Experience with BLOM and the ALE method in earth system modelling

Mats Bentsen[1] and Mehmet Ilicak[2,1]

[1]NORCE Research AS, Bjerknes Centre for Climate Research, Bergen, Norway.
[2]Eurasia Institute of Earth Sciences, Istanbul Technical University.

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Outline

- Bergen Layered Ocean Model (BLOM) vertical coordinate
- Adaptive reference density for hybrid coordinate
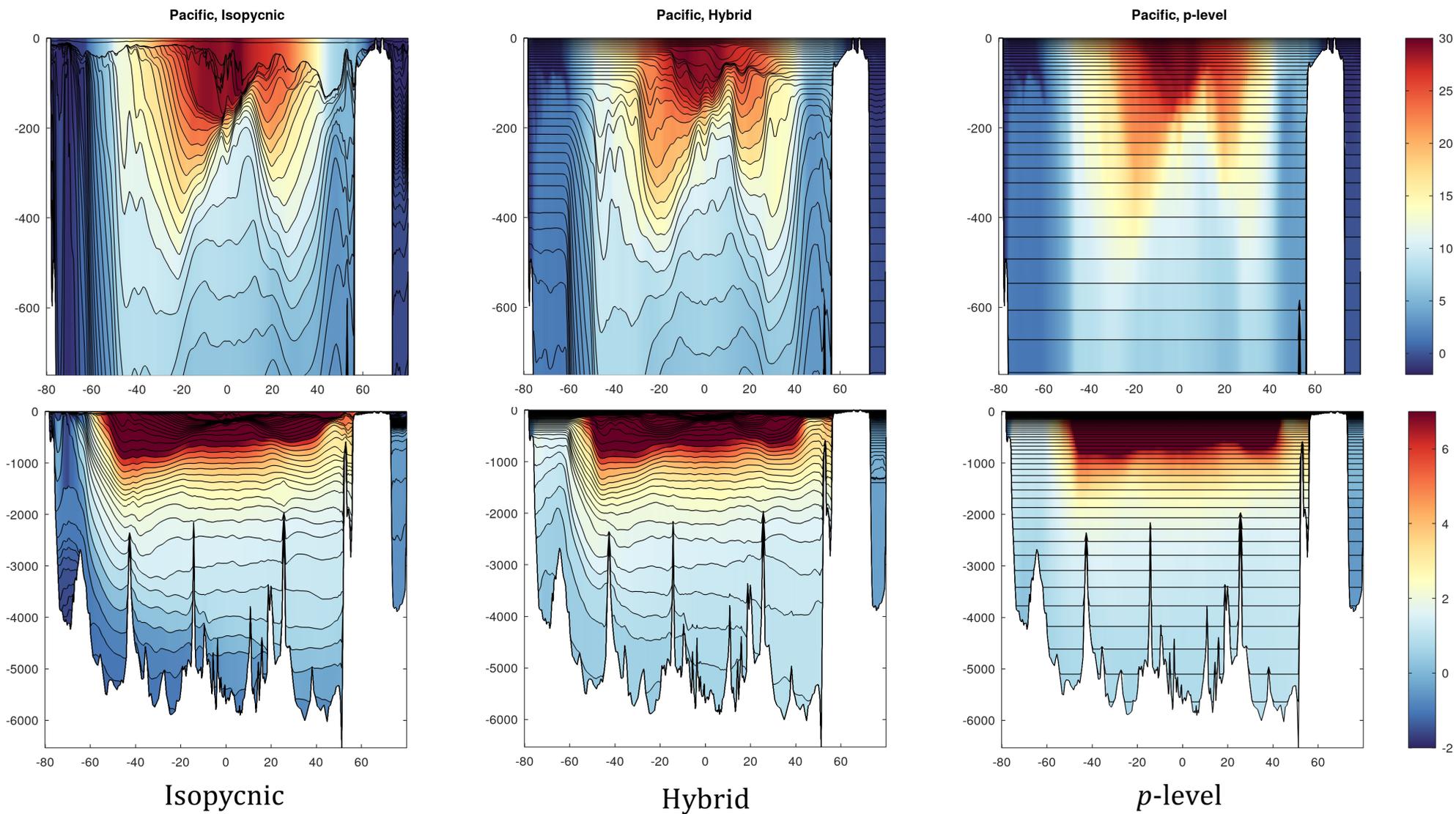- Mitigating slowly developing undesirable layer structure

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BLOM vertical coordinate

- The **arbitrary Lagrangian-Eulerian** (ALE) method has recently been implemented in BLOM in addition to the previously used bulk mixed layer and isopycnic formulation.

- The ALE method first integrates the layer conservation equations forward in a truly Lagrangian phase, then remap variables to a desired vertical grid in a second phase.

- A suitable regridding approach and accurate remapping is crucial for the application of the ALE method for ocean climate modelling.

