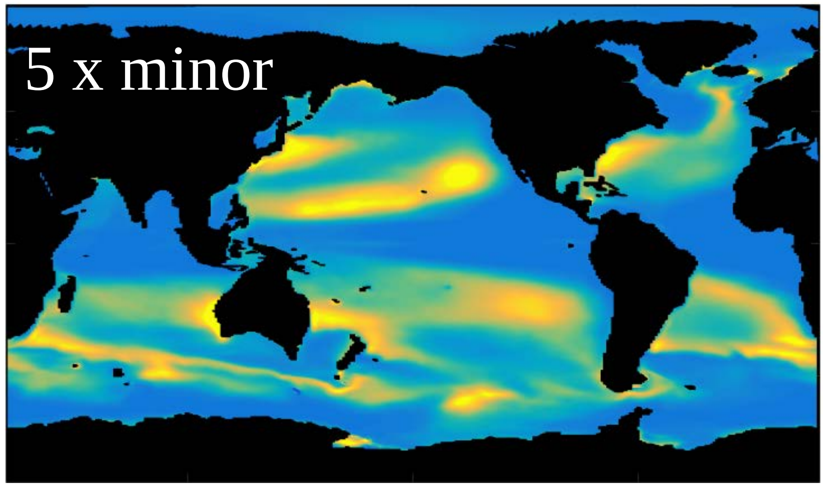
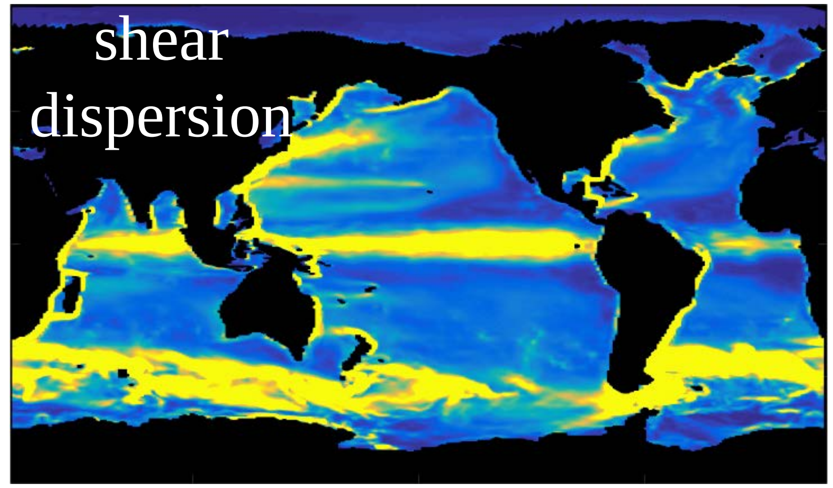
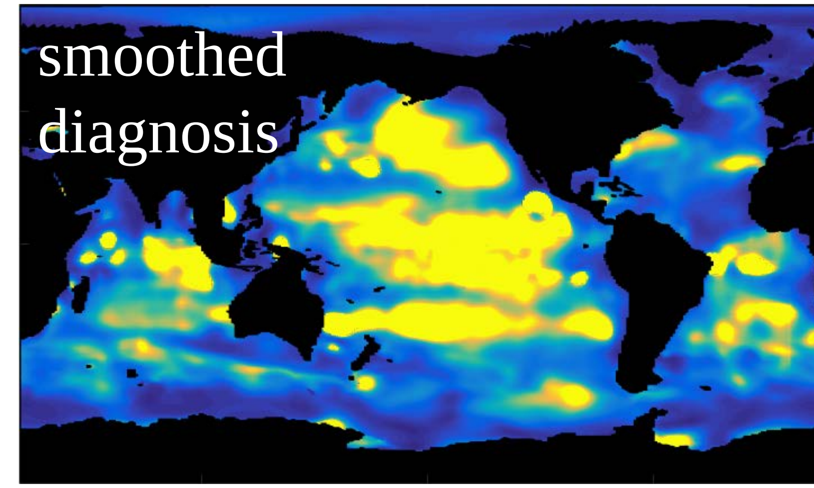
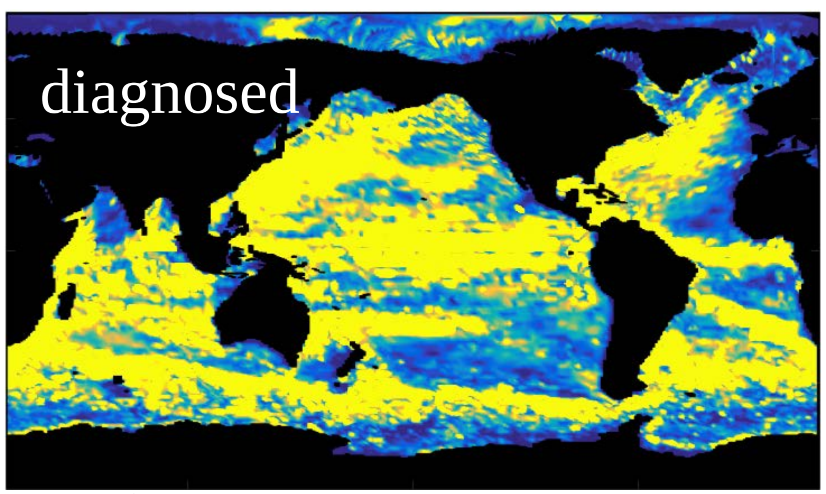






Anisotropic Mesoscale Eddy Parameterization for Shear Dispersion



Scott J. Reckinger*

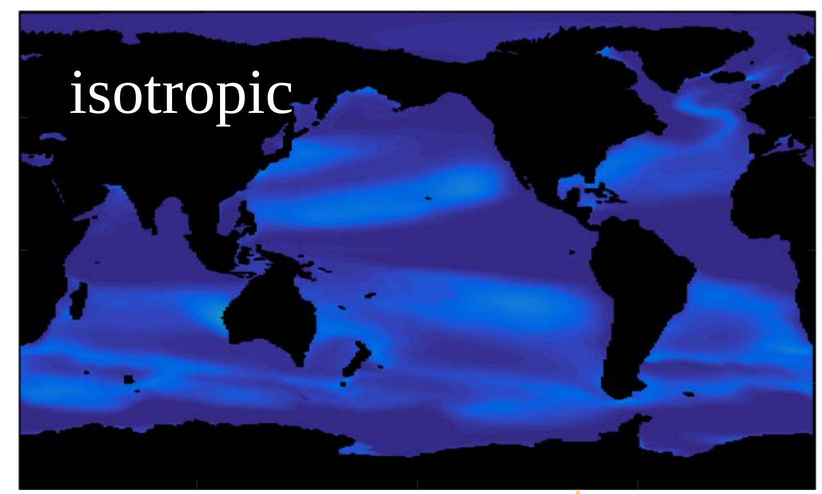
Baylor Fox-Kemper[+,++]

Scott Bachman[++]

Gokhan Danabasoglu**

John Truesdale**

Frank Bryan**



* Montana State Univ.
[+] Brown University
[++] Cambridge Univ.
** NCAR

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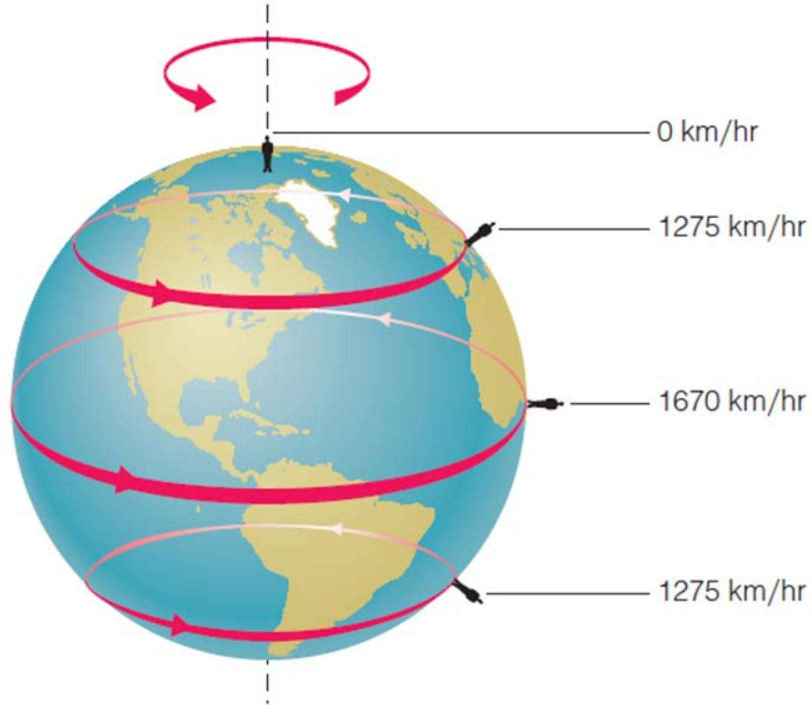
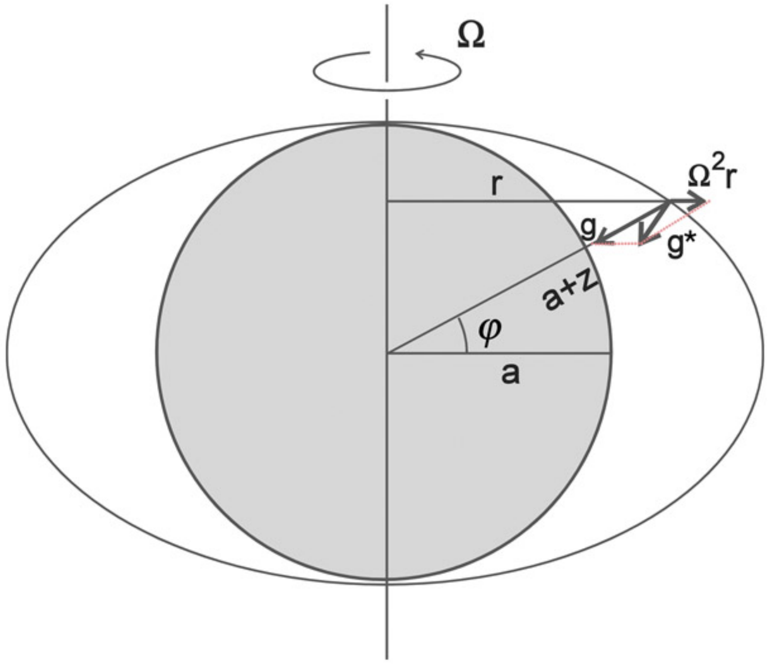
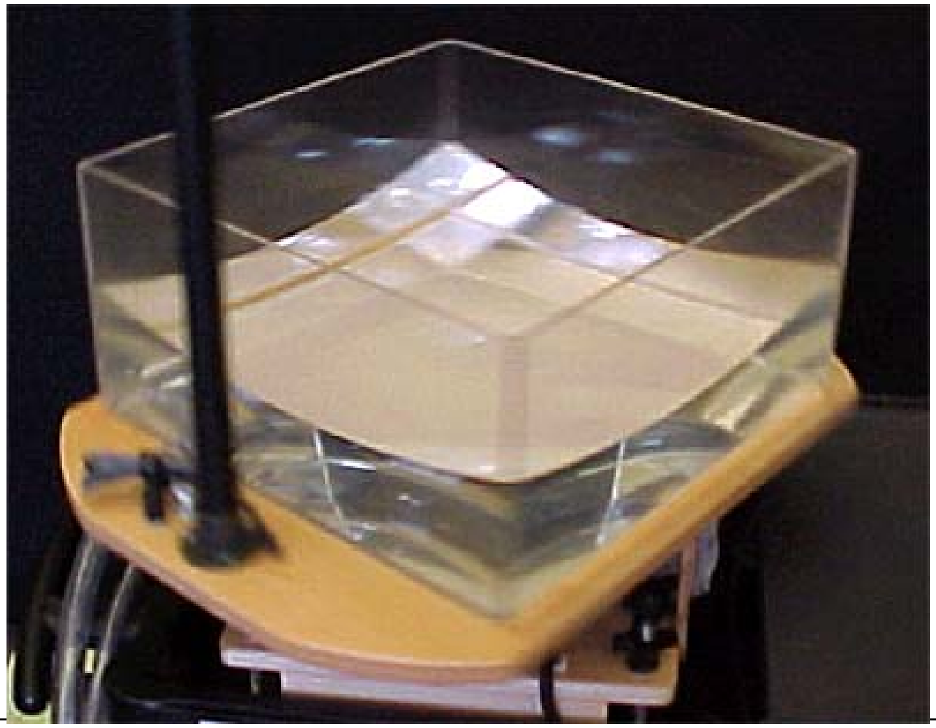
CESM OMWG Meeting
February 9th, 2016
Boulder, CO

