Improving Nordic overflows representation in global ocean models

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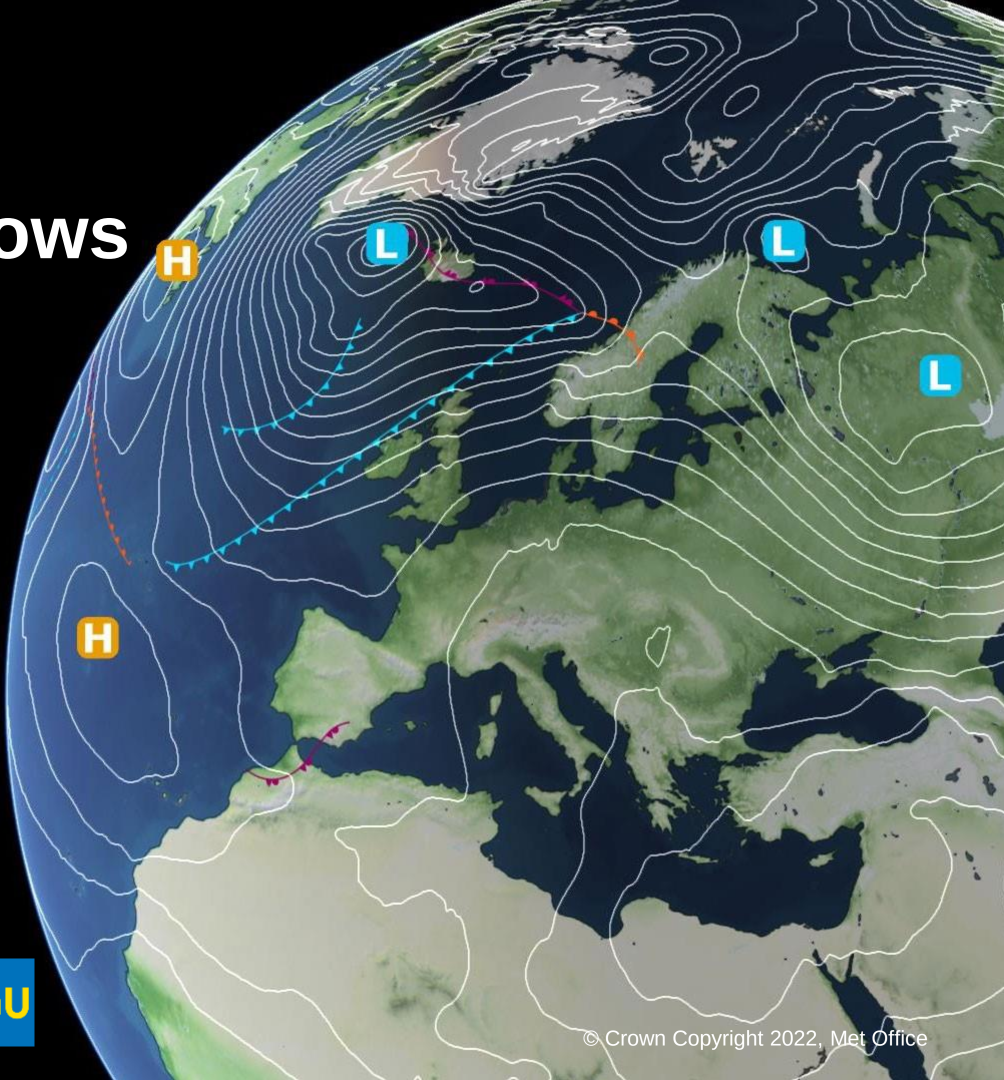
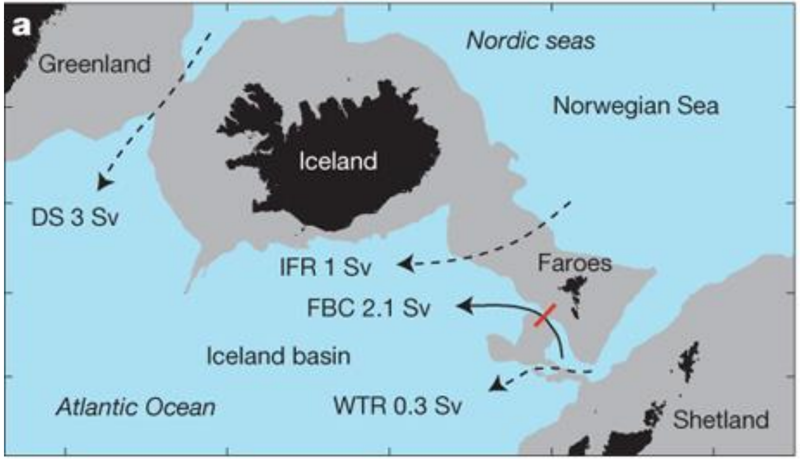
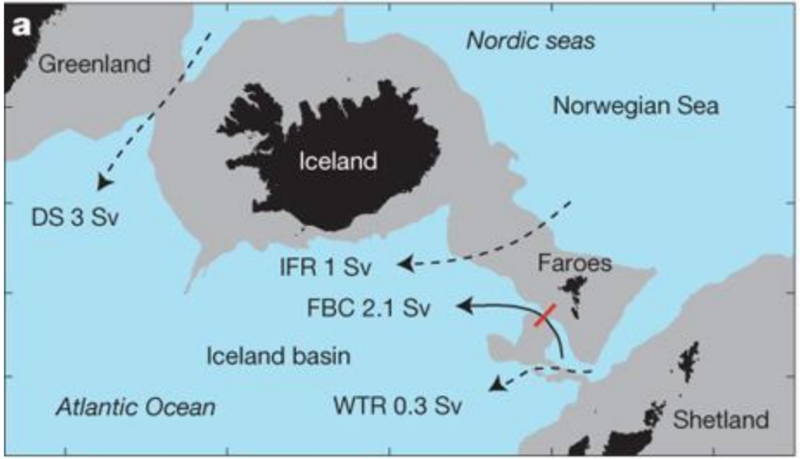


INTRODUCTION



- The **Nordic Overflows** generate **water-masses** with **specific hydrographic features** forming the lower limb of the **Atlantic Meridional Overturning Circulation** (AMOC).