Cell-mean data on old grid   High-order reconstruction   Regridding   Cell-mean data after remapping
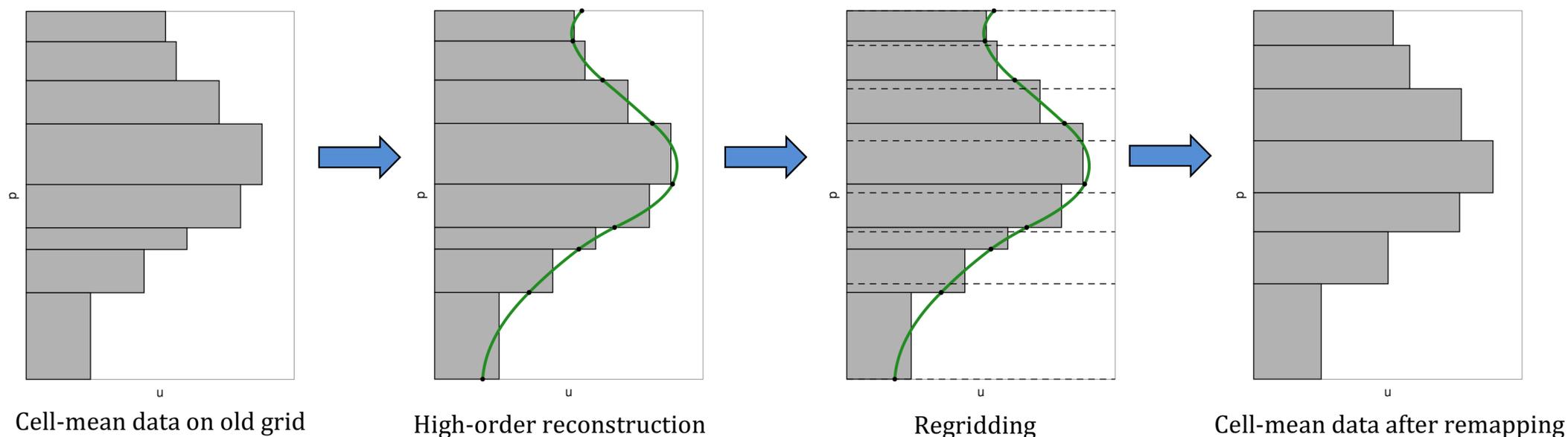
BLOM vertical coordinate

- Using the ALE method, BLOM currently supports regridding to the vertical coordinates: **p-level** and **hybrid**.

- Hybrid vertical coordinate:

  - Hybrid between **continuous isopycnals** (prescribed σ_2 at layer interfaces) and p-levels (prescribed pressure at layer interfaces).

  - In general, the maximum of regridded continuous isopycnals and p-levels is chosen to achieve desired vertical resolution in the PBL.

  - A **transition zone** between continuous isopycnals and p-levels are beneficial for a smoother change in vertical resolution.

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Pacific, Isopycnic   Pacific, Hybrid   Pacific, p-level

Isopycnic   Hybrid   *p*-level

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Reference density adaptation

Primary motivation: Ensure a coherent upper ocean layer structure for a wide range of forcing scenarios.

**Secondary motivation**: Ensure optimal use of the vertical resolution.

Layer index in a Pacific section at year 500 of NorESM2 CMIP6 piControl (upper panels) and $4xCO_2$ (lower panels) simulations.

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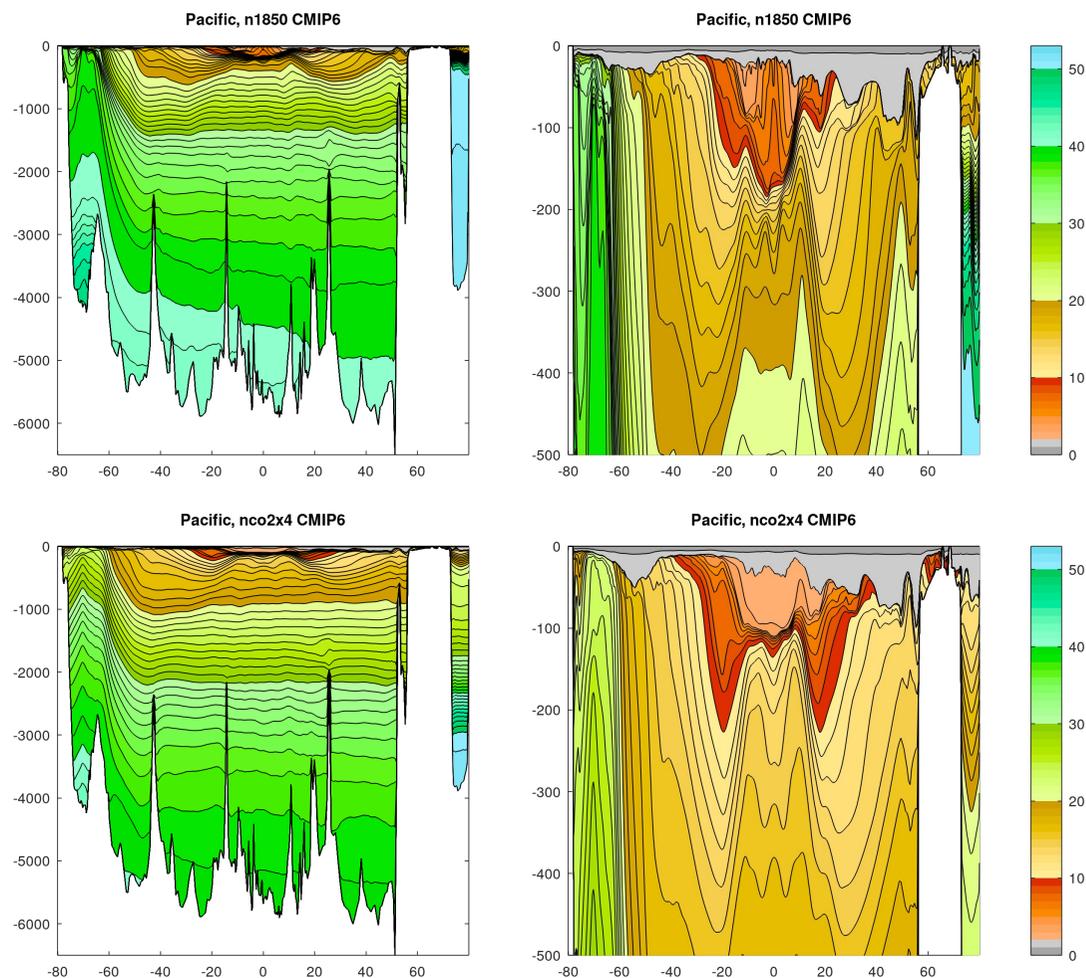
Reference density adaptation

