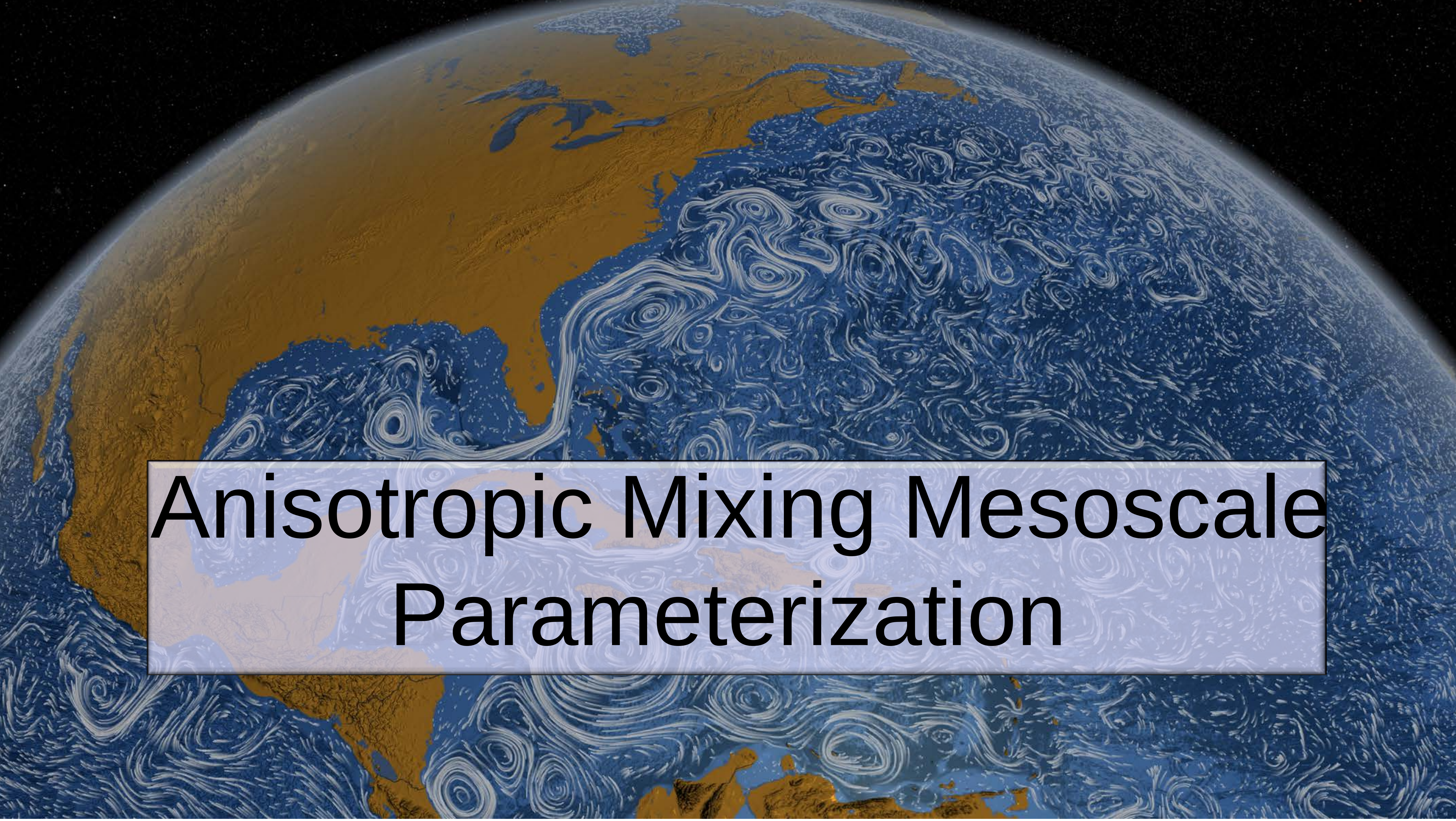


Anisotropic Mixing Mesoscale Parameterization

Scott J. Reckinger

Baylor Fox-Kemper

BROWN

NCAR Ocean Model Working Group Meeting
January 15th, 2014
Boulder, CO

Mesoscale Eddies

surface flow from observation data assimilation (NASA & MITgcm)

Eddies convert available potential every into kinetic energy:
energizes eddies, flattens isopycnal slopes, and mixes along isopycnals

Mesoscale Eddy Parameterization

- Reynolds averaged tracer equation with closure:

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

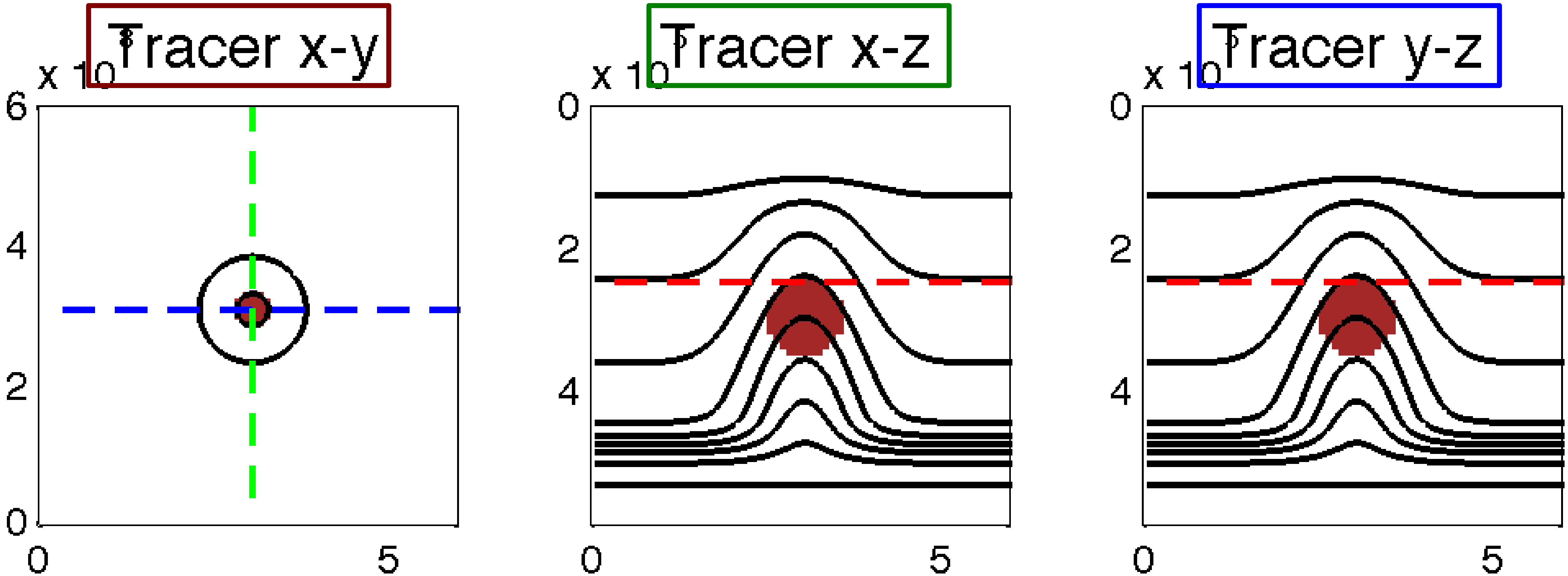
Redi	GM
mixing	stirring
dissipative	advective
symmetric	antisymmetric
eddy diffusivity	bolus velocity/SF
diffuses along isopycnals	flattens isopycnal slopes
reduce global tracer variance	zero tracer variance effect

eddy transport tensor

Eddy Diffusivity Tensor

diffuses along isopycnals

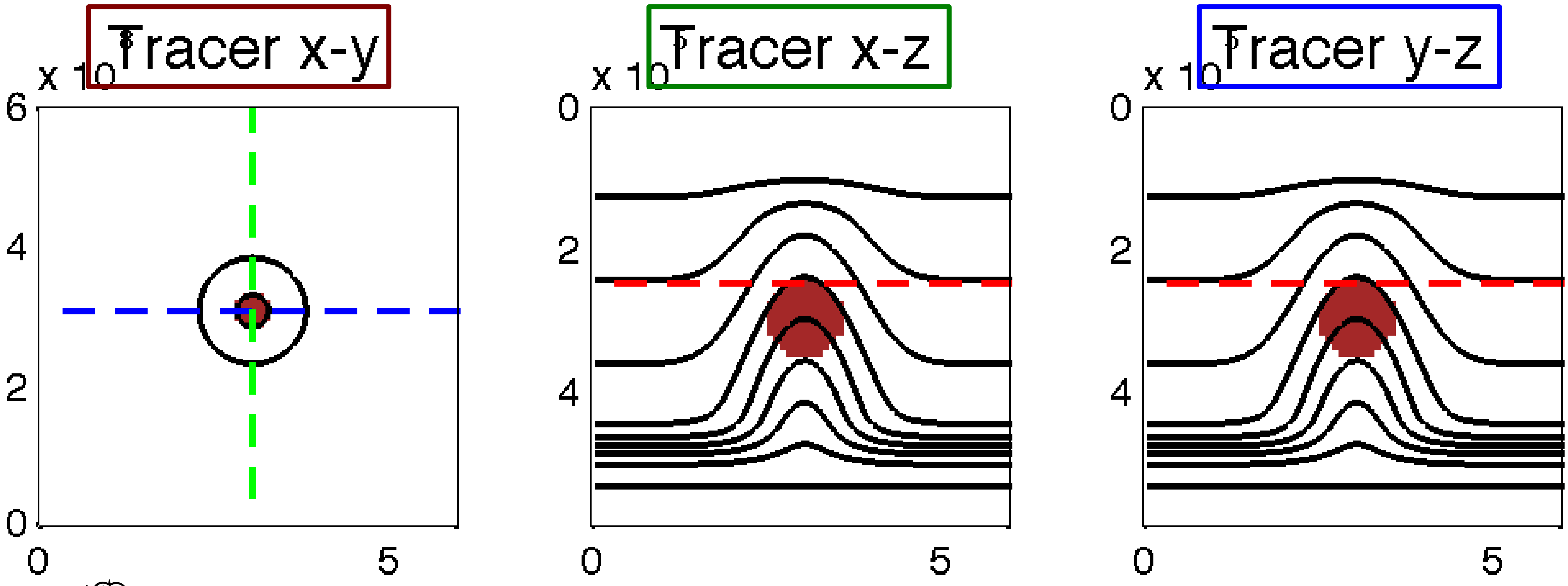
$$\partial_t \phi + \vec{u} \cdot \nabla \phi = \nabla \cdot \left(\bar{\bar{K}} + \bar{\bar{A}} \right) \cdot \nabla \phi$$



Eddy Advective Tensor

flattens isopycnal slopes

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



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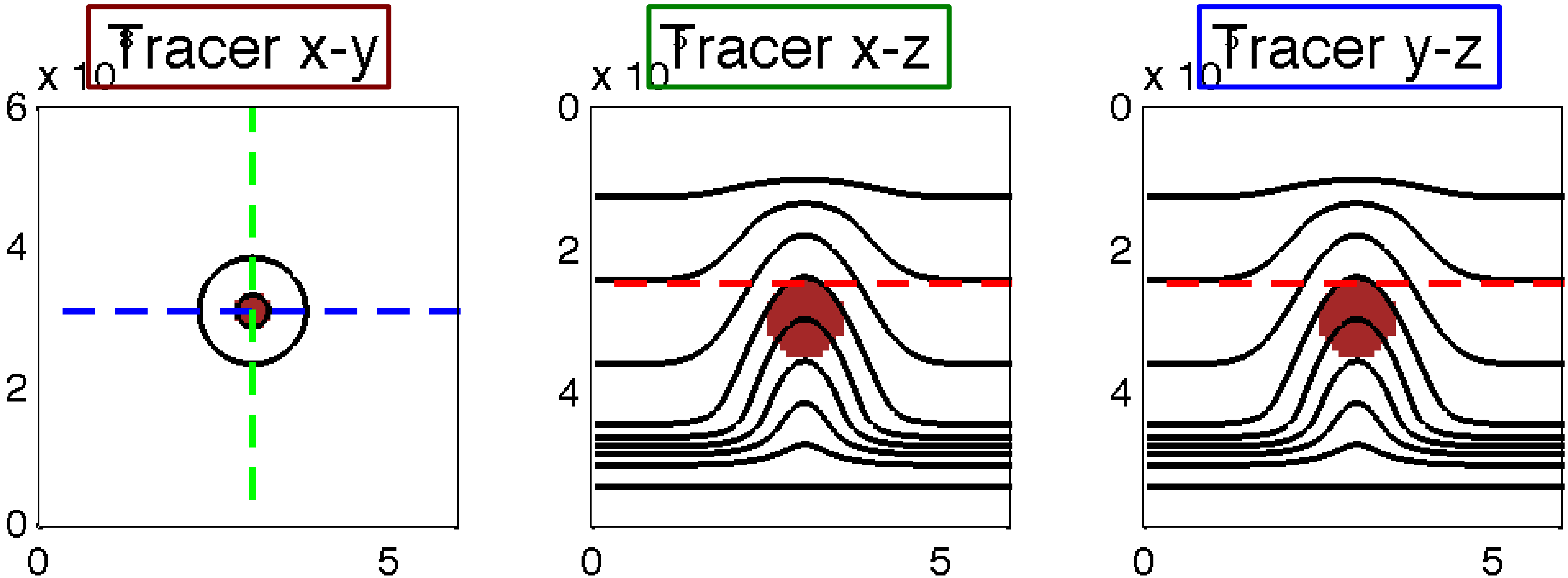
Eddy Transport Tensor

