical coordinates in local time-invariant targeted areas of quasi-Eulerian (QE) ocean models (*Bruciaferri et al. 2024)*:



Sketch of the **localization method** for the case of two localisation areas (n=2 and $1 \leq p \leq n$):

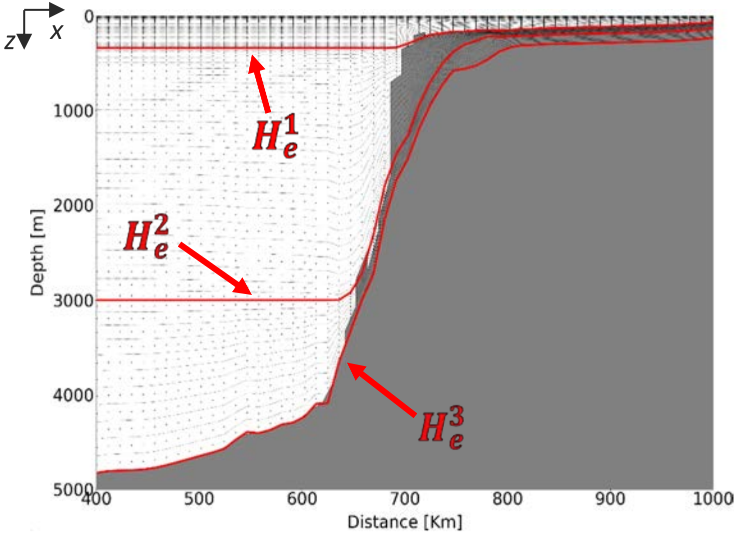
- area Ω: *global* Ω^V QE-GVC → $h_{k,\Omega}$
- areas Λ_p: *localised* Λ_p^V QE-GVC → h_{k,Λ_p}
- areas T_p: *transition zones*

$$h_{k,T_p} = W_p h_{k,\Omega} + (1 - W_p) h_{k,\Lambda_p}$$

where h_k is the thickness of model level k and $\mathrm{W_p(x,y)}$ is a function of the minimum Euclidean distances of points included in $\mathrm{T_p}$ from its boundaries

One possible solution could be …

Bruciaferri et al. 2024 uses **localized multi-envelope (ME) s-coordinates** to implement *quasi* terrain-following levels in the Greenland-Scotland ridge region in the Met Office z*ps based eddy-permitting GOSI9 configuration (Guiavarc'h et al. 2024) :



The **ME method** (*Bruciaferri et al., 2018, 2020, 2022; Wise et al., 2021*) defines QE computational levels that are adjusted to multiple *arbitrarily defined surfaces* (aka, envelopes H_e^i) rather than following geopotentials or the actual bathymetry:

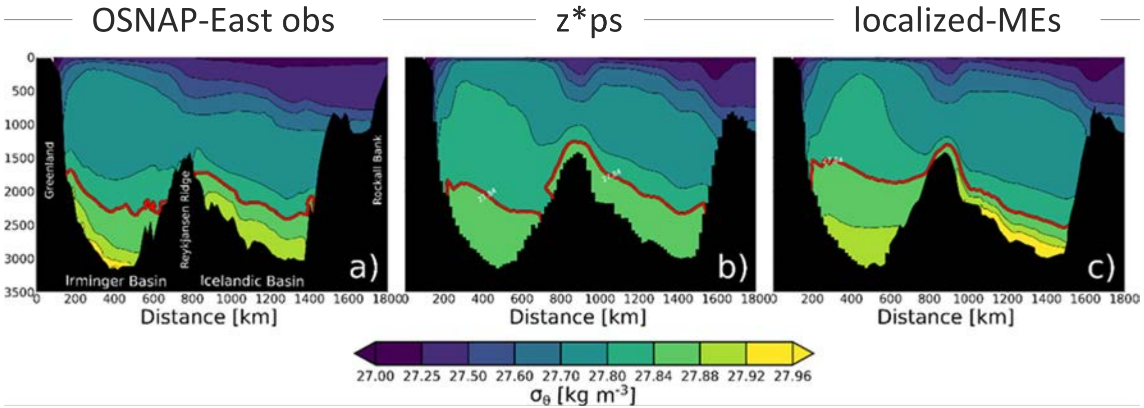
- model levels can be optimized to **prioritise the prevailing physical processes**
- significantly **reduce HPG errors** while keeping **a realistic bathymetry**

Shelf-break and continental slope of a model domain discretised with the ME method. In this example three envelopes are used:

- H_e^1 *is a smooth version of H up to 250 m*
- H_e^2 *is a smooth version of H where 300 m < z < 3000 m*
- H_e^3 *is a smooth version of H where z > 3500 m*