Approach:

- Reference potential densities described by a functional form (cubic Bezier curve + 2 parabolas) for $z \in [0, 1]$.

- Prescribed z-range of parabolas.

- Prescribed σ-slope of line containing Bezier points p_2, p_3 and p_4 and prescribed z-value of p_3.

- Adjust σ-value of p_4 and σ_{bot} to keep the mass fraction associated with the densest parabolic distribution to a prescribed fraction.

- Adjust σ-value of p_1 and z-value of p_2 to optimally occupy the mixed layer with constant pressure levels.

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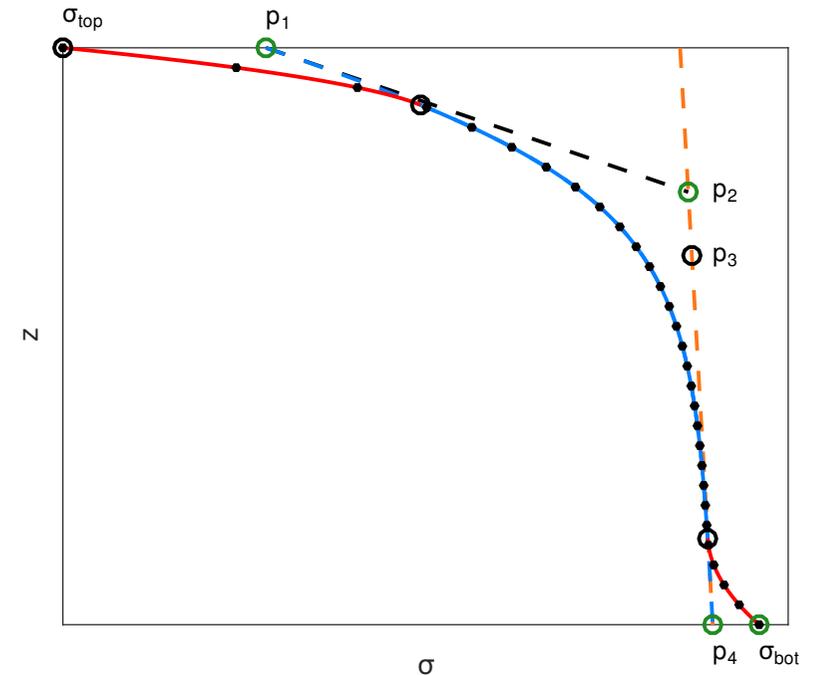
Reference density adaptation

Some details on the optimization:

- Uses monthly model climatology of various parameters from the preceding year.

- The target mass fraction within the densest parabolic distribution is currently 1%.

- Parameters p_1 and p_2 are adjusted to minimize the cost function

$$C = \sum_t \sum_i \sum_j A \ln^2 \left(\frac{p^*_{\text{ML}}}{p_{\text{ML}}} \right)$$