MOTIVATION



Gravity currents representation in ocean models is **sensitive** to the choice of the **vertical coordinates system**:

- **Geopotential z-coordinates**: bottom topography represented as a series of step-like structures **->** **too much spurious entrainment and mixing** (e.g., Legg et al. 2006).
- **Terrain-following coordinates:** natural representation of overflows but errors in the computation of the pressure-gradient force -> **their use in global configurations is challenging** (e.g., Lemarié et al. 2012).
- **Arbitrary-Lagrangian-Eulerian (ALE) coordinates**: can significantly reduce spurious mixing in the ocean interior but might introduce too large dilution in some regions where overflows occur (e.g. Adcroft et al. 2019) -> **they might be not the best solution for overflows**

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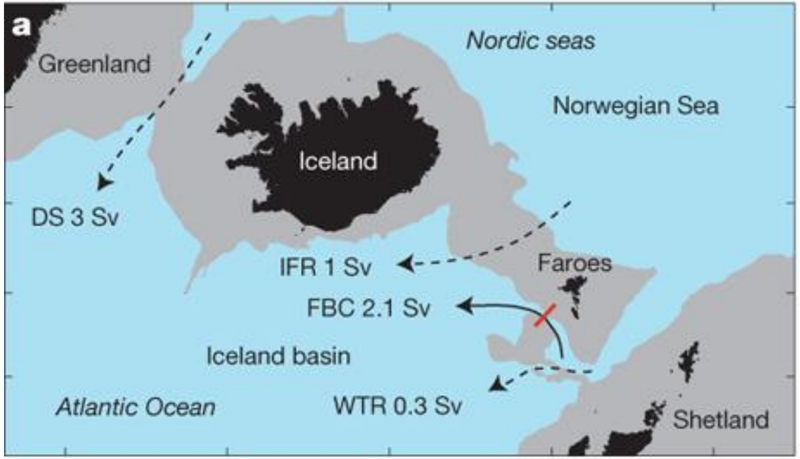

Colombo (2018) and **Mathiot et al. (2019)** proposed to use a **local-sigma** vertical coordinate: **quasi terrain-following** levels in the Greenland-Scotland ridge area, anywhere else standard **z-levels with partial steps (zps).**

The method showed **great potential.** However, **the development** of such a mesh resulted to be **not trivial** and **not easily generalizable**, **especially** when **defining the transition zone** between the two vertical coordinates or in terms of **horizontal pressure gradient errors**.

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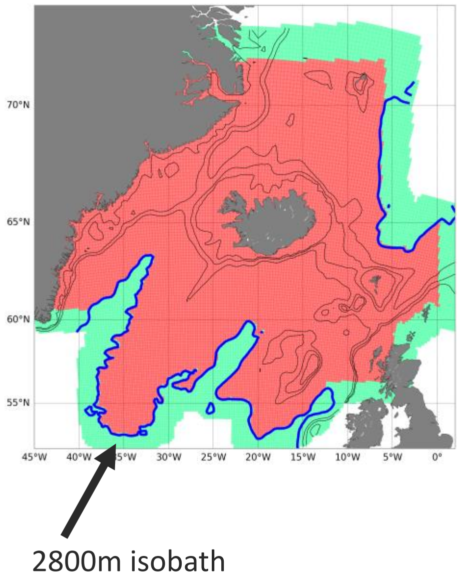
AIM OF THE STUDY

Can we develop a **GENERALISED** vertical coordinate system that LOCALLY employs **OPTIMISED** terrain-following computational surfaces while GLOBALLY uses geopotential z-levels with partial steps?

1. **GENERALISED**: as a study-case, it will be configured and tested for the Nordic overflows but should be easily applicable wherever we want.

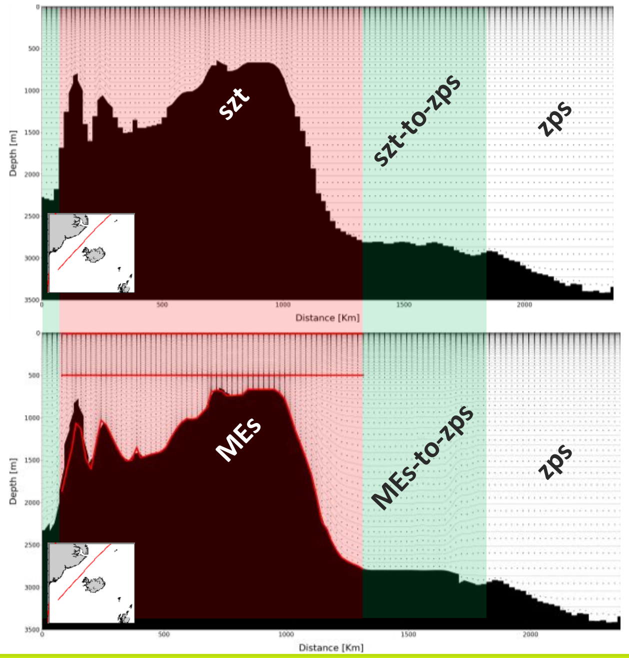
2. **OPTIMISED**: locally terrain-following levels should have low associated HPG errors but still able to offer a realistic representation of the bottom topography

METHODS



GENERALISED ALGORITHM to define:

- **Localisation area:** the model uses quasi **terrain-following** levels.
- **Global area**: the model uses **zps** levels.
- **Transition area:** model levels as a linear combination of terrain-following and zps levels, with weights defined as in **Mathiot et al. (2019).**

