MPAS-Ocean: a Multi-Scale Approach to Global Ocean Modeling

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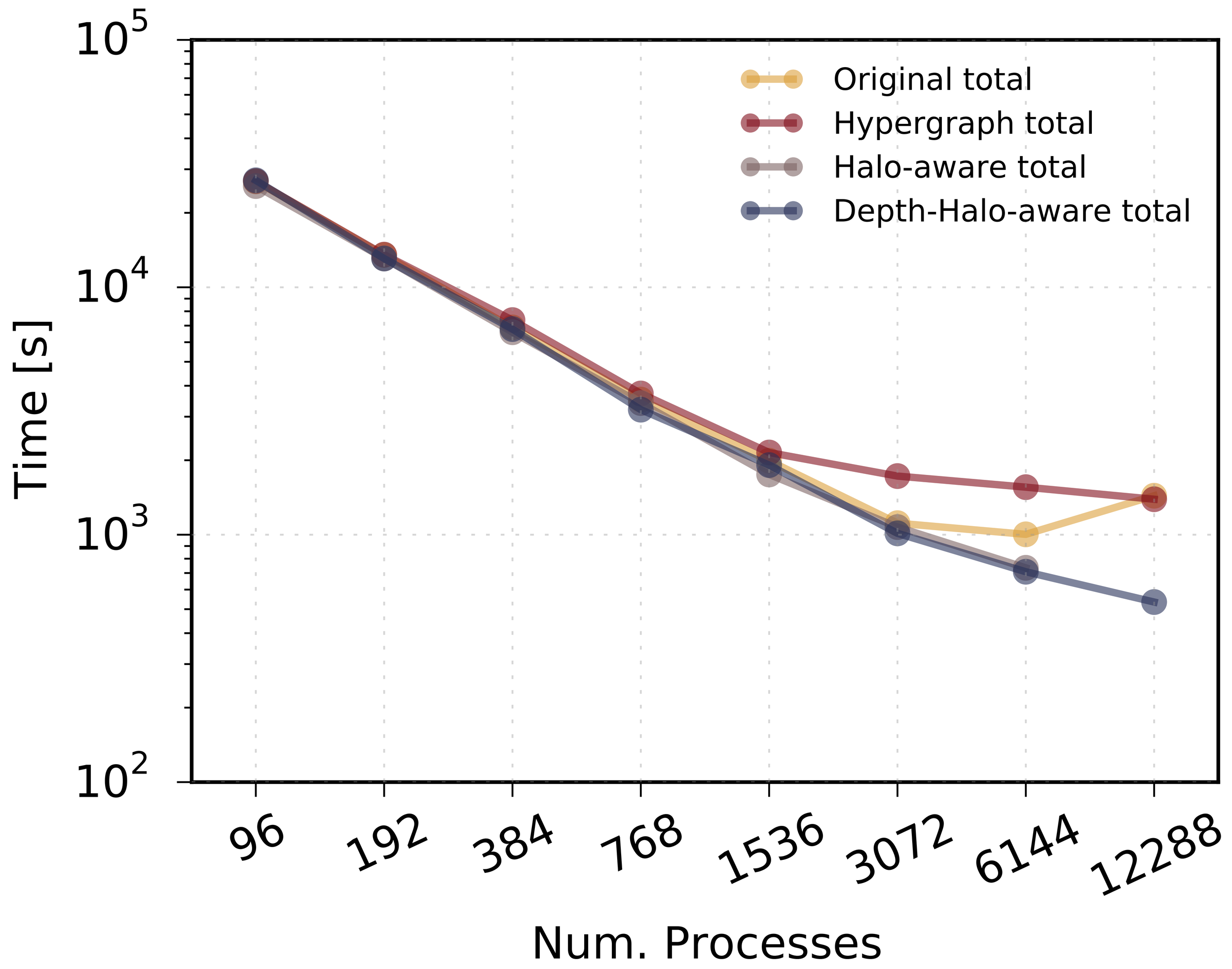
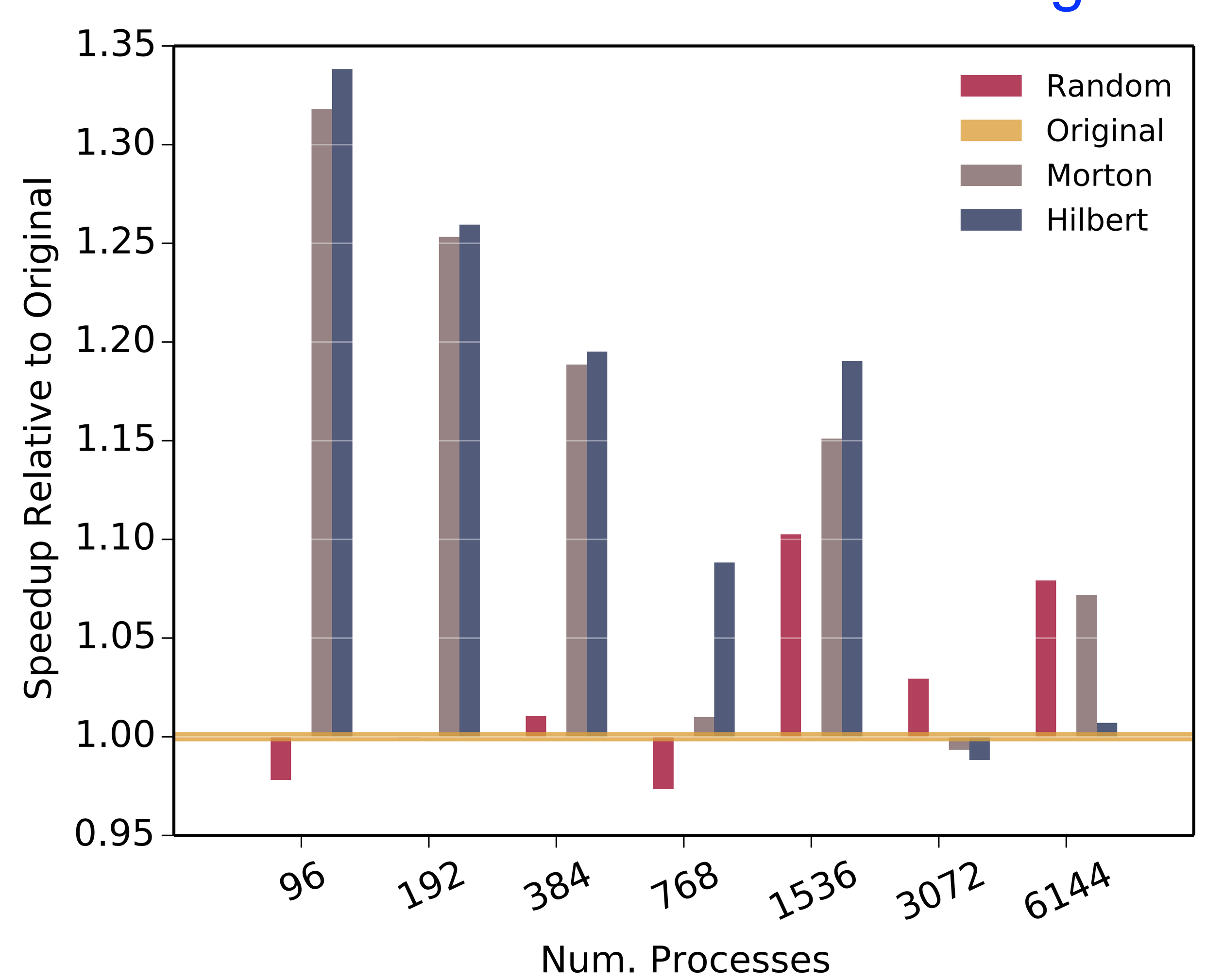
A Halo-Aware Mesh Partitioner



