Physics-constrained neural-network parameterization of mesoscale eddies in a global ocean model

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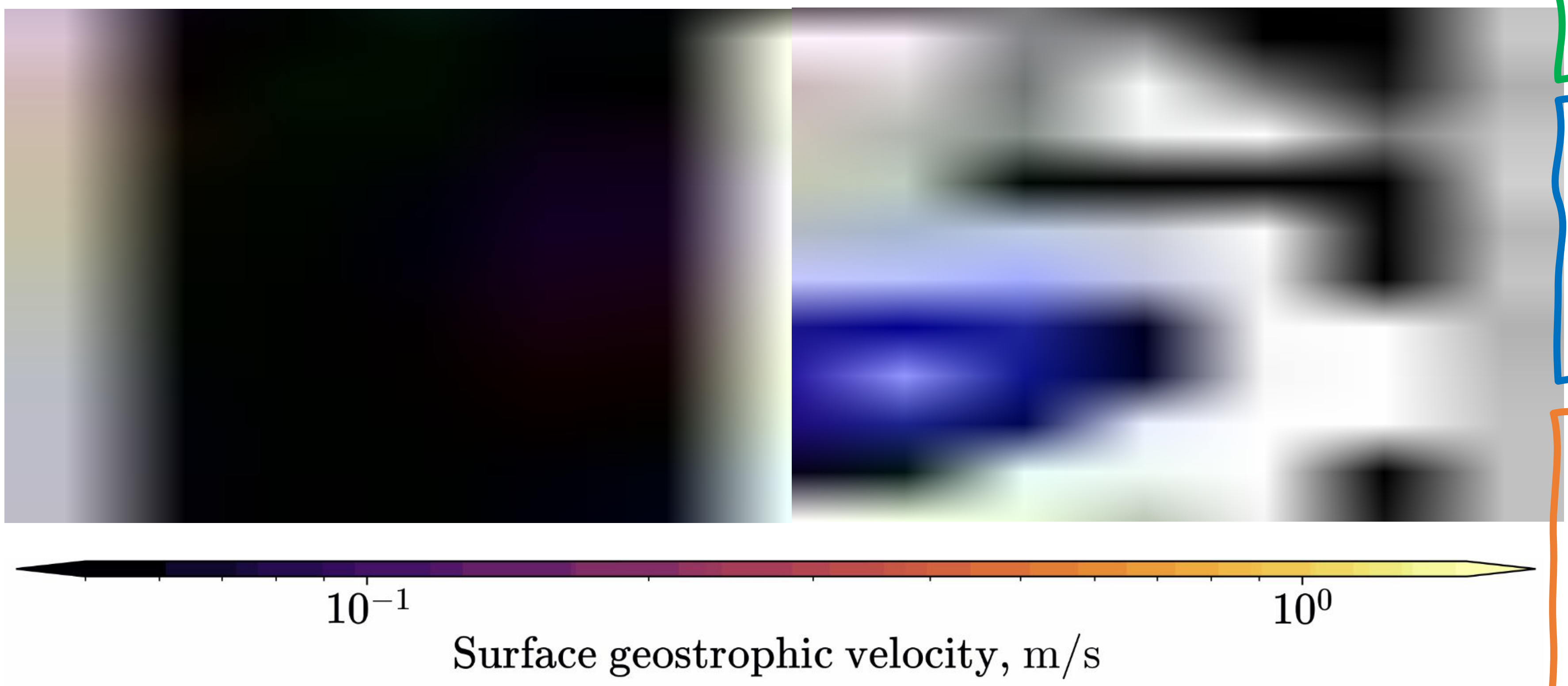
https://m2lines.github.io/

Plan of talk

- Representing mesoscale eddies in ocean models
- Learning parameterization from data
- Impact on the energetics and circulation of ocean

Mesoscale eddies in ocean models

Global ocean model OM4 (1/4° GFDL MOM6) | Observations (Copernicus)



Eddies:

- ❖ Size $\frac{NH}{f} \approx 10 - 100\text{km}$
- ❖ Responsible for horizontal mixing

Eddy-permitting (1/4°) models:

- ❖ Missing major part of eddy KE (EKE)
- ❖ Missing mixing can result in model biases

How to parameterize:

- ❖ Resolved eddies can be energized with **momentum fluxes** (backscatter, Jansen& Held 2014)
- ❖ Improving resolved mixing will fix other issues (release of APE, Yankovsky et al. 2024)