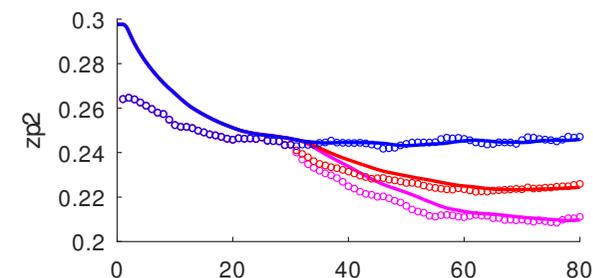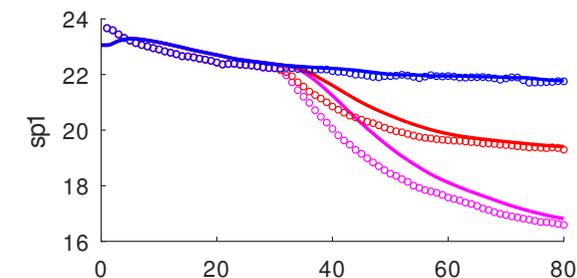- Annual optimization and slow final adjustment of function parameters ($\sim$ 10 years e-folding time-scale).
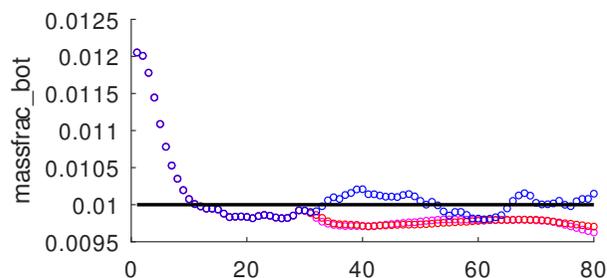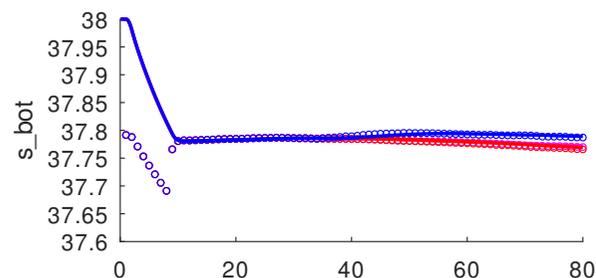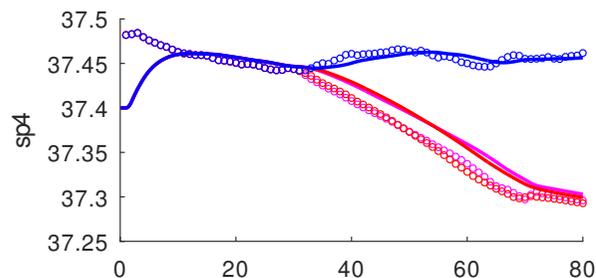
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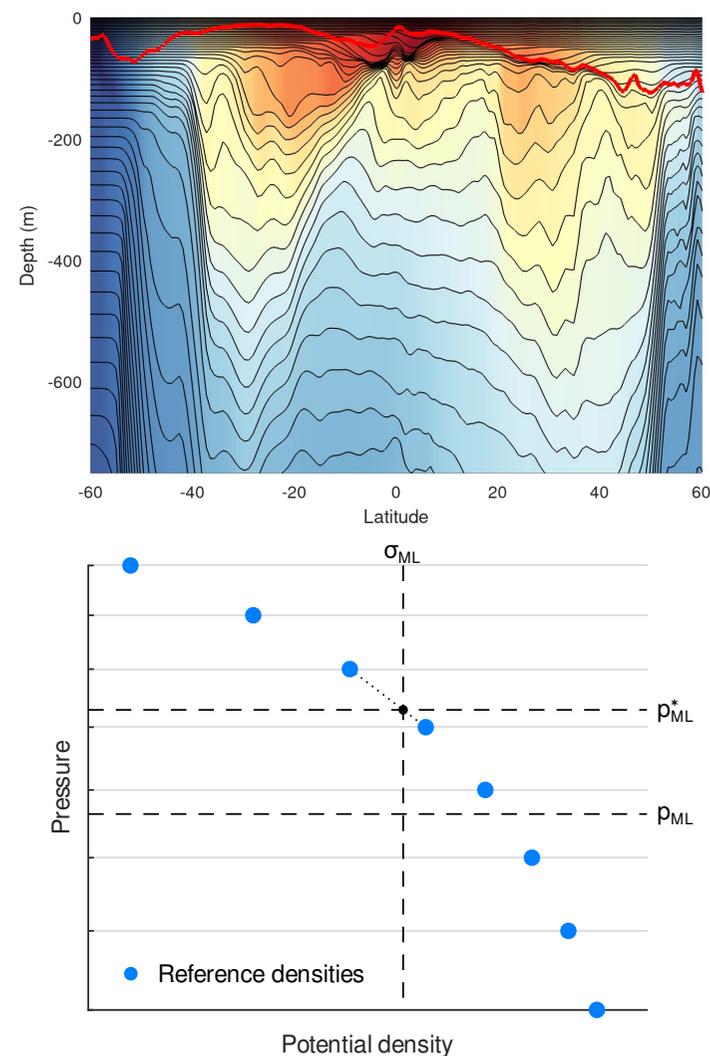
Reference density adaptation

- Test density adaptation in **piControl**, **4xCO₂** and **8xCO₂** simulations.

- 72 vertical layers in BLOM.

- piControl: 80 years.