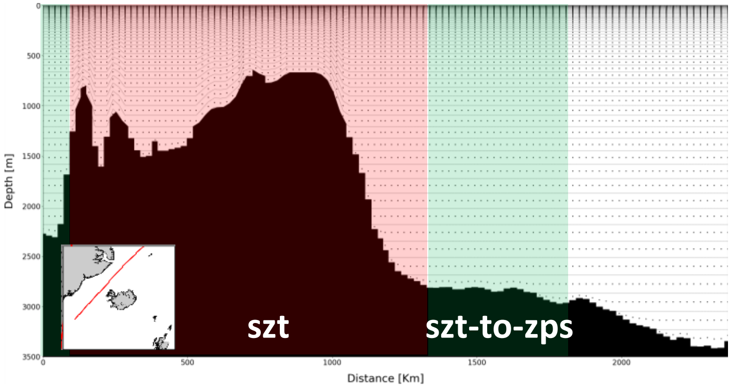


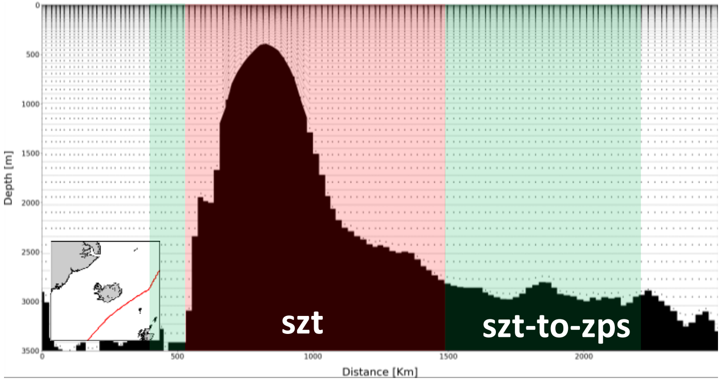
Two vertical coordinates are tested and implemented in the **localisation area**:

- **s transitioning** to **z** coordinate (**szt**): above 1200m quasi terrain-following levels, below smoothly transition into zps levels (Harle et al. 2013)
- **Multi-Envelope s**-coordinate (**MEs**): levels adjusted to multiple arbitrarily defined surfaces (aka envelopes) -> quasi terrain-following levels up to 2800m (Bruciaferri et al. 2018)

Slope parameter $r \equiv \frac{|H_b - H_a|}{H_b + H_a}$, with H_a and H_b the depths of adjacent grid cells

local-szt





- **Above** a user-defined depth, **model levels** follow a smoothed version of the actual bathymetry (aka envelope) while **below** that depth limit smoothly transition into **zps levels** (see Harle et al. 2013 and Wise et al. 2021 for the details).
- In this configuration we use **48 VQS levels** (up to ~1200 m) and an envelope smoothed to have maximum **slope parameter** rmax = 0.1 .

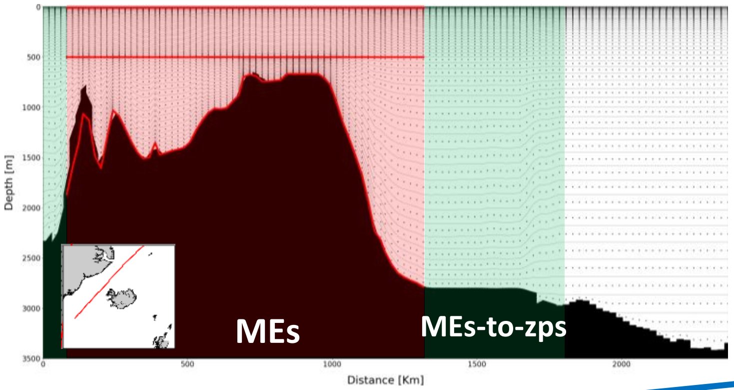
WHY SHOULD WE USE IT?

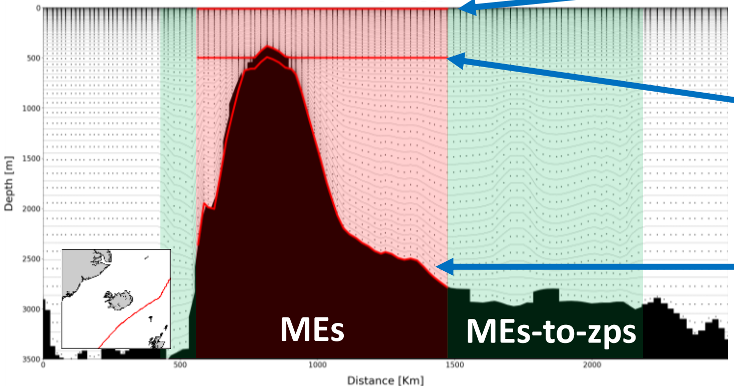
1. When numerically simulating gravity currents, most of the spurious mixing occurs at the beginning of the overflows (Ezer 2005, Legg et al. 2006): using local-szt levels may help to **mitigate numerical mixing when cascading is initiated.**
2. Since local-szt employs inclined levels only up to a certain depth, the **rmax value can be relaxed** (i.e., smoothing less the envelope bathymetry) wrt a configuration using local standard sigma-levels.
3. **Smooth transition** (by definition of the vertical coordinate system) between szt and zps at the bottom.
4. **General and easy to implement**

Slope parameter $r \equiv \frac{|H_b - H_a|}{H_b + H_a}$, with H_a and H_b the depths of adjacent grid cells

local-MEs

METHODS





- **Computational surfaces** are curved and adjusted to **multiple** arbitrarily defined **surfaces** (aka **envelopes**) rather than following geopotential levels or the actual bathymetry (see Bruciaferri et al. 2018, 2020 for the details).
- In this configuration we use **4 envelopes.**

WHY SHOULD WE USE IT?

1. **Model levels can be optimized for the prevailing physics:**
   - **Envelope 1** is a geopotential surface with depth = 10m -> near the surface constant model level thickness consistent with the global grid
   - **Envelope 2** is a smoothed (**rmax=0.12**) version of the bathymetry from 10 up to 500m -> quasi terrain-following levels to better resolve shelf cascading
   - **Envelope 3** is a smoothed (**rmax=0.12**) version of the bathymetry from 500 up to 2800m -> quasi terrain-following levels to better resolve overflows
   - **Envelope 4** is a geopotential surface with depth equal to the depth of last W-level of the global zps grid.