Parameterizing momentum fluxes

- Eddy fluxes $\mathbf{T}$ are diagnosed from high resolution climate model (CM2.6 with $1/10^{\circ}$ ocean)
- Fluxes are predicted with Neural Network using velocity gradients as input features

$\overline{(\cdot)}$ is Gaussian filter

$$\partial_t \overline{\mathbf{u}} = (\overline{\mathbf{u}} \cdot \nabla)\overline{\mathbf{u}} - \overline{(\mathbf{u} \cdot \nabla)\mathbf{u}} \approx \nabla \cdot \mathbf{T}$$

$$\mathbf{T} = \begin{pmatrix} \overline{u}\,\overline{u} - \overline{uu} & \overline{u}\,\overline{v} - \overline{uv} \\ \overline{u}\,\overline{v} - \overline{uv} & \overline{v}\,\overline{v} - \overline{vv} \end{pmatrix}$$

Physical constraints

Constraints by data augmentation:
- ❖ Rotation/reflection invariance

Hard physical constraints:
- ❖ Conservation of momentum and angular momentum
- ❖ Galilean invariance
- ❖ **Unit invariance**

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Unit invariance and generalization

- We use the length scale (Δ, grid spacing) to restore the unit invariance (Prakash et al. 2022)

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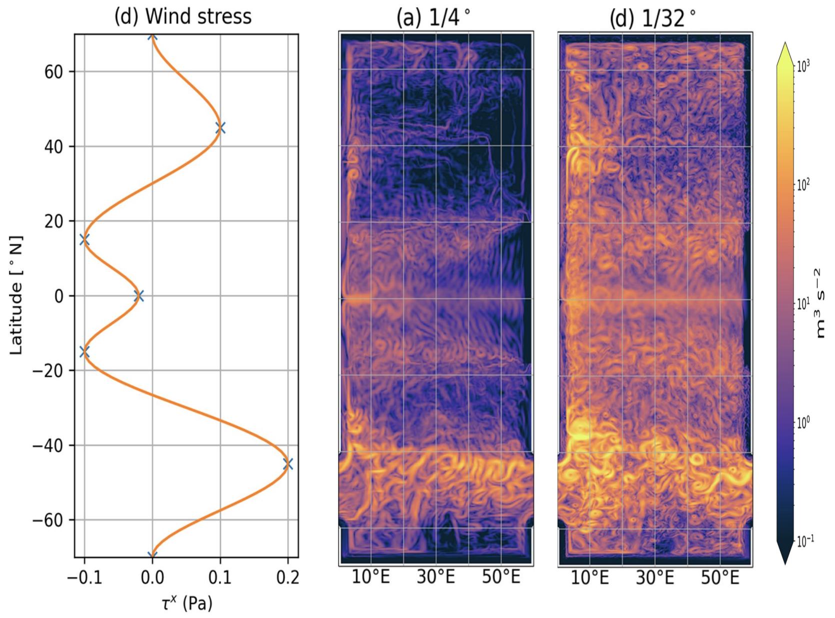
Unit invariance and generalization

- ❖ We use the length scale (Δ, grid spacing) to restore the unit invariance (Prakash et al. 2022)
- ❖ Unit invariance allows to **generalize to different grid spacings and depths** not seen during training

Evaluation in MOM6 ocean model

NeverWorld2 (Marques et al. 2022)

