Using Mesoscale Ocean Large Eddy Simulation Techniques in High-resolution POP

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Viscosity in POP

- Subgrid mixing should be **scale-aware** and **flow-aware**

- POP default: biharmonic viscosity (NOT flow-aware)

- Large eddy simulation (Leith, 1996) – viscosity chosen using 2D and QG turbulence theory

\[
\* = \left( \frac{x}{X} \right)^3 \sqrt{\left| \nabla_h q \right|^2 + \left| \nabla_h (\nabla_h \cdot u) \right|^2}
\]

**Scale Aware**

**Flow Aware**

\[
q = \nabla \times u
\]

**2D Leith**

\[
q = \nabla \times u + f + \frac{\partial}{\partial z} \left( \frac{f}{N^2} \frac{\partial b'}{\partial z} \right)
\]

**QG Leith**

\[
\begin{align*}
\nabla^2 (b_h \nabla^2 u) \\
b_h = 0 \left( \frac{A}{A_0} \right)^{3/2}
\end{align*}
\]
Leith viscosity setup

0.1° POP simulation

3 simulations; biharmonic (default), 2D Leith and QG Leith viscosity

Leith simulations use GM-Redi parameterization for tracer mixing. GM and Redi diffusivities are set equal to the Leith viscosities.

Results are from the second year of a spun up simulation.

How are simulations affected by different subgrid schemes?
Viscosity at 100 m depth

2D Leith

QG Leith

$m^2 s^{-1}$
Kinetic Energy

Biharmonic

2D Leith

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Kinetic Energy

Biharmonic

2D Leith

QG Leith

$E(k) \sim k^{-3}$

Energy density spectrum
Zonal transect 58°S
Dissipation of kinetic energy through horizontal friction (100m depth)
Largest dissipation regions at 100 m (95% of global dissipation)

Biharmonic

2D Leith

QG Leith

$log_{10}(\ ) \ [m^2s^{-3}]$
• Leith schemes lose less KE to horizontal friction

• Leith schemes lose more KE to bottom drag
Mass Transport

Antarctic Circumpolar Current

Indonesian Throughflow

Florida Strait

Time

Mass Transport (Sv)
Summary

• Choice of subgrid scheme affects ocean simulations; dynamics, energetic budgets, and large-scale transports.

• Leith subgrid schemes (relative to biharmonic):
  – Allow more kinetic energy, particularly at small scales – consistent with QG turbulence.
  – Reduce energy loss through horizontal friction, and increase energy loss through bottom drag.
  – Affect mass transport, but response is not monotonic across all regions.
2D Leith

- In 2D turbulence there is a downscale enstrophy cascade
- 2D Leith viscosity is designed to capture the enstrophy cascade

\[ q_{QG} = \nabla^2 + f + \frac{\partial}{\partial z} \left( \frac{f^2}{N^2} \right) \frac{\partial}{\partial z} \]

QG Leith viscosity proposed by Bachman & Fox-Kemper (in prep.)

Scale Aware
Flow Aware
Viscosity profiles
(median + interquartile range)
• Leith schemes lose less KE to horizontal friction

• Leith schemes lose more KE to bottom drag
K.E. Dissipation operators
(only shown for x-component)

Laplacian:
\[ u \nabla_h \cdot (\nabla_{2d} u) = \nabla_h \cdot [2d u \nabla_h u] - 2d [\nabla_h u \cdot \nabla_h u] \]

Biharmonic:
\[ u \nabla_h^2 (\nabla_{bh}^2 u) = bh (\nabla_{bh}^2 u)^2 + \nabla_h \cdot [u \nabla_h (\nabla_{bh}^2 u) (\nabla_{bh}^2 u)(\nabla_h u)] - \varepsilon_{bh} \]
Kinetic Energy