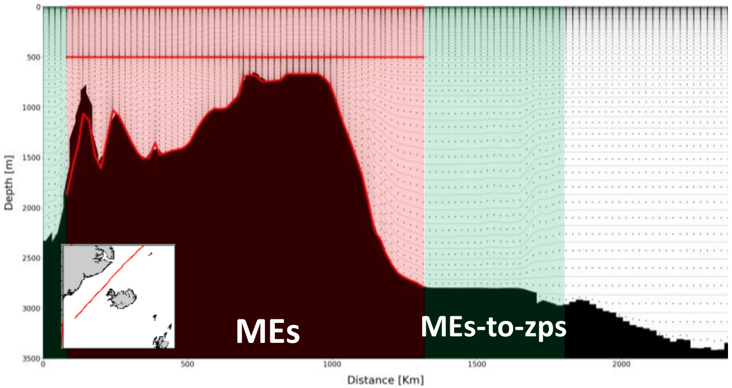
local-MEs

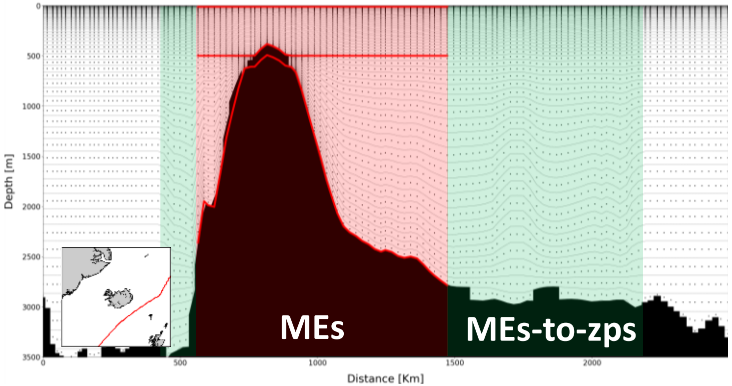
METHODS

- **Computational surfaces** are curved and adjusted to **multiple** arbitrarily defined **surfaces** (aka **envelopes**) rather than following geopotential levels or the actual bathymetry (see Bruciaferri et al. 2018, 2020 for the details).
- In this configuration we use **4 envelopes.**

WHY SHOULD WE USE IT?

2. **3D varying maximum slope parameter rmax:** we smooth only where it is needed
3. **Direct control on the design of model levels** in each vertical sub-zone.
4. **Reduced saw-tooth patterns** (by definition of the vertical coordinate): smooth transition between MEs and zps zones
5. **General and relatively easy methodology:** once the envelopes are identified (based of physical motivations), the number of levels to assign to each sub-zone is dictated by the number of levels possessed by the global zps grid at similar depths.





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COMMON NUMERICAL SETTING

- NEMO **4.0.4**
- **Met Office GOSI9 @ 1/4° of horizontal resolution and 75 model levels**
- **EOS**: TEOS10
- **TKE** turbulent closure scheme
- **Adv. scheme for tracers**: FCT (4^{th} ord. hor. / ver.)
- **Adv. scheme for mom.**: vector formalism and EEN scheme
- **Lateral diff for tracers:** isoneutral triad harmonic operator (nn_ahm_ijk_t=20), rn_Ud=0.011 m/s, rn_Ld=200000 m
- **Lateral diff for mom.:** along model levels bi-harmonic operator (nn_ahm_ijk_t=20), rn_Uv=0.0838 m/s, rn_Lv=10000 m
- **HPG scheme**: pressure Jacobian
- **Bottom friction: logarithmic formulation, drag coeff. = 3.0 x 10^{-3}**

IDEALISED EXPERIMENTS: HPG TEST

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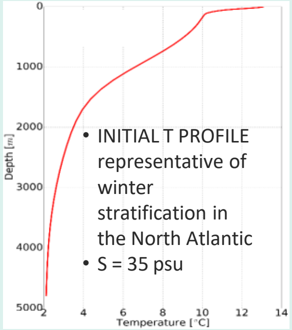
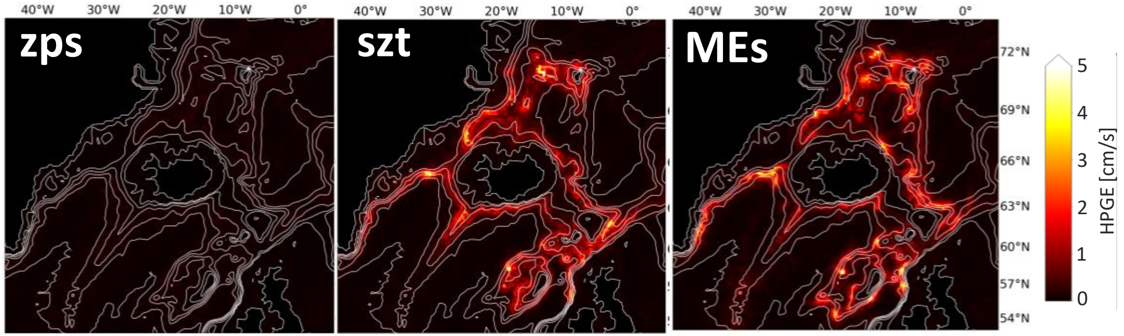
Initial condition obtained by horizontally spreading one single T/S profile so that

- **no initial HPG**
- **no initial circulation**
- **sea surface is flat**
- **No external forcing**



Maximum (in the vertical and time) HPG errors after 1 month of integrations



Computational surfaces of local-szt and local-MEs models **are optimised** with an iterative **“HPGE-aware” algorithm**: smoothing to reduce the steepness of model levels is applied only where the local HPGE > 0.05 m/s (value from Wise et al. 2021).

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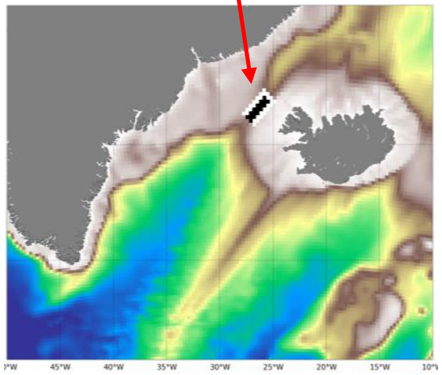
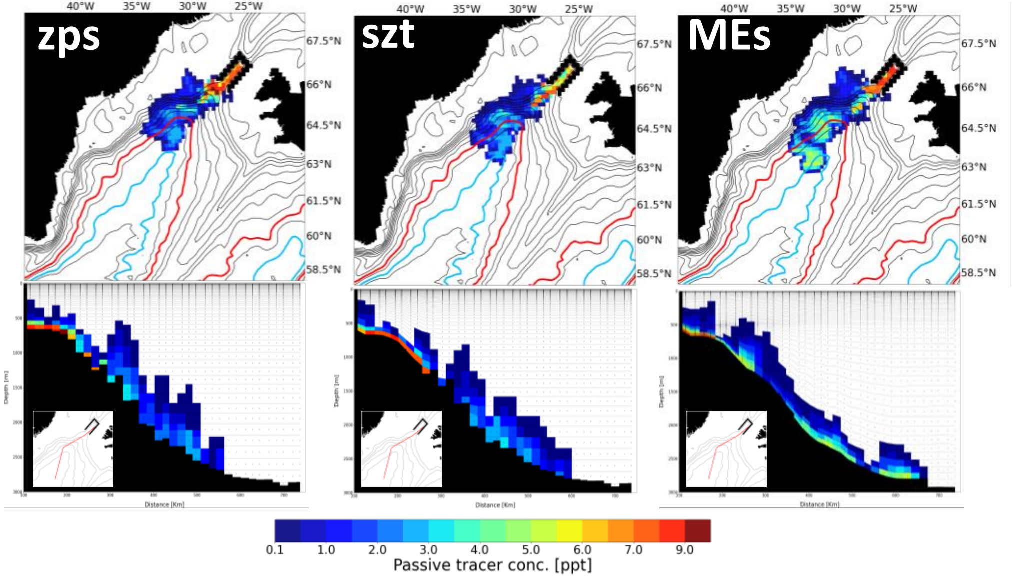
IDEALISED EXPERIMENTS: OVERFLOW