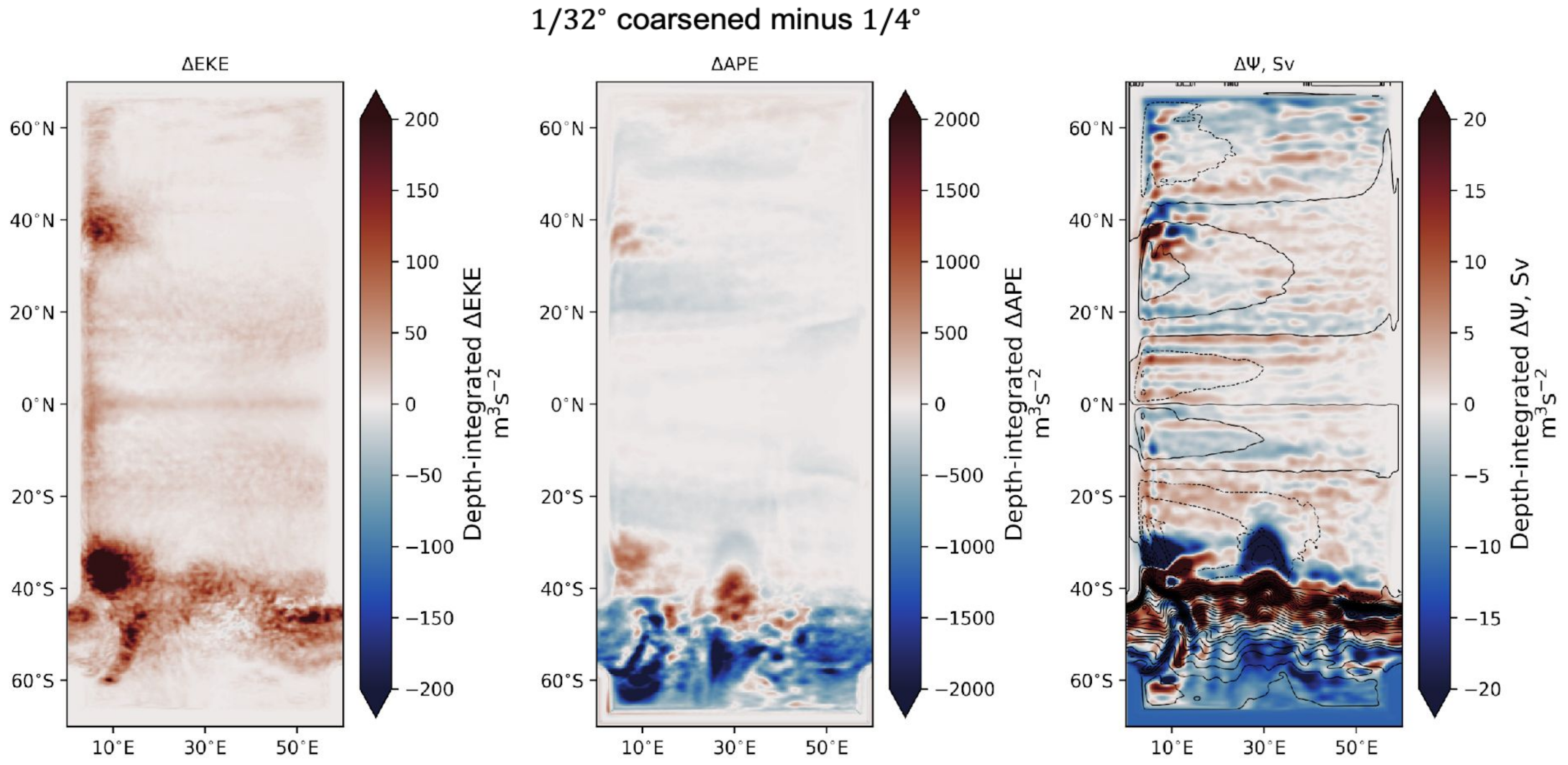


Global ocean model (OM4, Adcroft 2019)

- ❖ Resolution ¼°
- ❖ Coupled ocean and ice model
- ❖ 60-years forced simulations (CORE-II-AIF, 1948-2007)
- ❖ Initialized from spun-up state