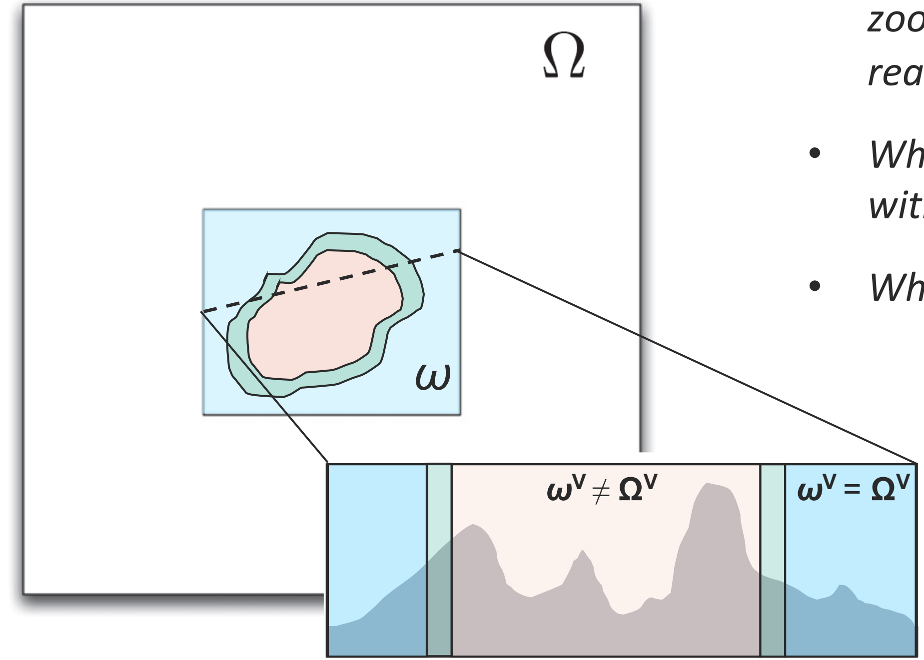
One possible solution could be …

Localized multi-envelope (ME) s-coordinates improve the representation of the Nordic Seas overflows in the Met Office eddy-permitting GOSI9 configuration:



Met Office
Hadley Centre

Our research questions are …

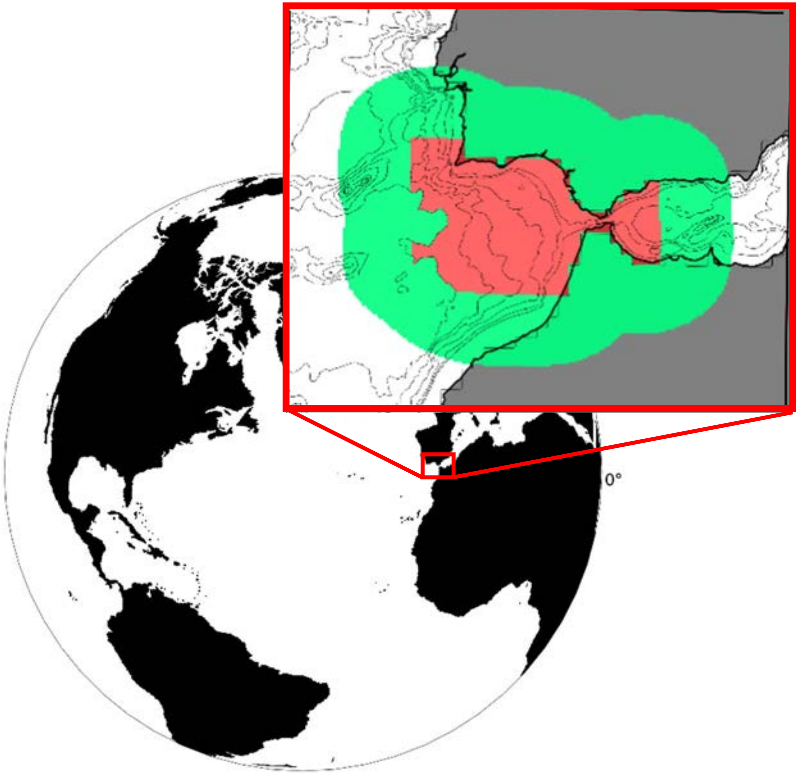


- *Can we use localized ME s-coordinates within AGRIF zooms to successfully implement vertical nesting in realistic applications?*
- *What is the impact of using vertical nesting along with horizontal nesting?*
- *What is the cost that we pay for it?*

$\omega^V = \Omega^V$ in blue area => **no vertical nesting**
$\omega^V \neq \Omega^V$ in red area (via the ME approach)
ω^V □ Ω^V in green area (via localization method)

Met Office Hadley Centre

Numerical experiments setup



Parent model:

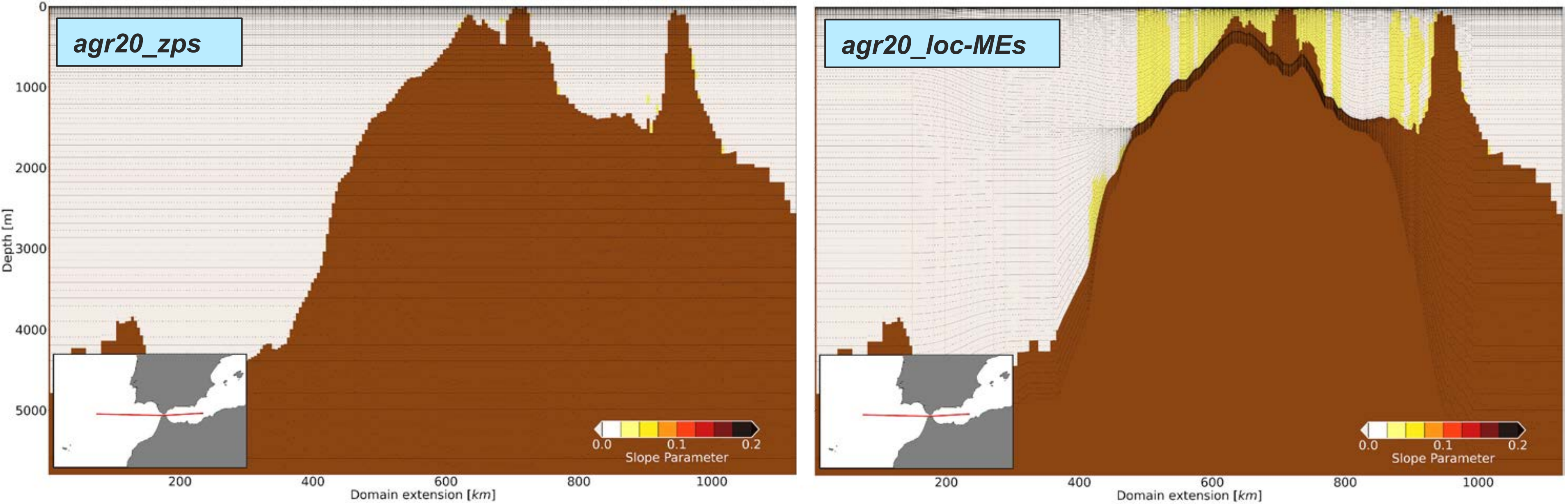
- **GOSI9** @ 1/4° of resolution (*Guiavarc'h et al 2024*) forced with JRA55 reanalysis