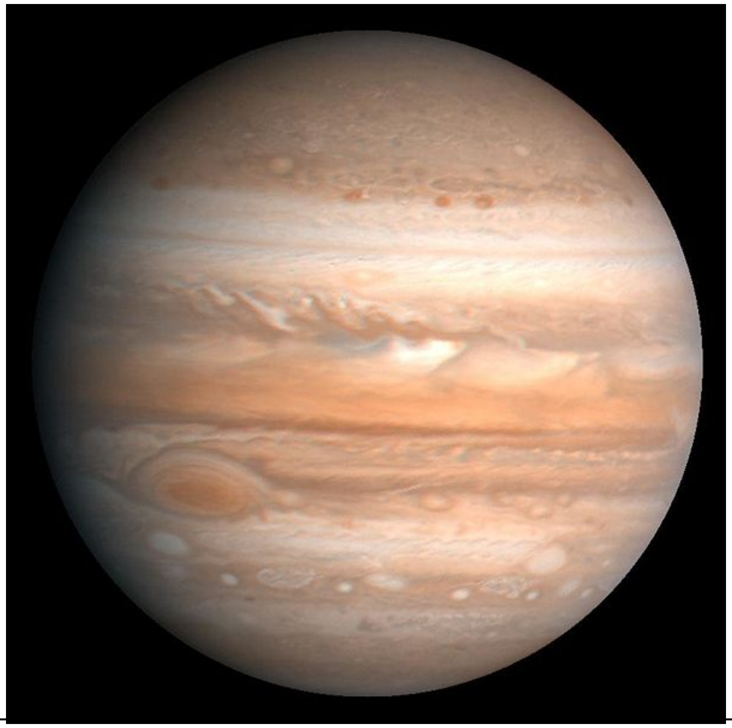
MONTANA STATE UNIVERSITY

Flow Viz – Solid Body Rotation









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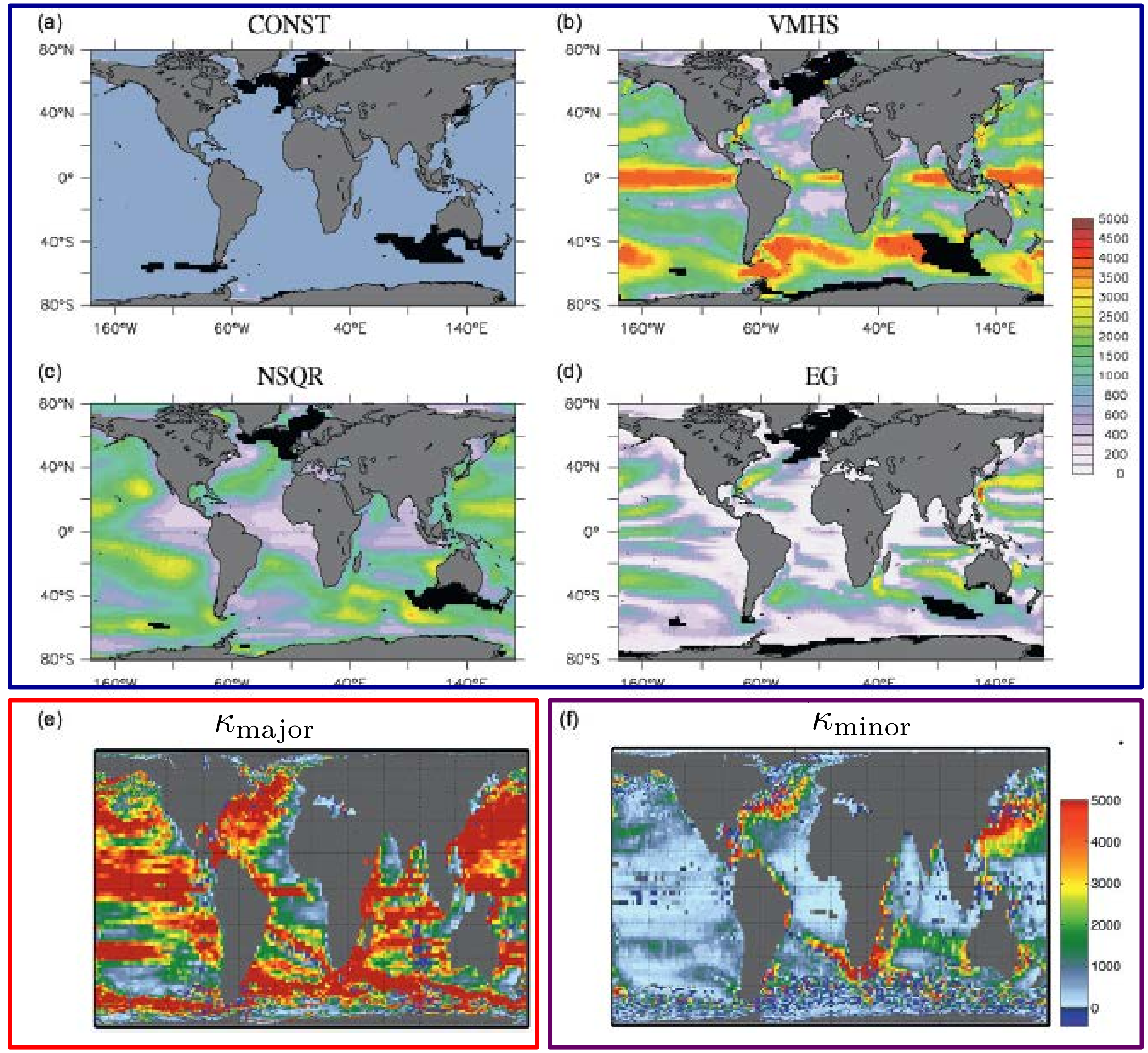
Mesoscale Eddy Parameterization

- Parameterizations previously used 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)

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:

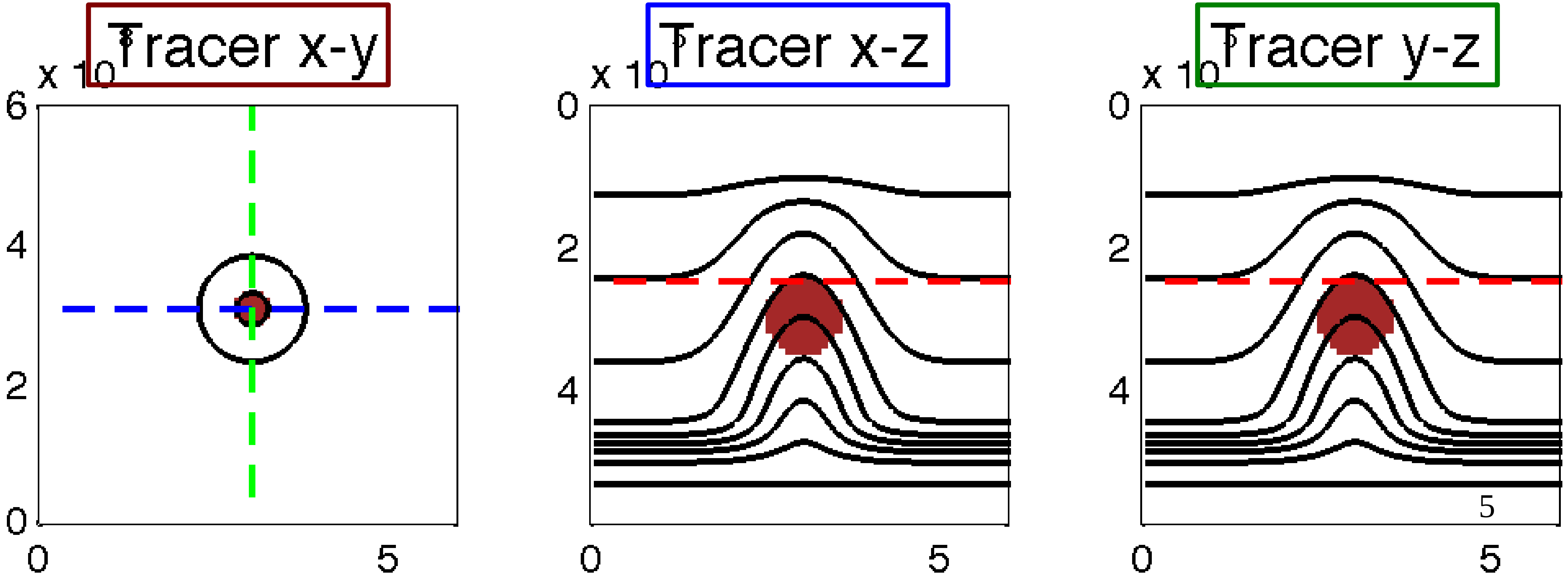
$$\partial_t \phi + \vec{u} \cdot \nabla \phi = \nabla \cdot \left(\bar{\bar{K}} + \bar{\bar{A}} \right) \cdot \nabla \phi$$

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 Diffusivity Tensor

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

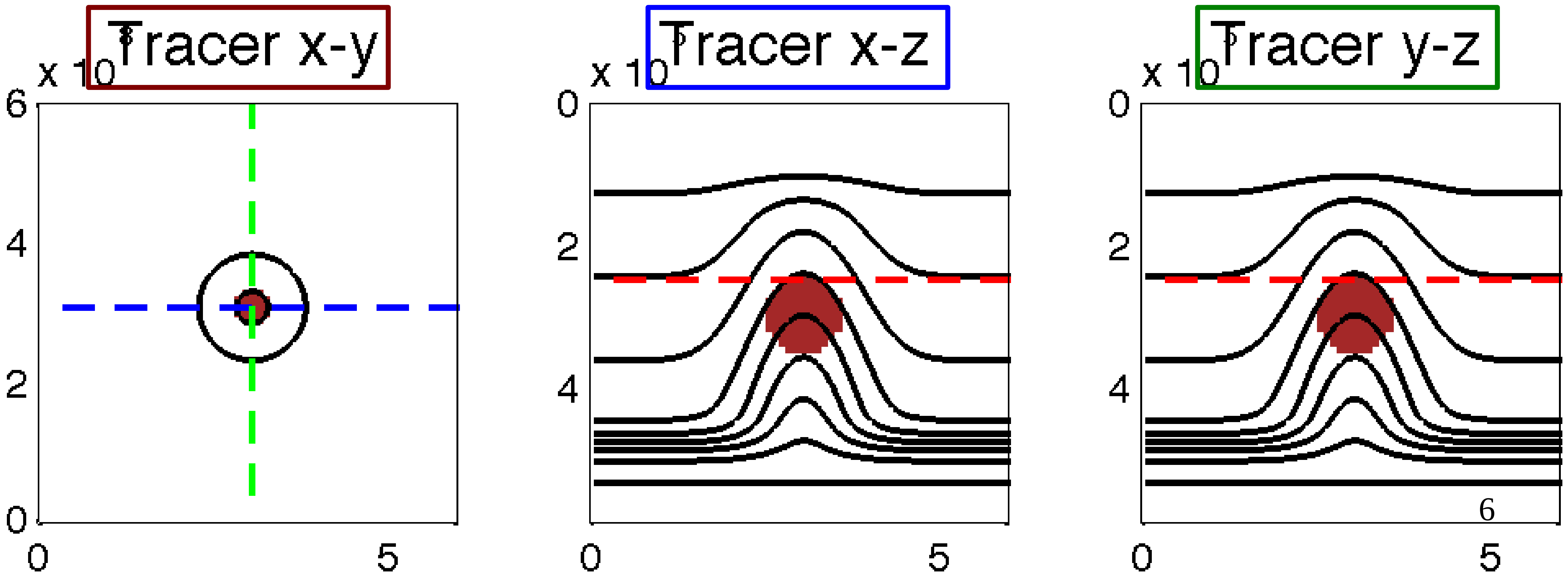
$$\partial_t \phi + \vec{u} \cdot \nabla \phi = \nabla \cdot \left(\bar{\bar{K}} + \bar{\bar{A}} \right) \cdot \nabla \phi$$



Eddy Advective Tensor

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

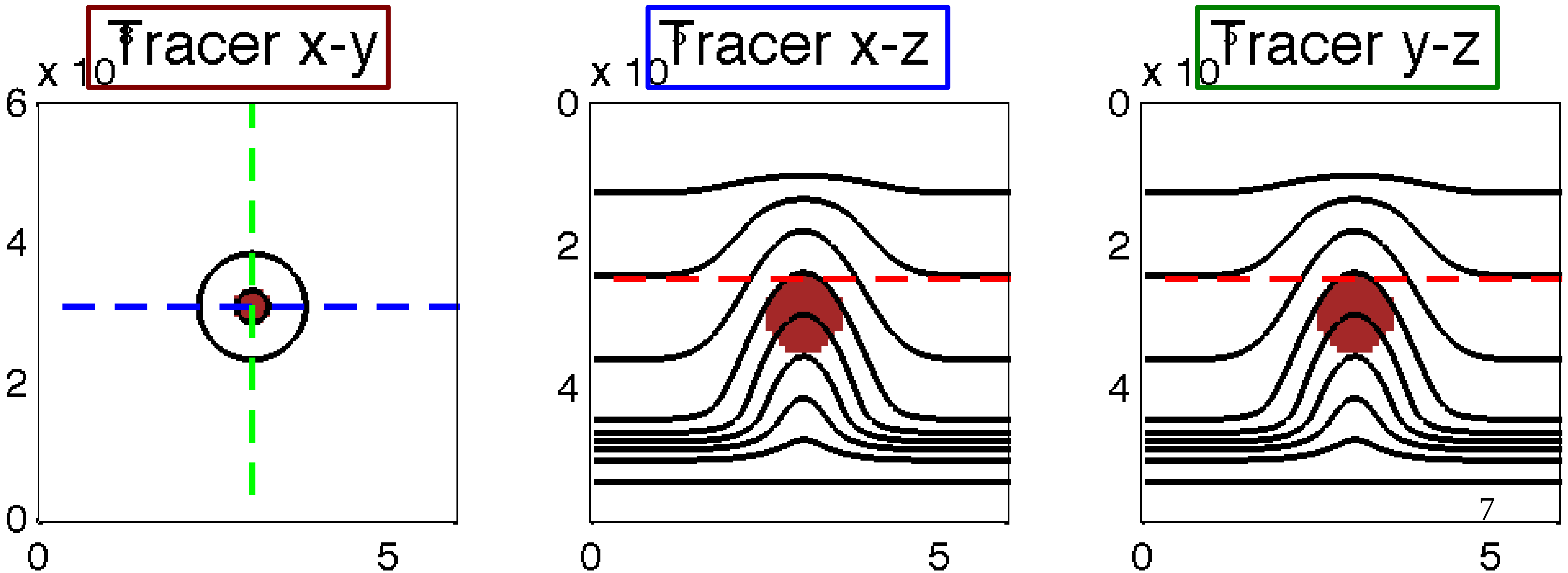
$$\partial_t \phi + \vec{u}\cdot\nabla\phi = \nabla\cdot\left(\bar{\bar{K}} + \bar{\bar{A}}\right)\cdot\nabla\phi$$