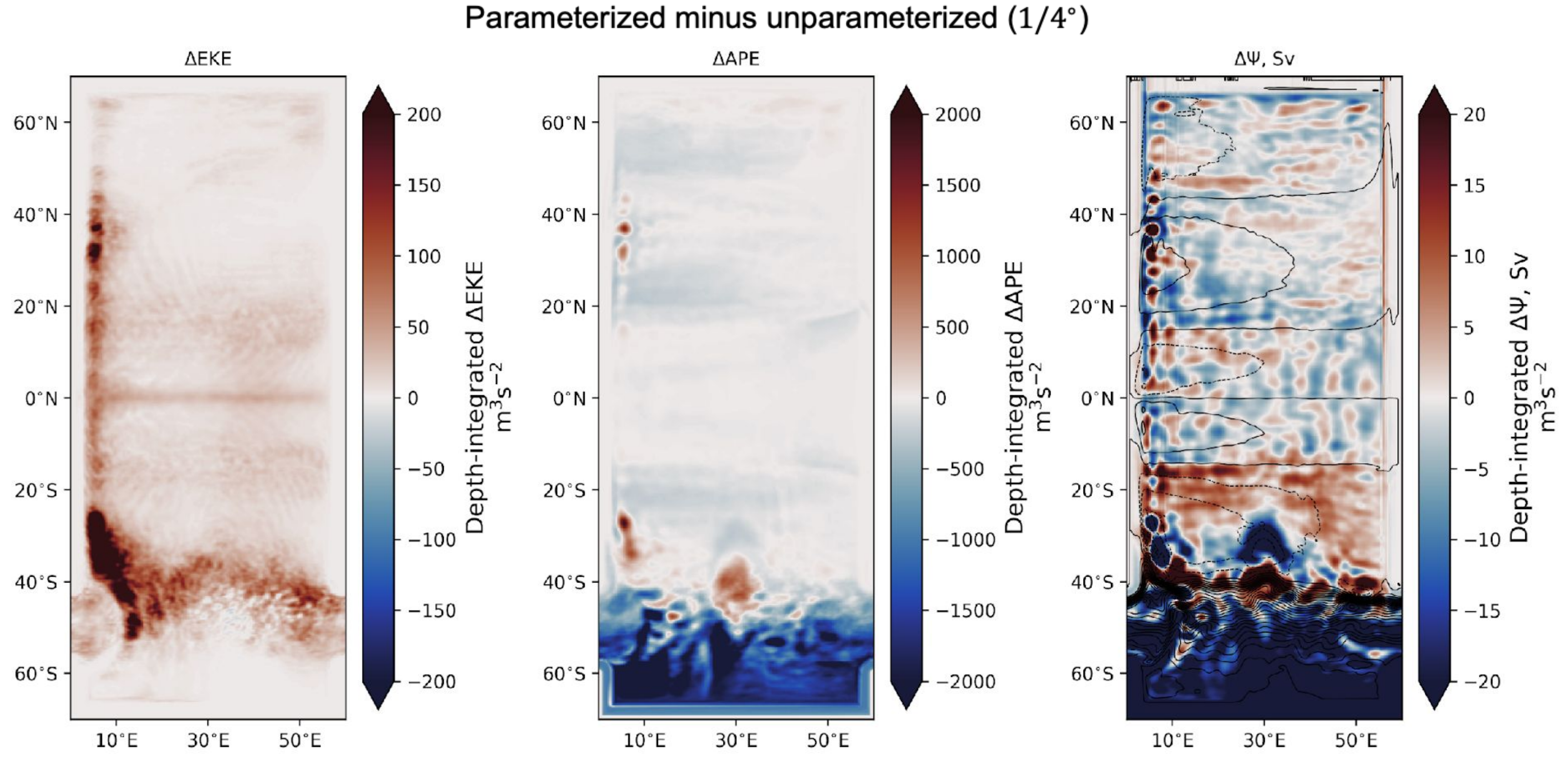
- ❖ Neural Network (NN) is used with biharmonic Smagorinsky model
- ❖ In idealized Double Gyre and global ocean model, NN works without tuning
- ❖ In idealized NeverWorld2 tuning for stability was required

NeverWorld2: Impact of the increasing resolution



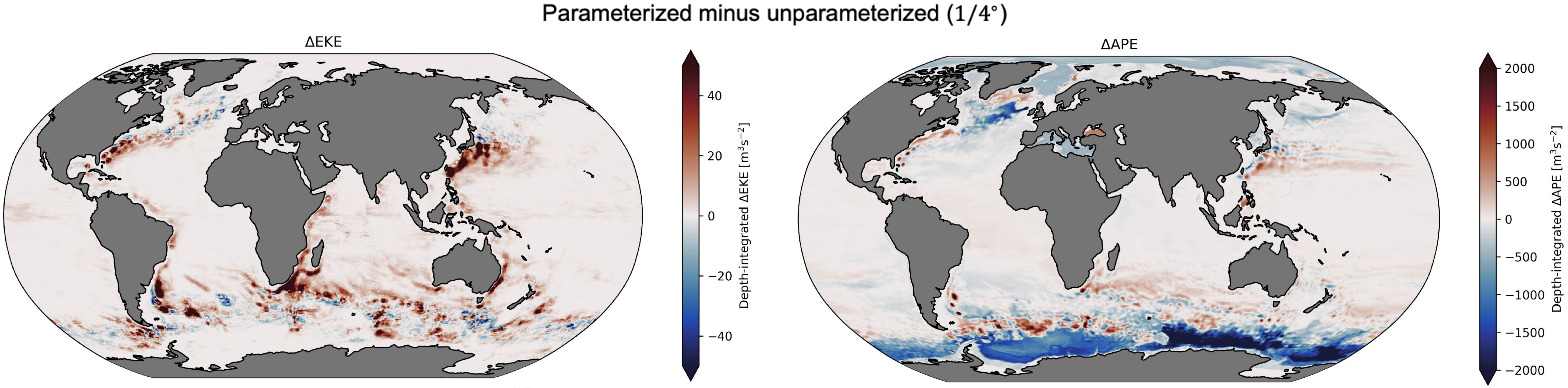
- ❖ Eddy KE (EKE) is increased near Western Boundaries and ACC
- ❖ Resolved eddies release APE from ACC current and Gyres
- ❖ ACC transport weakens and correlates with APE release