MED AGRIF zoom:

- 1/20° of resolution, 75 levels (as the parent)
- 5 times refinement in space and time
- Similar physics to the parent apart from:
  - Density Jacobian (djc) pressure gradient scheme
  - TRIAD scheme for isopycnal mixing
  - Logarithmic bottom friction
  - Smagorinsky scheme for viscosity
- Two configurations are compared:
  - *z** with partial steps (***agr20_zps***)
  - localized ME *s*-coordinates (***agr20_loc-MEs***)
- **Simulation period is 1976-2015**

Numerical experiments setup

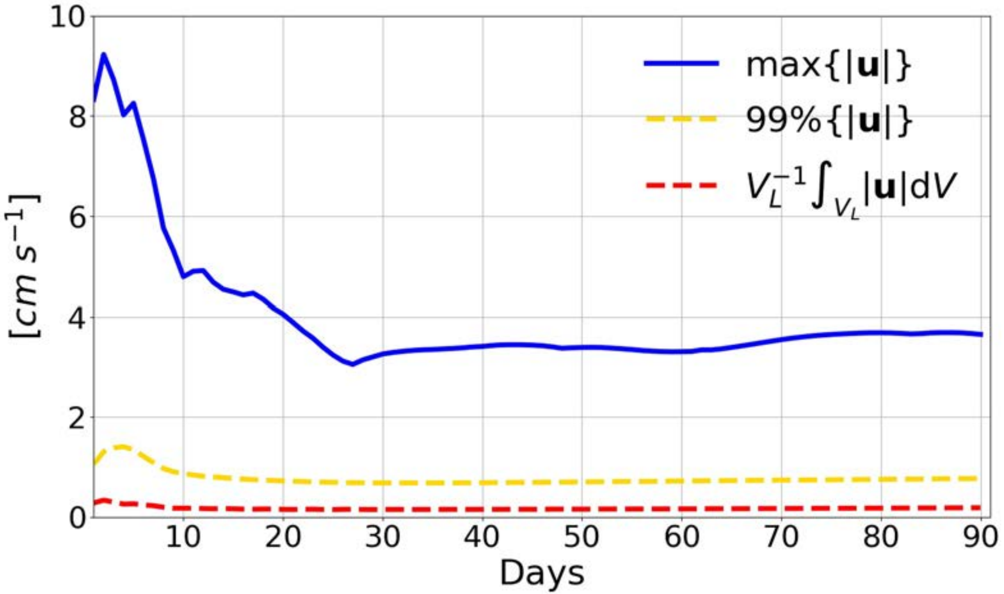
Vertical grids used in the AGRIF zooms:



agr20_loc-MEs uses 5 envelopes, 2 of which are quasi terrain-following with a max slope parameter rmax of 0.045.

Assessment of HPG errors

Three months long simulation with no external forcing, no explicit diffusion and initialized with a density profile ρ(z) from Shchepetkin & McWilliams 2003.

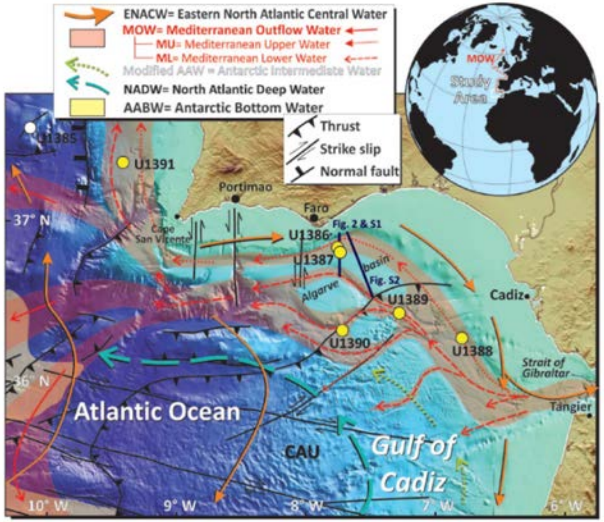


Time evolution of spurious currents (maximum, 99 percentile and average values) for *agr20_loc-MEs.*

