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- FESOM days 2020 -

FESOM2.0

New vertical geometric features implemented into FESOM2.0

Patrick Scholz (Patrick.Scholz@awi.de), Dmitry Sidorenko,
Sergey Danilov, Nikolay Koldunov

Energy Transfer in Atmosphere and Ocean, Topic S2: Improved parameterisations and numerics in climate models

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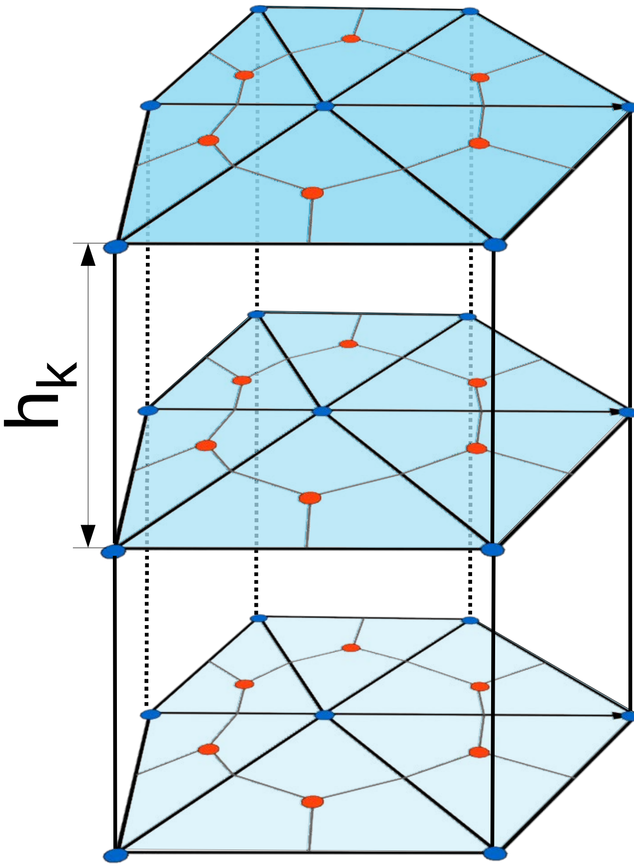
FESOM2.0 using ALE

- FESOM2.0 uses **A**rbitrary **L**agrangian-**E**ulerian **(ALE)** vertical coordinate approach

What is ALE?

- Achieved by introducing 3d layerthickness h(x,y,z,t) as a new variable which can be fixed in time or vary under certain constrains
- It allows vertical levels to be fixed in time (Eulerian) or to move with the flow (Lagrangian) or to be something in between
- ALE has the potential to reduce unwanted spurious cross isopycnal mixing effects



What can be implemented via ALE?

- Vertical discretisations for linear free surface (linfs), and full free surface (zlevel, zstar, ztilde)
- partial bottom cells, embedded sea ice, cavities
- Vanishing-Quasi-Sigma (VQS) coordinates, hybrid coordinates, isopycnal following coordinates.

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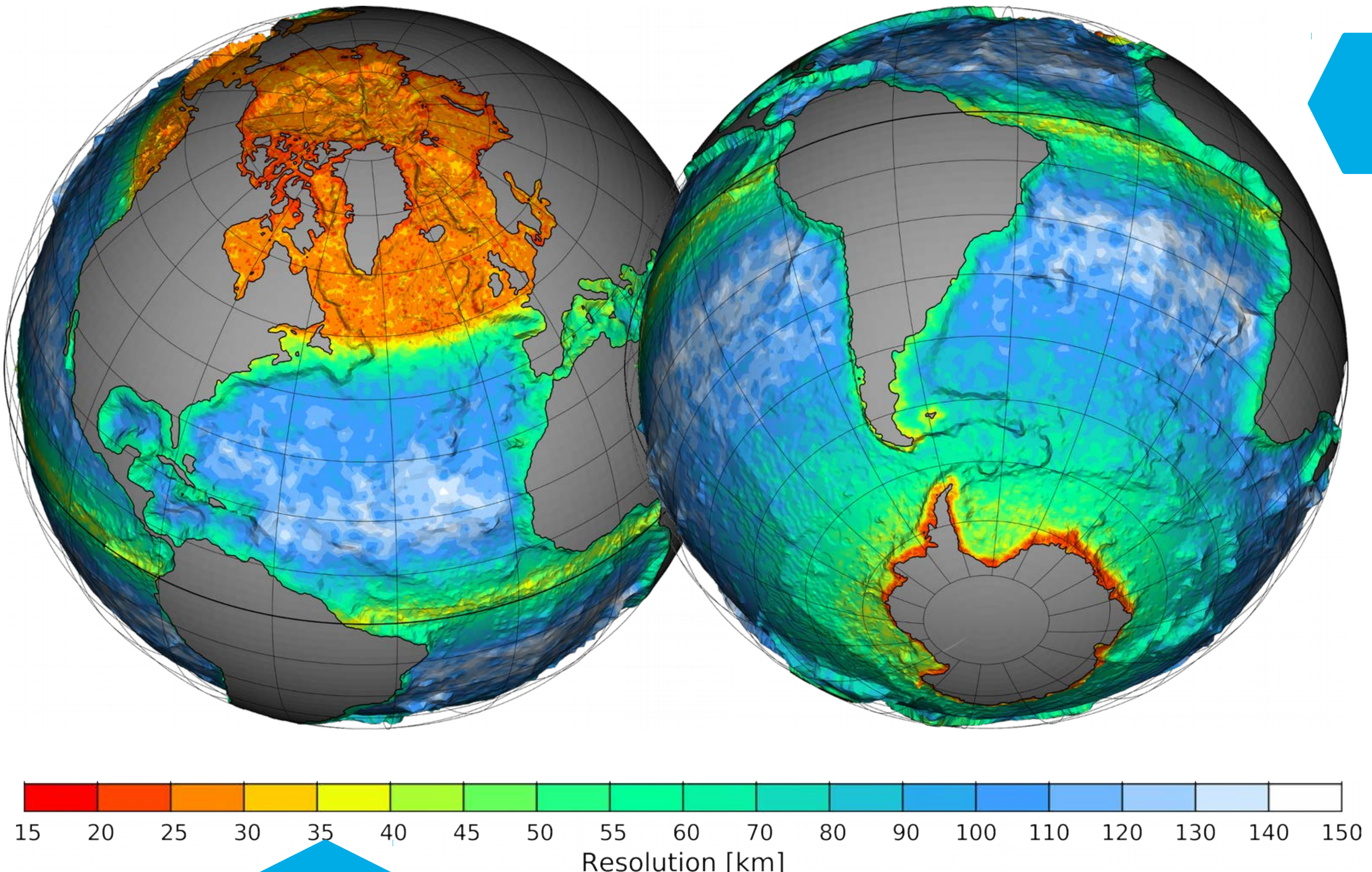
Model Setup



Forcing

- Coordinated Ocean-ice Reference Experiments data set, version 2 (Large and Yeager 2009)
- Period 1948-2009
- Applied 3 spinup cycles