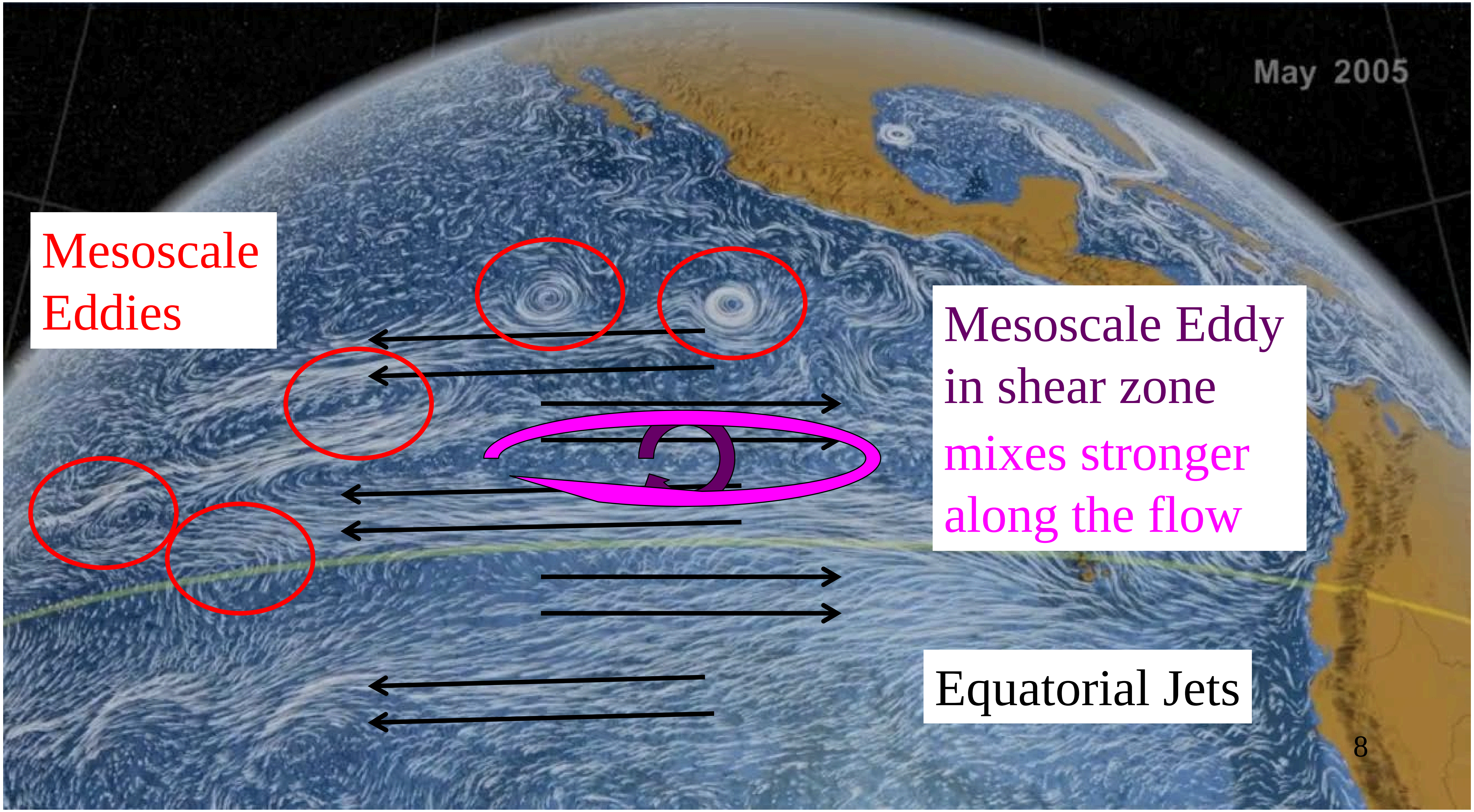
Eddy Transport Tensor

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

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



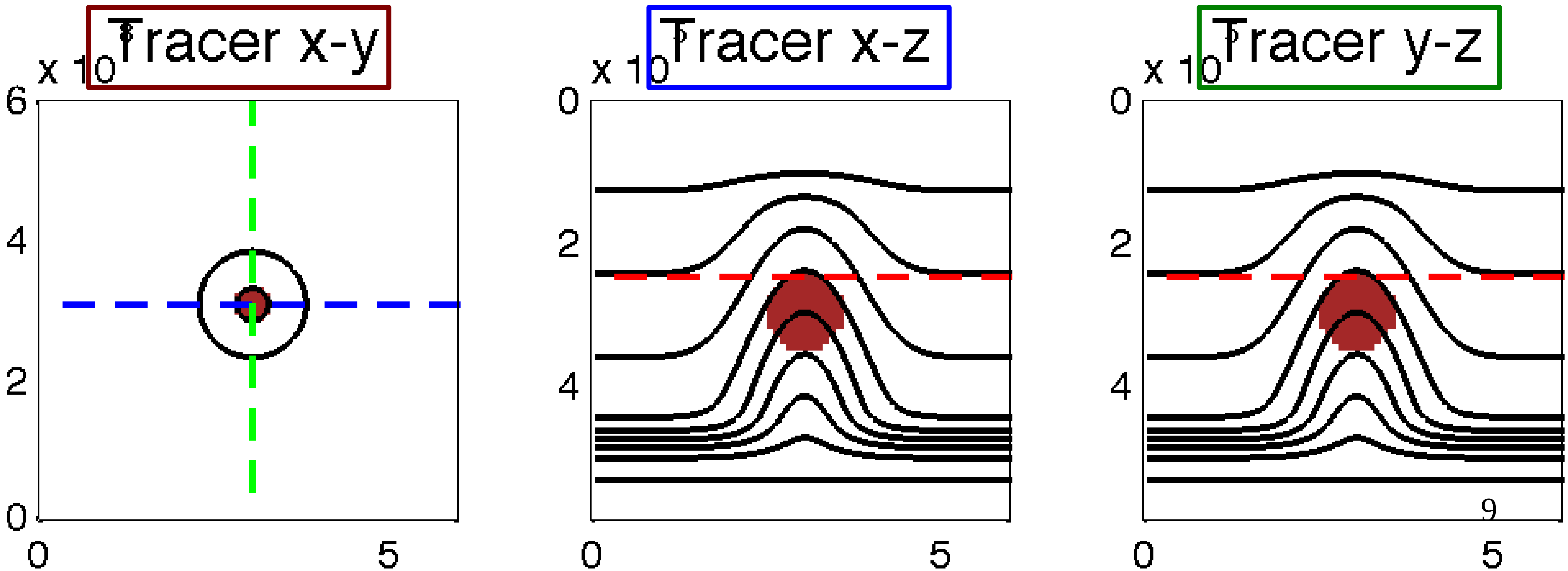
Anisotropy: Shear Dispersion



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.

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



Anisotropic GM/Redi

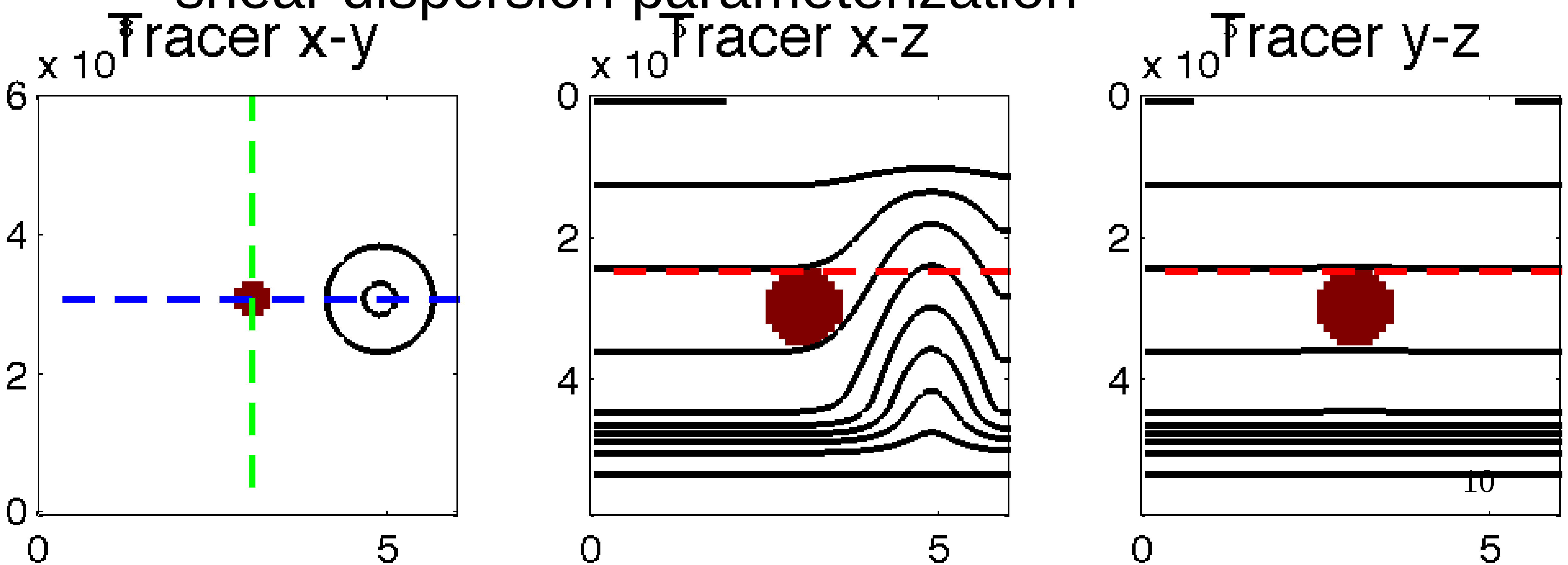
Investigate sensitivity to anisotropy…

$\kappa \rightarrow$ 1. κ_{minor} (suppression from background diffusivity, κ)

2. κ_{major} (enhancement from background diffusivity, κ)

3. $\sin(\theta)$ (alignment of principal axis of diffusion)

… to educate the development of the shear dispersion parameterization

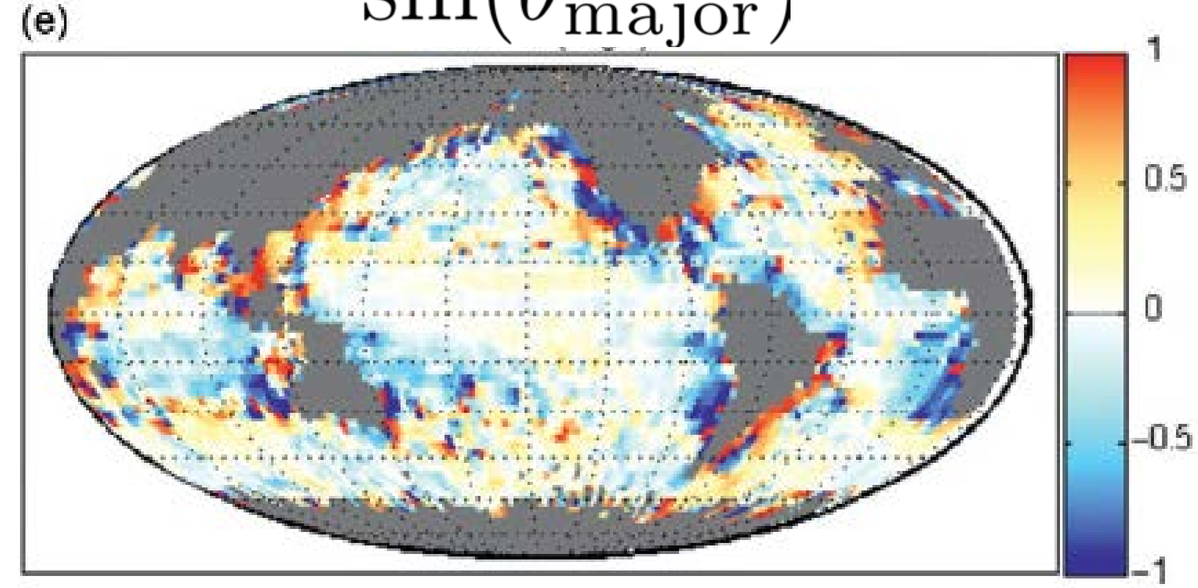


Drifter Observation Diffusivity Tensor

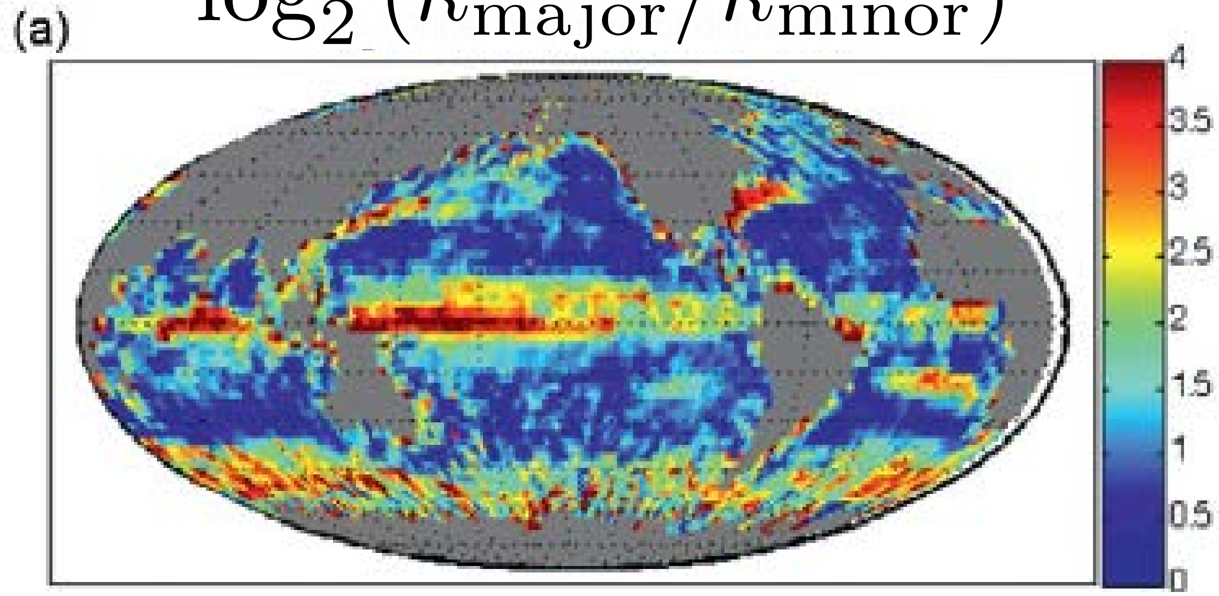
- Principal axis alignment
  - Major axis **aligned zonally** away from boundary currents
  - Major axis **aligned with the flow** near boundary currents

- $\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}}$
  - **> 16** in equatorial region
  - Typical ratio is **≈ 5**