- <u>Initial condition:</u>
  - ✓ **ocean at rest** with **3D uniform initial temperature (T=6 °C) and salinity (S=0) ;**
  - ✓ **Cold (T=1.5 °C, S=10)** water mass in an **artificial reservoir;**
- <u>EOS</u>: **linear** function of **only T -> S** is a **passive tracer;**





zps: largest entrainment and mixing.

Local-szt: able to reduce the large mixing in the first ~20 days, after too much mixing.

Local-MEs: able to significantly reduce passive tracer dilution during the whole simulation, retaining up to 50-60 % of the initial concentration down to ~3000 m after 40 days

REALISTIC EXPERIMENTS

- **Realistic experiments**:
  - **Initial condition**: T&S from EN4 climatology
  - **Atmospheric forcing**: JRA-55 with NCAR bulk formulae
  - **Simulation period**: 01-01-2010 / 31-12-2018

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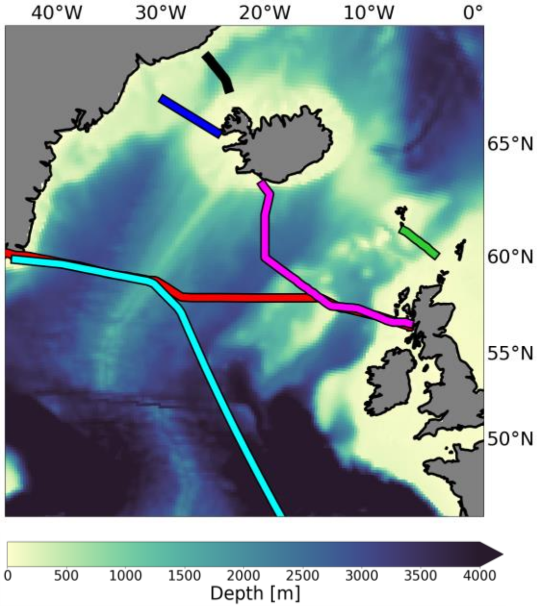
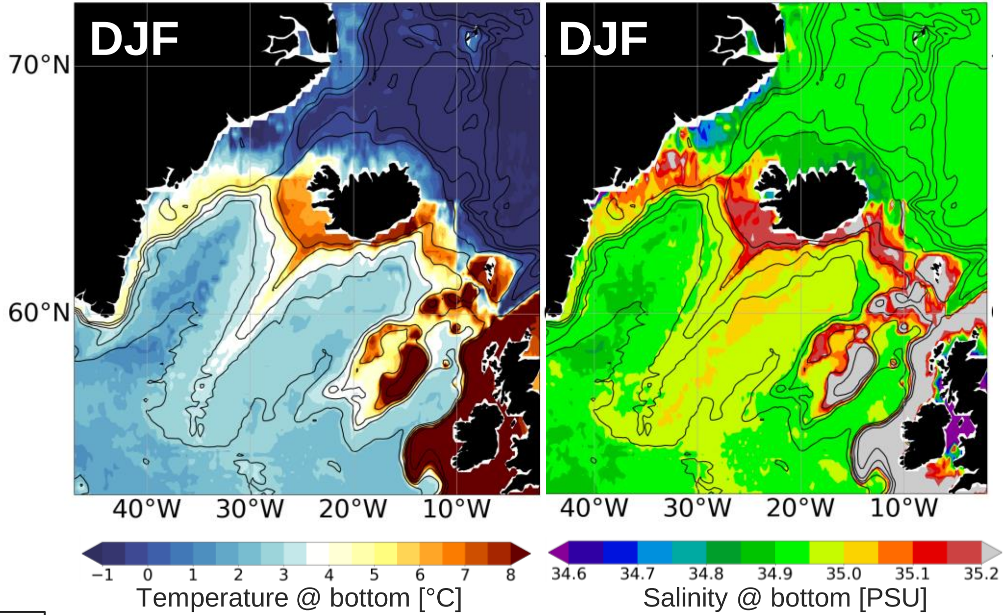
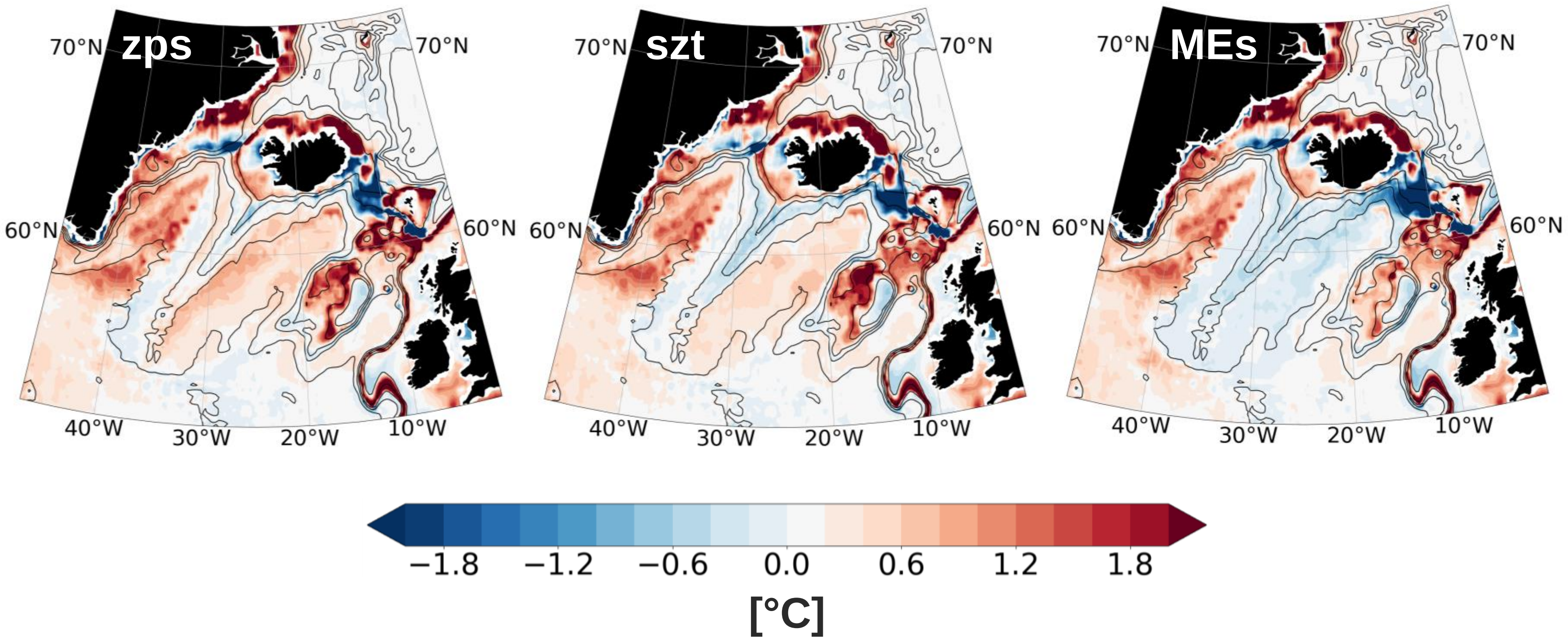
NOAA WOA 2018 climatology