Initialisation

- Polar science center Hydrographic Climatology (PHC3.0)

Mesh

- CORE2 mesh, minimum resolution ~20 km (#surface vertices: 126858, #layers: 48)
- Also used for CORE2 intercomparison project with FESOM1.4

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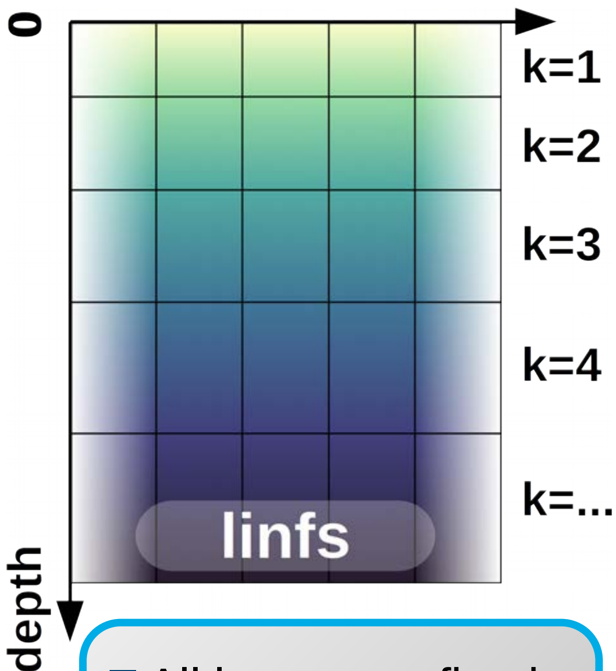
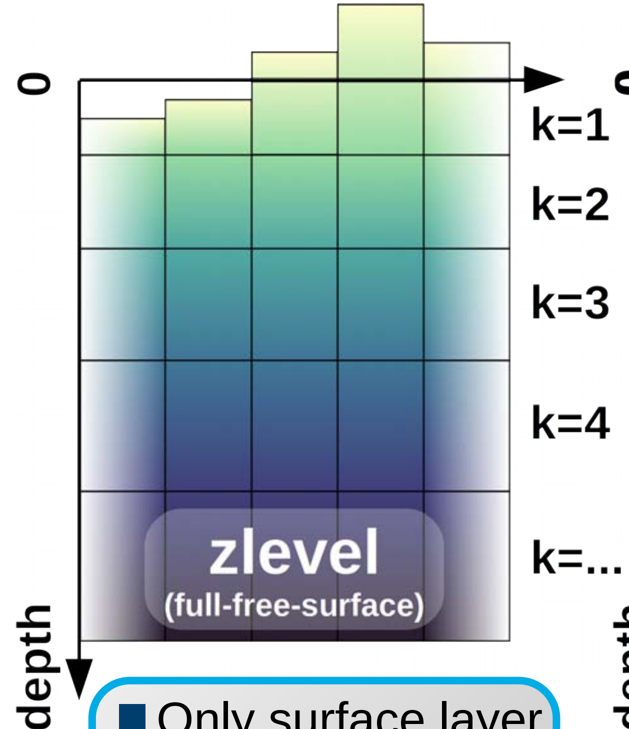
Linear- / Full free surface

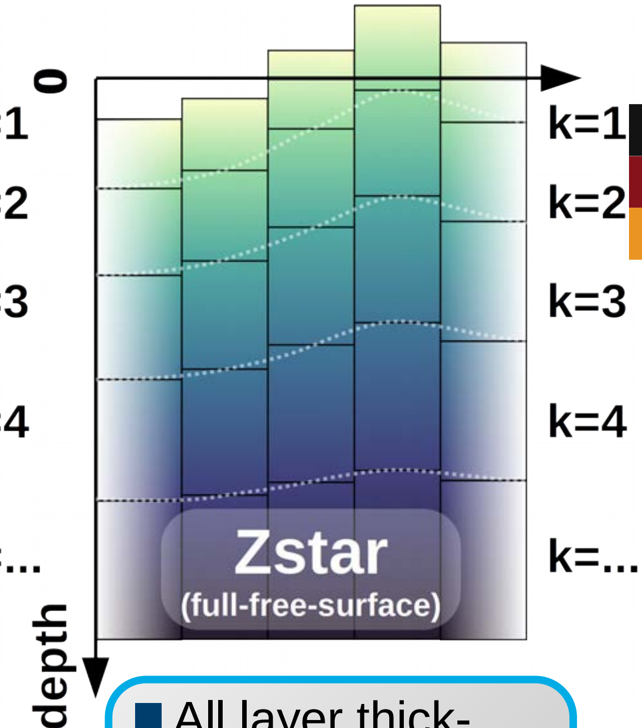
Linear free surface



- All layers are fixed
- Freshwater flux can not be taken into account it contributes by virtual salinity flux

Full (nonlinear) free surface





- Only surface layer thickness variates with dssh
- All layer thick-nesses variate with dssh
- Freshwater flux directly affects the volume of the first layer and thus alternates salinity

```
namelist.config: which_ALE =
 'linfs', 'zlevel', 'zstar'
```