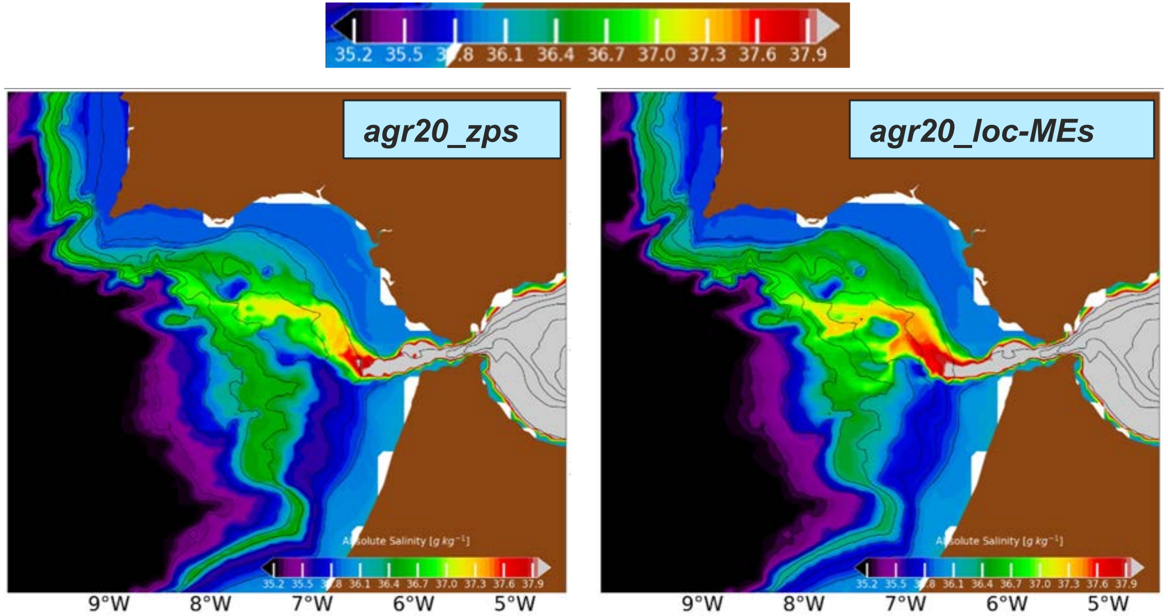
Looking at the solution of the zooms …

Bottom absolute salinity:

2010-2015 mean absolute salinity @ bottom



From *Hernandez-Moline et al. 2014*

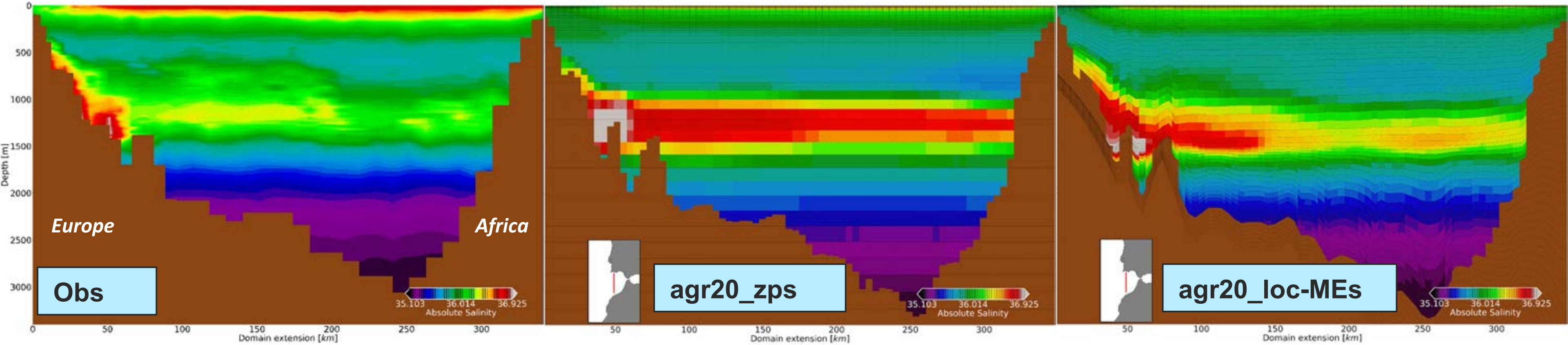


agr20_loc-MEs can correctly reproduce all the branches of the MED OVF, ***agr20_zps*** less so.

Looking at the solution of the zooms …

Absolute salinity transects:

2010-2015 mean absolute salinity



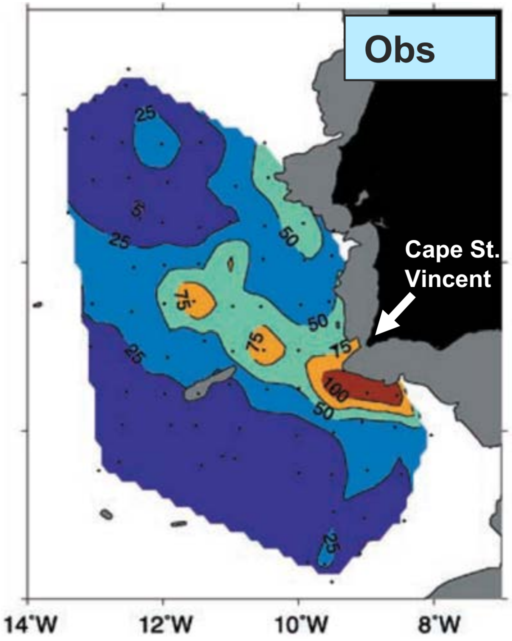
Transects I of ***Semane 2002*** campaign (Louarn et al 2011)

- Both zooms represent a **MED OVF** that **detaches** from the bottom topography **at the right depth**.
- ***agr20_zps*** simulates a plume that is too saline while the solution of ***agr20_loc-MEs*** agrees better with the observations.