- 4xCO₂ and 8xCO₂: 50 years, branched at year 30 from piControl
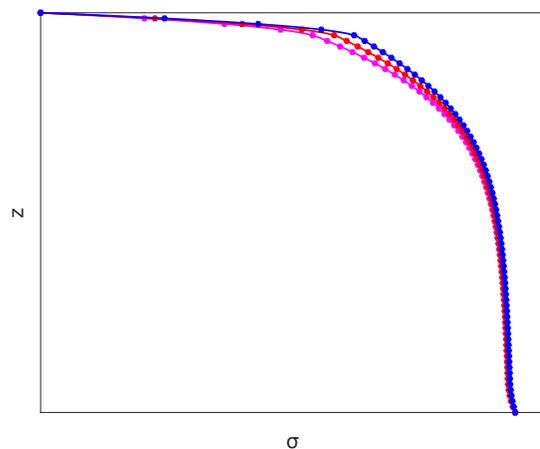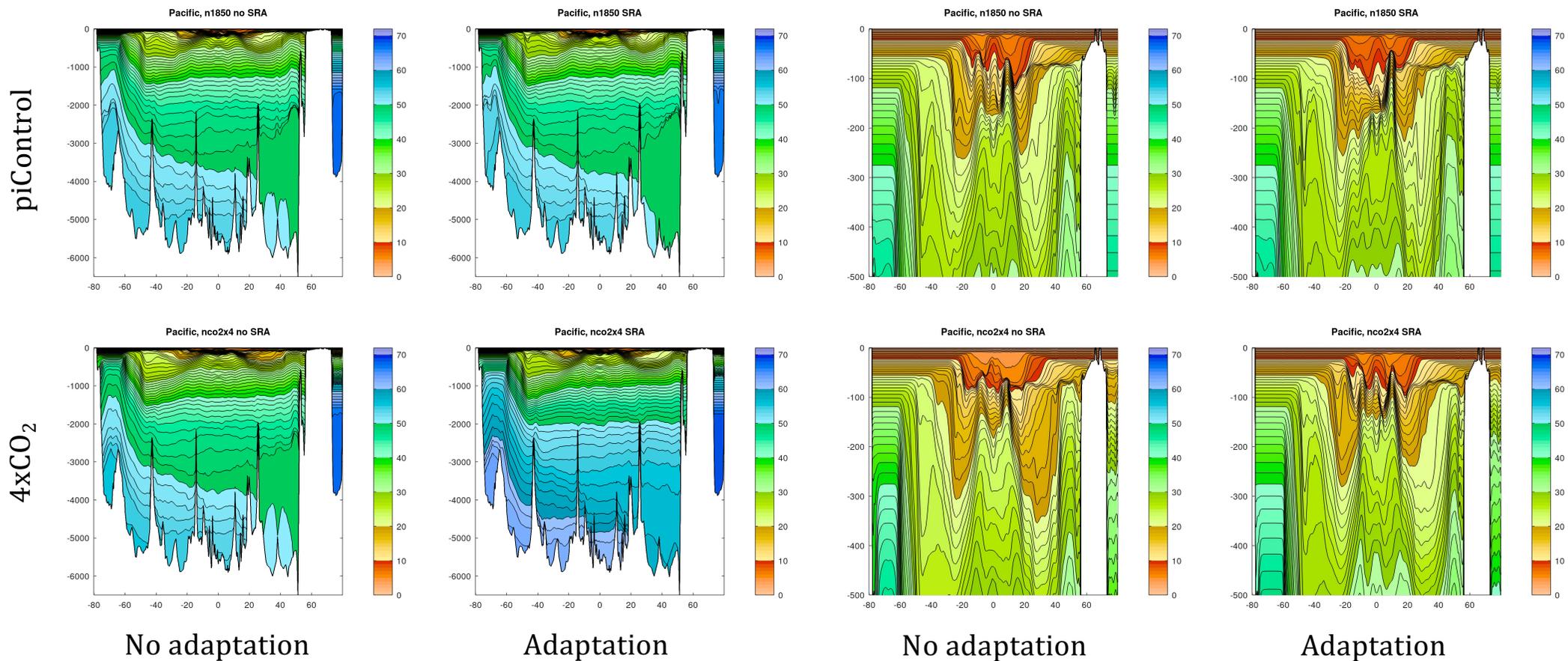

Reference densities at end of simulations

Upper 4 figures: Reference density function parameters. Circles are parameters after annual optimization, lines are actual applied parameters after time-filtering.

Lower figure: Circles are annual mass fraction of densest water masses. Black line is the target mass fraction.