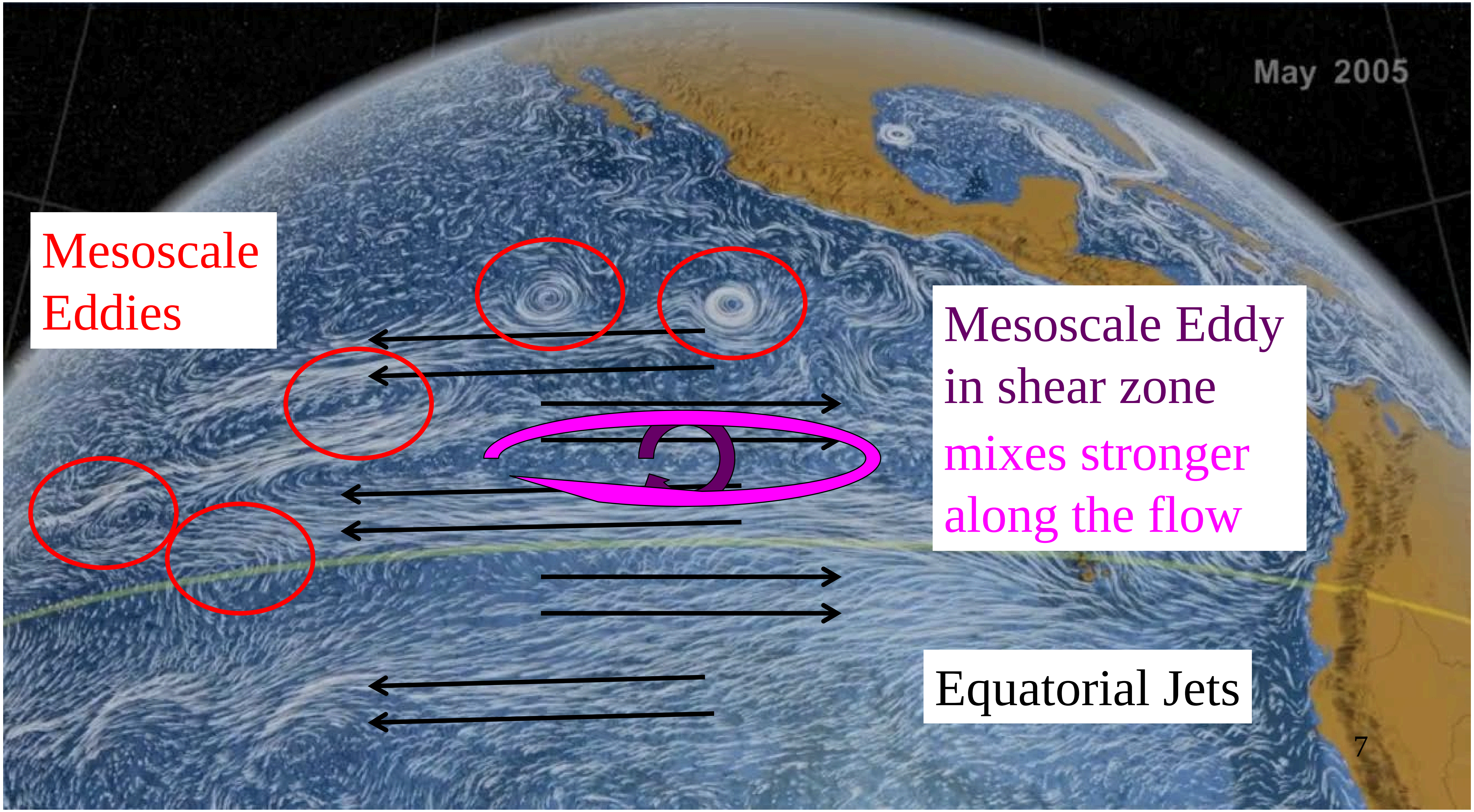
diffuses along isopycnals

flattens isopycnal slopes

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



Anisotropy: Shear Dispersion

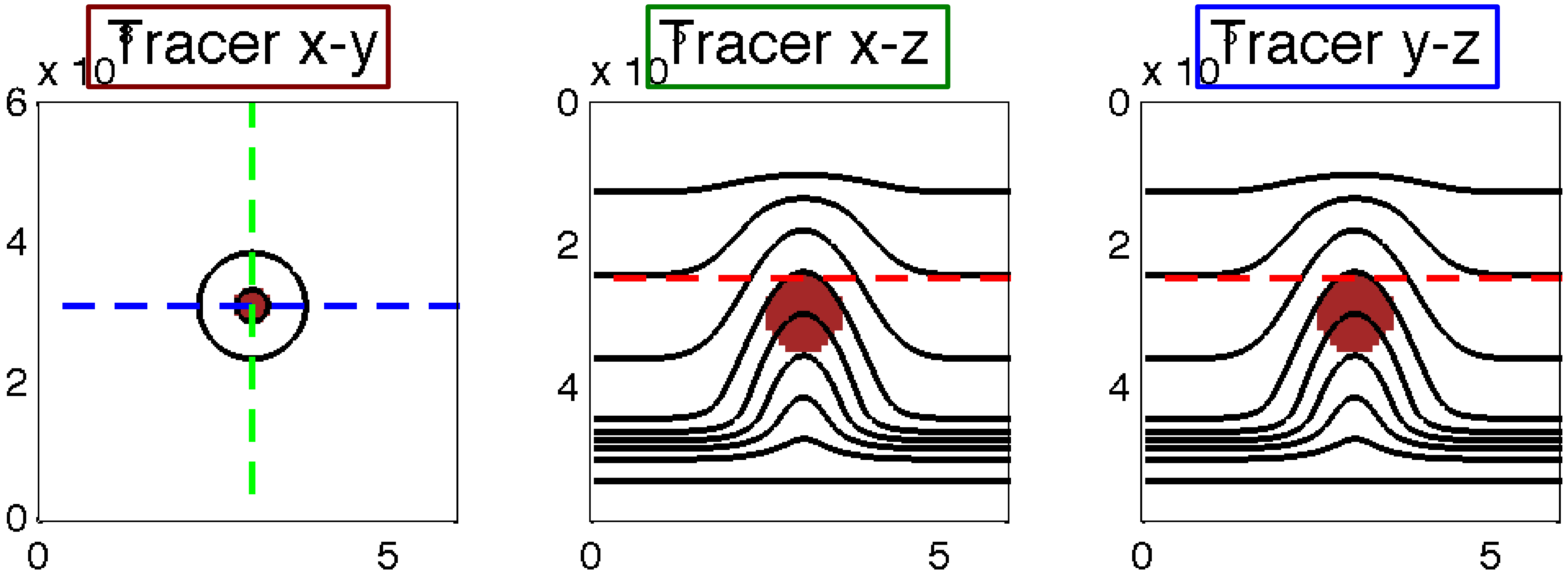


Anisotropic Eddy Transport Tensor

diffuses along isopycnals

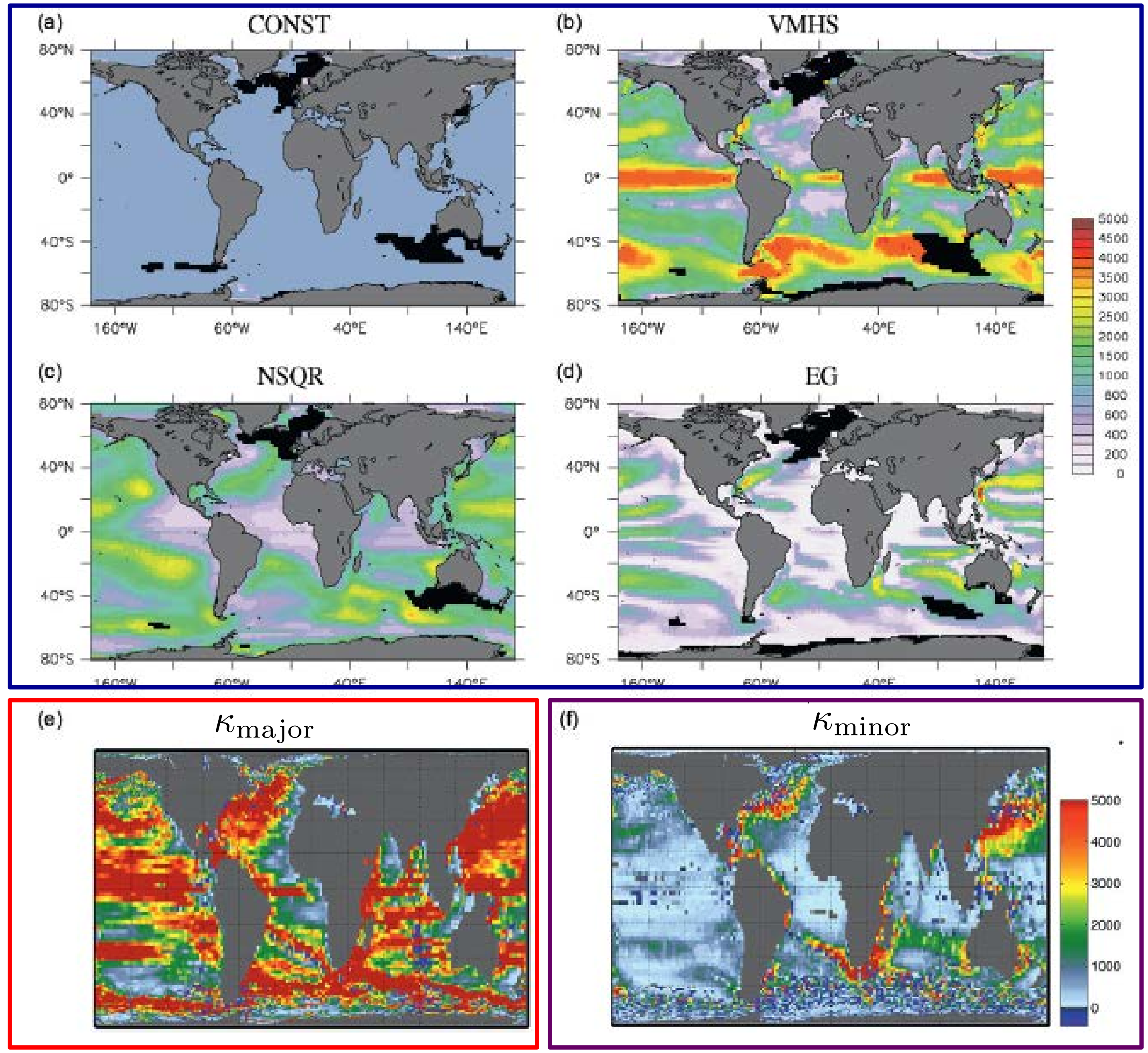
flattens isopycnal slopes

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



Mesoscale Eddy Parameterization

- Parameterizations currently use isotropic diffusivity κ
- Extend for anisotropy*
  - Principal axis alignment
  - $\kappa_{\mathrm{major}} / \kappa_{\mathrm{minor}}$
- 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)