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



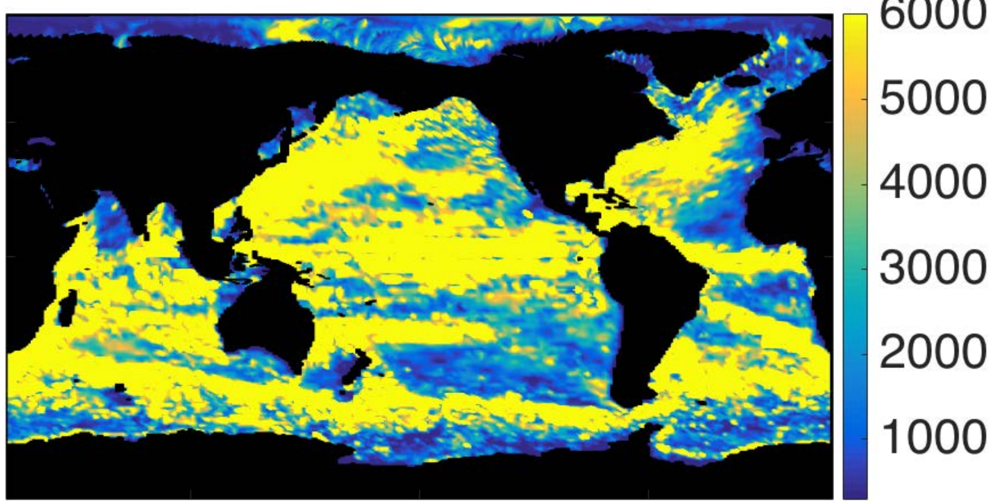
$\log_2(\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}})$



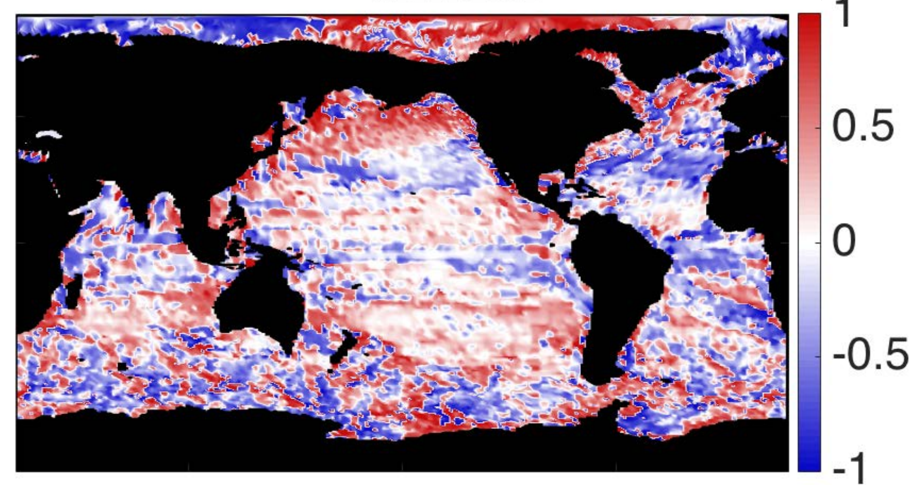
*Fox-Kemper et al (2013)

Hi-res Diagnosed Tensor

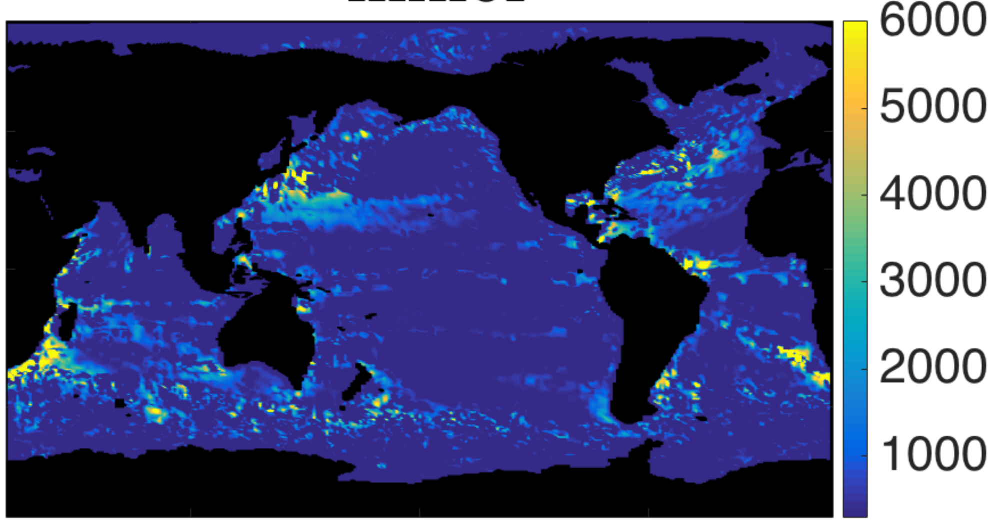
κ_{major}



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



κ_{minor}



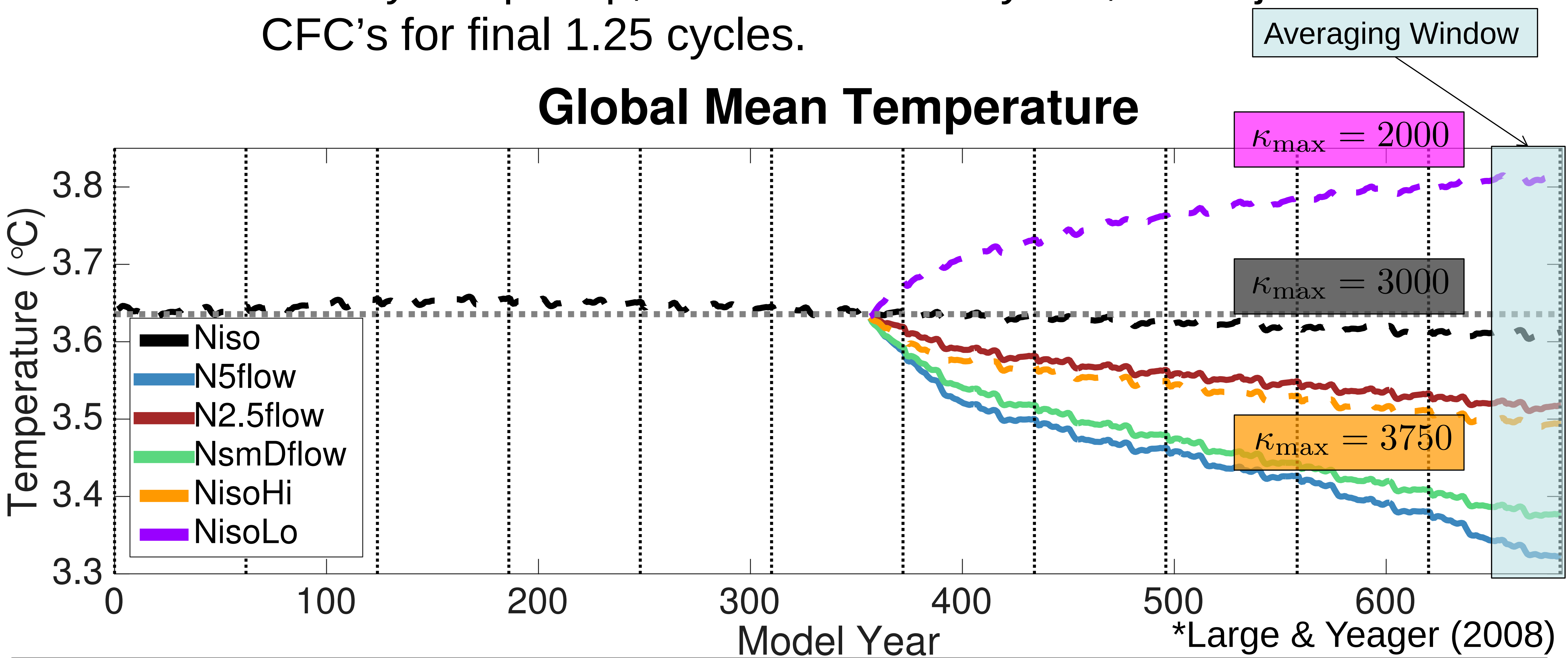
- 0.1 degree POP2 with 9 passive tracers (various orientation restoring)*
- Diffusivities calculated using least-squares
- Tensor applied statically in 1-degree tests (CORE-forced, 5 cycles)

*Bachman & Fox-Kemper (2013)

*Fox-Kemper et al (2013)

Summary of Numerical Experiments

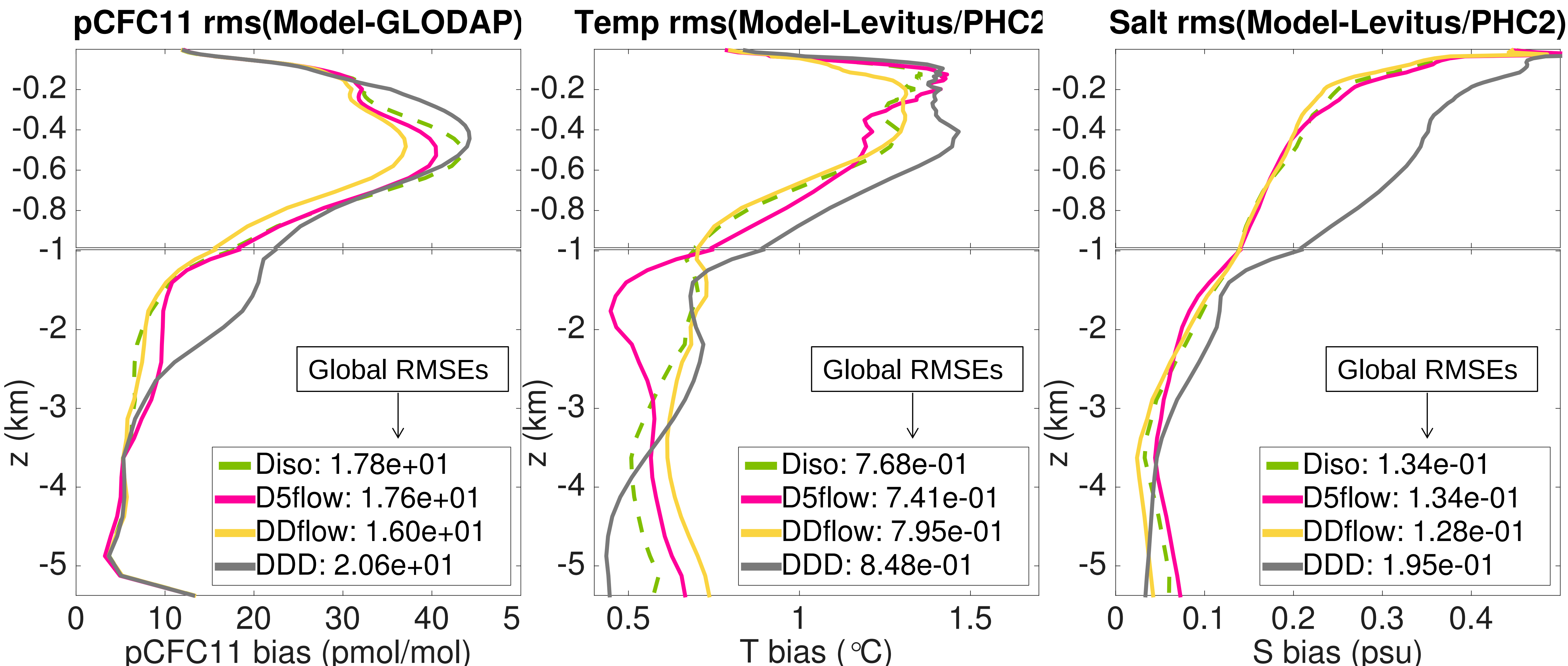
- Community Earth System Model (CESM1.2)
  - CORE 62-year interannual forcing (GIAF compset)*
  - 1° resolution (gx1v6 grid)
  - 5.75 cycle spin-up, branch for 5.25 cycles, and inject CFC's for final 1.25 cycles.



*Large & Yeager (2008)

Larger diffusivities = cooling drift, smaller diffusivities = warming drift

Hi-res Diagnosed Tensor Study



Isotropic version of diagnosis

minor only: ratio=5, flow-aligned

major & minor only: flow-aligned

full diagnosed tensor

High sensitivity to orientation!