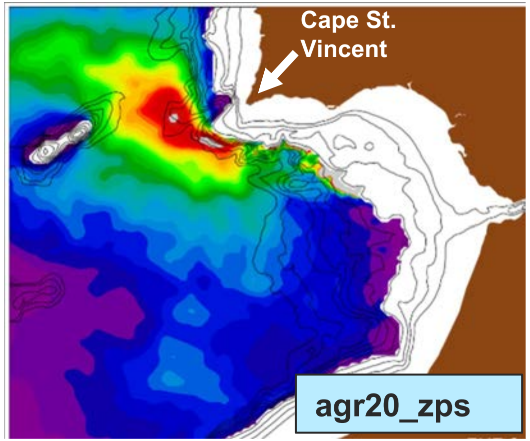
Looking at the solution of the zooms …

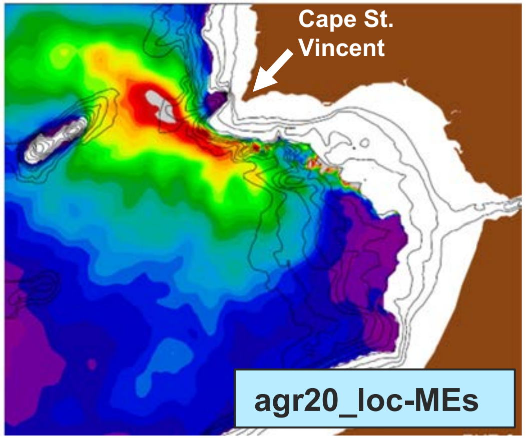
EKE @ 1000 m :

2010-2015 mean EKE [cm^2/s^2]



From *Bower et al. 2002*





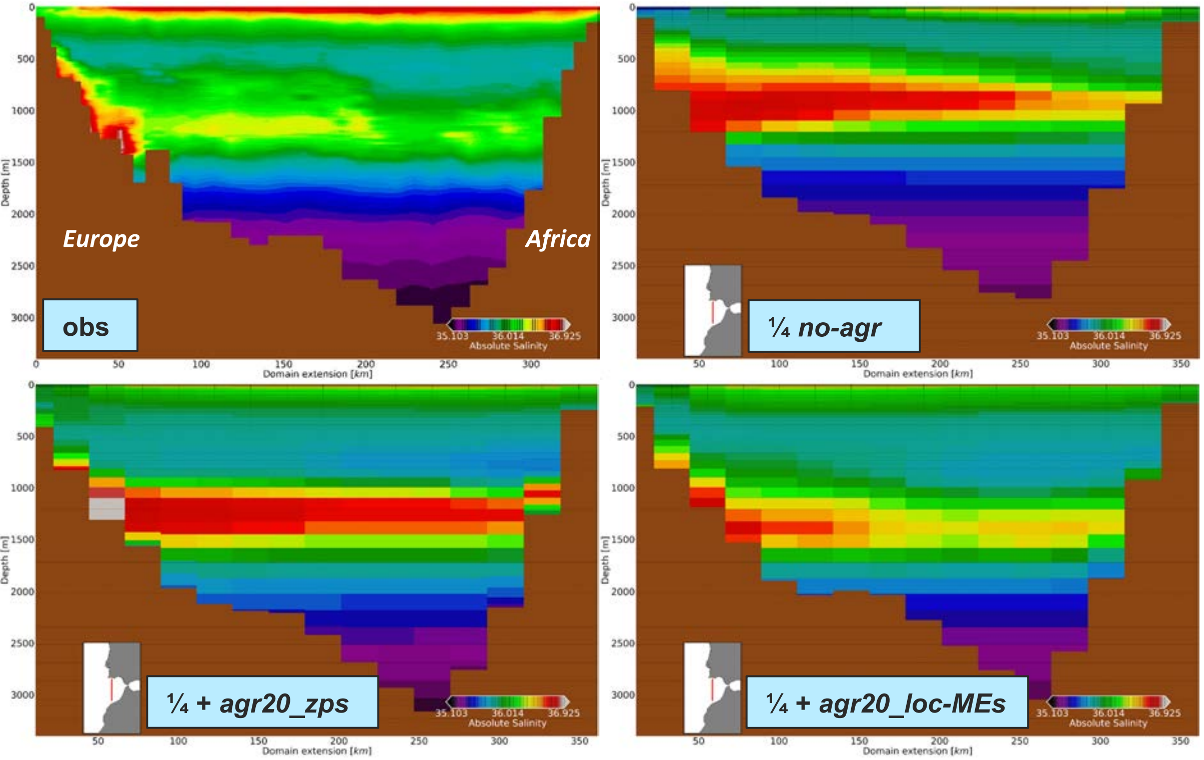
- In both zooms, the **EKE @ 1000 m is too weak** (~ by a factor 3) wrt obs: **Meddies** have radius between 10 and 50 km (Bower et al. 1997) ⍰ **at 1/20º (~4.5 km) the smallest Meddies can be barely resolved**
- EKE of ***agr20_loc-MEs*** agrees better with obs in comparison to ***agr20_zps,*** both in terms of magnitude and location.