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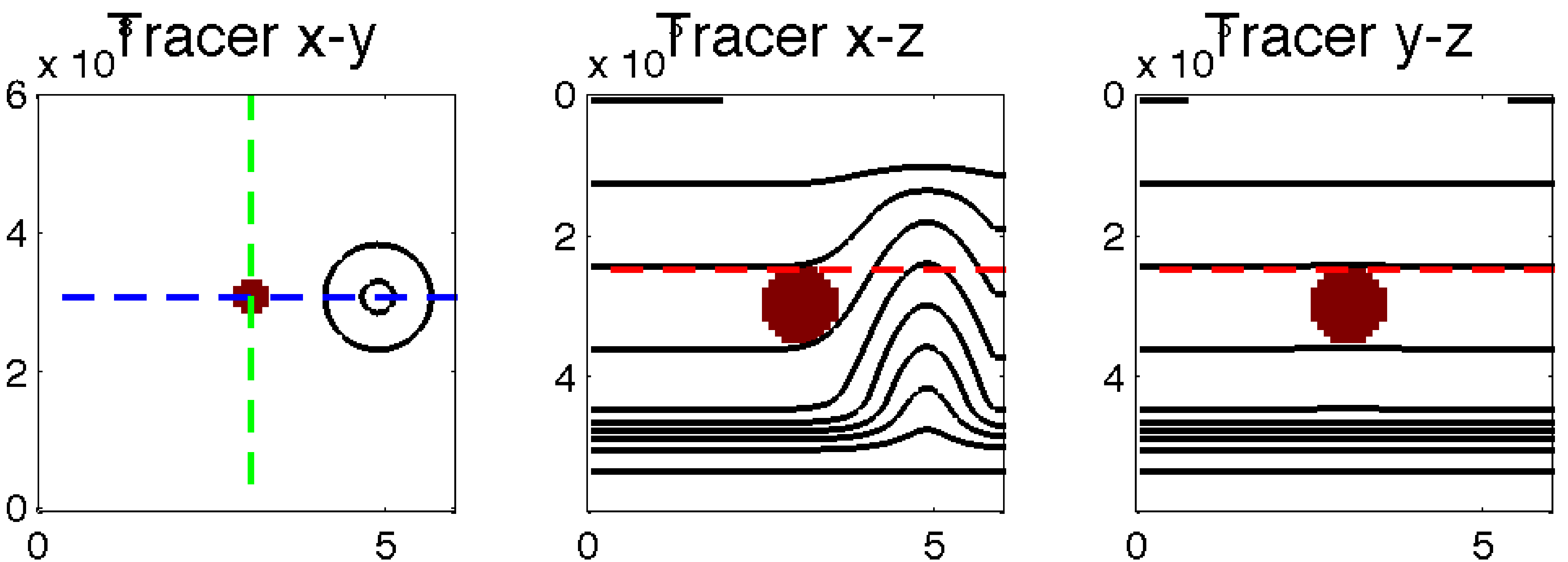
Anisotropic GM/Redi

- Model anisotropic transport mechanisms in the ocean through parameterizations of:

$\kappa \Rightarrow$

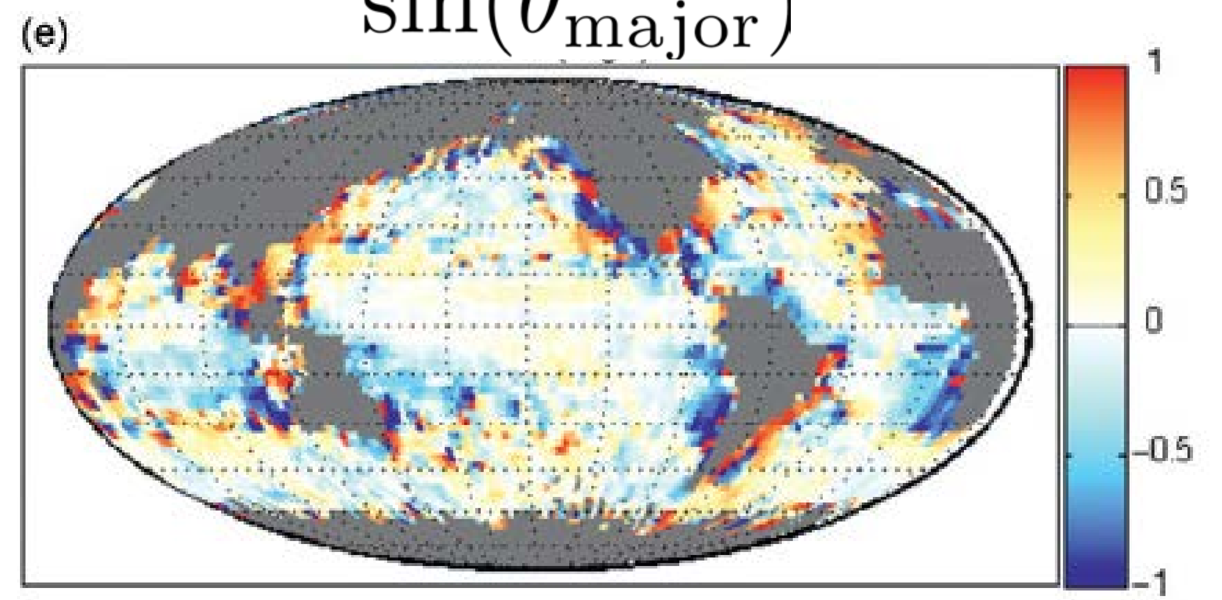
1. κ_{minor} (suppression from background diffusivity)
2. κ_{major} (enhancement from background diffusivity)
3. $\sin(\theta)$ (alignment of principal axis of diffusion)



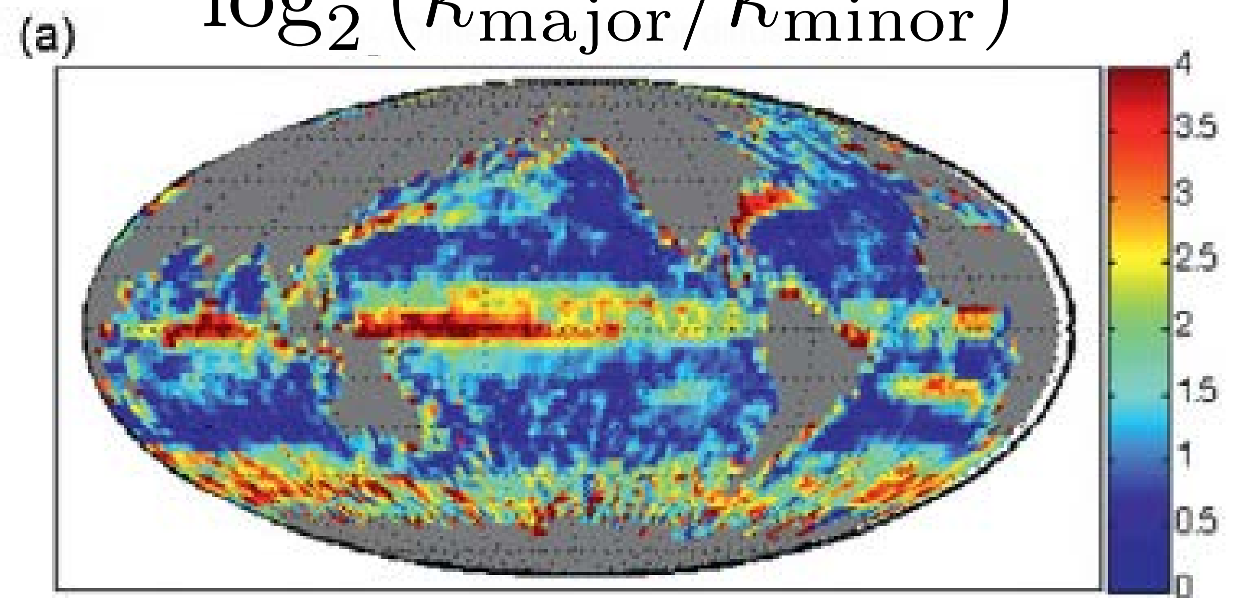
Drifter Observation Diffusivity Tensor

- Principal axis alignment
  - Major axis **aligned zonally** away from boundary currents
  - Major axis **aligned with the flow** near boundary currents
- $\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}}$
  - **> 16** in tropical regions
  - Typical ratio is **≈ 5**

$\sin(\theta_{\mathrm{major}})$



$\log_2(\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}})$



*Fox-Kemper et al (2013)

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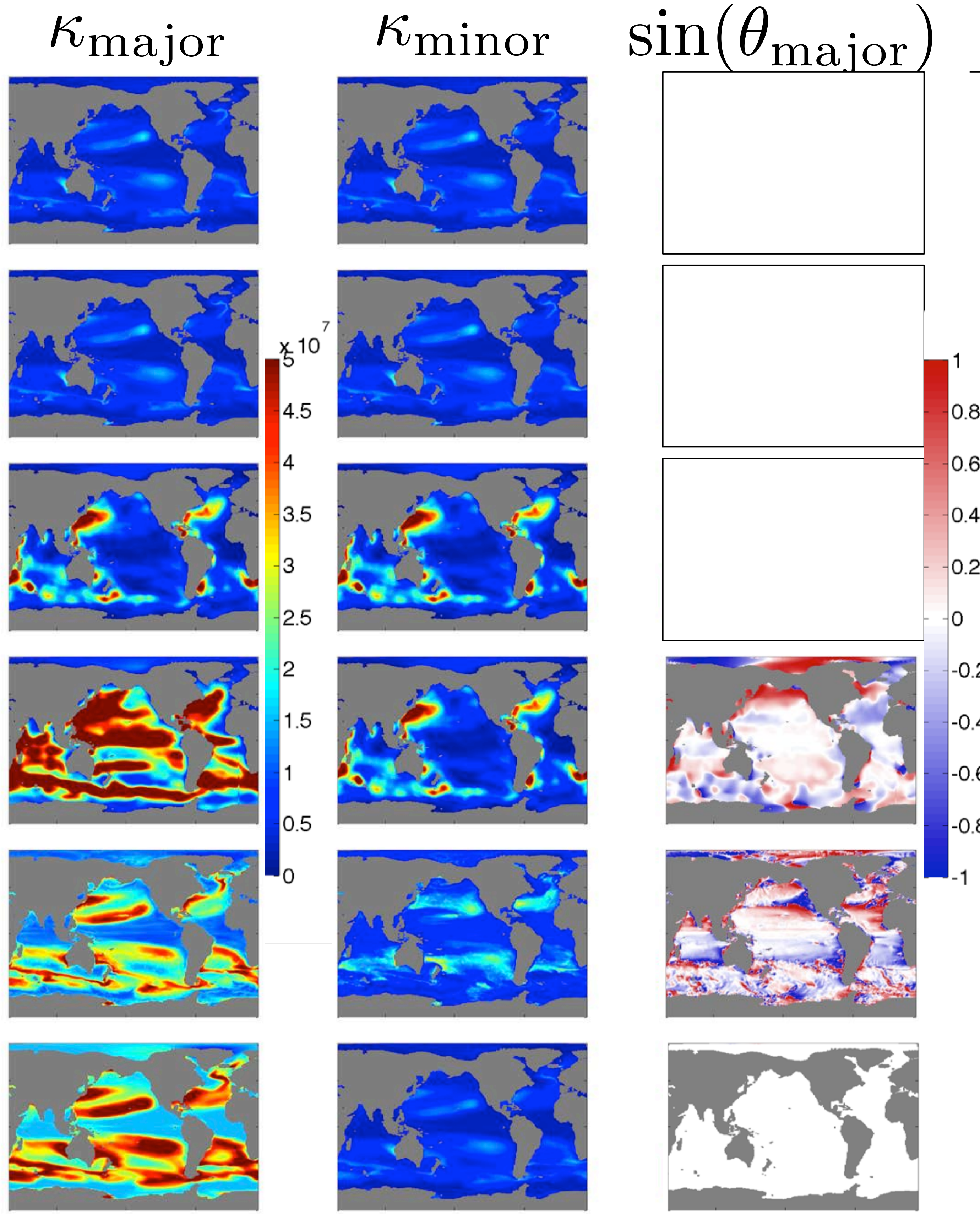
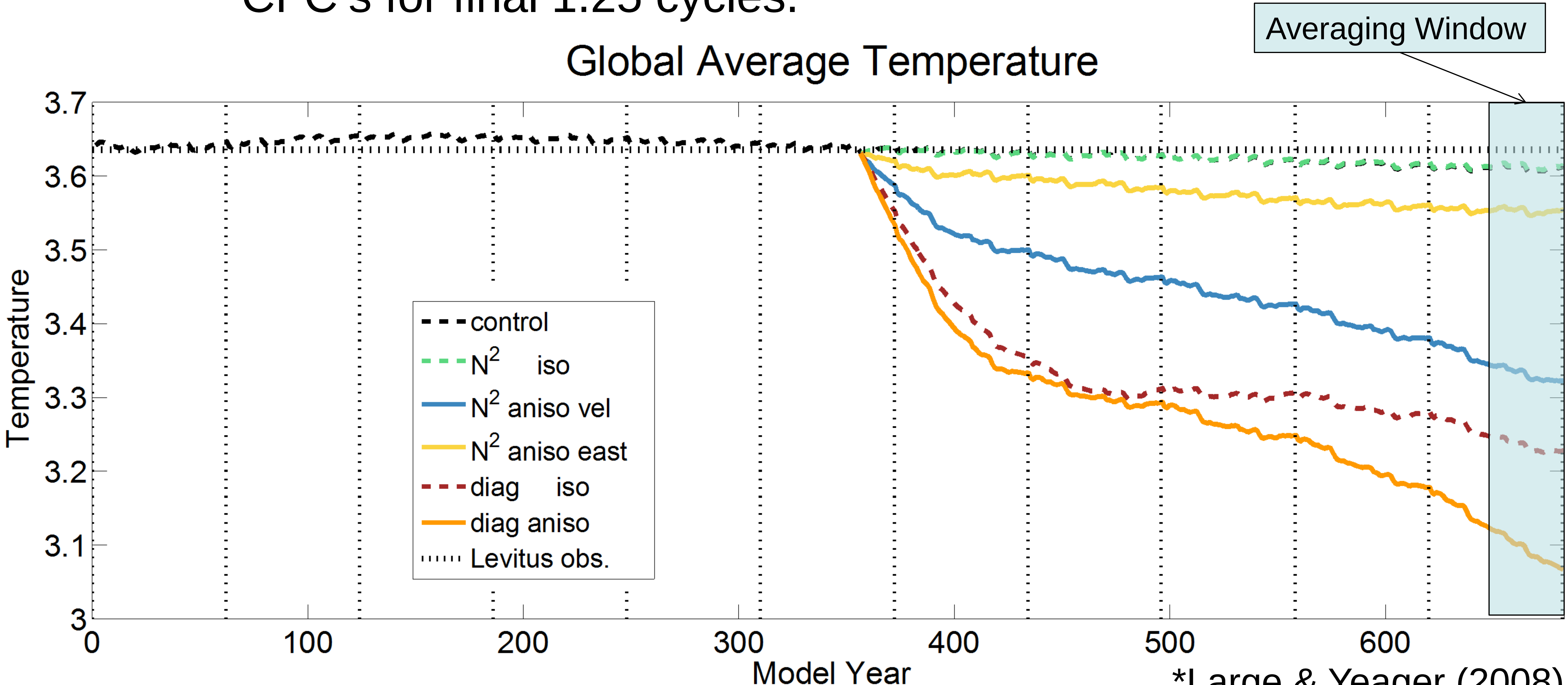
Summary of Numerical Experiments