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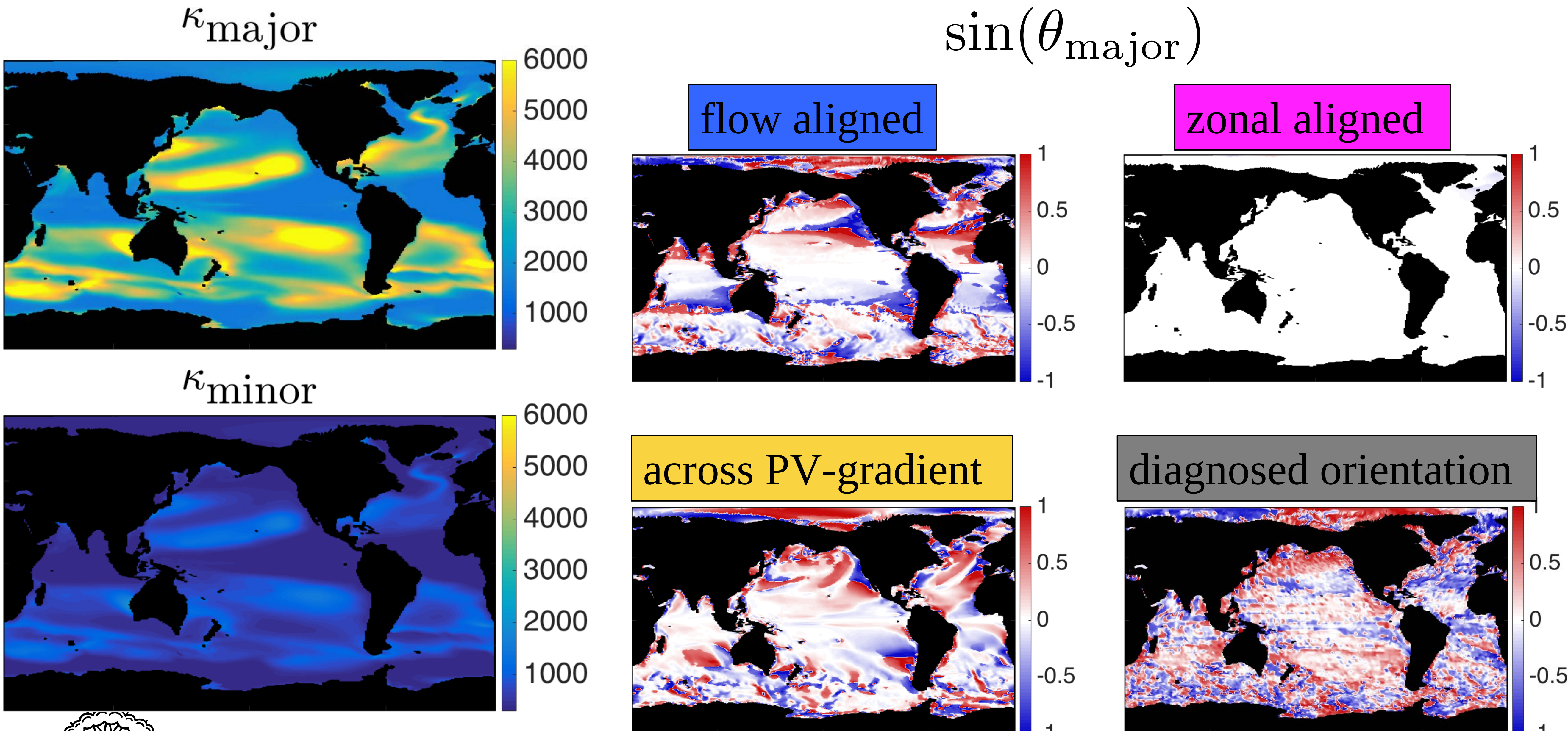
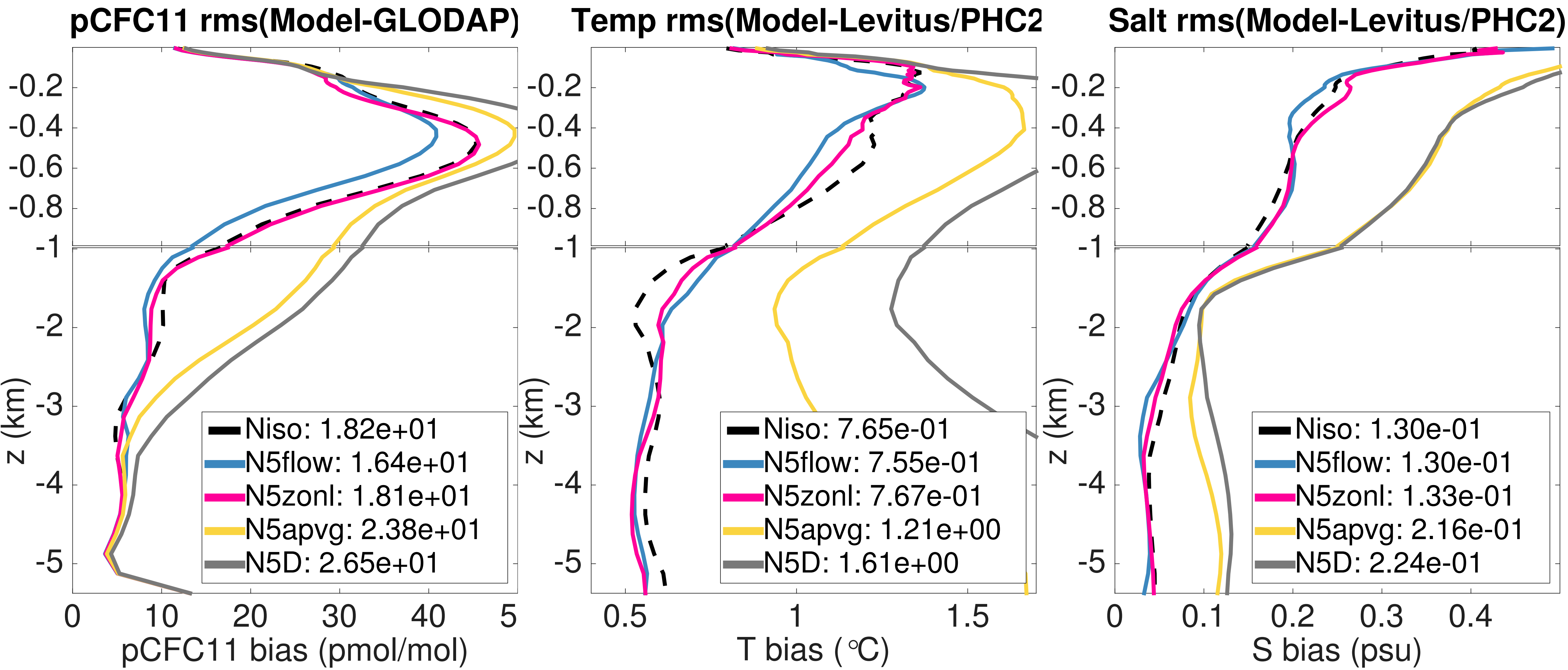
Major Axis Alignment Study

- N^2 parameterization for minor, ratio=5



Major Axis Alignment Study



N^2 isotropic | flow aligned | zonal aligned | across PV-gradient | diagnosed

Flow alignment is best!

Anisotropic GM/Redi

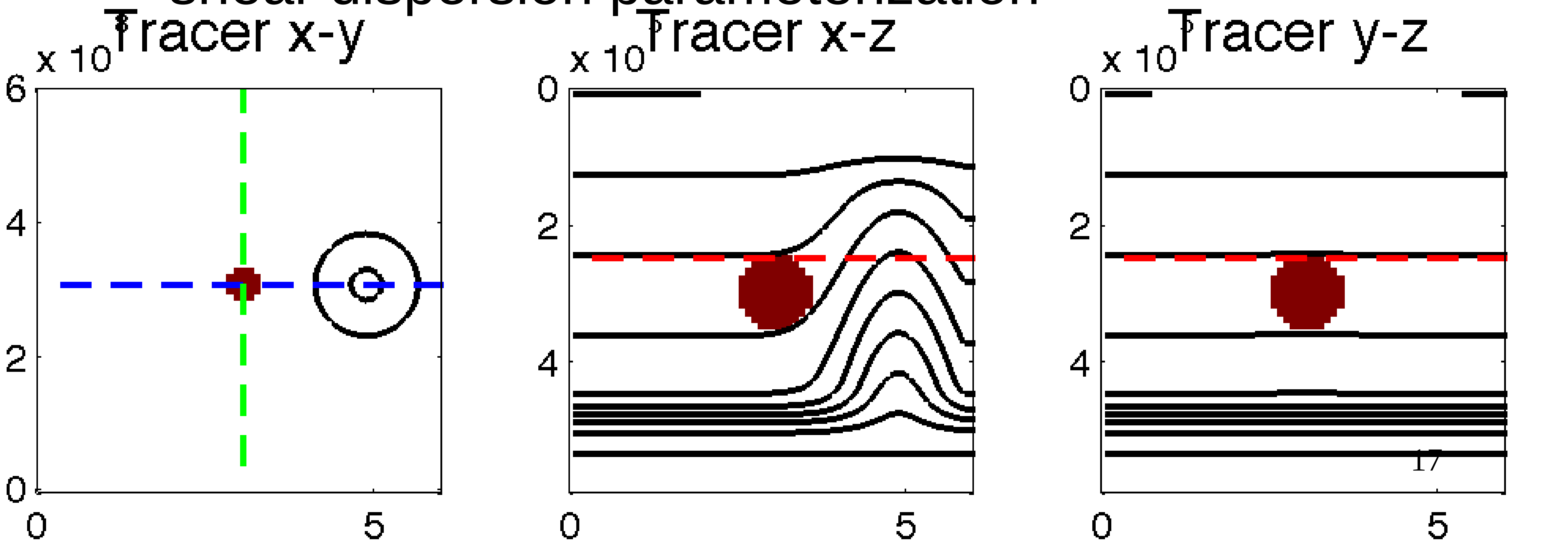
Investigate sensitivity to anisotropy…

κ →

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

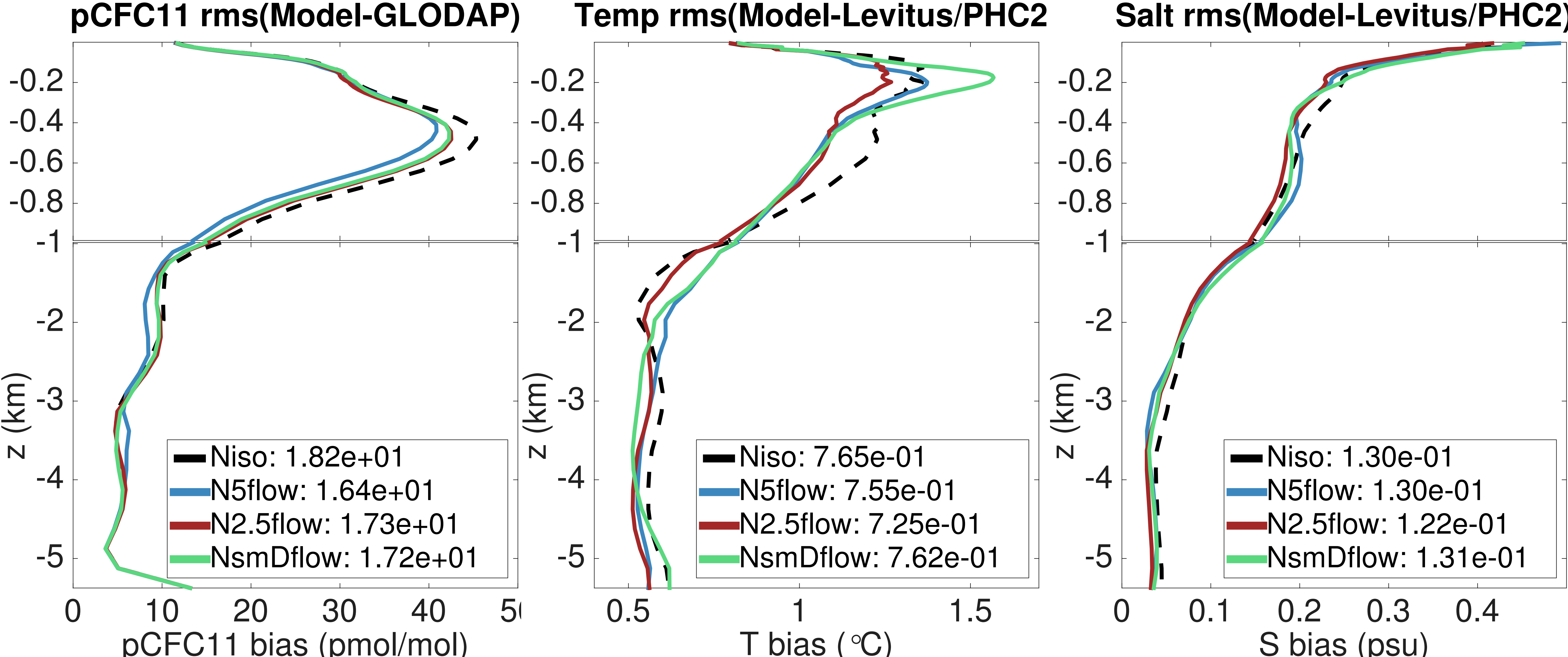
flow-alignment is best, consistent with shear dispersion

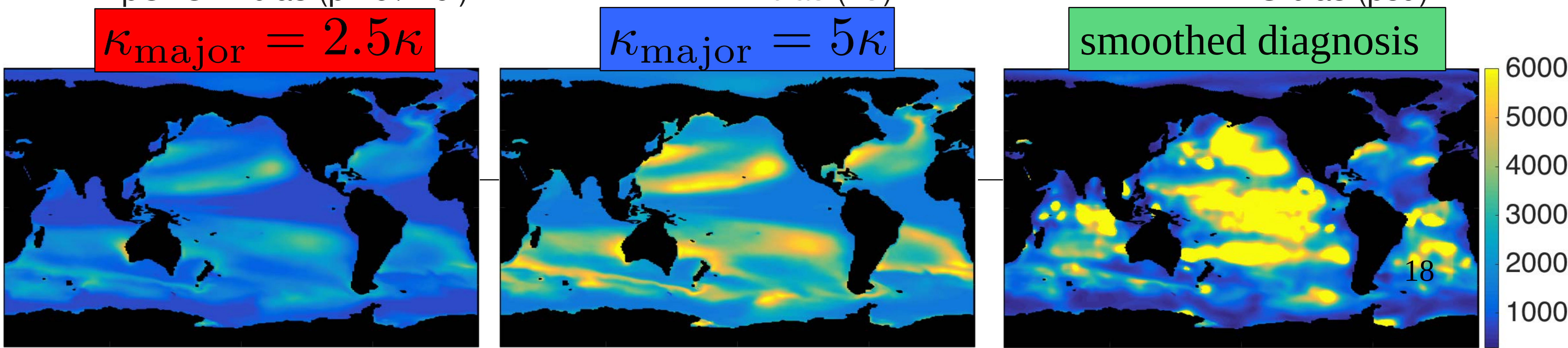
… to educate the development of the shear dispersion parameterization