- Kögur
- Látrabjarg
- OSNAP East
- OVIDE
- EEL
- Hansen & Osterhus 2000

$T_{model} - T_{NOAA}$ @ bottom (DJF)



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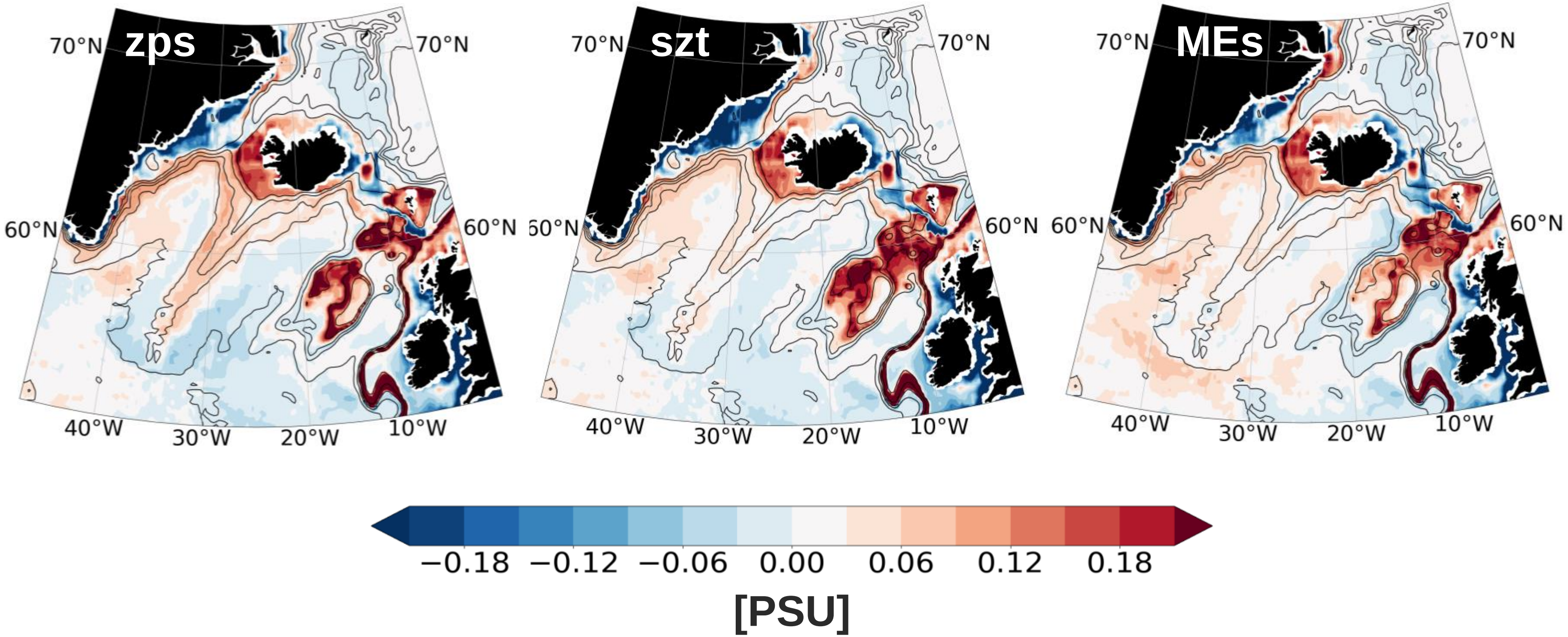
$S_{model} - S_{NOAA}$ @ bottom (DJF)