	κ_{minor}	$\kappa_{\text{major}}/\kappa_{\text{minor}}$	alignment
Control	N^2	1	$\sim$
N^2 Isotropic	N^2	1	$\sim$
Diagnosed Isotropic	diagnosed	1	$\sim$
Diagnosed Anisotropic	diagnosed	diagnosed	diagnosed
N^2 Anisotropic Flow	N^2	5	with flow
N^2 Anisotropic East	N^2	5	zonally

Summary of Numerical Experiments

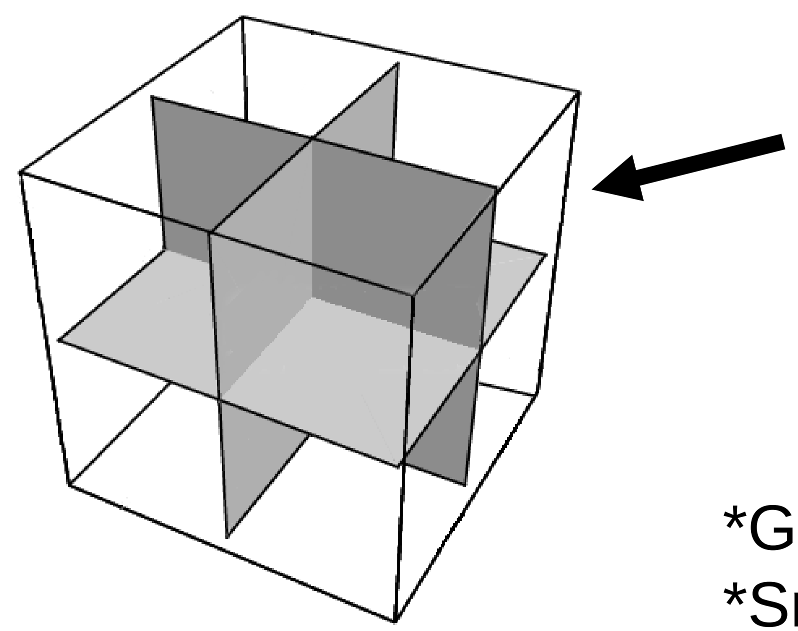
- Community Earth System Model (CESM1.2)
  - CORE 62-year interannual forcing (GIAF compset)*
  - 1° resolution (gx1v6 grid)
  - 5.75 cycle spin-up, branch for 5.25 cycles, and inject CFC's for final 1.25 cycles.

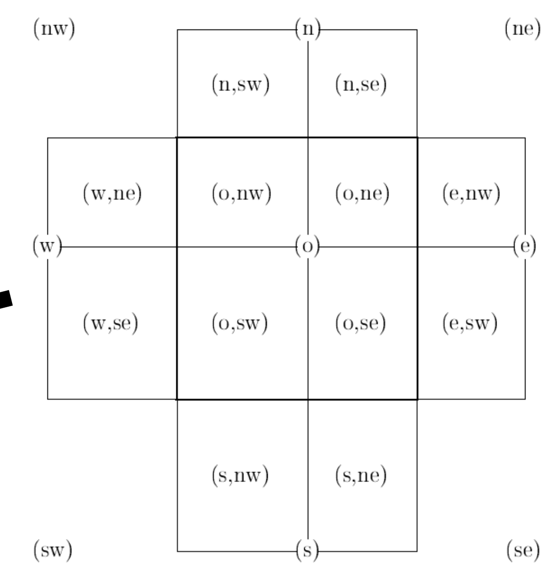


*Large & Yeager (2008)

Discretization of the Anisotropic Operator

- Requires 3D volume integration*
  - Terms with derivatives in all 3 dimensions, e.g. $\partial_y \left[K_{xy} S_x \partial_z \phi\right],\ \partial_z \left[K_{xy} S_y \partial_x \phi\right],\ \partial_z \left[K_{xy} S_x S_y \partial_z \phi\right]$
- Minor change to the treatment of transition layer physics**
- Sensitive to local variations in grid spacing
- **Natural implementation of partial bottom cells**