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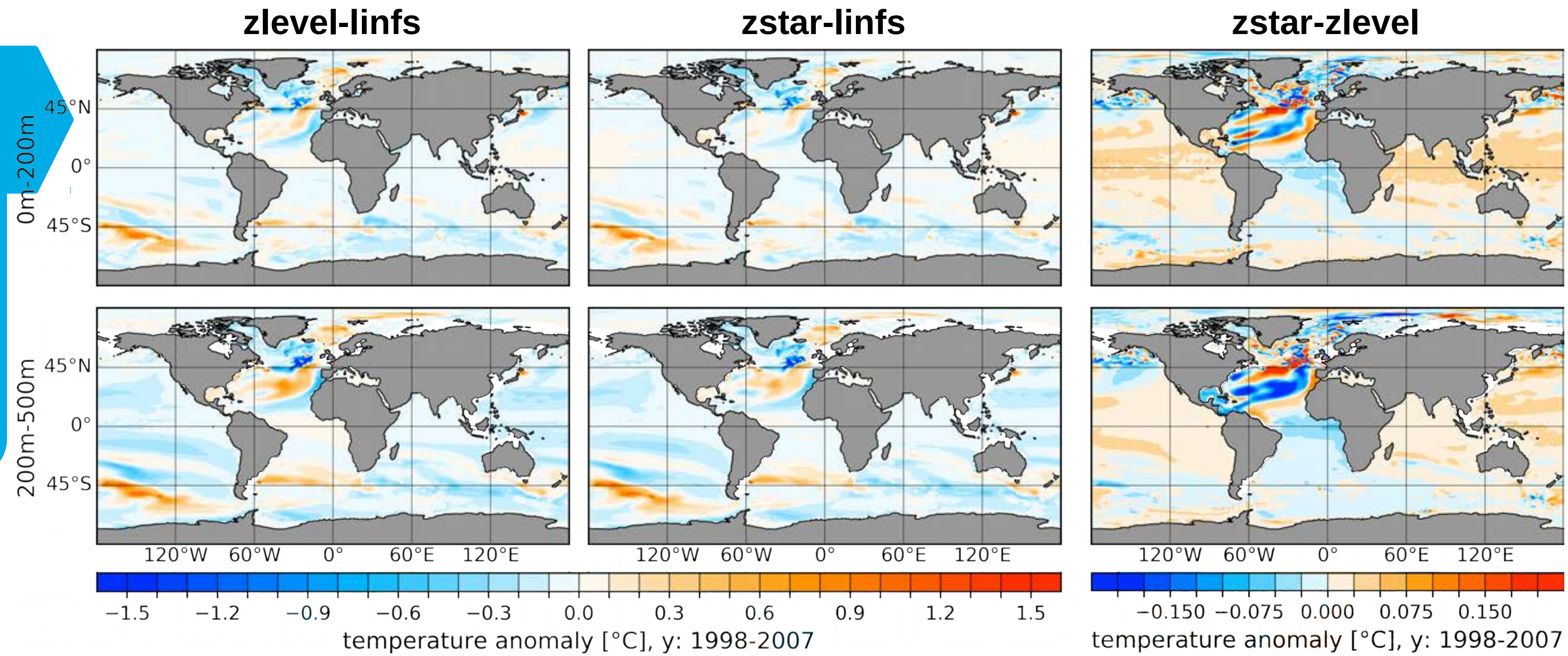
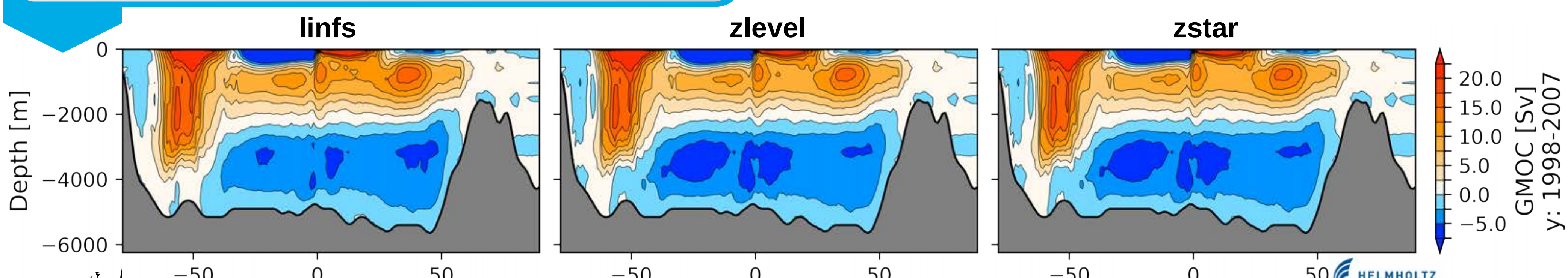
Linear- / Full free surface

- Temperture bias between zlevel/zstar and linfs (left + middle) and between zlevel and zstar (right panel)



- Global Meridional Overturning Circulation (MOC) for linfs, zlevel and zstar



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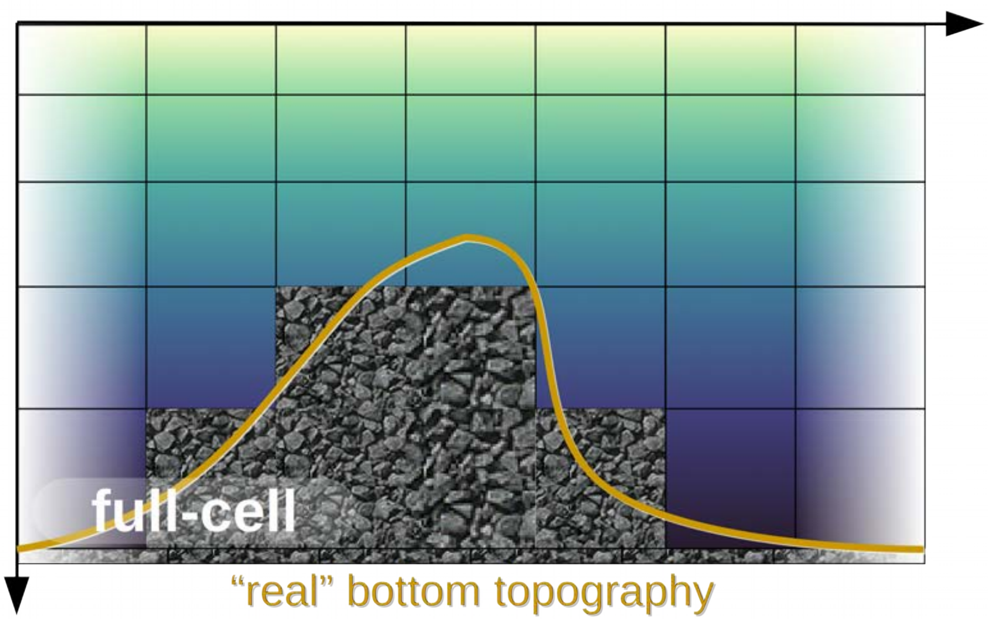
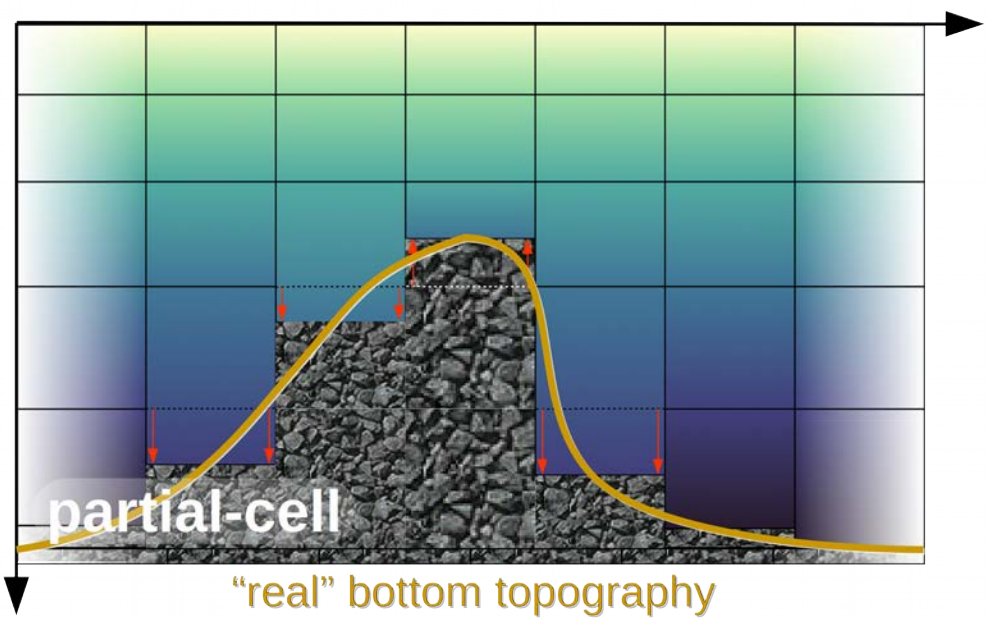
Partial Cells