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Reference density adaptation

Layer index in a Pacific section at end of piControl and $4xCO_2$ simulations.

piControl

$4xCO_2$

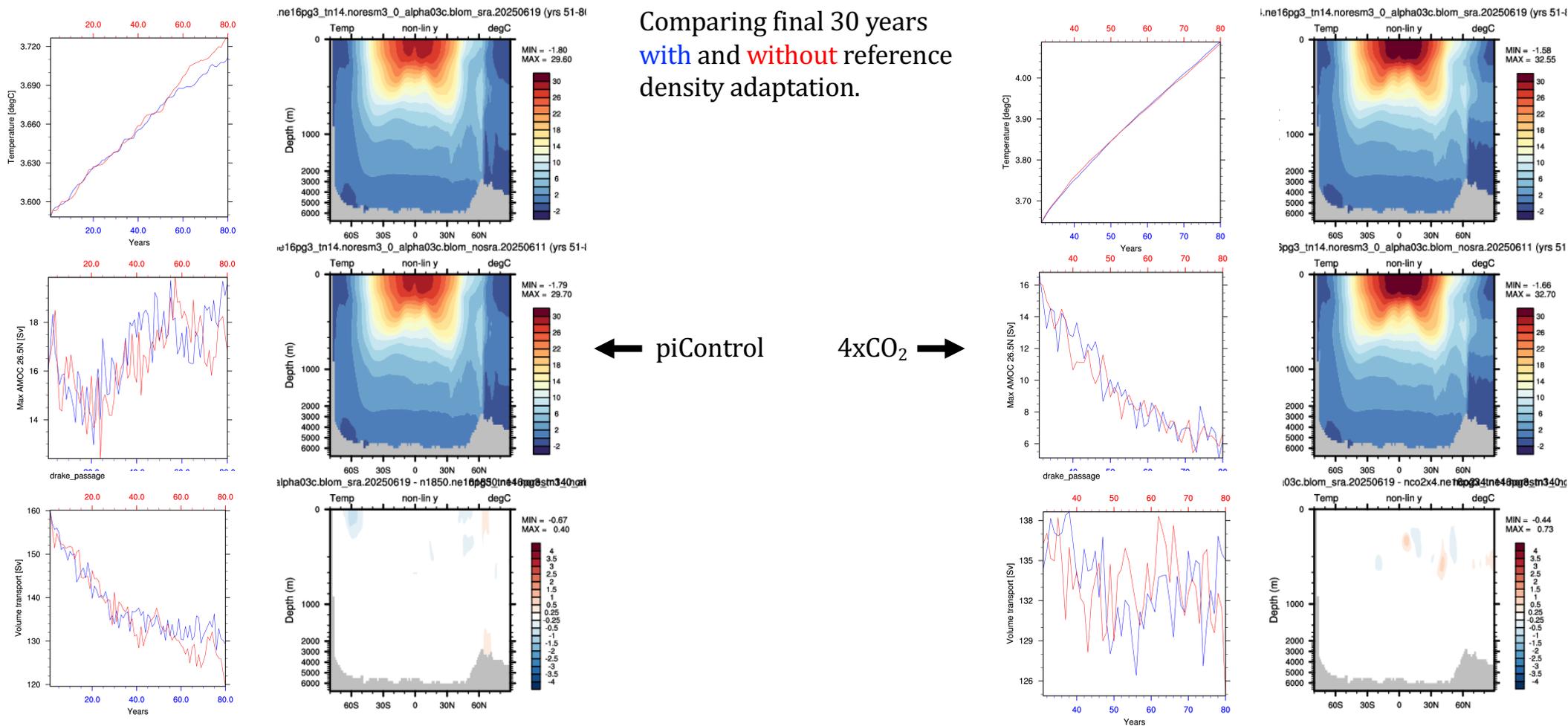No adaptation

Adaptation

No adaptation

Adaptation

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Reference density adaptation

Layer index in a Pacific section at end of piControl and $8xCO_2$ simulations.

Reference density adaptation

Comparing final 30 years
with and without reference
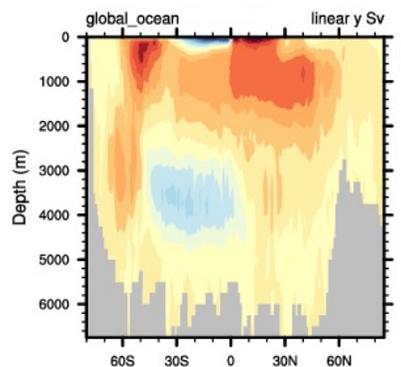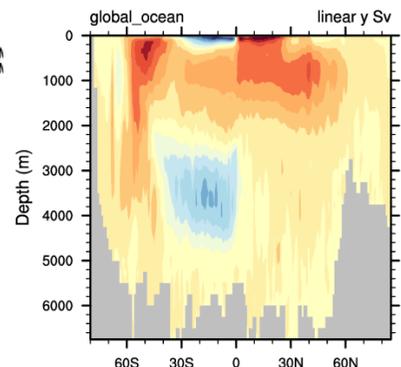density adaptation.