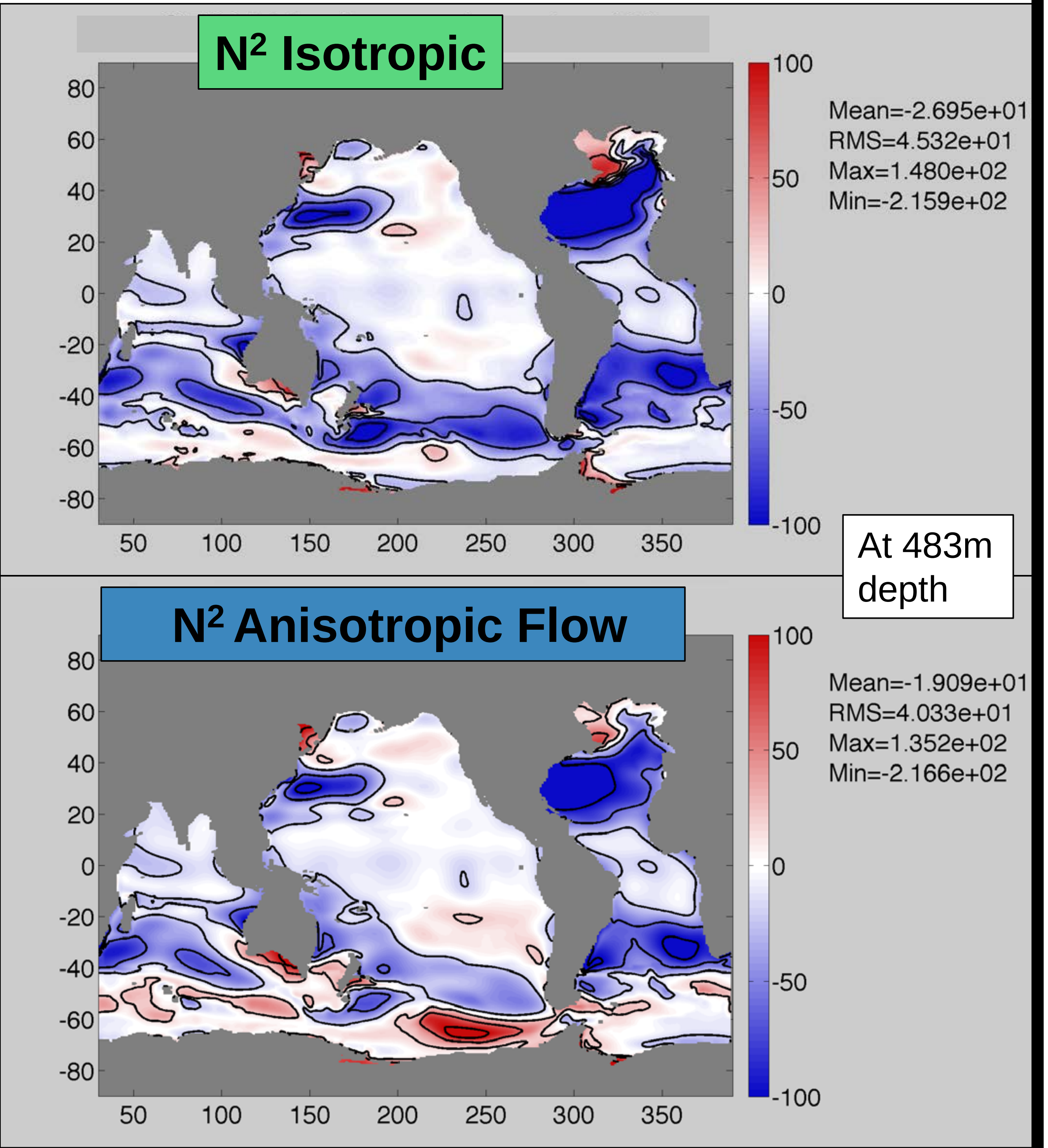


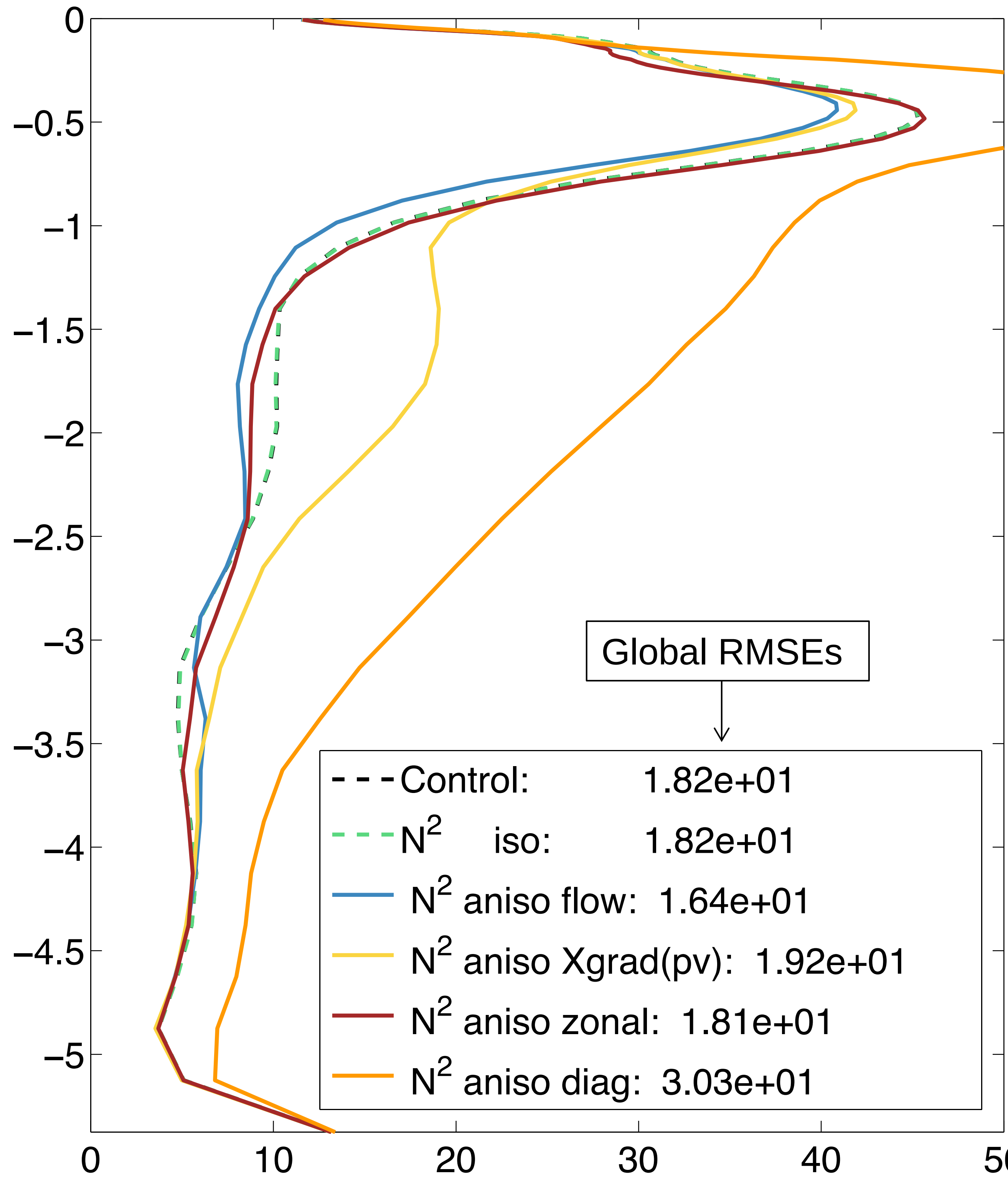
*Griffies (1998)
*Smith & Gent (2002)

**Ferrari et al (2008)
**Danabasoglu et al (2008)

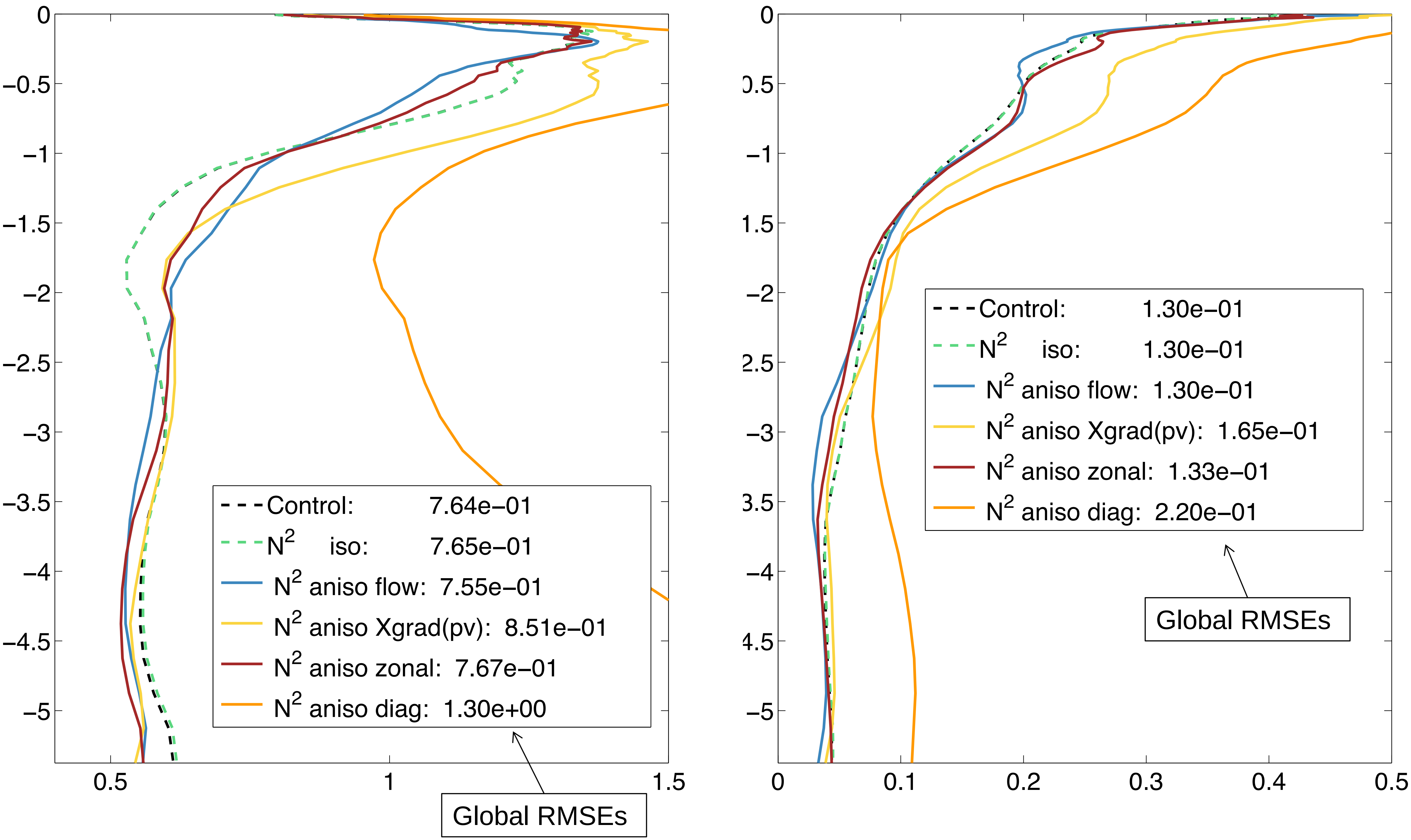
Alignment – pCFC11 Bias

Flow aligned anisotropy leads to large increase in ventilation
(Kuroshio & Gulf Stream extensions, Southern Ocean)