- Adapt bottom layer thickness away from full cell thickness towards a more realistic bottom representation (`namelist.config: use_partial_cell=.true.`)
- Bottom thickness limitation:

$$0.5 * hbot_{\text{full cell}} <= hbot_{\text{partial cell}} <= 1.5 * hbot_{\text{full cell}}$$





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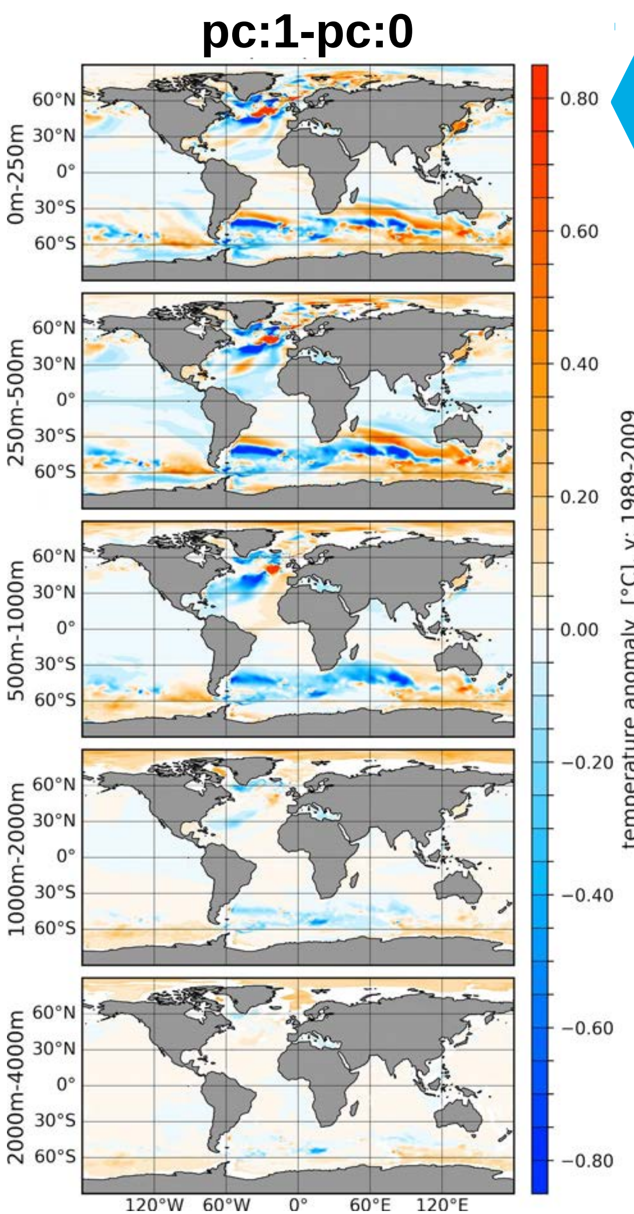
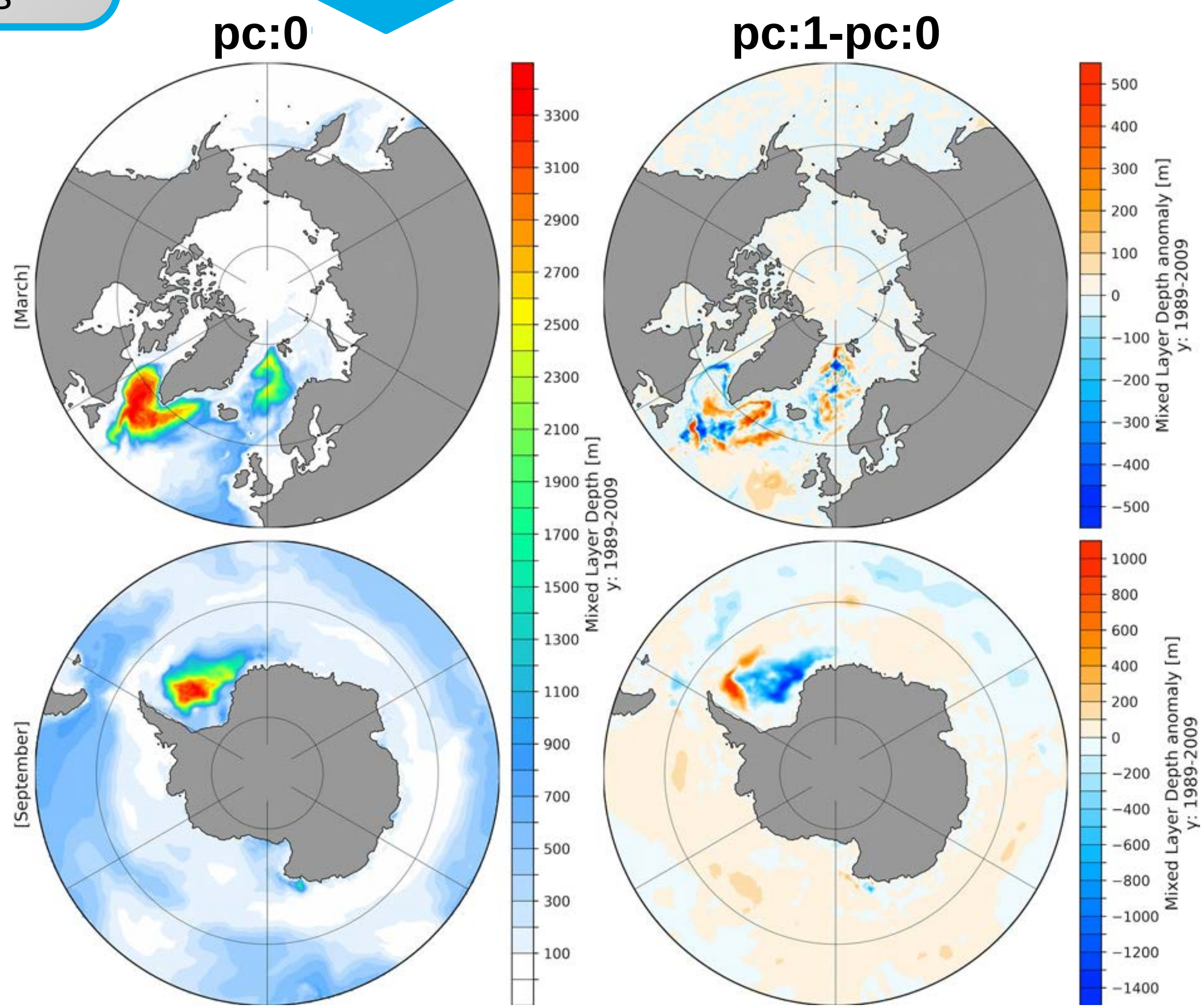
Partial Cells