- MPAS-Ocean uses deep "halo" layers at mesh partition boundaries. Available mesh partitioners do not take halo cells into account and this leads to significant load imbalance during the application execution due to the unstructured nature of the mesh.
- We developed a halo-aware partitioning tool that iteratively refines partitioning using information about halo cells and individual cell weights representing the ocean depth. The approach to mesh partitioning resulted in significant speedups and improved scaling at high concurrencies (see above).

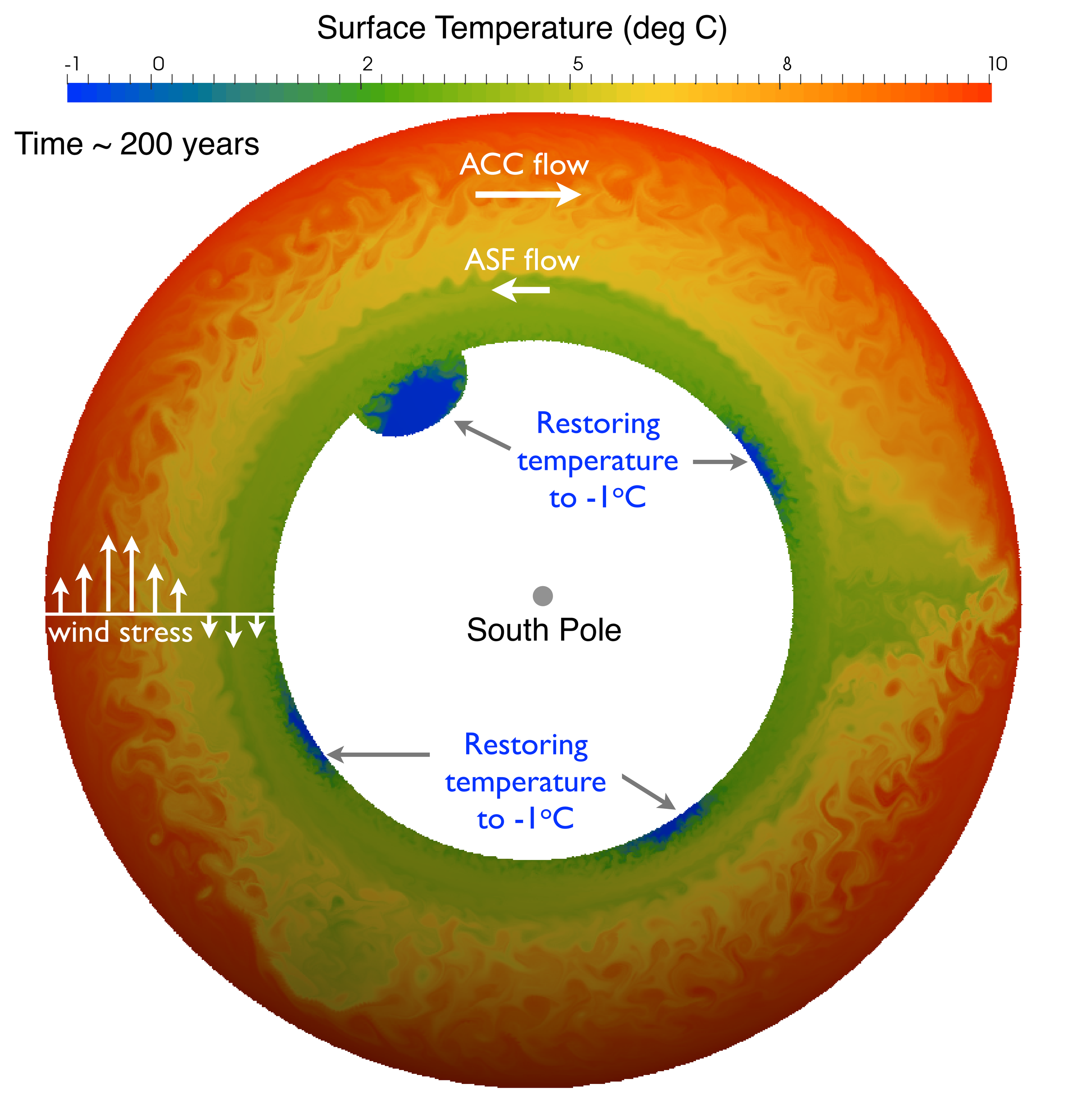
SFC-based Data Re-ordering

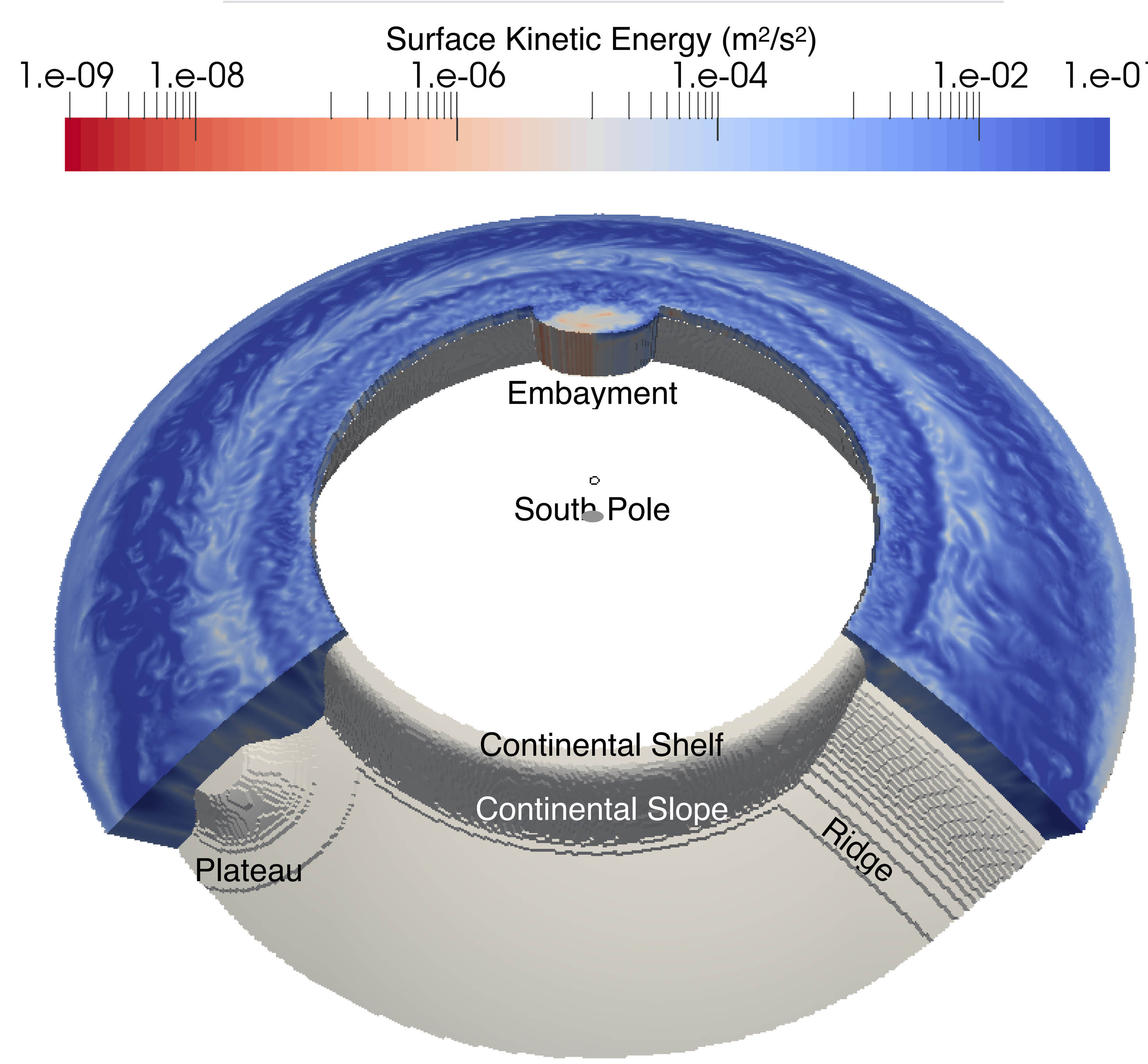


- With unstructured meshes used in MPAS-Ocean, data access patterns are unstructured as well. These lead to significant on-node performance degradation. To improve cache efficiency, and hence improve on-node performance, we developed a scheme to reorder mesh cells according to Space-Filling Curves (SFCs). SFCs have properties which maintain spatial data locality.