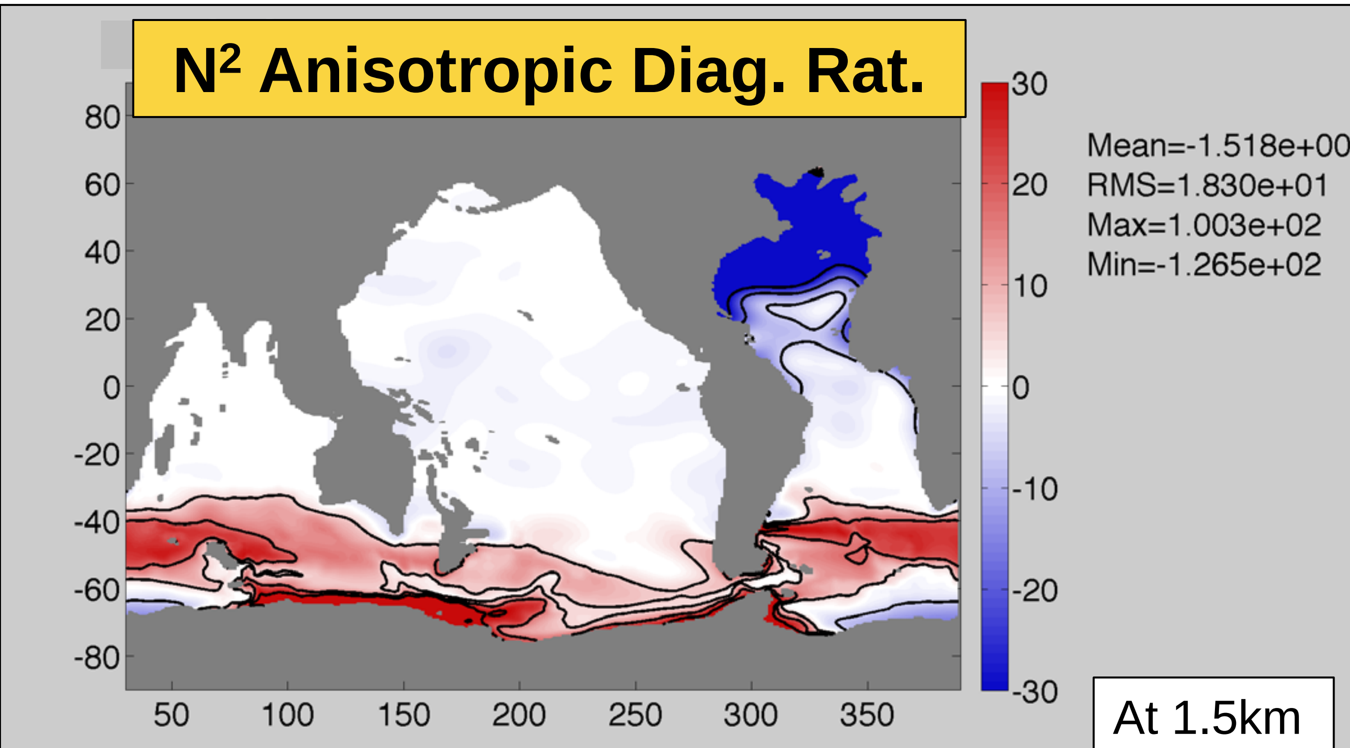


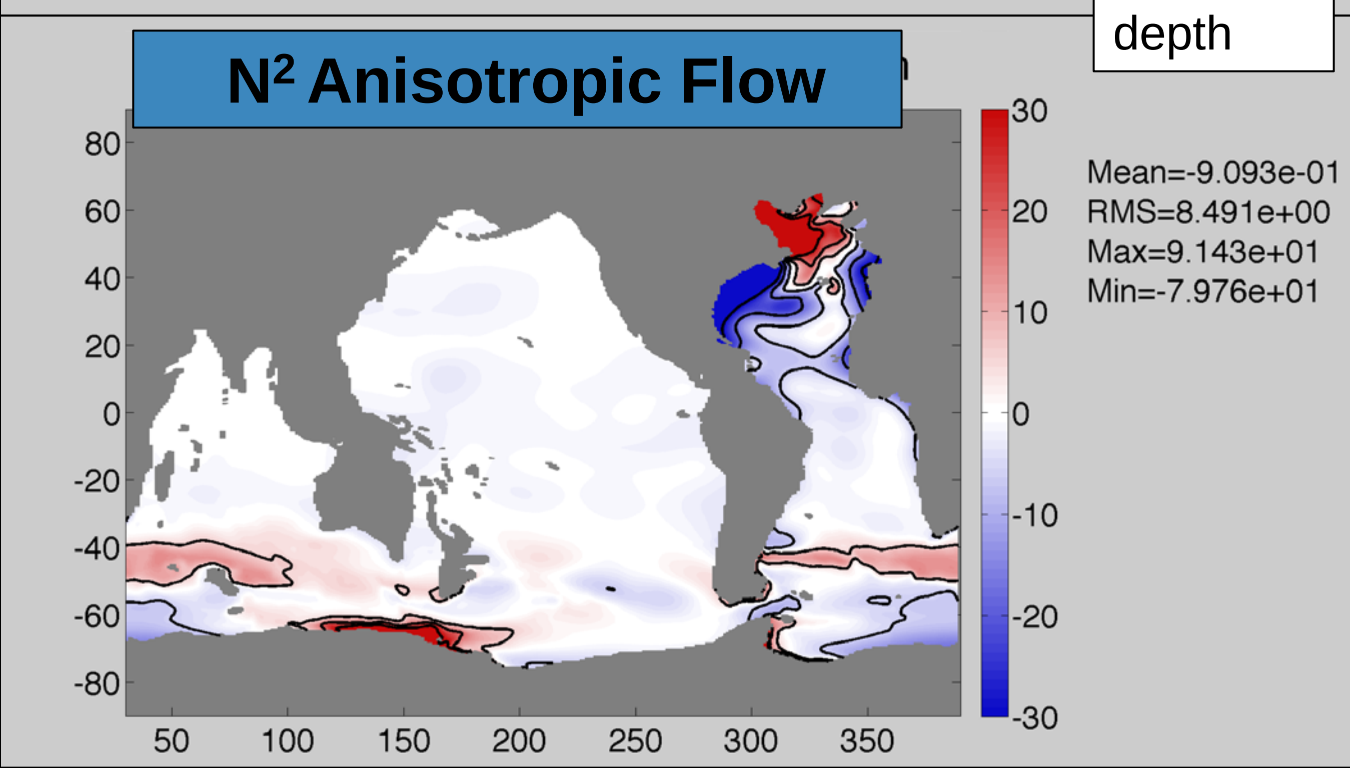
Alignment – T & S Bias



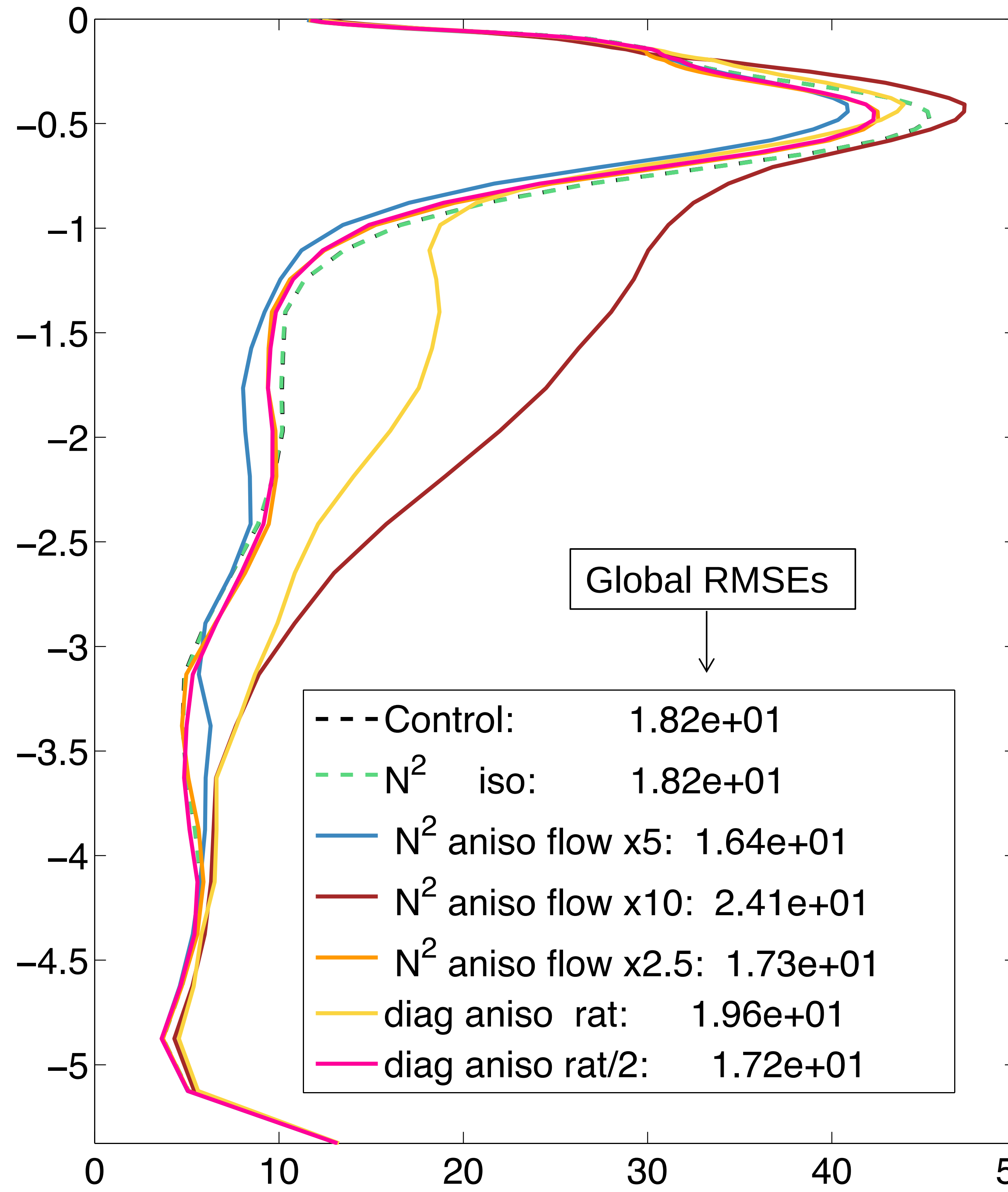
Diffusivity Ratio – pCFC11 Bias

Too much ventilation in Southern ocean when diagnosed diffusivity ratios are used