- Mean temp. anomaly: with minus without partial cells



- Absolute mixed layer depth (MLD) without partial cells and MLD anomaly: with minus without partial cells



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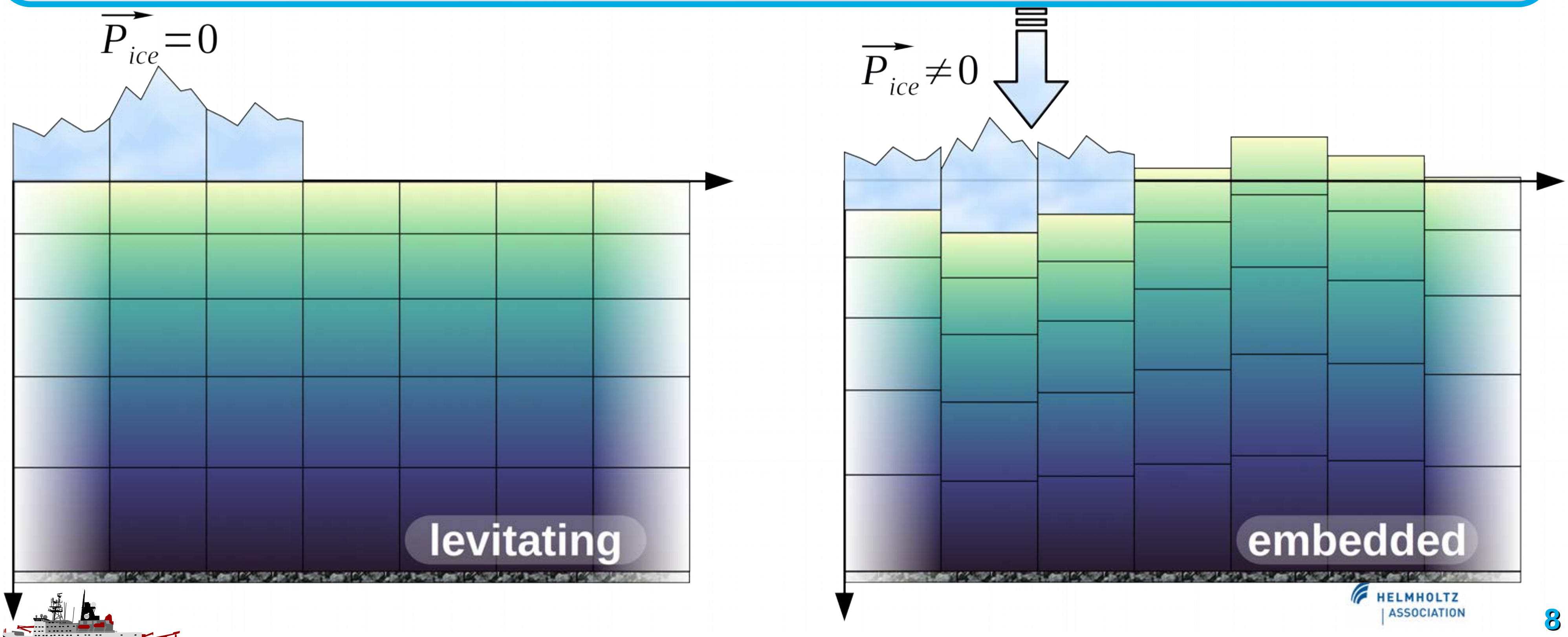
Embedded sea ice

- Add pressure from sea ice loading to hydrostatic pressure (`namelist.config: use_floatice = .true.`)
- freezing and melting have no effect on the oceanic pressure but divergence of the ice transport, modifying the ice-loading fields does contribute to the hydrostatic pressure
- sea ice dynamics in combination with the ice-loading coupling can be a source of oceanic variability especially near the ice edge where ice divergence/convergence is large (Campin et al., 2008)



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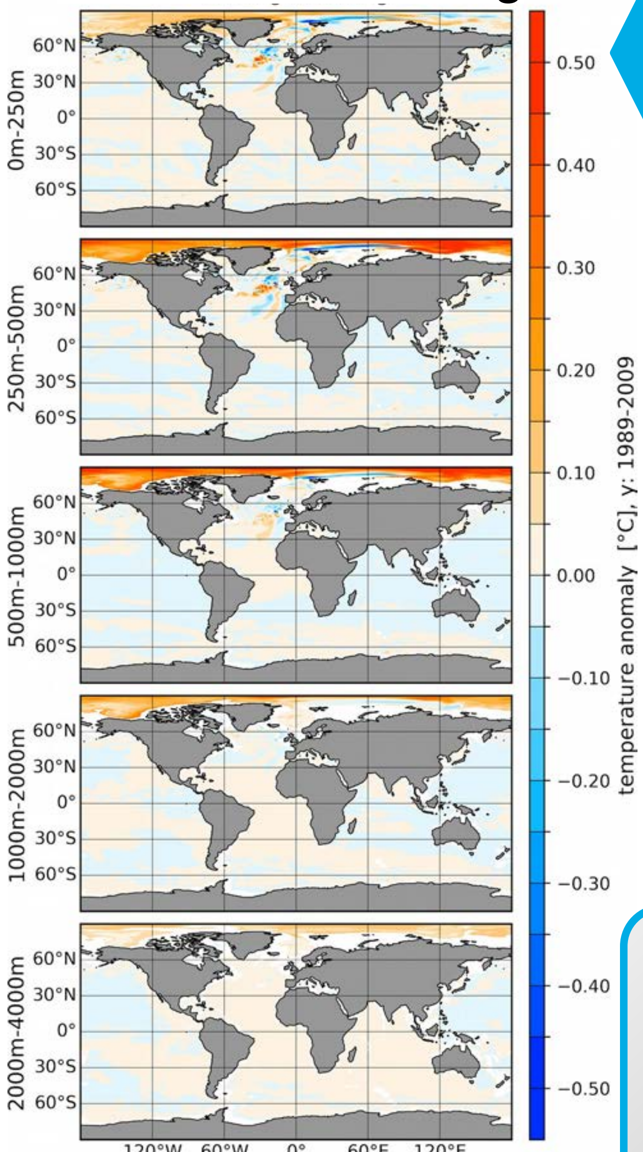
Embedded sea ice