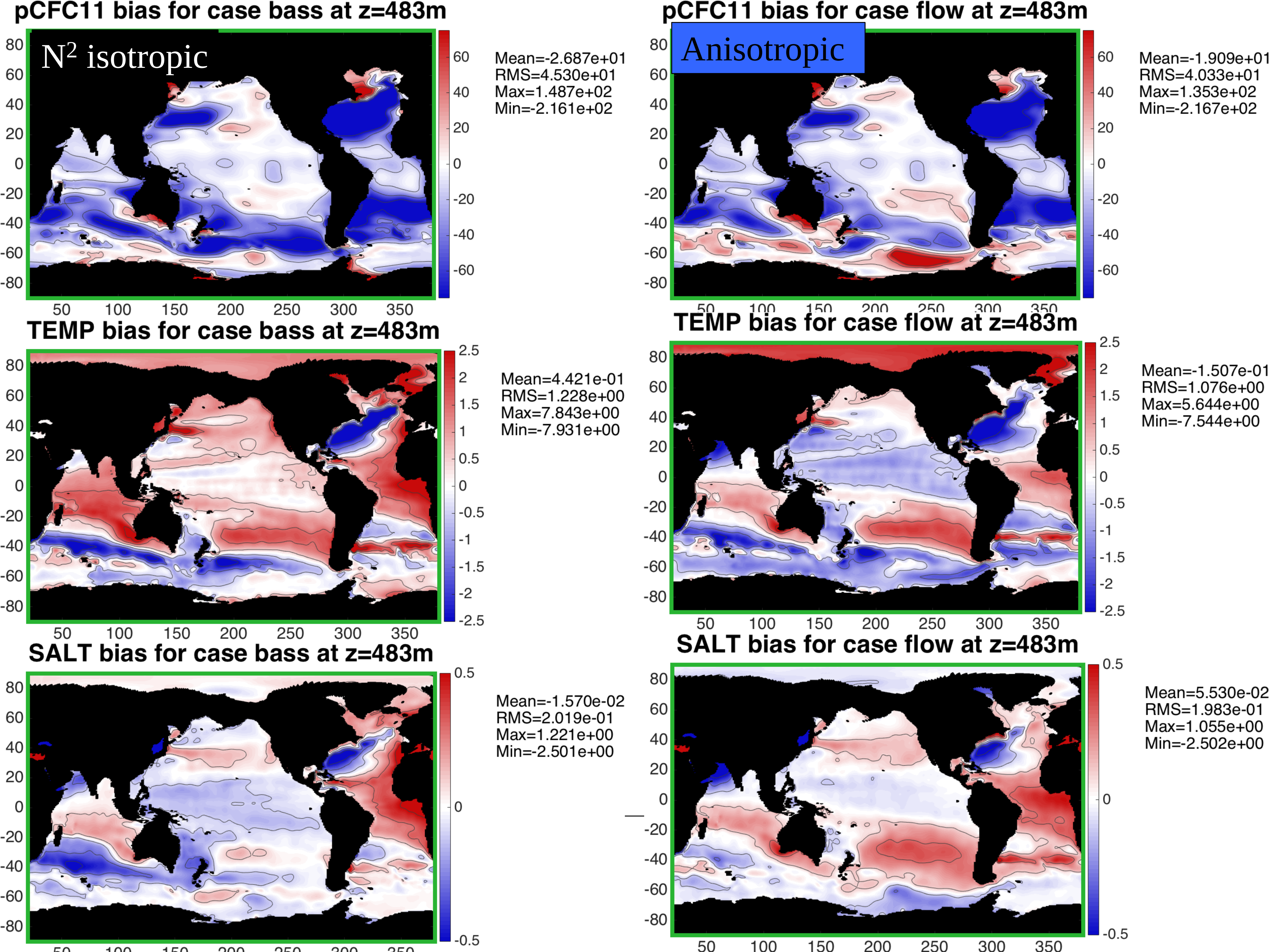


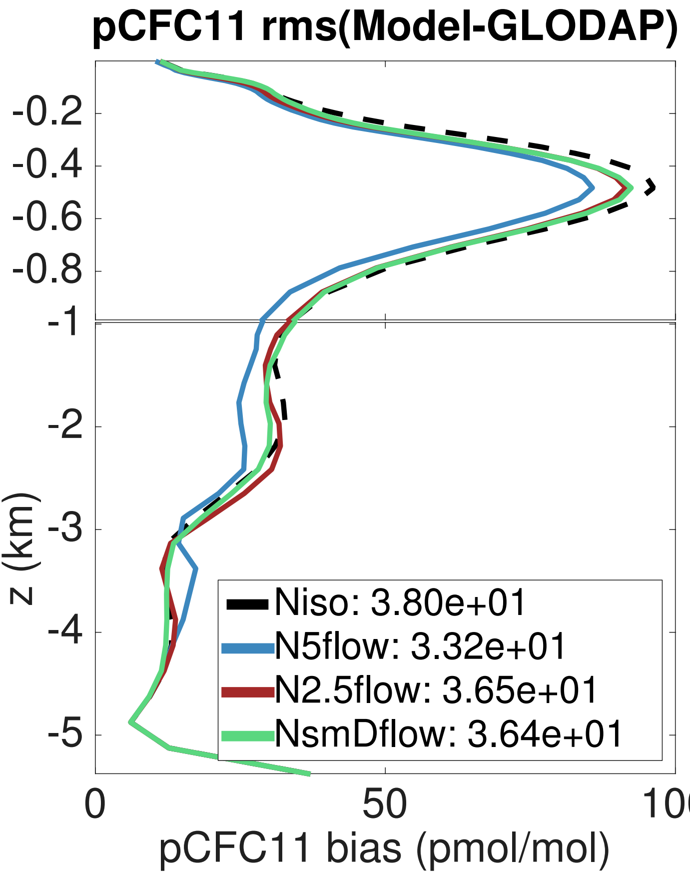
Diffusivity Ratio Study

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

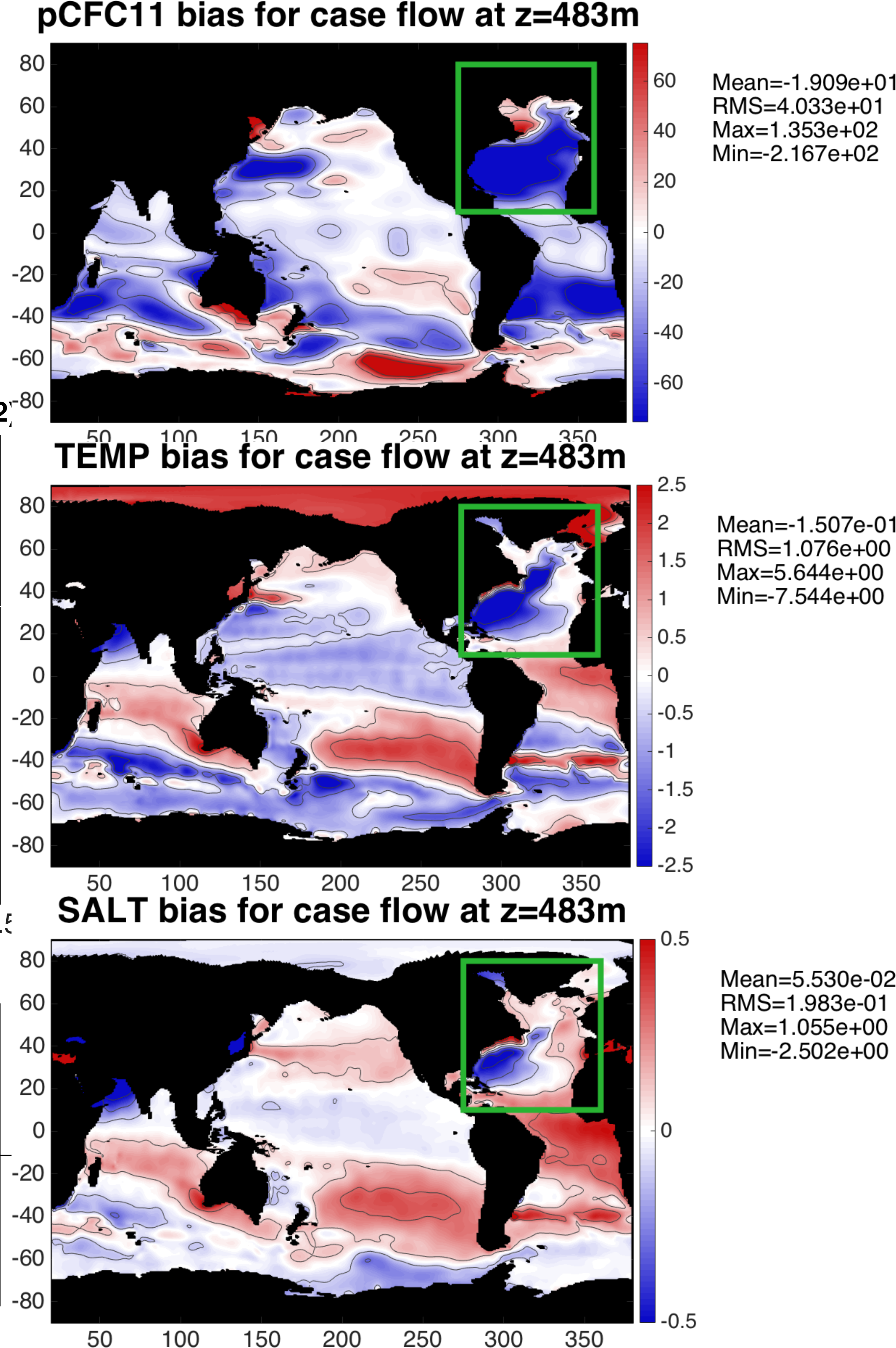


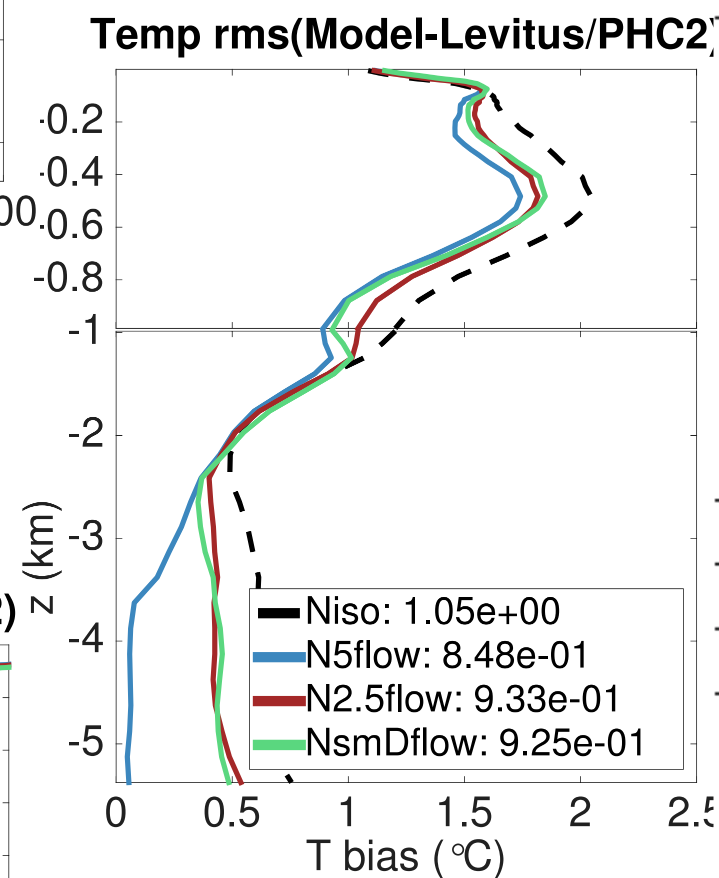


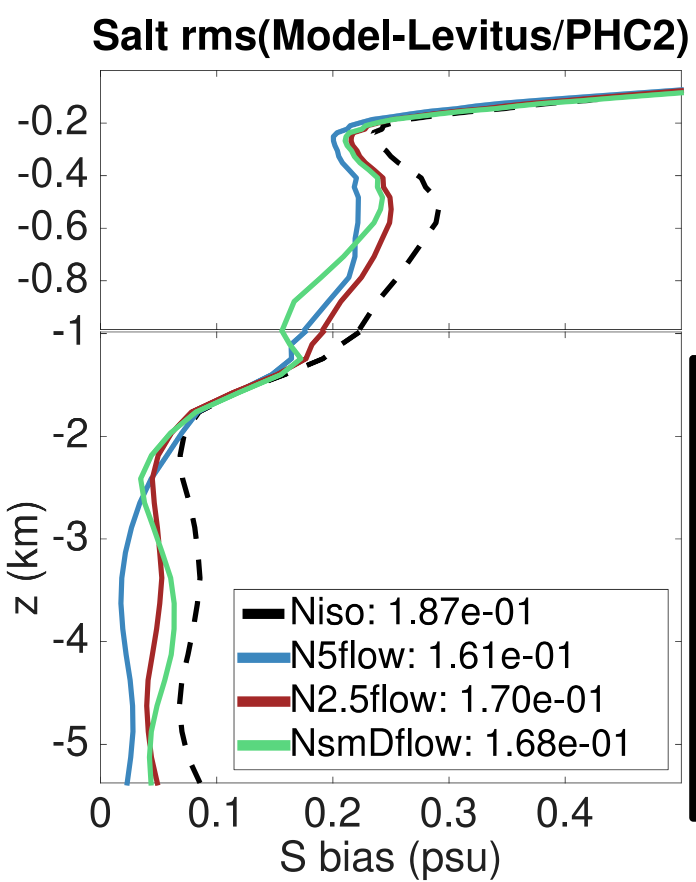

pCFC11 bias for case bass at z=483m
N² isotropic
Mean=-2.687e+01
RMS=4.530e+01
Max=1.487e+02
Min=-2.161e+02
pCFC11 bias for case flow at z=483m
Anisotropic
Mean=-1.909e+01
RMS=4.033e+01
Max=1.353e+02
Min=-2.167e+02
TEMP bias for case bass at z=483m
Mean=4.421e-01
RMS=1.228e+00
Max=7.843e+00
Min=-7.931e+00
TEMP bias for case flow at z=483m
Mean=-1.507e-01
RMS=1.076e+00
Max=5.644e+00
Min=-7.544e+00
SALT bias for case bass at z=483m
Mean=-1.570e-02
RMS=2.019e-01
Max=1.221e+00
Min=-2.501e+00
SALT bias for case flow at z=483m
Mean=5.530e-02
RMS=1.983e-01
Max=1.055e+00
Min=-2.502e+00