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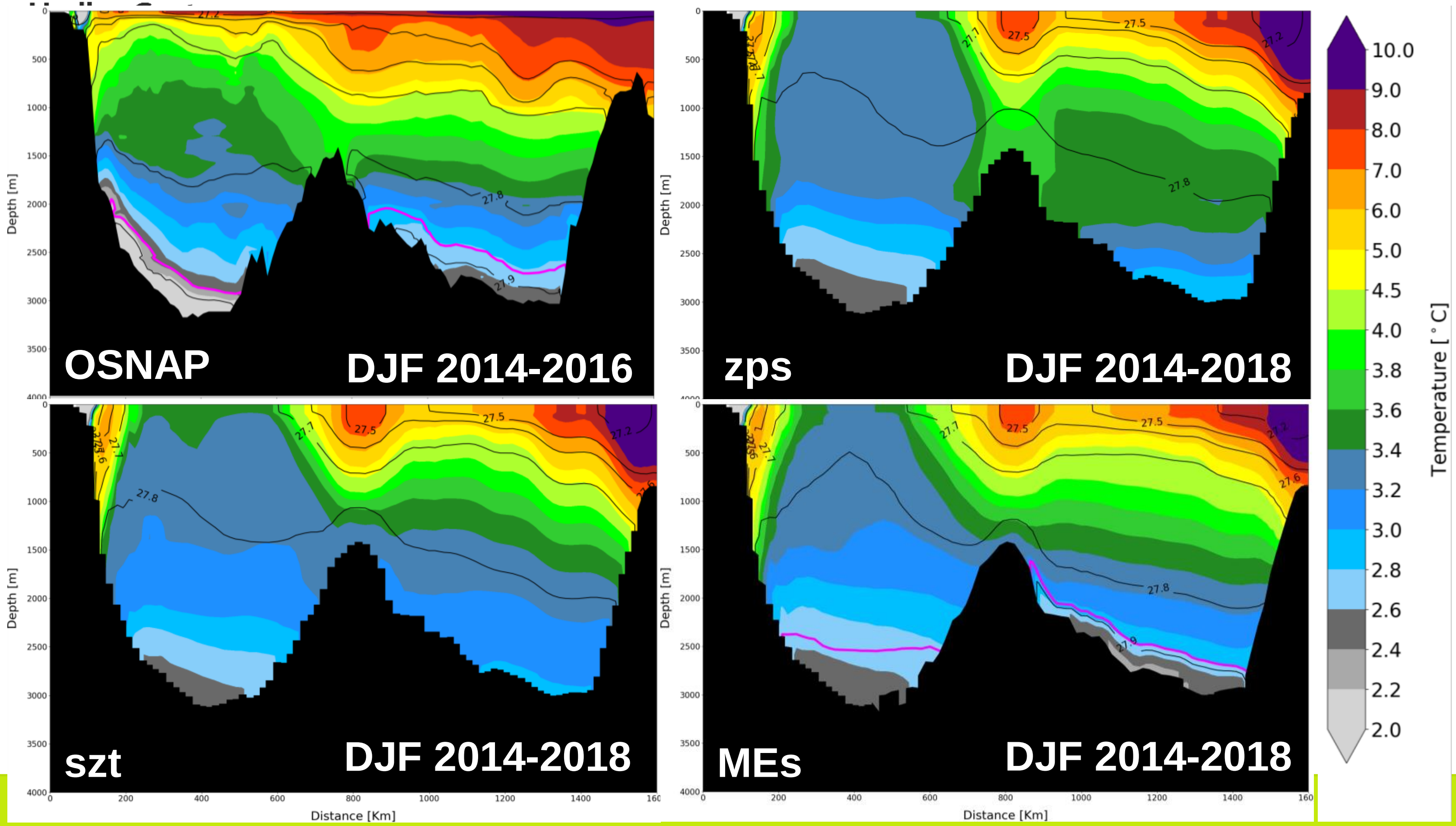
RESULTS



RESULTS

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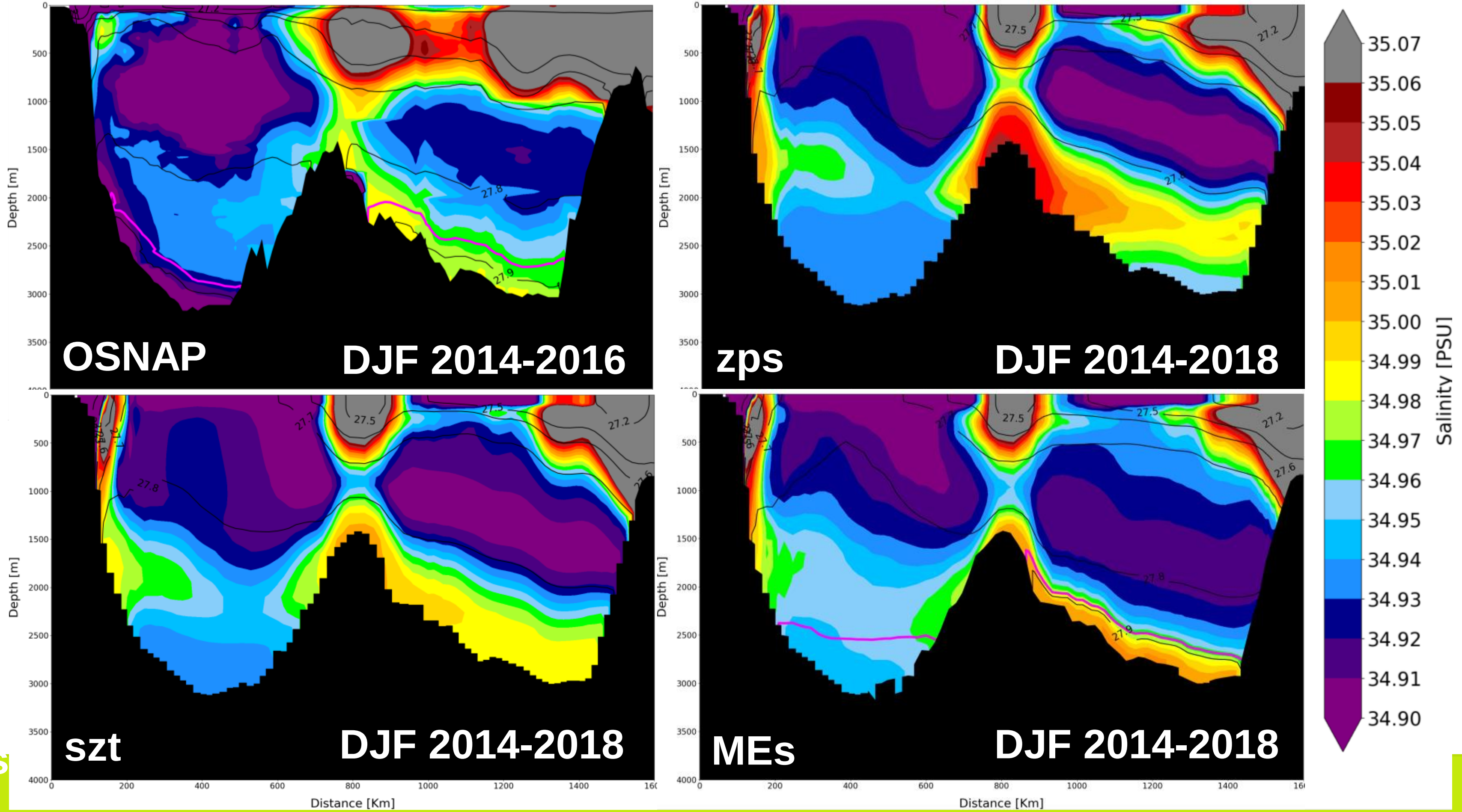