TRR181

AWI

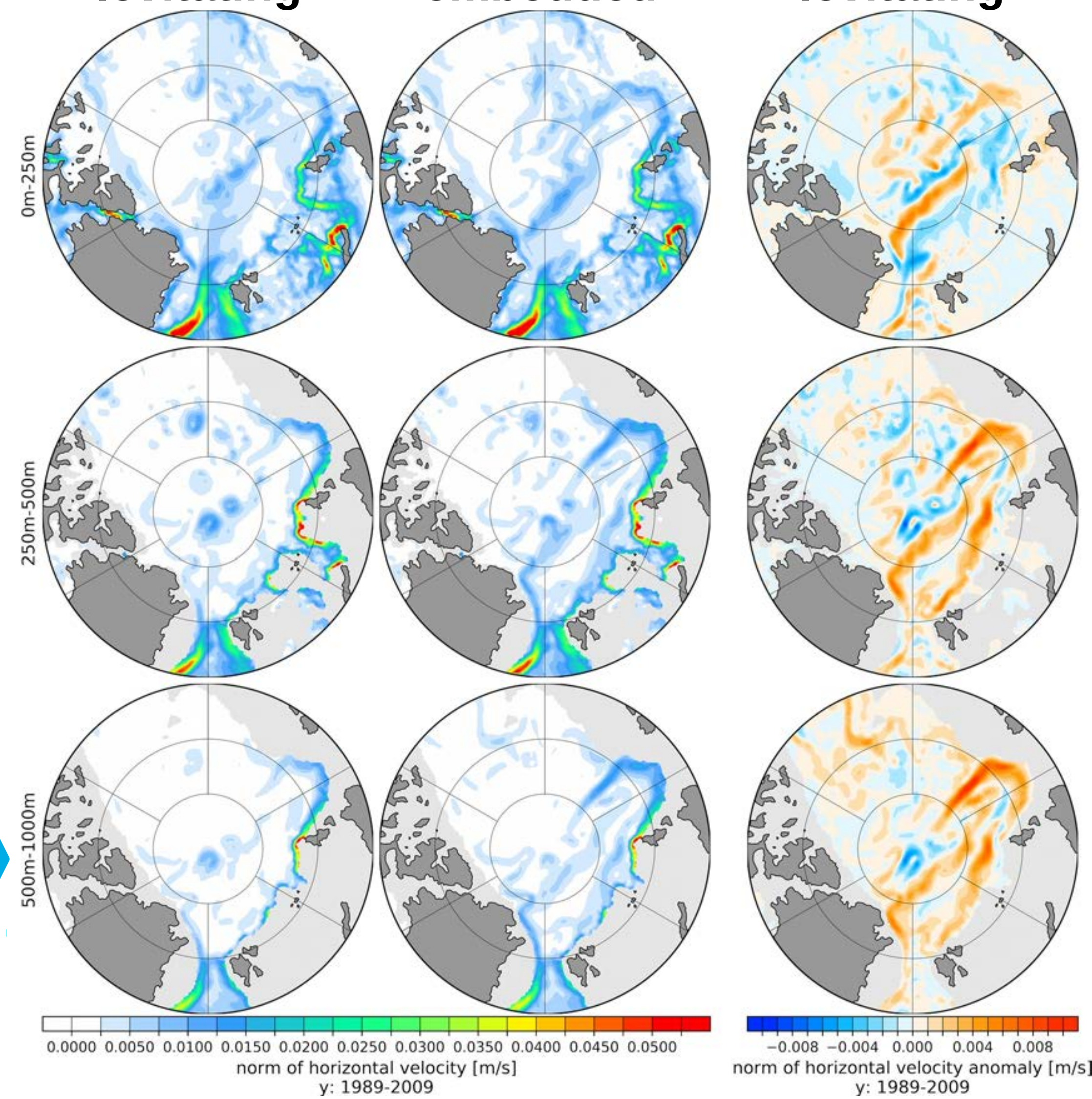
embedded-levitating



- Mean temp. difference between floating and levitating sea ice

- Norm of horiz. ocean velocity for levitating and embedded sea ice

levitating **embedded** **embedded-levitating**



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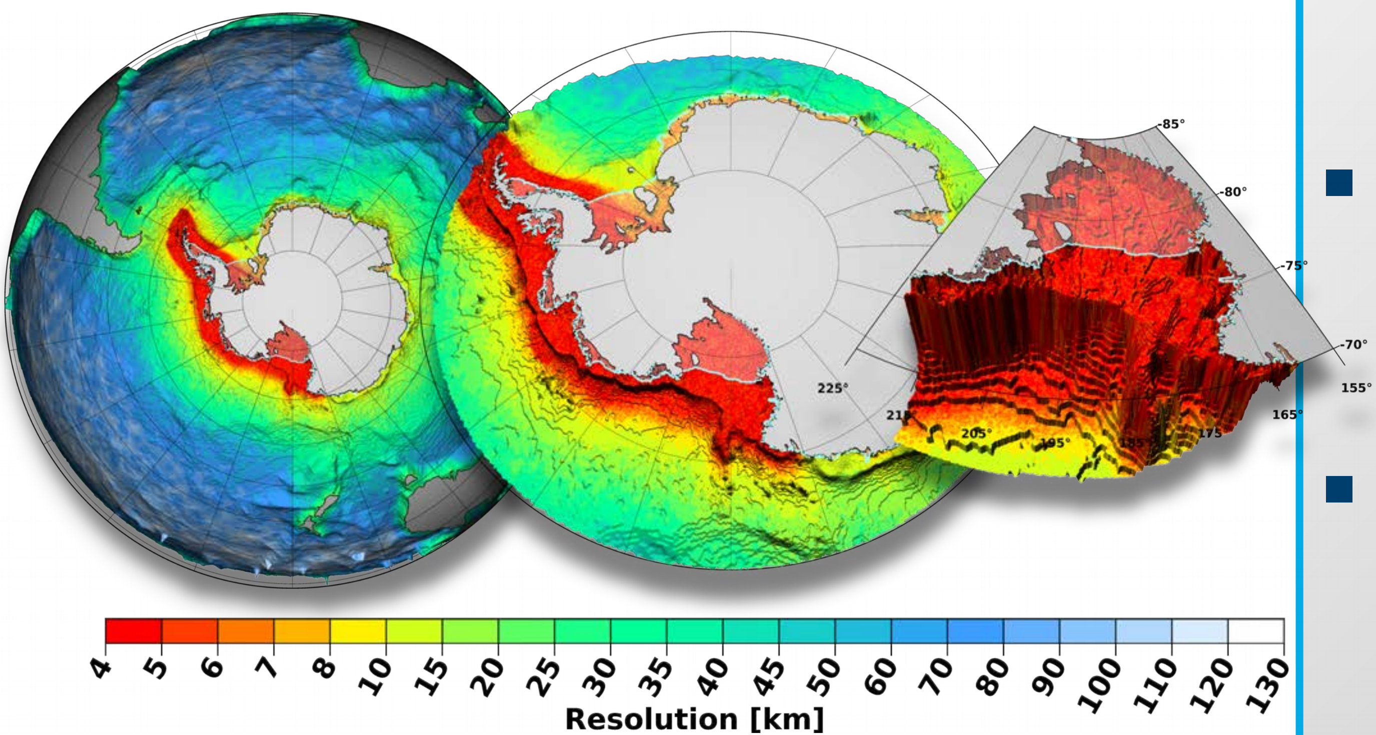
Cavity