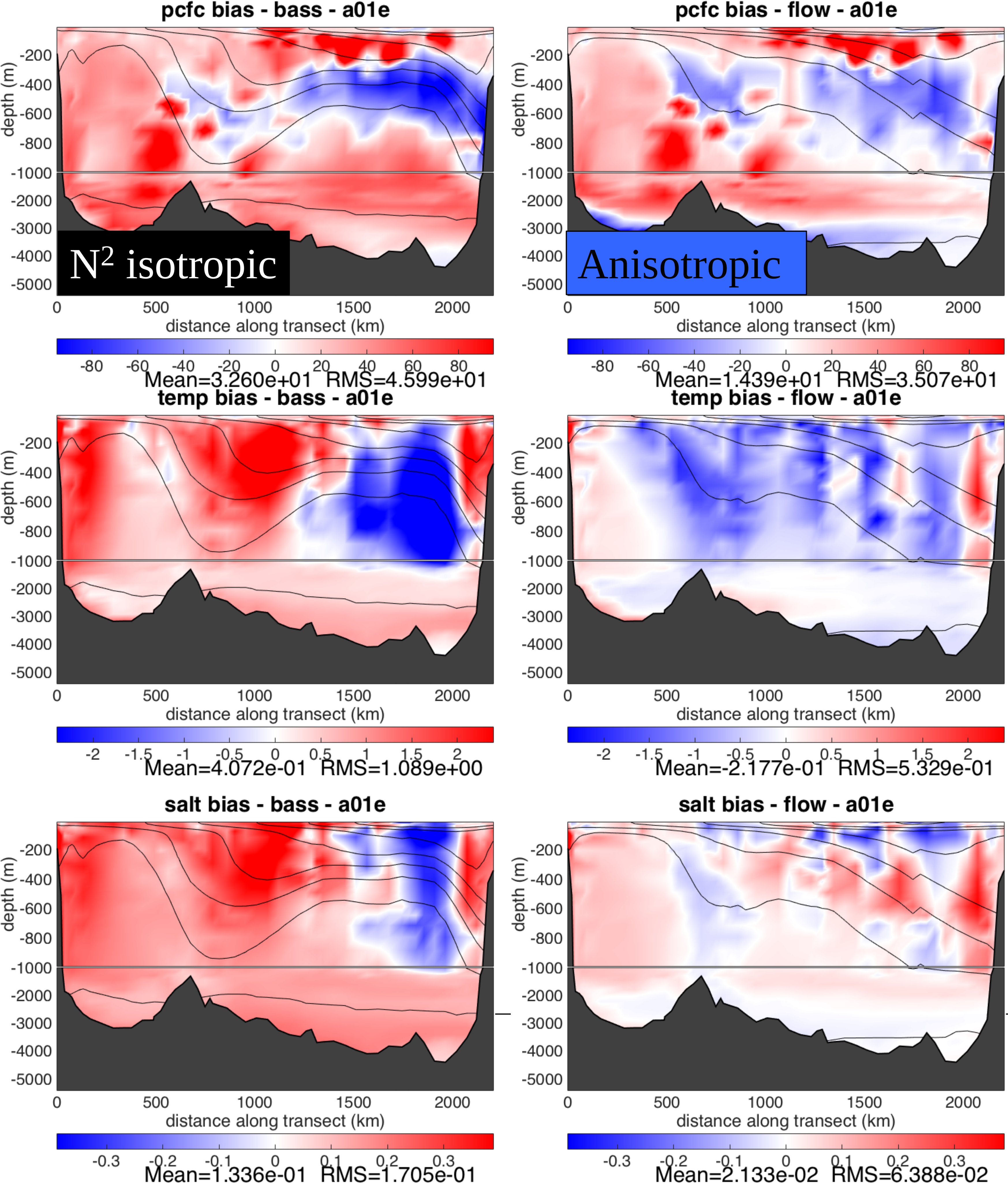
Large bias reductions in the North Atlantic



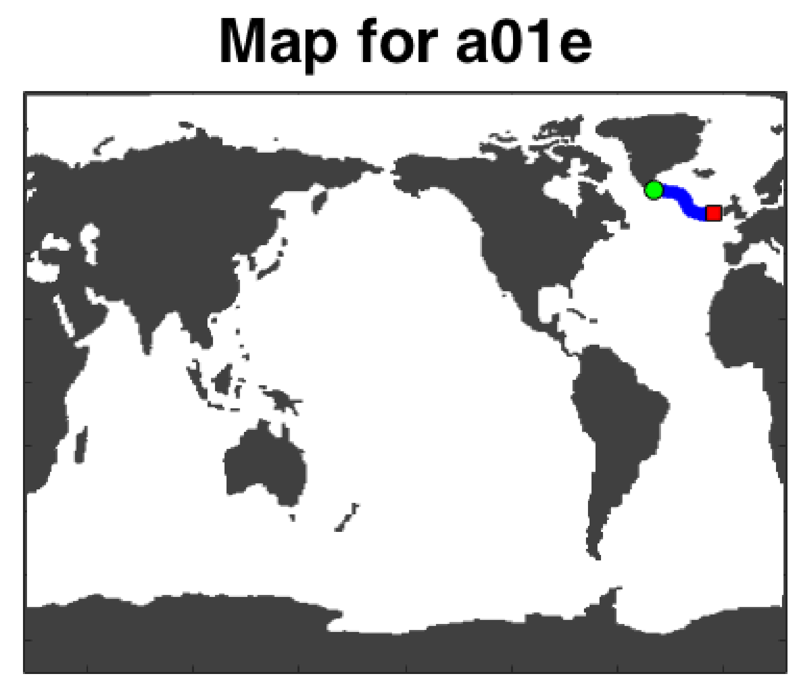




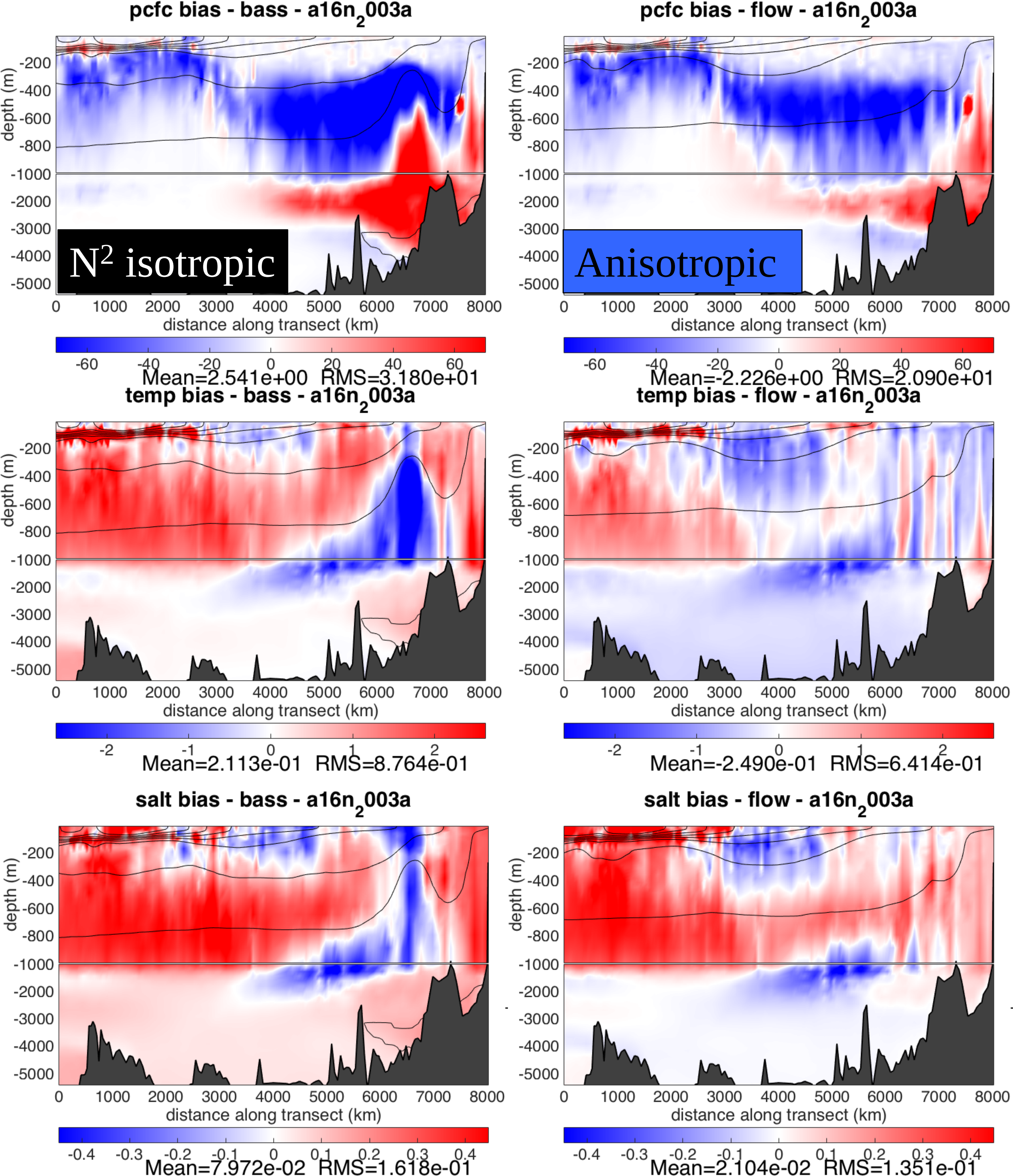
Overaggressive diffusion can cause AMOC shutdown



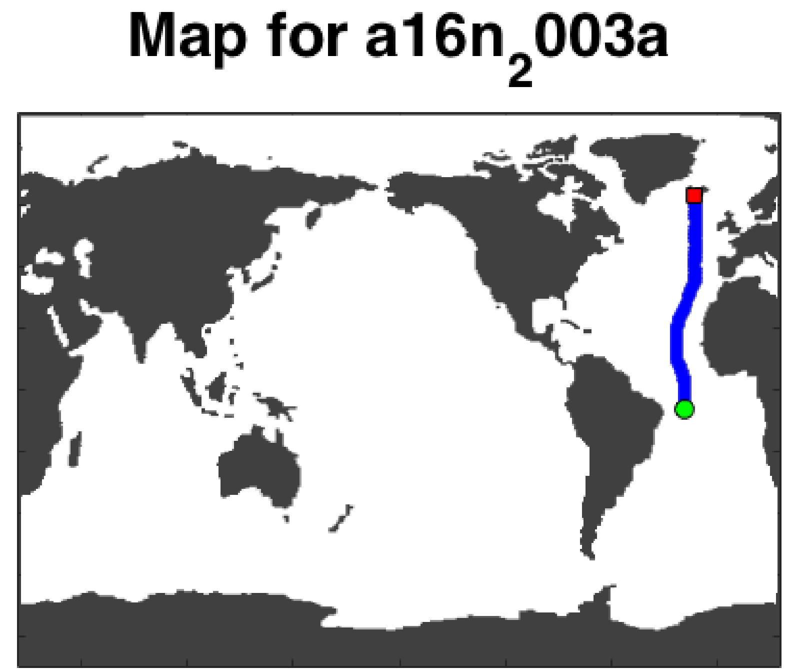
Along WOCE Transect



Anisotropy drastically reduces biases:
pCFC by 24%
Temp by 48%
Salinity by 63%



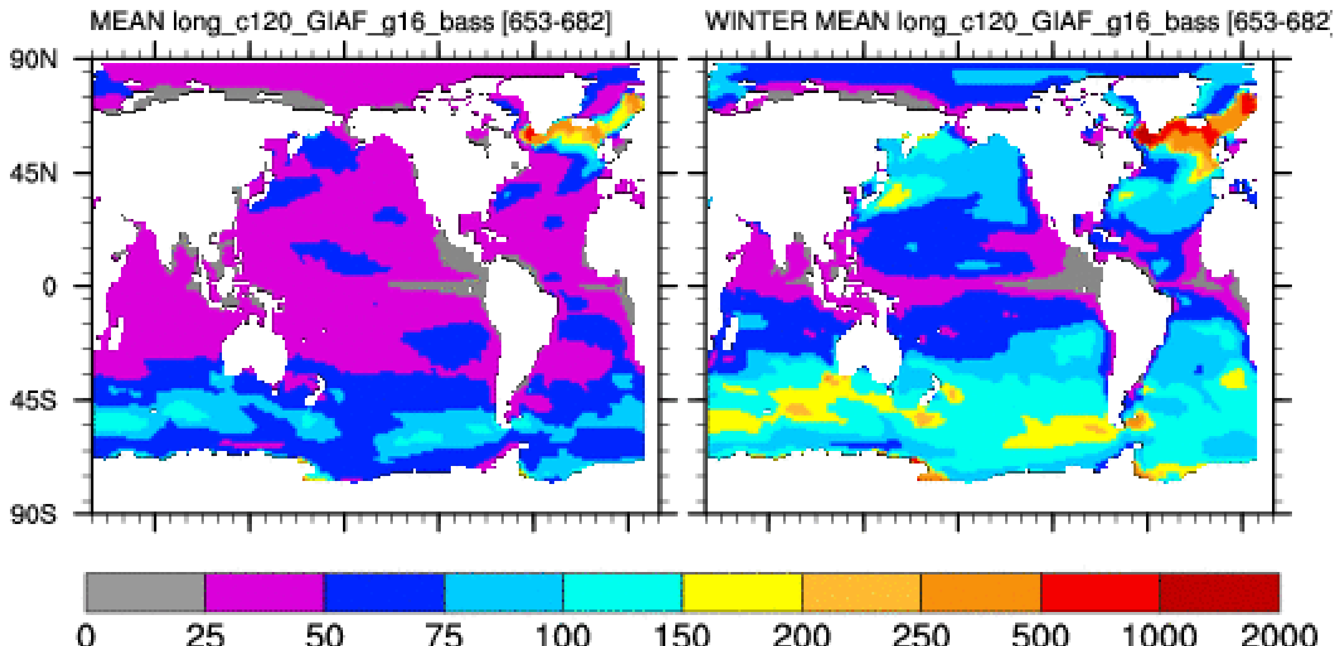
Along WOCE Transect



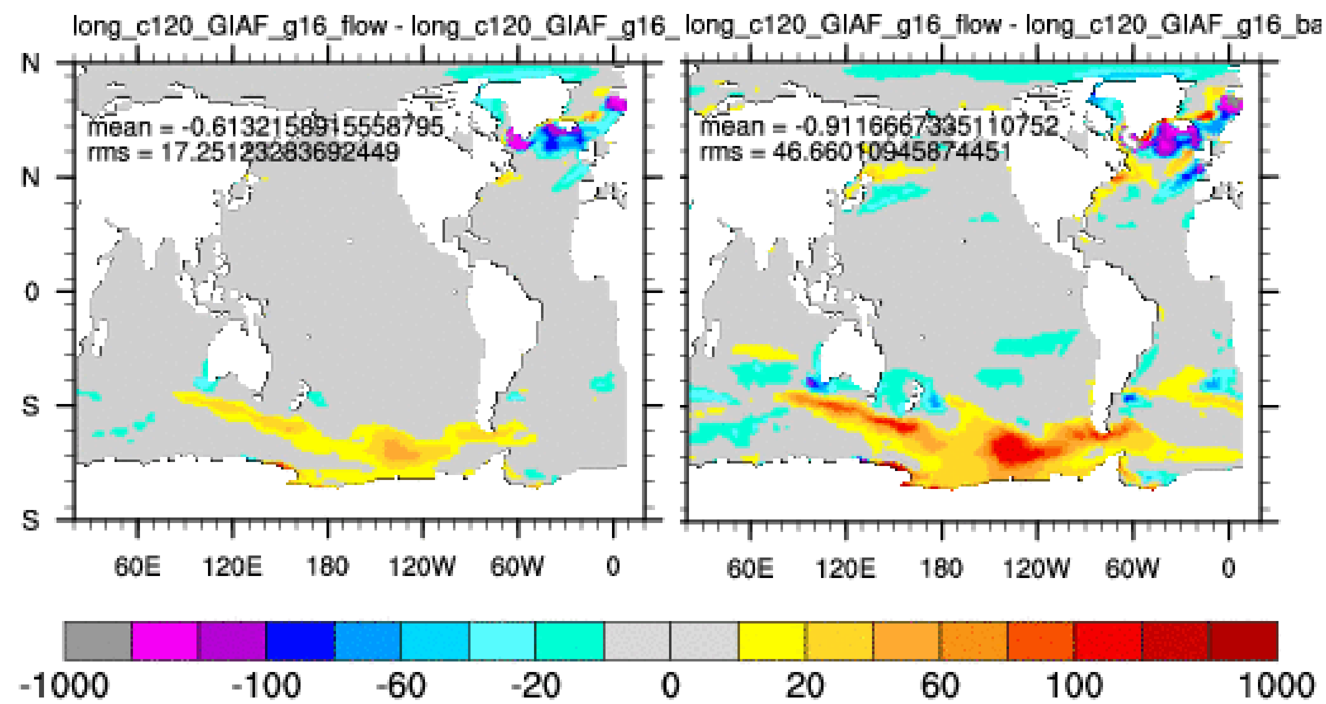
Anisotropy also reduces biases in equatorial Atlantic