RESULTS

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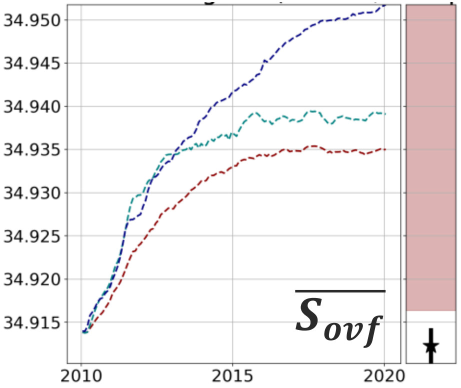
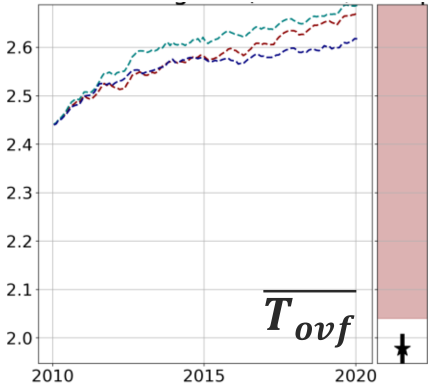
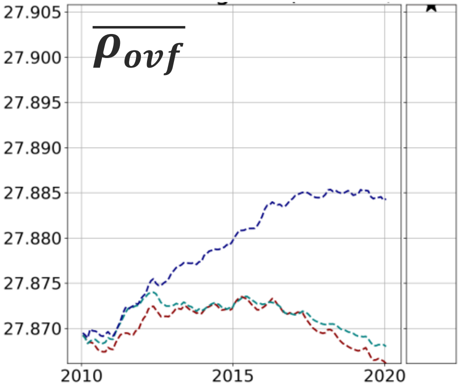
IRMINGER BASIN



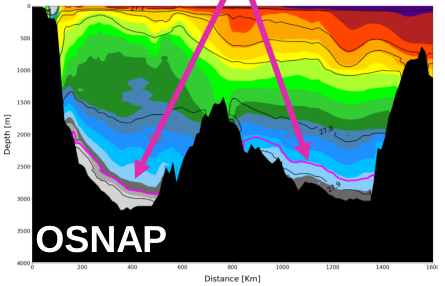




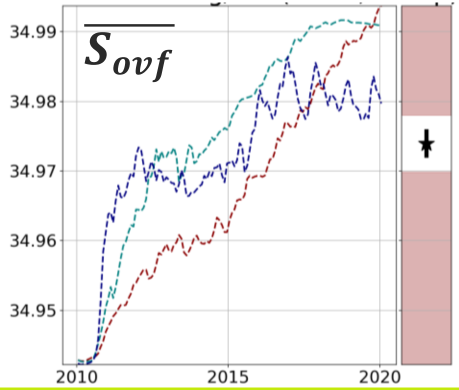
$\phi = S, T, \rho$

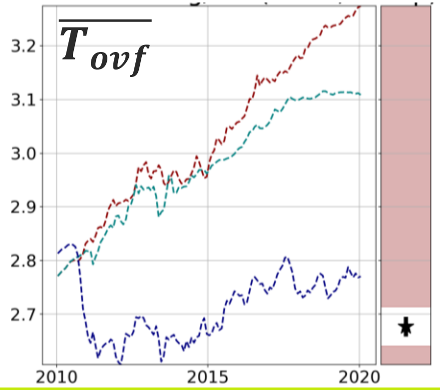
$$\overline{\phi_{ovf}} = \frac{1}{V_{ovf}} \int_{V_{ovf}} \phi dV$$

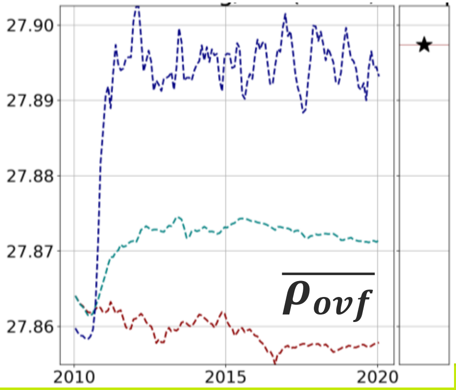
V_{ovf} = vol. of water with $\rho \geq 28.88\ kgm^{-3}$ in OSNAP observations



ICELANDIC BASIN







- - - - zps
- - - - szt
- - - - MEs

CONCLUSIONS

- **Generalized methodology** to implement **localised** szt and MEs vertical coordinates systems within a **global NEMO configurations** employing z-levels with partial steps.
- Both local-szt and local-MEs have been **optimized to have HPG errors < 0.05 m/s.**
- **Idealised overflows experiments** show that
  - ➢ **zps:** largest entrainment and mixing.
  - ➢ **Local-szt:** able to reduce the large mixing in the first ~20 days, after too much mixing.
  - ➢ **Local-MEs:** able to significantly reduce passive tracer dilution during the whole simulation.
- **Realistic experiments** show that
  - ✓ **local-MEs** represents the more realistic overflows' characteristics, with large improvements in the Icelandic basin.
  - ✓ **In the Irminger basin**, large scale salinity biases dominate with all coordinate systems. Salinity biases are being investigated and are likely linked to the models' inability to reproduce the correct dynamic in the subpolar gyre.

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