- Added ice cavity in FESOM2.0 only for geopotential vertical coordinates (terrain following & vanishing quasi sigma functionality will follow during 2nd phase of TRR181, `namelist.config: use_cavity=.true.`)



- Only need to provide one file cavity_depth.out with cavity geometry during partitioning
- To improve cavity-ocean boundary, surface partial cells possible at ocean-cavity edge (`use_cavity_partial_cell=.true.`)
- Heat flux, fresh-water flux and surface-stress parameterization at ocean-cavity boundary are taken from Ralph Timmermann's FESOM1.4 cavity implementation

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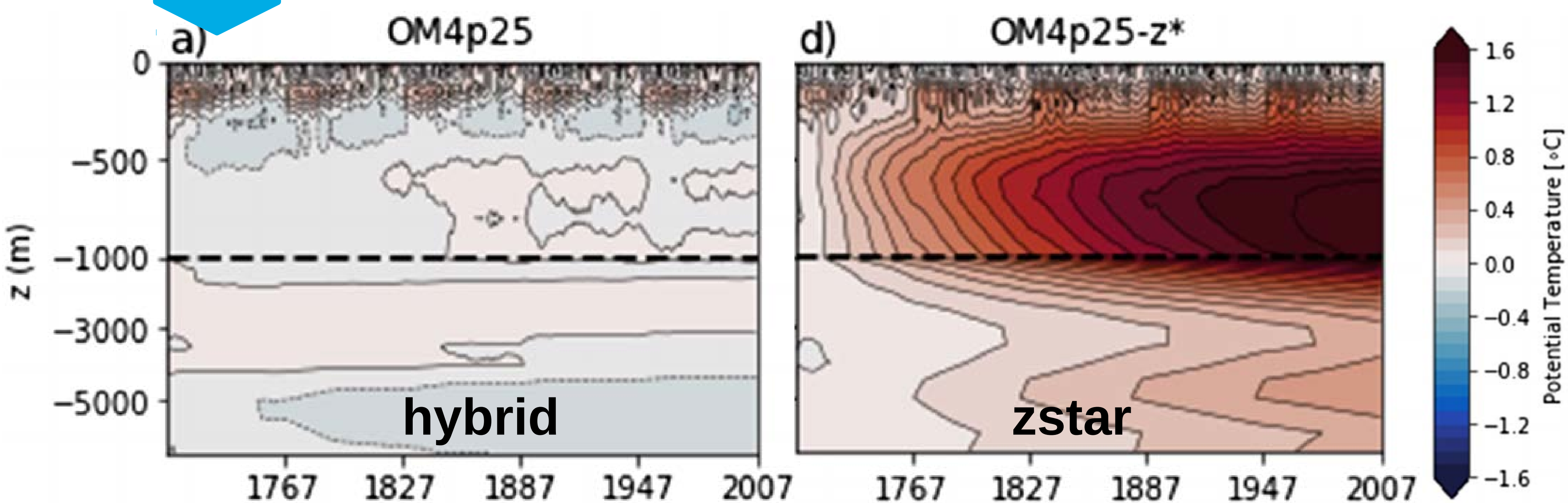
Outlook

Geometric features to come

- Terrain following coordinates, vanishing quasi sigma (VQS) hybrid coordinates
- Long term goal: Relaxation of layer thicknesses towards isopycnal layers and combine with hybrid coordinates

- GFDL OM4 ocean sea ice model (ocean component uses MOM6, ¼ degree resolution) using hybrid (OM4p25) and zstar (OMp25-z*) vertiical coordinates.
- Shown is temperature drift with respect to first year of simulation
- Adcroft et al. 2019, 10.1029/2019MS001726



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Finish

FESOM2.0

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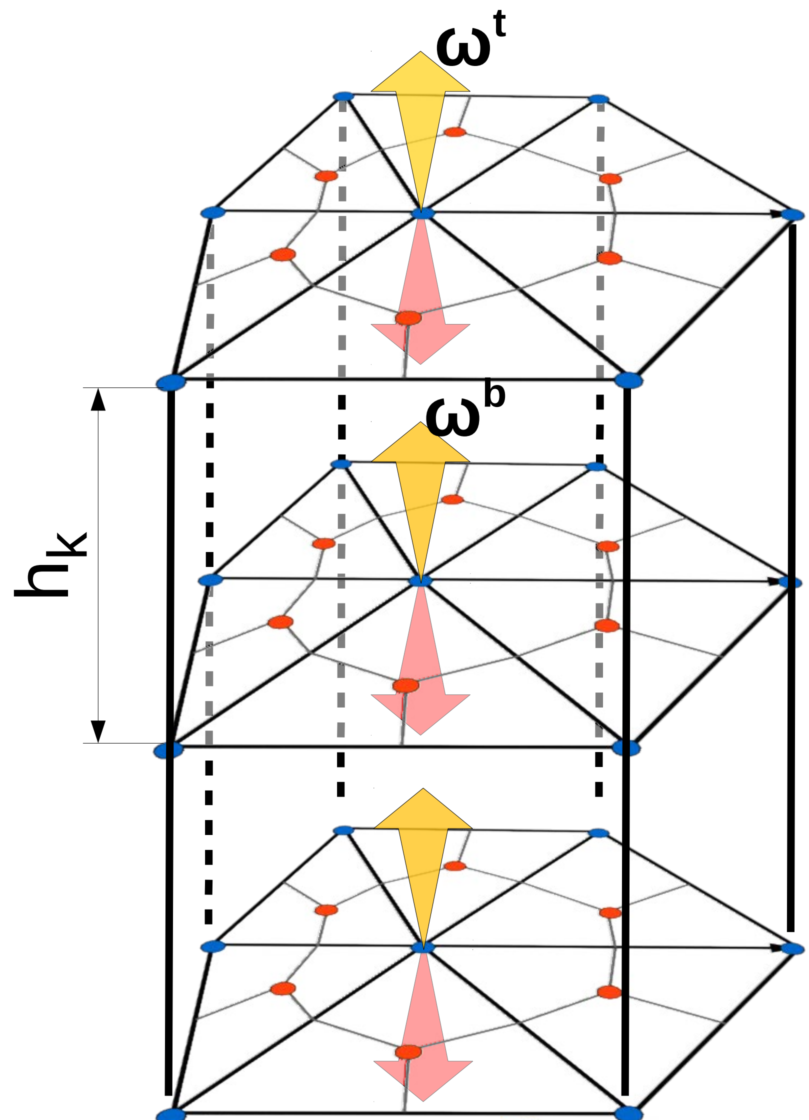
Implementation of ALE vertical coordinates

How we introduce ALE ?