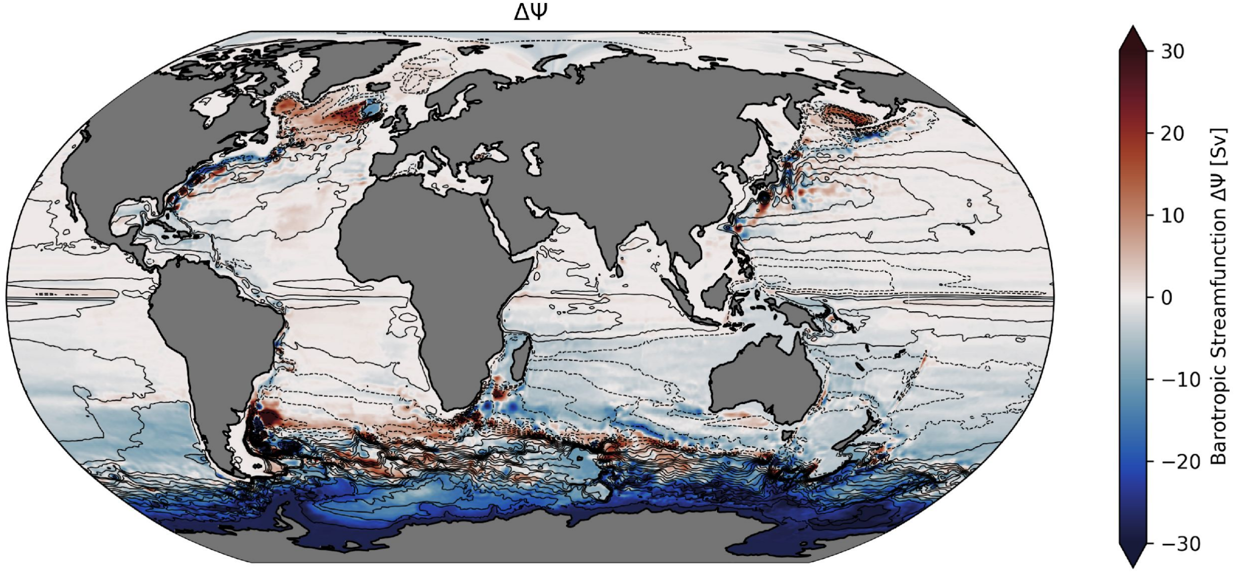
NeverWorld2: Impact of the parameterization