Bower et al. 1997 – JPO, 27
Bower et al. 2002 – JGR-Oc., 107

Met Office Hadley Centre

Meanwhile, in the parent model …

Absolute salinity transects:



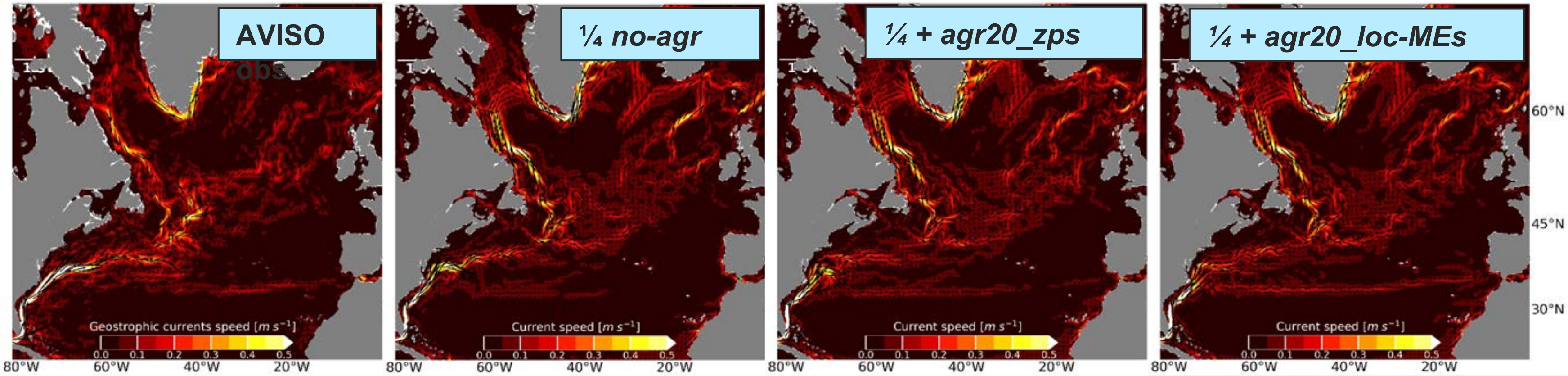
2010-2015 mean absolute salinity

- The control ¼ ***no-agr*** model simulates a MED overflow that is too weak and shallow
- *The solution of the zooms consistently feedbacks to the parent models, improving the MED OVF, especially in the case of* ***¼ + agr20_loc-MEs.***

Observations are from transects I of ***Semane 2002*** campaign (Louarn et al 2011, Alves et al. 2011).

Meanwhile, in the parent model …

2010-2015 mean ocean currents @ surface :



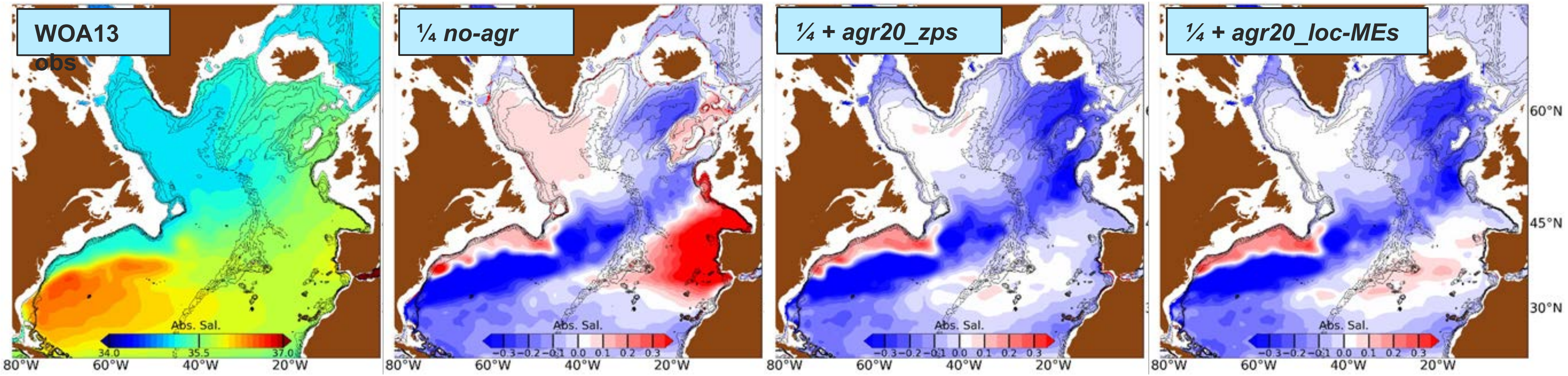
Models with a more realistic MED OVF simulate an Azores current that agrees well with AVISO geostrophic currents:

β-plume mechanism (*Stommel 1982, Pedlosky et al. 1997, Spall 2000*) **in action** as shown by *Jia 2000, Özgömen et al. 2000, Lamas et al. 2010.*

Stommel 1982 – Earth & Plan. Sc. Lett., 61
Pedlosky et al. 1997 – JMR, 55
Spall 2000 – JMR, 58
Jia 2000 – JPO, 30
Özgömen et al 2000 – JPO, 31
Lamas et al. 2010– GRL, 37

Meanwhile, in the parent model …

2010-2015 mean Absolute salinity bias (model-obs) @ 550 m:



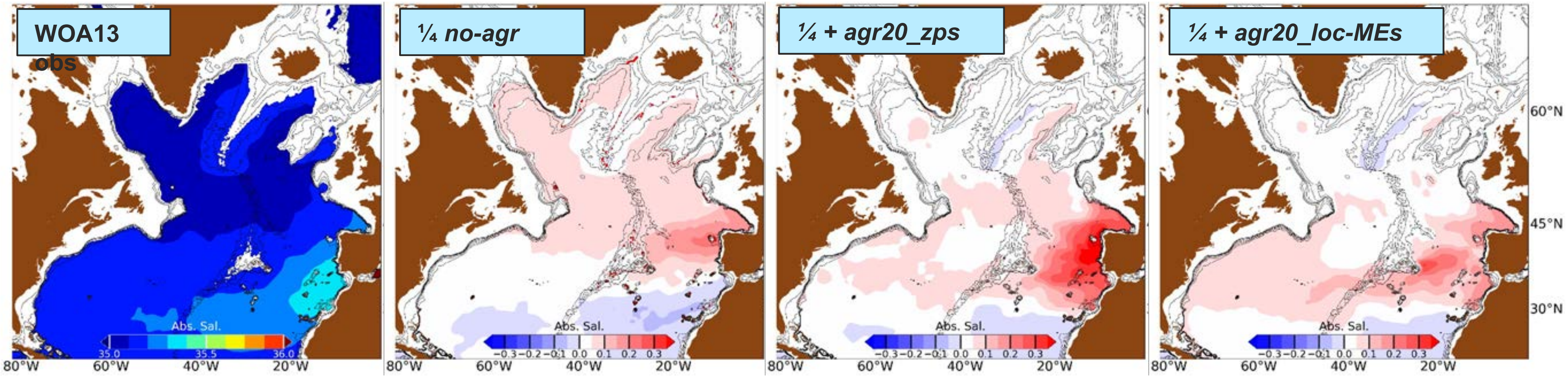
Models with **mesh refinement** in the MED OVF area can **significantly reduce** the strong **salinity biases affecting** the control **¼ *no-agr*** model in the east STNA and west SPNA.

There are **small differences** between the **¼ + *agr20_zps*** and **¼ + *agr20_loc-MEs*** models, but not a clear winner.

Met Office Hadley Centre

Meanwhile, in the parent model …

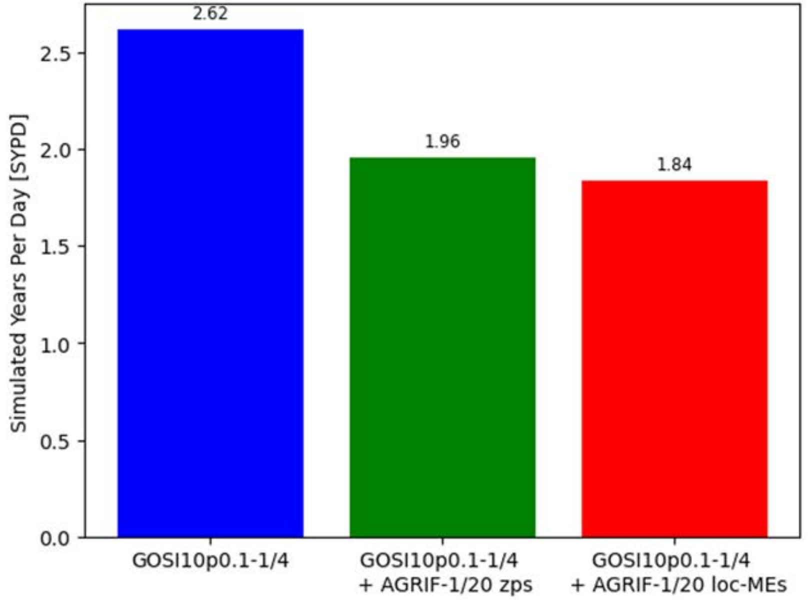
2010-2015 mean Absolute salinity bias (model-obs) @ 1950 m:



In comparison to ***¼ no-agr:***

- ***¼ + agr20_zps*** has larger +ve biases in the eastern STNA and smaller +ve biases in the western SPNA.
- ***¼ + agr20_loc-MEs*** has reduced +ve salinity biases in the entire SPNA but is too "salty" in the central and western part of the STNA.

How much will this cost?



- **Same number of CPUs** (345) allocated to NEMO in the three configurations
- **Large improvements in the entire NA** (especially when combining AGRIF with localized ME s-coordinates) with **small additional computational cost**
- **Vertical nesting** seems to have **little detrimental impact** on the efficiency of the model

In conclusion …

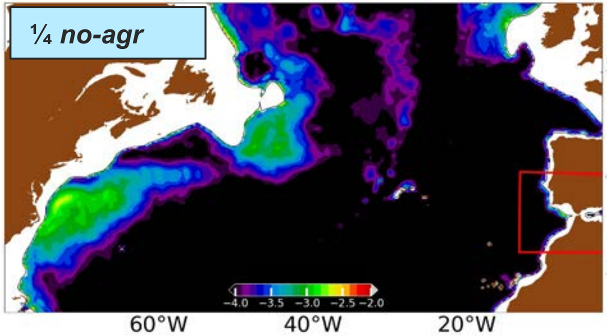
- We have used the localization method to successfully implement ME terrain-following coordinates in a 1/20° AGRIF zoom of the MED overflow nested in a 1/4° global configuration employing z-levels with partial steps.
- Local ME s-coordinates seems to be a viable option to implement vertical nesting and changing the type of vertical coordinates in two-way AGRIF zooms used for realistic applications.
- Using local ME terrain-following levels allows to reproduce a MED overflow that agrees much better with observations in comparison to geopotential coordinates.
- Two-way horizontal/vertical nesting methods is a viable option to implement multi-scale capabilities in structured QE ocean models used for climate studies and improve their representation of flow-topography interactions in local strategic areas.
- The computational cost for a single small zoom using the “maximum” space/time refinement factor is small; the question now is to see how efficient running multiple nests in parallel is …
- Improving the representation of the MED overflow and the associated mesoscale activity (i.e., Meddies) has large non-trivial impacts on the entire NA: the MED outflow seems to play an important role on the salinity biases documented in many eddy permitting/rich ocean models (e.g., *Treguier et al. 2005*, *Marzocchi et al. 2015*).