← piControl   4xCO$_2$ →

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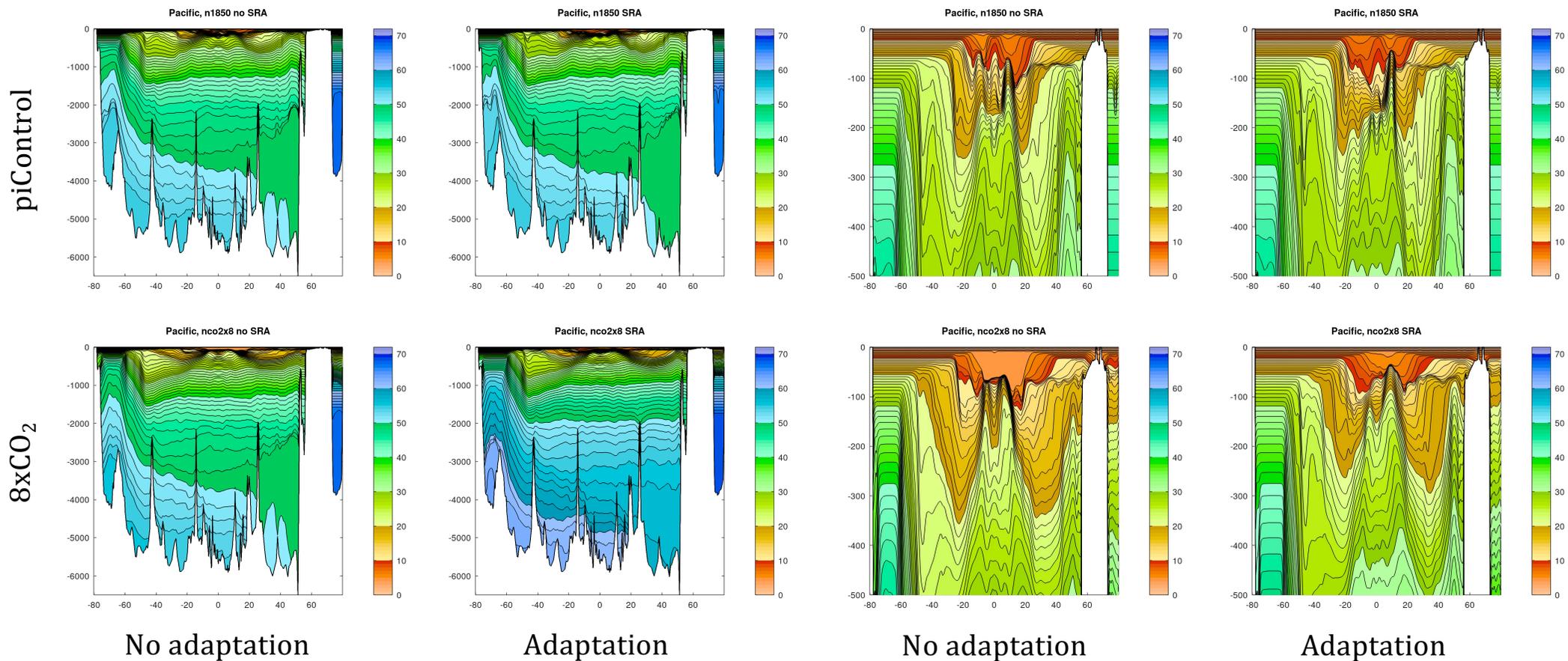
Mitigating undesirable layer structure