- With new orderings based on Morton and Hilbert SFCs, significant speedups in overall performance are observed (see above.) This is due to a reduction in cache misses by up to an order of magnitude. The benefits are greater at lower concurrencies when the caches are too small to contain all the cells in a partition.

Idealized Southern Ocean Testbed

- The Idealized Southern Ocean testbed captures important processes related to multi-scale eddy-mean flow interactions in the Southern Ocean and in the margins of Antarctica. The configuration includes idealized representations of the Antarctic Circumpolar Current (ACC) and Antarctic Slope Front (ASF).
- This configuration will be used to diagnose the EPFT and related quantities in order to investigate multi-scale eddy-mean flow interactions and to inform eddy parameterization.





TWA Equations for the Residual Mean Flow and the EPFT

- Thickness-weighted averaging (TWA) of the Boussinesq equations in buoyancy coordinates results in exact equations governing 3D residual-mean flow (Young 2012).
- Eddy-mean flow interactions appear in the horizontal momentum equations as the divergence of the Eliassen-Palm Flux Tensor (EPFT) (Maddison and Marshall 2013).

eddy stresses

x momentum $$\frac{D^\sharp \hat{u}}{Dt} - f\hat{v} + \frac{\partial p^\sharp}{\partial x} + \boxed{\nabla \cdot \mathbf{E}^u} = \hat{R}_x,$$

y momentum $$\frac{D^\sharp \hat{v}}{Dt} + f\hat{u} + \frac{\partial p^\sharp}{\partial y} + \boxed{\nabla \cdot \mathbf{E}^v} = \hat{R}_y,$$

hydrostatic balance $$\frac{\partial p^\sharp}{\partial z} = b^\sharp,$$

continuity $$\frac{\partial \hat{u}}{\partial x} + \frac{\partial \hat{v}}{\partial y} + \frac{\partial w^\sharp}{\partial z} = 0,$$

buoyancy $$\frac{D^\sharp b^\sharp}{Dt} = 0,$$

ensemble average at fixed x, y, b, t

TWA velocity: $\hat{u} = \frac{\overline{u\sigma}}{\overline{\sigma}}$

thickness: $\overline{\sigma} = \left(\frac{\partial b^\sharp}{\partial z}\right)^{-1}$

fluctuations: $u'' = u - \hat{u}$, $\zeta' = \zeta - \overline{\zeta}$

$$\frac{D^\sharp}{Dt} = \frac{\partial}{\partial t} + \hat{u}\frac{\partial}{\partial x} + \hat{v}\frac{\partial}{\partial y} + \hat{w}\frac{\partial}{\partial z}$$