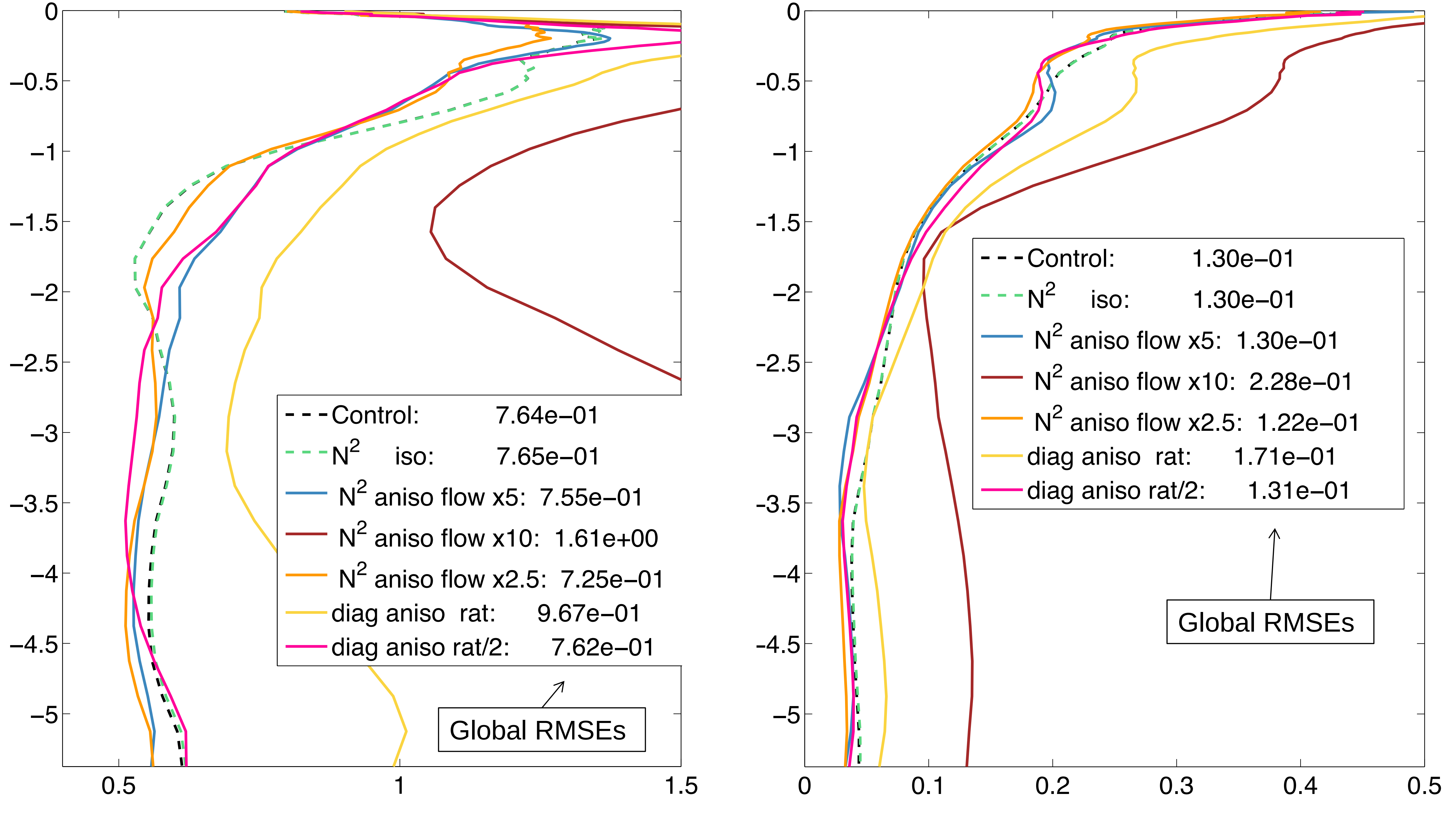




At 1.5km depth



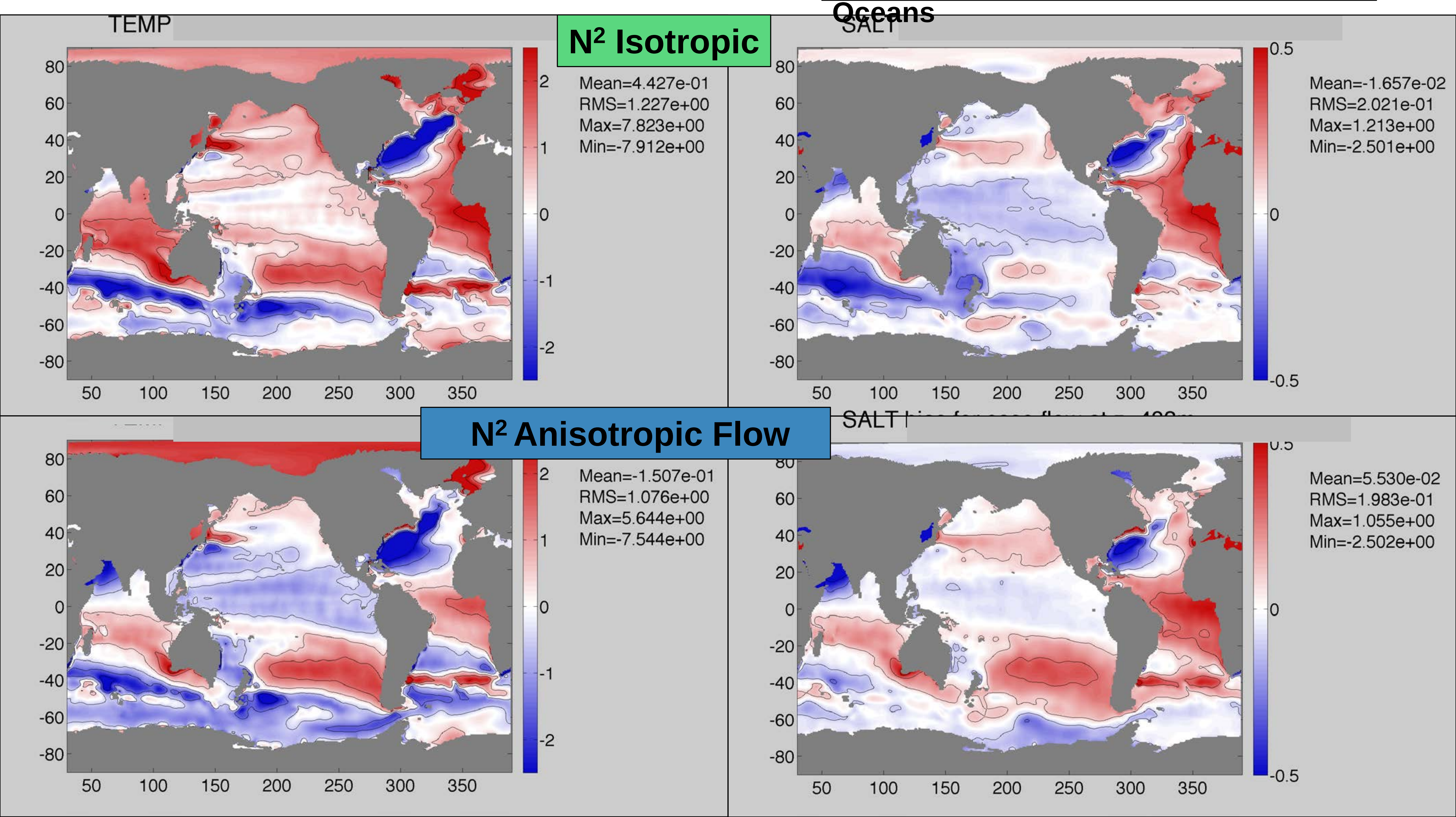
Diffusivity Ratio – T & S Bias



T & S Bias at z=483m

Nearly ubiquitous temperature bias reduction

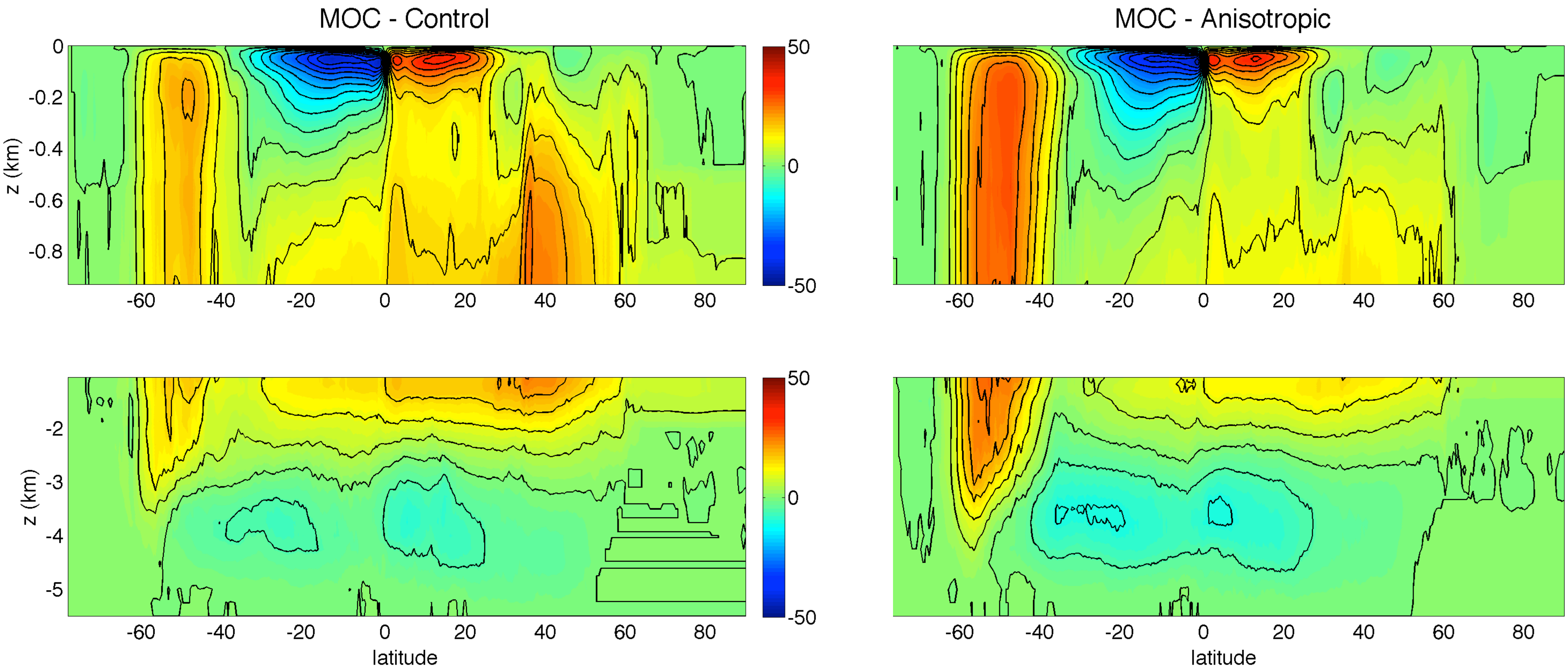
Large salinity bias reduction in Atlantic (North & Tropics) and Southern Oceans



MOC

Anisotropy weakens* MOC

N² Isotropic | **N² Anisotropic Flow**



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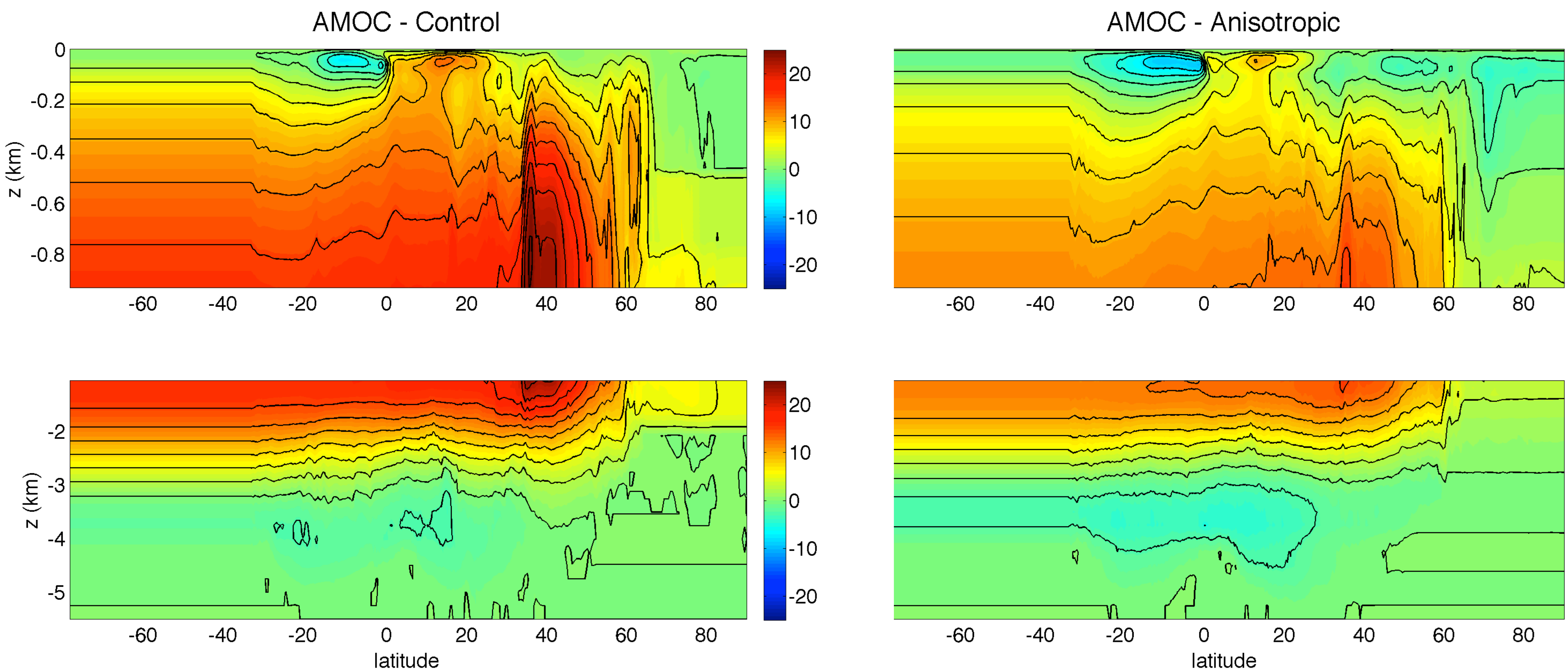
*CESM1 has one of the strongest AMOC among CORE-II simulations (Danabasoglu, 2014)

AMOC

Anisotropy **weakens*** MOC

N^2 Isotropic

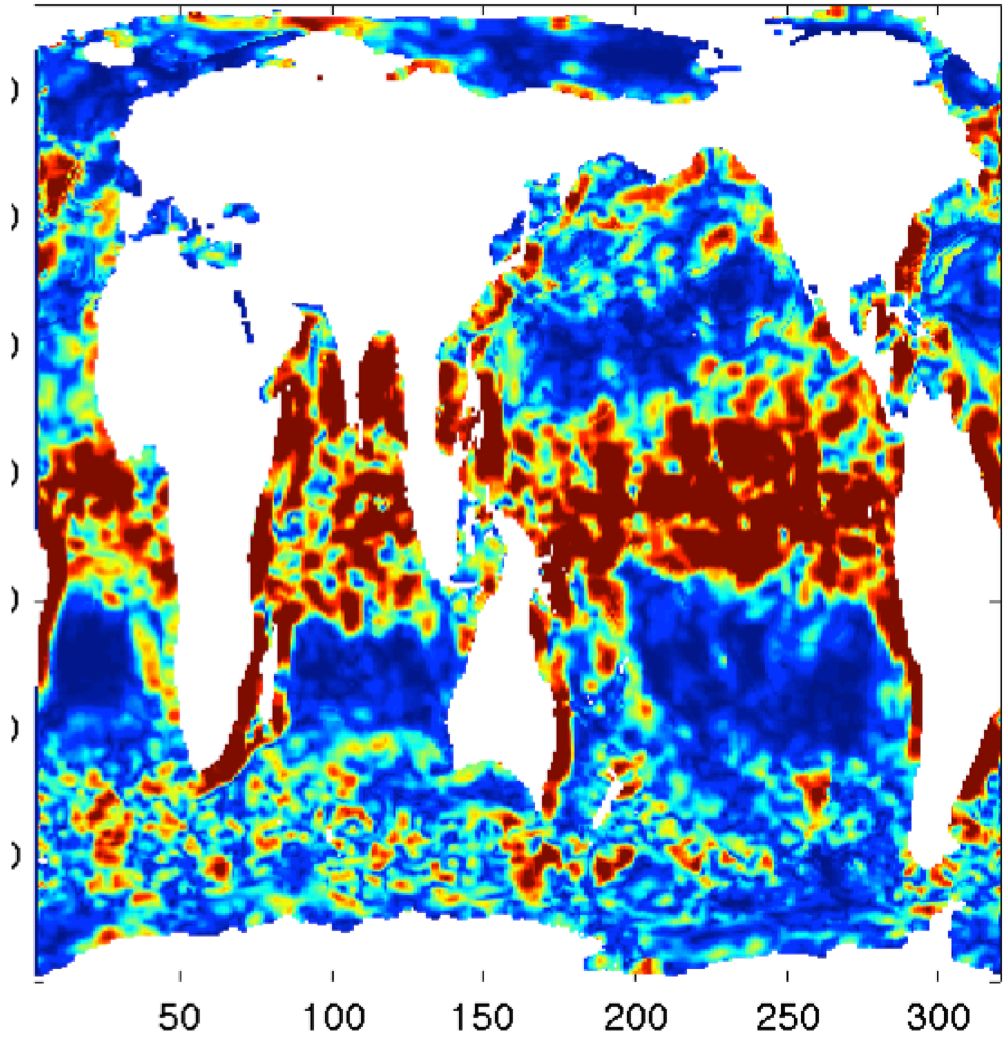
N^2 Anisotropic Flow



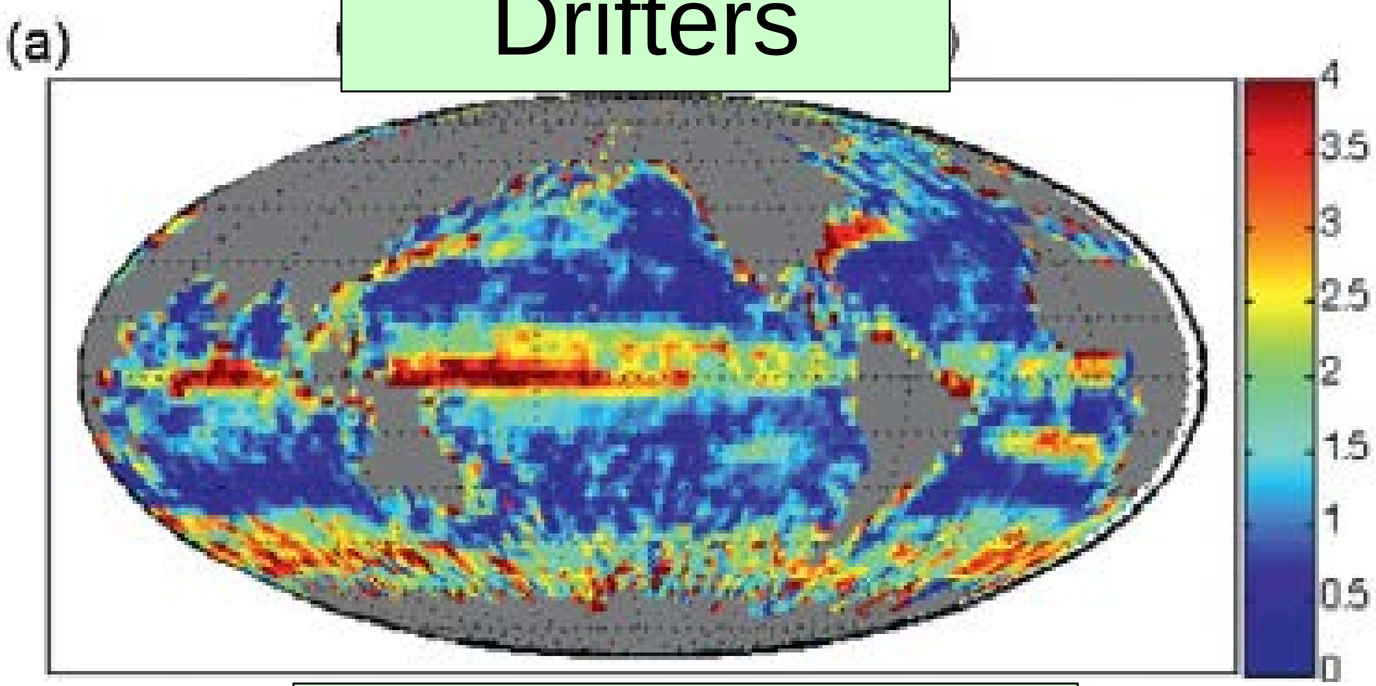
*CESM1 has one of the strongest AMOC among CORE-II simulations (Danabasoglu, 2014)

