Anisotropic Mesoscale Eddy Parameterization for Shear Dispersion

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Flow Viz – Solid Body Rotation
Mesoscale Eddy Parameterization

- Parameterizations previously used isotropic diffusivity $\kappa$
- Extend for anisotropy*
  - Principal axis alignment
  - $\kappa_{\text{major}} / \kappa_{\text{minor}}$
- What will be gained?
  - Shear dispersion
  - PV-gradient suppression
  - Better ventilation of passive and biogeochemical tracers

* Bachman & Fox-Kemper (2013)
* Fox-Kemper et al (2013)
Mesoscale Eddy Parameterization

- Baroclinic instability energizes mesoscale eddies by converting available potential energy to kinetic energy, anisotropically mixing along isopycnals and flattening isopycnal slopes.

- Reynolds averaged tracer equation with closure:

\[
\partial_t \phi + \bar{u} \cdot \nabla \phi = \nabla \cdot \left( \bar{K} + \bar{A} \right) \cdot \nabla \phi
\]

- Redi mixing
  - dissipative
  - symmetric
  - eddy diffusivity
  - diffuses along isopycnals
  - reduce global tracer variance

- GM stirring
  - advective
  - antisymmetric
  - bolus velocity/SF
  - flattens isopycnal slopes
  - zero tracer variance effect
Baroclinic instability energizes mesoscale eddies by converting available potential energy to kinetic energy, anisotropically mixing along isopycnals and flattening isopycnal slopes.

\[ \partial_t \phi + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \left( \mathbf{K} + \mathbf{A} \right) \cdot \nabla \phi \]
Eddy Adveective Tensor

- Baroclinic instability energizes mesoscale eddies by converting available potential energy to kinetic energy, anisotropically mixing along isopycnals and flattening isopycnal slopes.

\[
\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \left( \bar{K} + \bar{A} \right) \cdot \nabla \phi
\]
Baroclinic instability energizes mesoscale eddies by converting available potential energy to kinetic energy, anisotropically mixing along isopycnals and flattening isopycnal slopes.

\[ \partial_t \phi + \vec{u} \cdot \nabla \phi = \nabla \cdot \left( \vec{K} + \vec{A} \right) \cdot \nabla \phi \]
Anisotropy: Shear Dispersion

Mesoscale Eddies

Mesoscale Eddy in shear zone mixes stronger along the flow

Equatorial Jets
Anisotropic Eddy Transport Tensor

- Baroclinic instability energizes mesoscale eddies by converting available potential energy to kinetic energy, anisotropically mixing along isopycnals and flattening isopycnal slopes.

\[
\partial_t \phi + \vec{u} \cdot \nabla \phi = \nabla \cdot \left( \vec{K} + \vec{A} \right) \nabla \phi
\]
Anisotropic GM/Redi

Investigate sensitivity to anisotropy...

1. $\kappa_{\text{minor}}$ (suppression from background diffusivity)
2. $\kappa_{\text{major}}$ (enhancement from background diffusivity)
3. $\sin(\theta)$ (alignment of principal axis of diffusion)

... to educate the development of the shear dispersion parameterization
Drifter Observation Diffusivity Tensor

- Principal axis alignment
  - Major axis **aligned zonally** away from boundary currents
  - Major axis **aligned with the flow** near boundary currents

- $\kappa_{\text{major}} / \kappa_{\text{minor}}$
  - $> 16$ in equatorial region
  - Typical ratio is $\approx 5$

*Fox-Kemper et al (2013)
Hi-res Diagnosed Tensor

- $\kappa_{\text{major}}$
- $\kappa_{\text{minor}}$

- 0.1 degree POP2 with 9 passive tracers (various orientation restoring)*
- Diffusivities calculated using least-squares
- Tensor applied statically in 1-degree tests (CORE-forced, 5 cycles)

$\hat{\mathbf{i}} \cdot \hat{n}_{\text{minor}} = \sin(\theta_{\text{major}})$

*Bachman & Fox-Kemper (2013)

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*Fox-Kemper et al (2013)
Summary of Numerical Experiments

- Community Earth System Model (CESM1.2)
  - CORE 62-year interannual forcing (GIAF compset)*
  - 1° resolution (gx1v6 grid)
  - 5.75 cycle spin-up, branch for 5.25 cycles, and inject CFC’s for final 1.25 cycles.

Larger diffusivities = cooling drift, smaller diffusivities = warming drift
Hi-res Diagnosed Tensor Study

- Isotropic version of diagnosis: ratio=5, flow-aligned
- Anisotropic Mesoscale Eddy Parameterization

High sensitivity to orientation!
Major Axis Alignment Study

- $N^2$ parameterization for minor, ratio=5

$\kappa_{\text{major}}$ flow aligned

$\kappa_{\text{minor}}$ across PV-gradient

$\sin(\theta_{\text{major}})$ diagnosed orientation

zonal aligned

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Flow alignment is best!
Anisotropic GM/Redi

Investigate sensitivity to anisotropy...