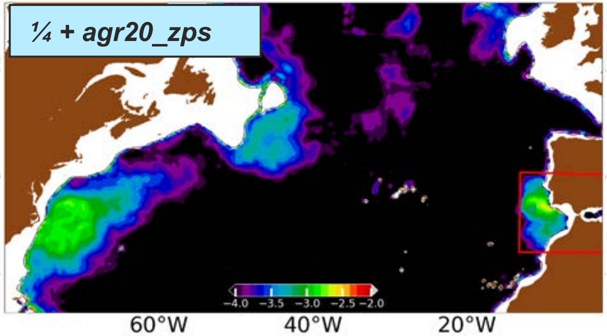
Treguier et al. 2005 – JPO, 35
Marzocchi et al. 2015 – JMS, 142

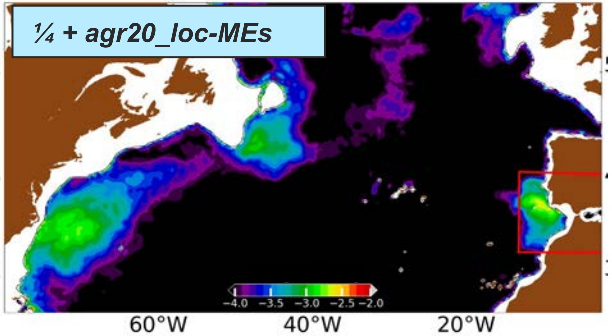
Met Office Hadley Centre

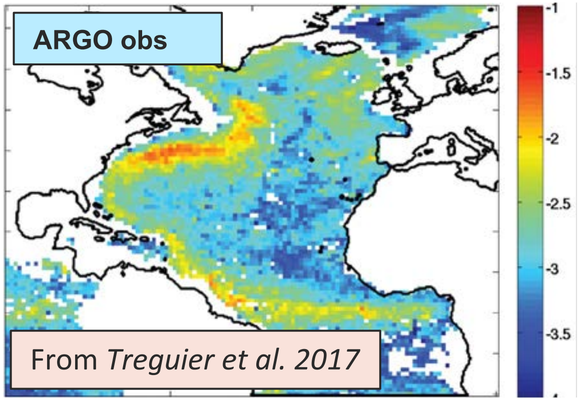
Meanwhile, in the parent model …

2010-2015 mean Log(EKE) @ 1000 m:









From *Treguier et al. 2017*

- The results of the zooms consistently feedback to the parent model: both models using mesh refinement present higher EKE @ 1000m than the control ***¼ no-agr*** model near Gibraltar strait. This is more in agreement with ARGO obs, although the magnitude is too weak.
- Consistently with the solution of the zooms, the EKE of the ***¼ + agr20_loc-MEs*** model interests a larger area than the one of the ***¼ + agr20_zps*** model, nicely propagating also beyond the boundary of the mesh refinement.

Met Office Hadley Centre

EXTRA SLIDES

Meanwhile, in the parent model …

Ocean currents speed @ 1000 m:

The picture can't be displayed

¼ *no-agr*

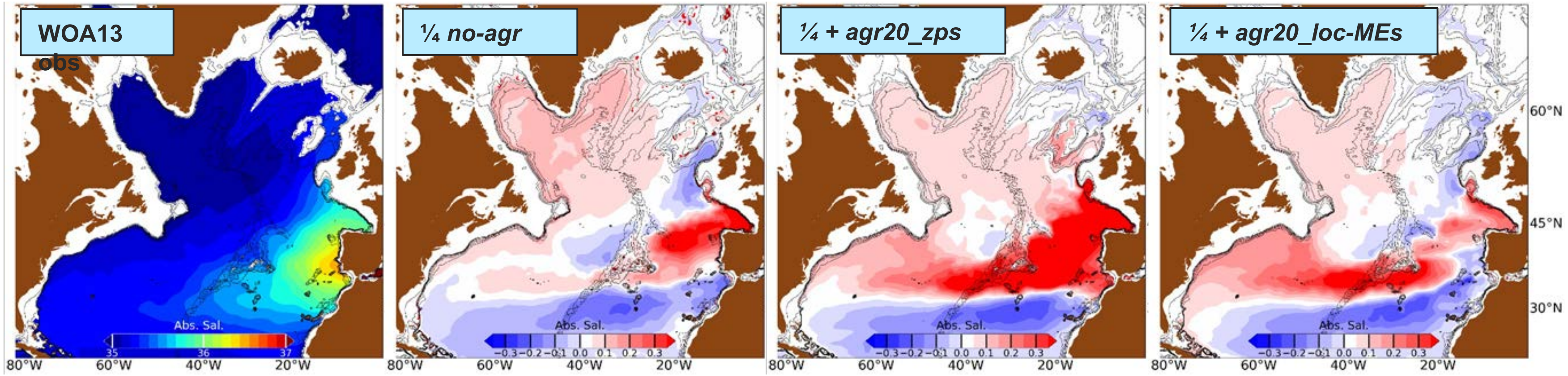
¼ + *agr20_zps*

¼ + *agr20_loc-MEs*

Only in the case of the ¼ + ***agr20_loc-MEs*** model eddies at 1000 m propagates westward outside the boundaries of the zoom, although the coarser resolution of the parent seems to partially degrade the structure of the smallest eddies.

Meanwhile, in the parent model …

2010-2015 mean Absolute salinity bias (model-obs) @ 1150 m:



In comparison to the control ***¼ no-agr*** model:

- ***¼ + agr20_zps*** has larger +ve biases in the STNA and smaller +ve anomalies in the western SPNA.
- ***¼ + agr20_loc-MEs*** has reduced +ve biases in the eastern STNA and SPNA but larger +ve anomalies in the central and western part of the STNA.