During NorESM3 development,
unsatisfactory layer structure slowly formed
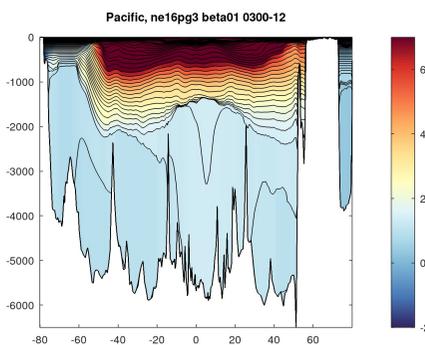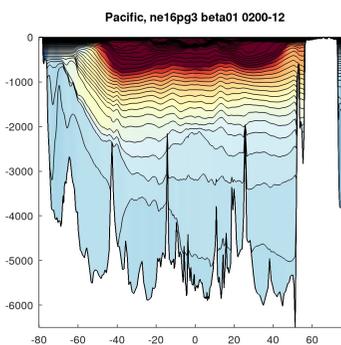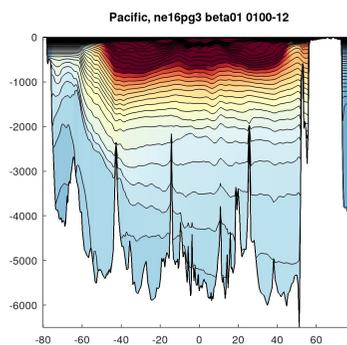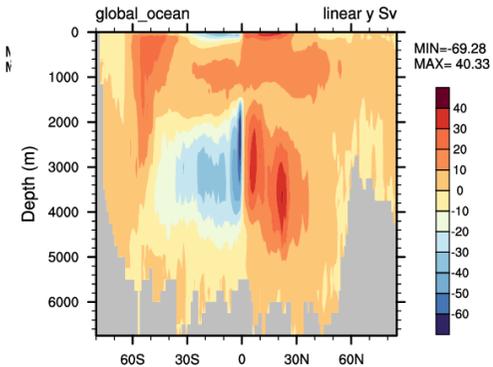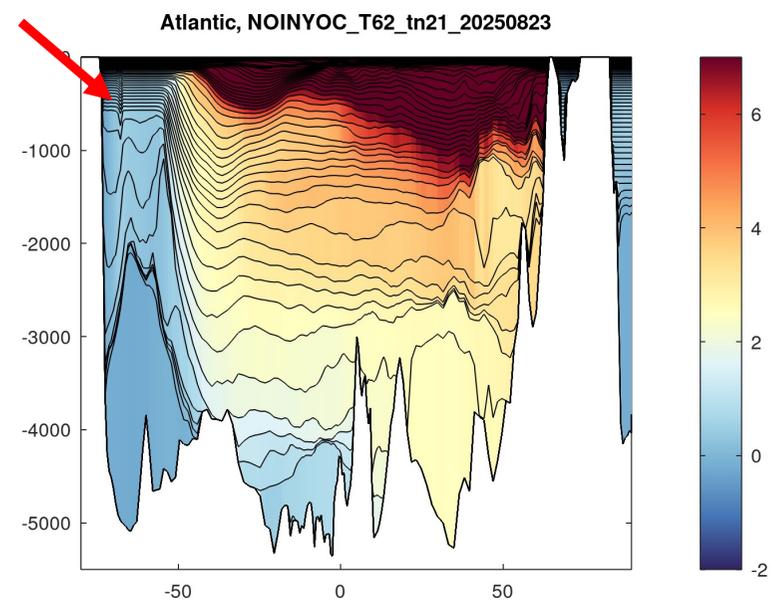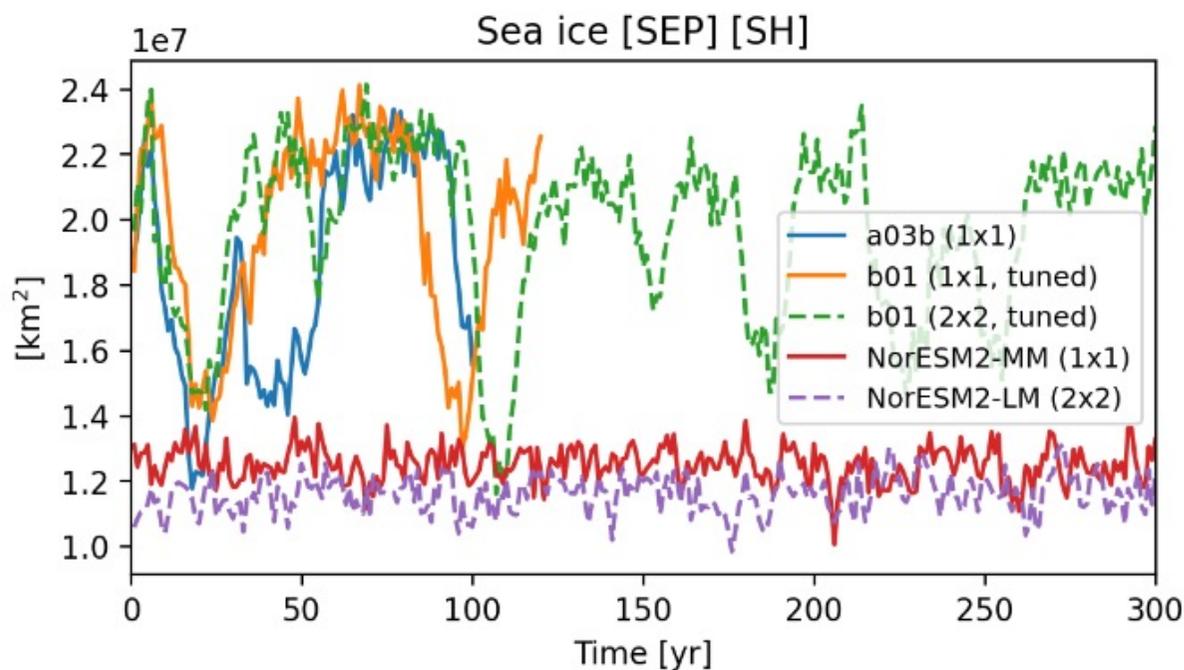in multicentury piControl simulations.

Years 81-100   Years 171-200   Years 271-300

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Mitigating undesirable layer structure

- Strong variability in Southern Ocean sea-ice extent.

- Detailed and high-frequency inspection of layer structure also revealed spikes in layer structure due to deep MLDs causing FFH08 restratification to behave erratic.

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Mitigating undesirable layer structure

Our solution:

- Constraining local vertical thickness variation by enforcing

$$\Delta p_{k,\min} = \frac{\gamma}{3}\left(\Delta p_{k-1} + \Delta p_k + \Delta p_{k+1}\right)$$

- Enforcing $MLD^* = \min(MLD, \beta \cdot BLD)$, where MLD^* is used in the restratification parameterization (FFH08 or Bodner et al., 2023).

Atlantic potential temperature section after 200 years of JRA55 forced simulations.

$\gamma = 0.6, \ \beta = 3.0$ $\gamma = 0.7, \ \beta = 3.0$ $\gamma = 0.8, \ \beta = 3.0$

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