1. $\kappa_{\text{minor}}$ (suppression from background diffusivity, $\kappa$)
2. $\kappa_{\text{major}}$ (enhancement from background diffusivity, $\kappa$)
3. $\sin(\theta)$ (alignment of principal axis of diffusion)

... to educate the development of the shear dispersion parameterization

flow-alignment is best, consistent with shear dispersion
Diffusivity Ratio Study

High diffusivities cause drastic biases due to suppression of deep water formation & AMOC shutdown.

$\kappa_{\text{major}} = 2.5\kappa$

$\kappa_{\text{major}} = 5\kappa$

smoothed diagnosis
Large bias reductions in the North Atlantic

Overaggressive diffusion can cause AMOC shutdown
Along WOCE Transect

Anisotropy drastically reduces biases:
- pCFC by 24%
- Temp by 48%
- Salinity by 63%
Anisotropy also reduces biases in equatorial Atlantic.
Mixed Layer Depth [Annual, Winter]

- Anisotropy deepens MLD in Southern Ocean (where control is too shallow)
- Shallows MLD in North Atlantic (where control is too deep)
- Reduces winter mean rms bias 15%
- Reduces annual mean rms bias 18%
Ideal Age and Oxygen Minimum Zones

N² isotropic

IAGE for case bass at z=483m

IAGE bias for case diah at z=483m

N² isotropic

smth. diag. ratio —

IAGE for case bass at z=985m

IAGE bias for case diah at z=985m

blue = younger than cntl

red = older than cntl

OMZ are ventilated with strong along-flow diffusion (anisotropy)
(A)MOC Sensitivity to Anisotropy

N² isotropic

Anisotropic: ratio=5

Strong suppression of AMOC
Summary of Numerical Experiments

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  - 5.75 cycle spin-up, branch for 5.25 cycles, and inject CFC’s for final 1.25 cycles.

Best case for CFC, T, & S bias reduction has largest drift
Minor Diffusivity Reduction

All solid lines are anisotropic: flow-aligned, $\kappa_{\text{major}} = 5\kappa_{\text{minor}}$

Remove drift while maintaining rms bias reduction

$\kappa_{\text{minor}}$

$0.45\kappa_{\text{iso}}$

$0.60\kappa_{\text{iso}}$

$0.70\kappa_{\text{iso}}$

$0.80\kappa_{\text{iso}}$

$0.66\kappa_{\text{iso}}$

$1.00\kappa_{\text{iso}}$
Minor Diffusivity Reduction

N² isotropic

AMOC for case bass

AMOC for case flrx

Slight increase in AMOC
Shear Dispersion Parameterization

Taylor (1953) pipe flow

\[ \kappa_{\text{flow}} = \kappa + \frac{U^2 R^2}{48\kappa} \]

Smith (2005) QG jet (shear dispersion)

\[ \kappa_{\text{flow}} = \kappa + \kappa^{-1} \sum_n \frac{|\hat{U}_n|^2}{k_n^2} \]

\[ U(y) = \sum_{n=-\infty}^{\infty} \hat{U}_n e^{-i k_n y} \]

Shear dispersion parameterization

\[ \kappa_{\text{major}} = \kappa + \frac{a}{2\pi^2 \kappa} \left\langle \left( (u \Delta y)^2 + (v \Delta x)^2 \right) \right\rangle \]

Parameter \( a \) sets scale of shear dispersion.

Use reduction of \( \kappa_{\text{minor}} \) to fix AMOC suppression and temperature drift?

Average over neighboring 4 U-cells

Model shear dispersion effects at largest unresolved scale: \( a = 1 \)
Shear Dispersion Parameterization

\[ \kappa_{\text{major}} = \kappa + \frac{\alpha}{2\pi^2\kappa} \left\langle \left( u\Delta y \right)^2 + \left( v\Delta x \right)^2 \right\rangle \]

shear dispersion

\[(\alpha = \pi^2)\]

Shear dispersion scale too high!

pCFC bias reduction; strong diffusion in Lab Sea prevents deep water formation & AMOC weakening
Minor Diffusivity Reduction – Shear Dispersion

\[ \kappa_{\text{major}} = \kappa + \frac{a}{2\pi^2 \kappa} \left< (u\Delta y)^2 + (v\Delta x)^2 \right> \]

Global Mean Temperature

Remove drift… while maintaining rms bias reduction?
Conclusions and Future Work

• Sensitivity to anisotropy:
  – Alignment: high sensitivity; flow-alignment performs best (reduction in CFC, T, & S bias) and is justified by anisotropic transport mechanisms (shear dispersion, across-jet suppression, etc.).
  – Diffusivity ratio: with N^2 for minor diffusivity, constant ratios of 2.5 and 5 reduce biases, but 10 is too large. Spatial variability using hi-res diagnosis or shear dispersion parameterization improves BGC ventilation.
  – (A)MOC: high sensitivity; large bias reductions in the North Atlantic despite suppression of AMOC and global mean temperature drift, which can be corrected through minor diffusivity.
  – MLD: Southern Ocean deepening; North Atlantic shallowing; rms bias reduction.

• Tuned shear dispersion parameterization (α and κ\textsubscript{minor}) must be tested for centuries-long run.

• Better background diffusivity, κ? Minor suppression κ\textsubscript{minor}?