Effect of NN parameterization is qualitatively similar to increasing resolution

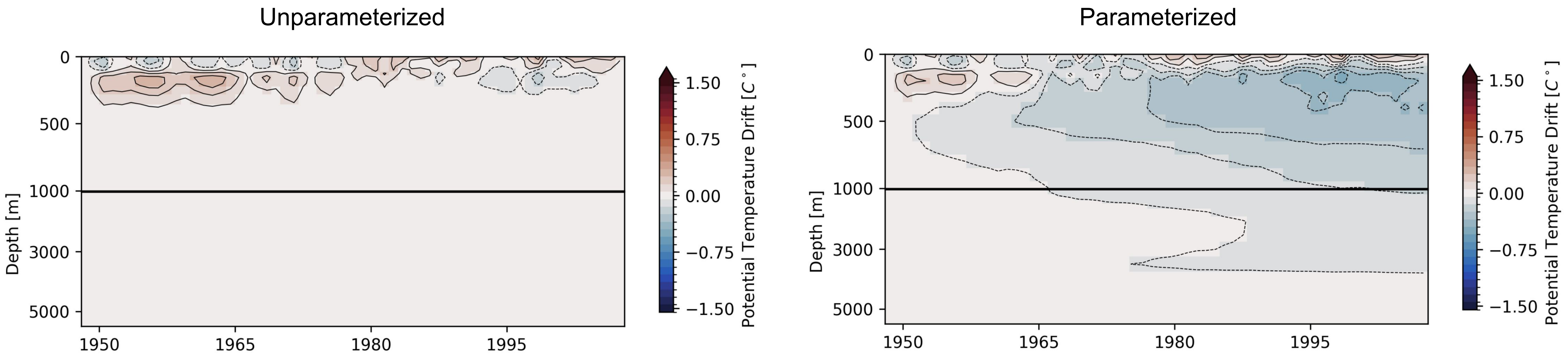
Global ocean OM4: Impact of the parameterization





- ❖ Eddy KE (EKE) is increased near Western Boundaries and ACC
- ❖ Resolved eddies release APE from ACC current and Gyres
- ❖ **ACC transport weakens** and correlates with APE release

Temperature drift

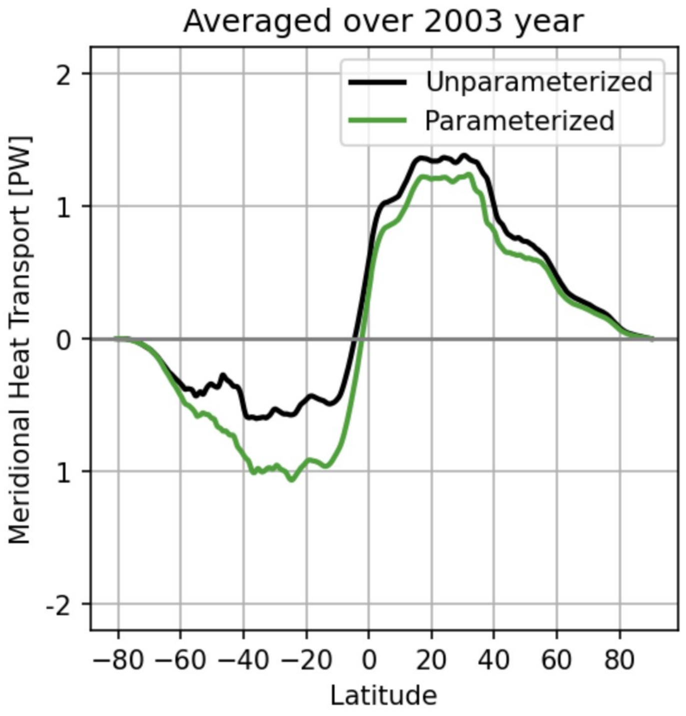


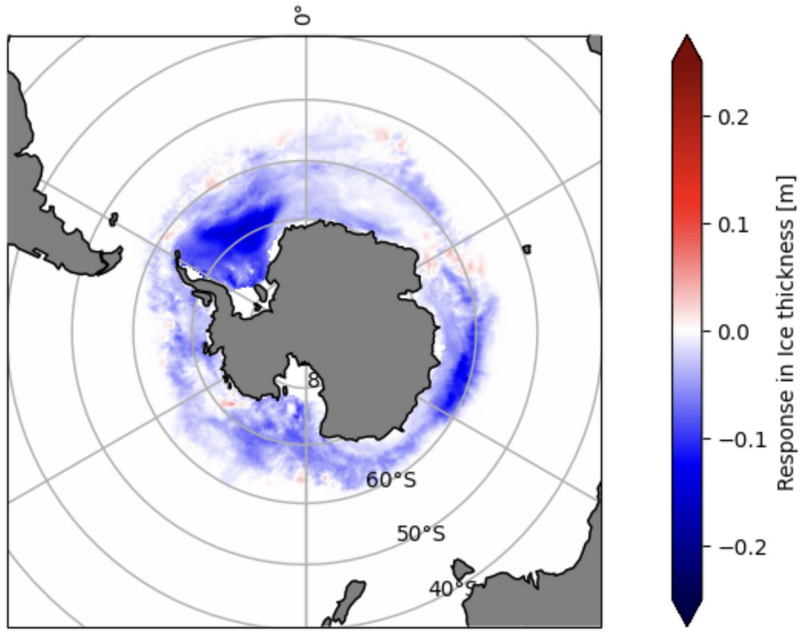
- ❖ Release of APE is accompanied by restratification (redistribution of heat upward)