Shear Dispersion Parameterization – Diffusivity Ratio Maps

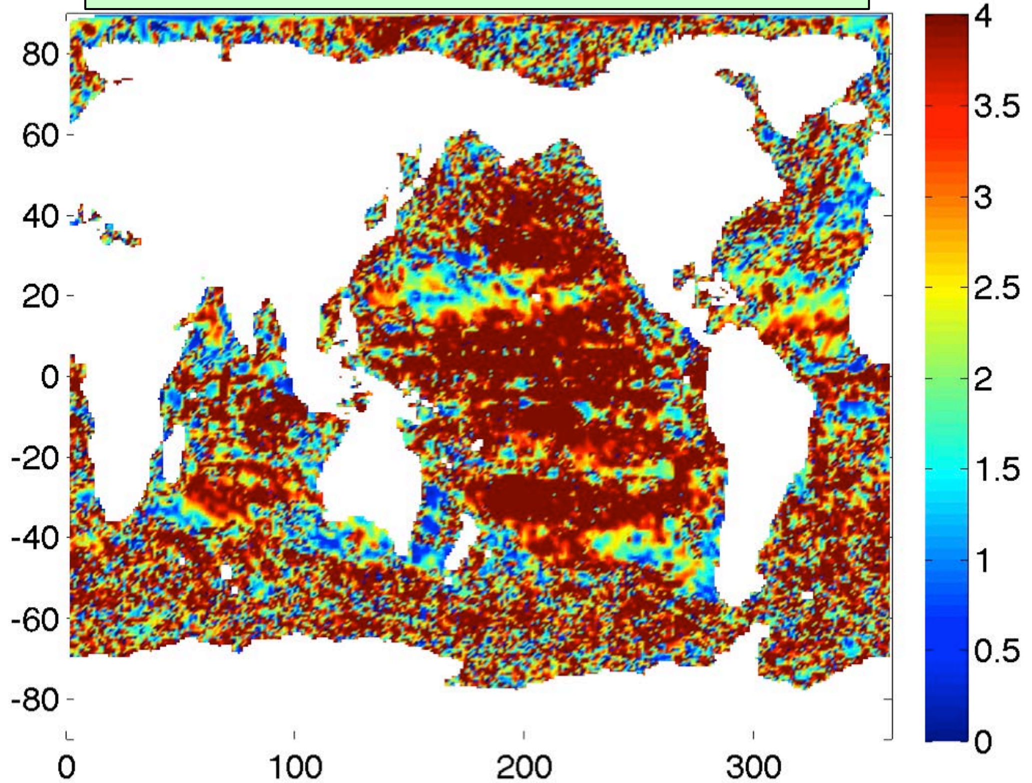
Preliminary Calculation



Drifters



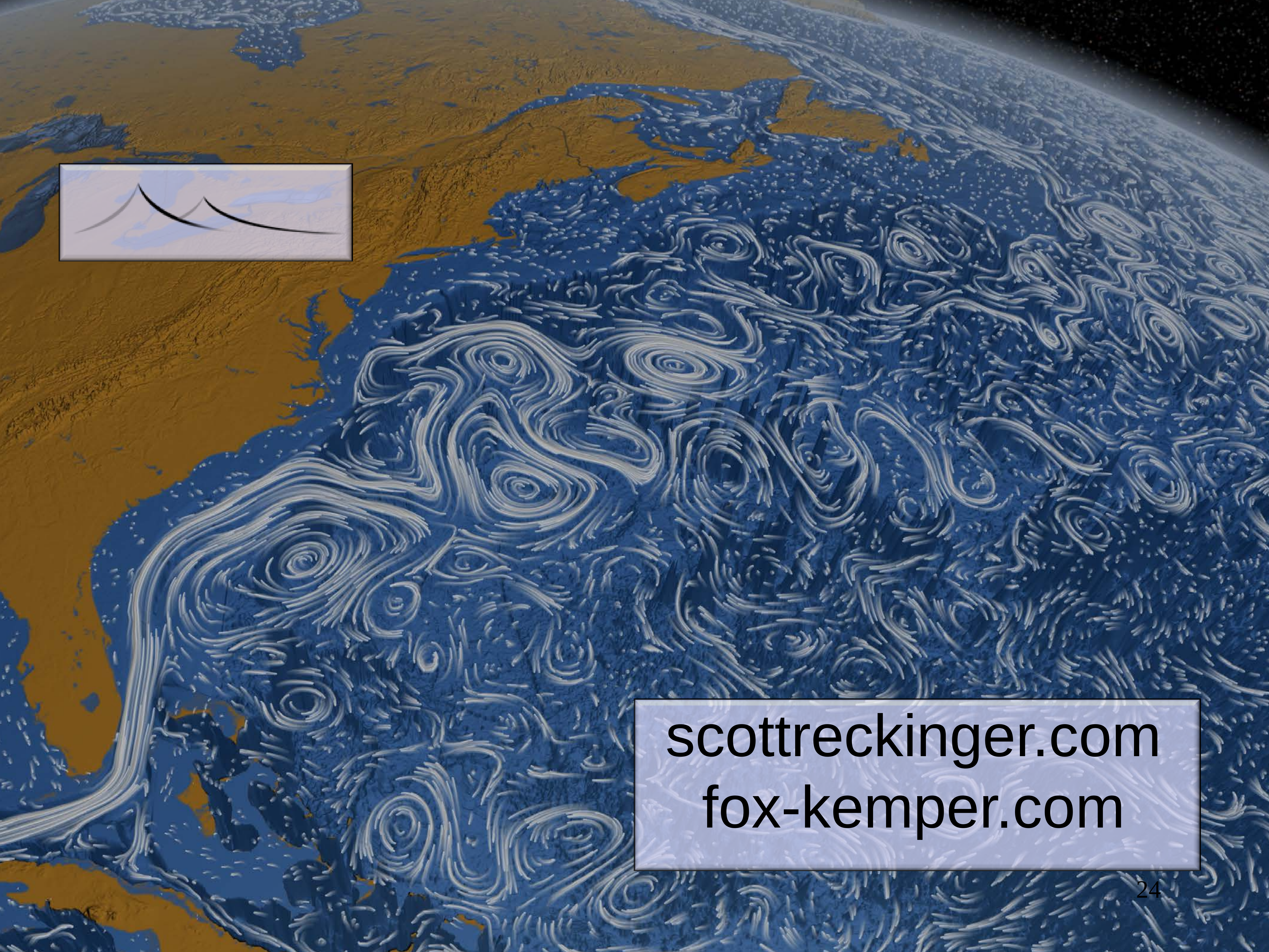
Hi-res diagnosis



Early stage of parameterization development produces diffusivity ratio map similar to drifters

Conclusions and Future Work

- Mesoscale eddies **anisotropically diffuse** along and **flatten** isopycnals
- Anisotropic GM/Redi: control the eddy transport processes in a way that is **justified theoretically**, **matches observations**, and can be **diagnosed from high resolution simulations**
- **Parameters**: major diffusivity, minor diffusivity, & orientation
- Implemented and tested with **PBCs**
- Prognostic utilization of diagnosed diffusivity tensor consistently mixes too strongly
- Simple idea, $\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}} = 5$, aligned with flow, **improves biogeochemical tracer ventilation** and **reduces temperature and salinity biases**
- Next step: parameterize anisotropic transport mechanisms
(Shear dispersion – major enhancement, PV-barriers – minor suppression, etc.)
- Important factors not explored: background diffusivity, relationship between isotropic diffusivity and background diffusivity, near surface transition, etc.


scottreckinger.com
fox-kemper.com

Diffusion and Sources of Anisotropy

- Taylor (1921) – Diffusivity: time rate of change of displacement covariance

(eddy) diffusivity for homogeneous, isotropic (turbulent) field

(eddy) decorrelation timescale

$$\kappa \propto (E)KE * T$$

- Prandtl (1925)

$$\kappa \propto \sqrt{(E)KE} * L$$

(eddy) mixing lengthscale

$$L \propto \sqrt{(E)KE} * T$$

- Taylor (1953) – laminar pipe flow

$$\kappa_{\text{along}} = \kappa + \frac{U^2 a^2}{48\kappa}$$

- Smith (2005) –
QG jet (shear dispersion)

$$\kappa_{\text{along}} = \kappa + \kappa^{-1} \sum_n \frac{|\hat{U}_n^2|}{k_n^2}$$

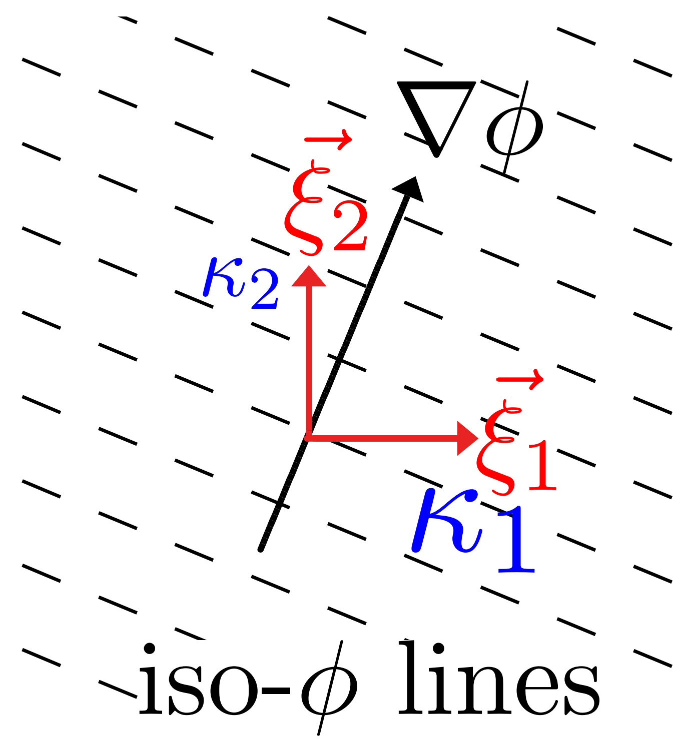
- Ferrari & Nikurashin (2010) – diffusivity suppression in cross-jet or PV-gradient direction

$$\kappa_{\text{across}} = \frac{\kappa}{1 + T^2 L^{-2} U^2}$$

Anisotropic Gent-McWilliams/Redi

- Generalize to anisotropic horizontal diffusion*
  - Symmetric horizontal diffusivity tensor (3 parameters)
    - real eigenvalues => diffusivities (2)
    - orthogonal eigenvectors => principal axes (1)

$$\bar{\bar{K}}_H \vec{\xi}_i = \kappa_i \vec{\xi}_i$$



$$\bar{\bar{K}}_H = \begin{pmatrix} K_{xx} & K_{xy} \\ K_{xy} & K_{yy} \end{pmatrix}$$

$$\vec{S} = \text{isopycnal slope}$$

$$\bar{\bar{K}} = \begin{pmatrix} \bar{\bar{K}}_H & \bar{\bar{K}}_H \cdot \vec{S} \\ \vec{S} \cdot \bar{\bar{K}}_H & \vec{S} \cdot \bar{\bar{K}}_H \cdot \vec{S} \end{pmatrix}$$

$$\bar{\bar{A}} = \begin{pmatrix} 0 & 0 & \multirow{2}{*}{$-\bar{\bar{K}}_H \cdot \vec{S}$} \\ 0 & 0 & \\ \multicolumn{2}{c}{\vec{S} \cdot \bar{\bar{K}}_H} & 0 \end{pmatrix}$$

*Smith & Gent (2004)

Current Timing

- Current Aniso-GM runs a factor of ~2 times slower than Iso-GM CESM1.2 out-of-box
- Greatest cost to BGC, but this is where the most will be gained
- Minor speed reduction (~ 4-7 %) for GIAF compset runs with only 1 passive tracer (IAGE)

Yet to be explored

- Minor suppression
- Background diffusivity
- Relationship between isotropic diffusivity and background diffusivity
- Near surface transition