S. Danilov et al. 2017

- Introduce space-time dependent layer thickness $h_k=h_k(x,y,t)$, (k...layer index),
- h_k becomes part of continuity-, tracer-, momentum- and elevation equation by integrating verticaly
- Introduce transport velocities ω^t and ω^b through top and bottom boundary
- The different vertical ALE coordinates are implemented via the continuity equation for the layer thickness



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ALE vertical coordinates

Layer Equations:

S. Danilov et al. 2017

- Equation of motion, continuity- and tracer equation are integrated vertically over the layers → continuity equation becomes the equation on layer thicknesses

$$\partial_t h_k + \nabla \cdot (\boldsymbol{u} h)_k + \left(w^{\mathrm{t}} - w^{\mathrm{b}}\right)_k + W \delta_{k1} = 0, \qquad (3)$$

- the tracer equation becomes

$$\partial_t (hT)_k + \nabla \cdot (\boldsymbol{u} hT)_k + \left(w^{\mathrm{t}} T^{\mathrm{t}} - w^{\mathrm{b}} T^{\mathrm{b}}\right)_k + W T_W \delta_{k1}$$

$$= \nabla_3 \cdot h_k \mathbf{K} \nabla_3 T_k. \qquad (4)$$

- Integrating eq. (3) vertically and assuming $\omega^{t} = 0$ at the free surface → obtain the elevation equation

$$\partial_t \eta + \nabla \cdot \sum_k h_k \boldsymbol{u}_k + W = 0. \qquad (5)$$

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ALE vertical coordinates

S. Danilov et al. 2017

- The layer-integrated momentum equation in the flux form

$$\begin{aligned}\partial_t(h\boldsymbol{u}) &+ \nabla\cdot(h\boldsymbol{u}\,\boldsymbol{u}) + w^{\mathrm{t}}\boldsymbol{u}^{\mathrm{t}} - w^{\mathrm{b}}\boldsymbol{u}^{\mathrm{b}} + f\boldsymbol{k}\times\boldsymbol{u}h \\ &+ h\left(\nabla p + g\rho\nabla Z\right)/\rho_0 \\ &= D_{u\,h}\boldsymbol{u} + (\nu_{\mathrm{v}}\partial_z\boldsymbol{u})^{\mathrm{t}} - (\nu_{\mathrm{v}}\partial_z\boldsymbol{u})^{\mathrm{b}}, \qquad (6)\end{aligned}$$

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ALE vertical coordinates

How to implement different vertical ALE coordinates ?

- The different vertical ALE coordinates for the ...
  - linear free surface (all layers are fixed) and …
  - full free surface (layer can move vertically)

mode are implemented via the continuity equation for the layer thickness and the resulting calculation of the vertical velocity

$$\partial_t h_k + \nabla \cdot (\boldsymbol{u}h)_k + \left(w^{\mathrm{t}} - w^{\mathrm{b}}\right)_k + W\delta_{k1} = 0$$

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ALE vertical coordinates

Asynchronous time stepping

- FESOM 1.4 uses asynchronous time stepping → horizontal velocities and scalars shifted by a half time step.
- adapt to FESOM2.0 → elevation (+velocities) defined at full-time levels, layer thicknesses (+tracers) defined at half-time levels

$$h^{n+1/2} - h^{n-1/2} = -\tau \left[\nabla \cdot \left(\boldsymbol{u}^n h^* \right) + w^{\mathrm{t}} - w^{\mathrm{b}} + W^{n-1/2} \delta_{k1} \right] \tag{9}$$

$$h^{n+1/2} T^{n+1/2} - h^{n-1/2} T^{n-1/2} = -\tau \left[\nabla \cdot \left(\boldsymbol{u}^n h^* T^n \right) + w^{\mathrm{t}} T^{\mathrm{t}} - w^{\mathrm{b}} T^{\mathrm{b}} + W^{n-1/2} T_W \delta_{k1} \right] + D_T \tag{10}$$

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ALE vertical coordinates

- The elevation at full time steps and the total thickness on half-steps, given by the vertical sum of h_k , may become decoupled due to numerical errors.
- suppress decoupling, by maintaining consistency between the physical layer thickness (h, used with tracers) and dynamical thickness (dependent on the elevation η).

$$\bar{h} = \sum_k h_k - H, \tag{11}$$

- H … is the unperturbed ocean thickness.

$\bar{h}$ ... elevation from derived from thickness → would be identical to the elevation η in the continuous world, but not in the discrete formulation here

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ALE vertical coordinates

- write for the elevation

$$\eta^{n+1} - \eta^{n} = -\tau \left(\alpha \left(\nabla \cdot \int^{\overline{h}^{n+1/2}} \boldsymbol{u}^{n+1} \mathrm{d}z + W^{n+1/2} \right) + (1-\alpha) \left(\nabla \cdot \int^{\overline{h}^{n-1/2}} \boldsymbol{u}^{n} \mathrm{d}z + W^{n-1/2} \right) \right). \qquad (12)$$

- Eq. for thicknesses can be vertically integrated (with condition that the surface value of $\omega^t = 0$ vanishes

$$\overline{h}^{n+1/2} - \overline{h}^{n-1/2} = -\tau \nabla \cdot \int^{\overline{h}^{n-1/2}} \boldsymbol{u}^{n} \mathrm{d}z - \tau W^{n-1/2}. \qquad (13)$$

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ALE vertical coordinates

- Expressing the rhs in the formula for η through the difference in surface displacements h --> η and ħ can be made consistent if

$$\eta^n = \alpha \overline{h}^{n+1/2} + (1-\alpha)\overline{h}^{n-1/2}. \tag{14}$$

- To avoid diverging of η and ħ:
    - Compute η^n from eq. 14
    - Estimate η^{n+1} from dynamical equation (stiffnes matrix needs to be updated every time step) use only to compute u^{n+1}
    - on new time step a “copy” of η_{n+1} will be created from the respective fields ħ of eq. 14

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Solution strategy ALE vertical coordinates

- Compute η^n from $\bar{h}$ by…

$$\eta^n = \alpha \overline{h}^{n+1/2} + (1-\alpha)\overline{h}^{n-1/2} \qquad \overline{h} = \sum_k h_k - H$$

- Actualize stiffness matrix to calculate elevation η
- Compute RHS of elevation equation and solve for elevation
  → $d\eta = \eta^{n+1} - \eta^n$
- Update horizontal velocity:

$$\boldsymbol{u}^{n+1} - \boldsymbol{u}^* = -g\tau\theta\nabla\left(\eta^{n+1} - \eta^n\right)$$

- Compute $\bar{h}^{n+3/2}$ with actualized horizontal velocities from...

$$\overline{h}^{n+1/2} - \overline{h}^{n-1/2} = -\tau\nabla\cdot\int^{\overline{h}^{n-1/2}} \boldsymbol{u}^n \mathrm{d}z - \tau W^{n-1/2}$$

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Solution strategy ALE vertical coordinates

- Calculate layer thicknesses and ω from continuity equation with different options for: linfs, zlevel and zstar ...

$$\partial_t h_k + \nabla \cdot (\boldsymbol{u}h)_k + \left(w^{\mathrm{t}} - w^{\mathrm{b}}\right)_k + W\delta_{k1} = 0$$

- Calculate tracer advection and diffusion.