Reynolds stresses — eddy potential energy — eddy form drag

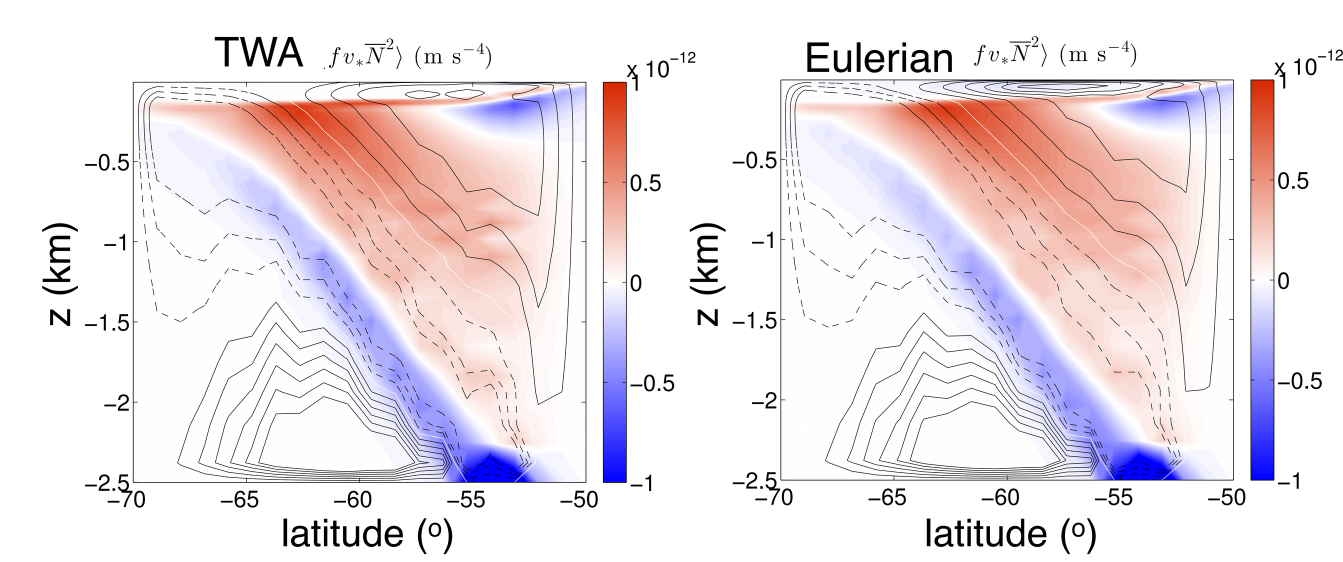
$\mathbf{E}^u$ and $\mathbf{E}^v$ are the first and second columns of the Eliassen-Palm flux Tensor:

$$\mathbf{E} = \begin{pmatrix} \widehat{u''u''} + \frac{1}{2\overline{\sigma}}\overline{\zeta'^2} & \widehat{u''v''} & 0 \\ \widehat{u''v''} & \widehat{v''v''} + \frac{1}{2\overline{\sigma}}\overline{\zeta'^2} & 0 \\ \frac{1}{\overline{\sigma}}\overline{\zeta' m'_{\tilde{x}}} & \frac{1}{\overline{\sigma}}\overline{\zeta' m'_{\tilde{y}}} & 0 \end{pmatrix}$$

Parameterizing the EPFT

- The TWA framework and the EPFT are amenable to the parameterization of meso-scale eddies in a dynamically consistent manner, conserving potential vorticity, energy and momentum.
- We have developed a hierarchy of parameterizations for the divergence of the EPFT, ranging from the standard Gent-McWilliams (GM) parameterization with constant diffusivity, to a prognostic parameterization in which eddy viscosity is related to sub-grid eddy energy.

GM parameterization: $$\nabla \cdot \mathbf{E}^u \approx -f\frac{\partial}{\partial z}\left(\kappa \frac{\rho_y^\sharp}{\rho_z^\sharp}\right) \qquad \kappa = \frac{N^2}{f^2}\mu$$



Prognostic eddy energy: $$\frac{\partial E_e}{\partial \tilde{t}} + \hat{\mathbf{u}} \cdot \nabla E_e - \hat{u}\nabla \cdot \mathbf{E}^u - \hat{v}\nabla \cdot \mathbf{E}^v + \nabla \cdot \mathbf{T} = \mathcal{D}_e$$

$$\nabla \cdot \mathbf{E}^u \approx \frac{\partial}{\partial z}\left(\frac{\overline{\zeta' m'_x}}{\overline{\sigma}}\right) = -\frac{\partial}{\partial z}\left(\mu \frac{\partial \hat{u}}{\partial z}\right)$$

$$\mu = \Gamma\, \mathcal{T}_e\, E_e = \Gamma \sqrt{E_e}\, \mathcal{L}_e$$

eddy time and length scales: $\mathcal{T}_e\, , \mathcal{L}_e$