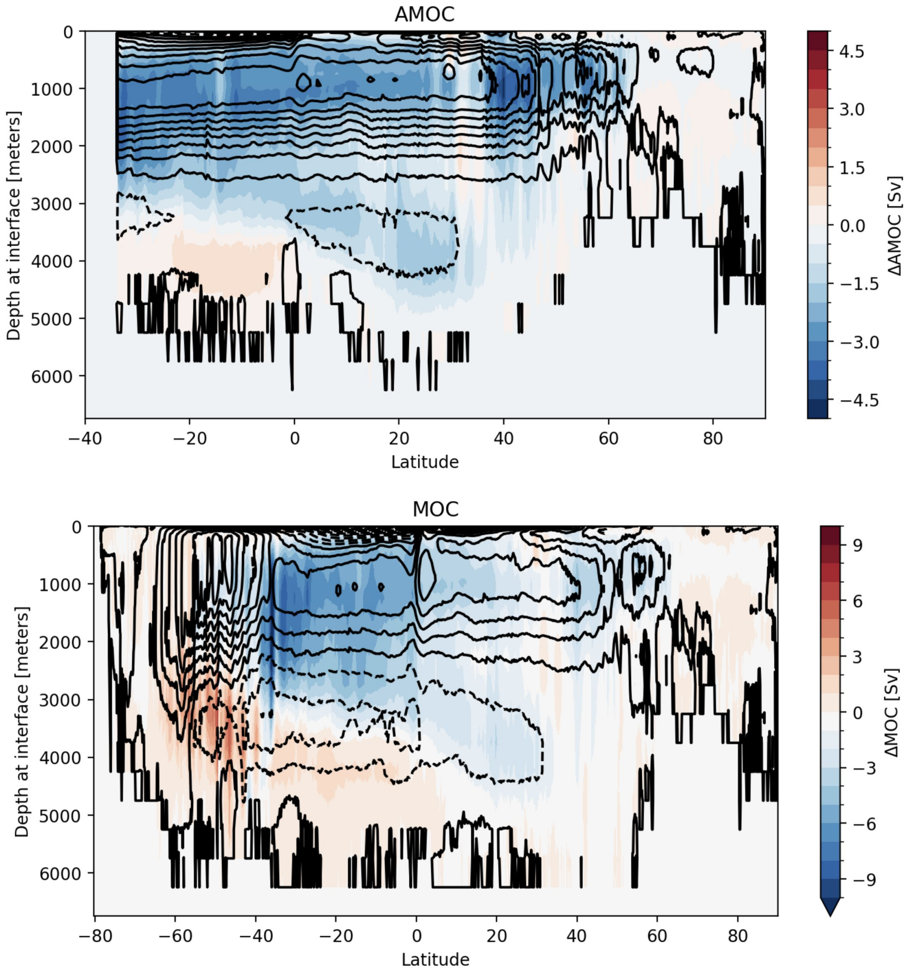
Cool drift is expected for:

- ❖ Increasing horizontal resolution (Adcroft et al. 2019)
- ❖ Gent-McWilliams parameterization (Adcroft et al. 2019)
- ❖ Isopycnal diffusion (Marques OMWG 2024)

Poleward transport







- ❖ Increased southward heat transport can (probably) be related to release of APE
- ❖ Thus, Antarctic ice melting (similarly to backscatter by Juricke et al. 2020)
- ❖ Weaker AMOC is consistent with reduction of northward heat flux

Conclusions

- We propose a single data-driven parameterization of mesoscale eddies for a range of resolutions and depths:
  - We show the importance of unit invariance for generalization
- The impact of parameterization is similar to increasing resolution:
  - EKE increase
  - APE release
  - ACC weakening
  - Cool temperature drift
- Less obvious effects:
  - AMOC weakening
  - Stronger Southward heat transport
- Tuning:
  - OM4 was tuned to eliminate temperature drift
  - Thus, including any mesoscale parameterization will induce drift
  - Thus, It is unlikely to reduce systematic, but not regional, biases
  - Our parameterization can be used as a tuning knob at eddy-permitting resolution