Mixed Layer Depth [Annual, Winter]

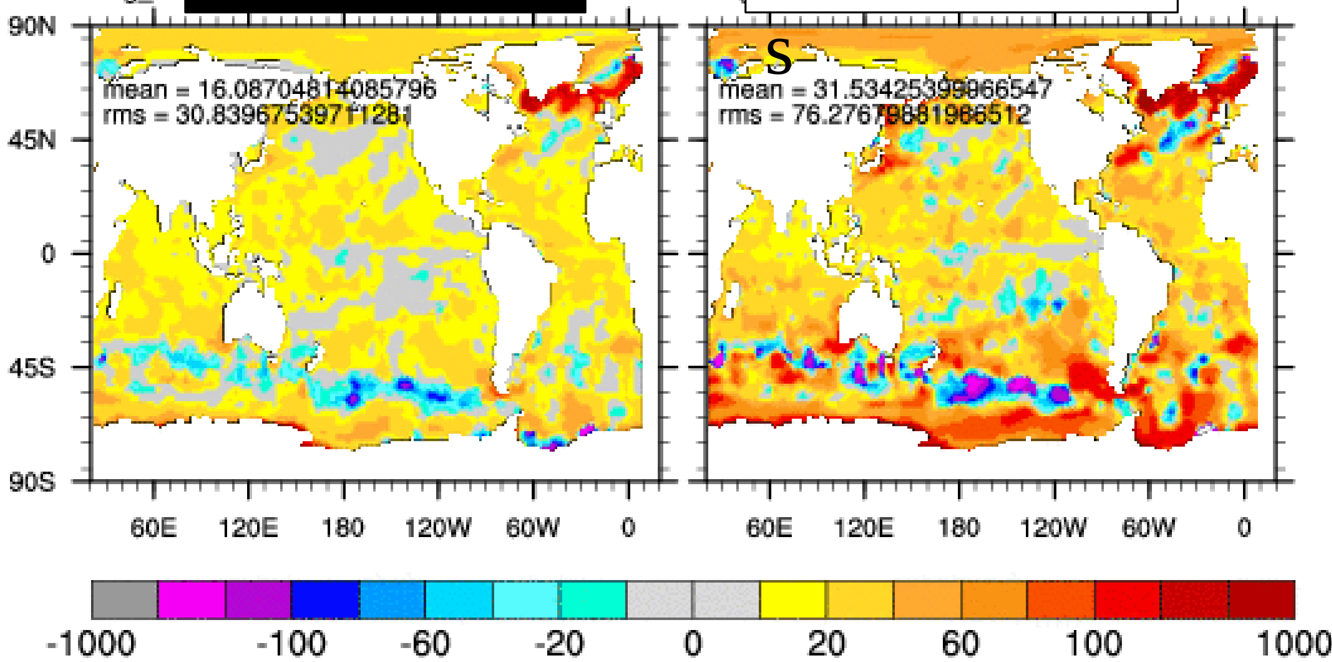
N^2 isotropic



Anisotropic: ratio=5 — N^2 isotropic



N^2 isotropic — Observations



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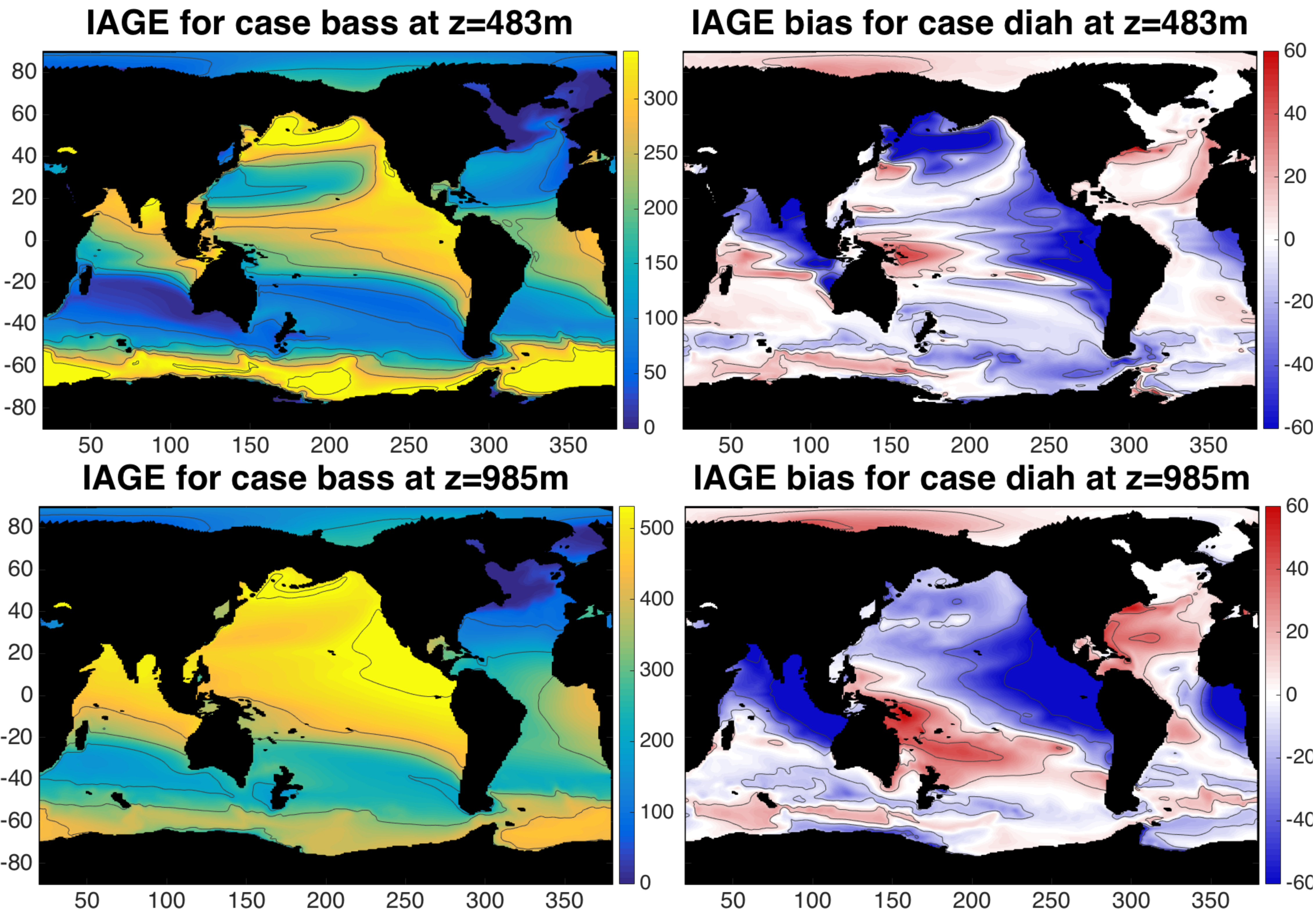
Anisotropy…
-deepens MLD in Southern Ocean (where control is too shallow)
-shallows MLD in North Atlantic (where control is too deep)
-reduces winter mean rms bias 15%
-reduces annual mean rms bias 18%

Ideal Age and Oxygen Minimum Zones

N^2 isotropic

smth. diag. ratio — N^2 isotropic



blue = younger than cntl

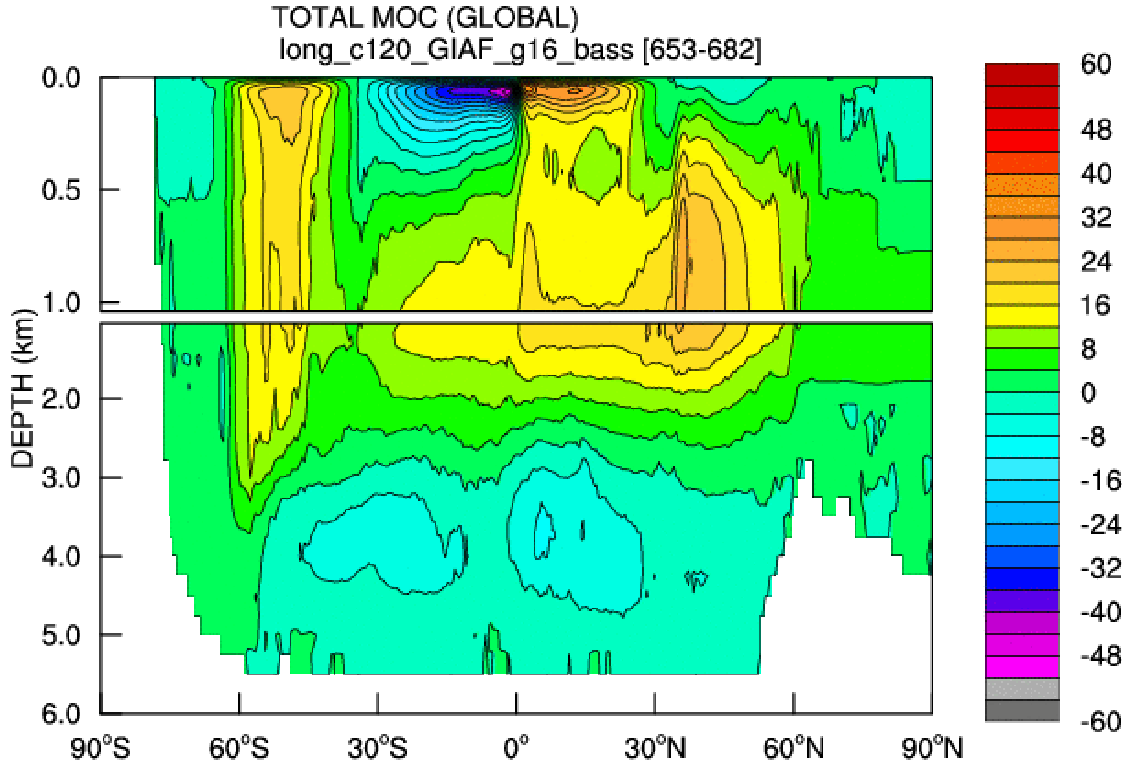
red = older than cntl

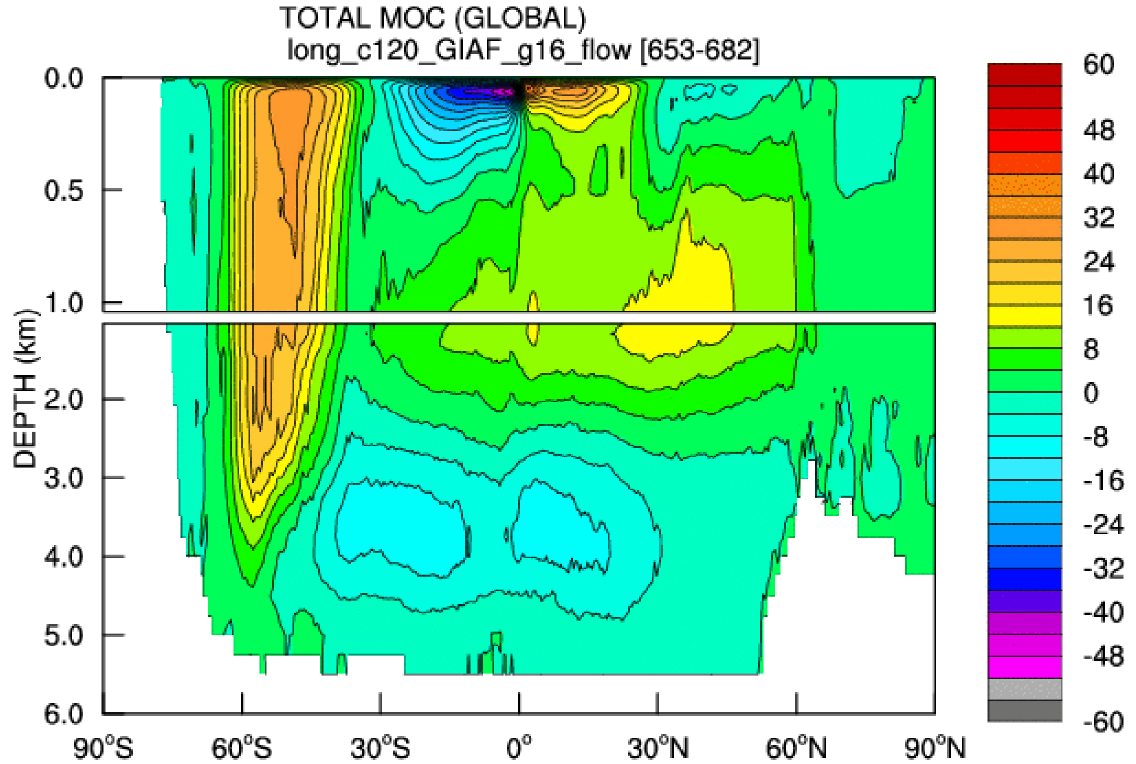
OMZ are ventilated with strong along-flow diffusion (anisotropy)

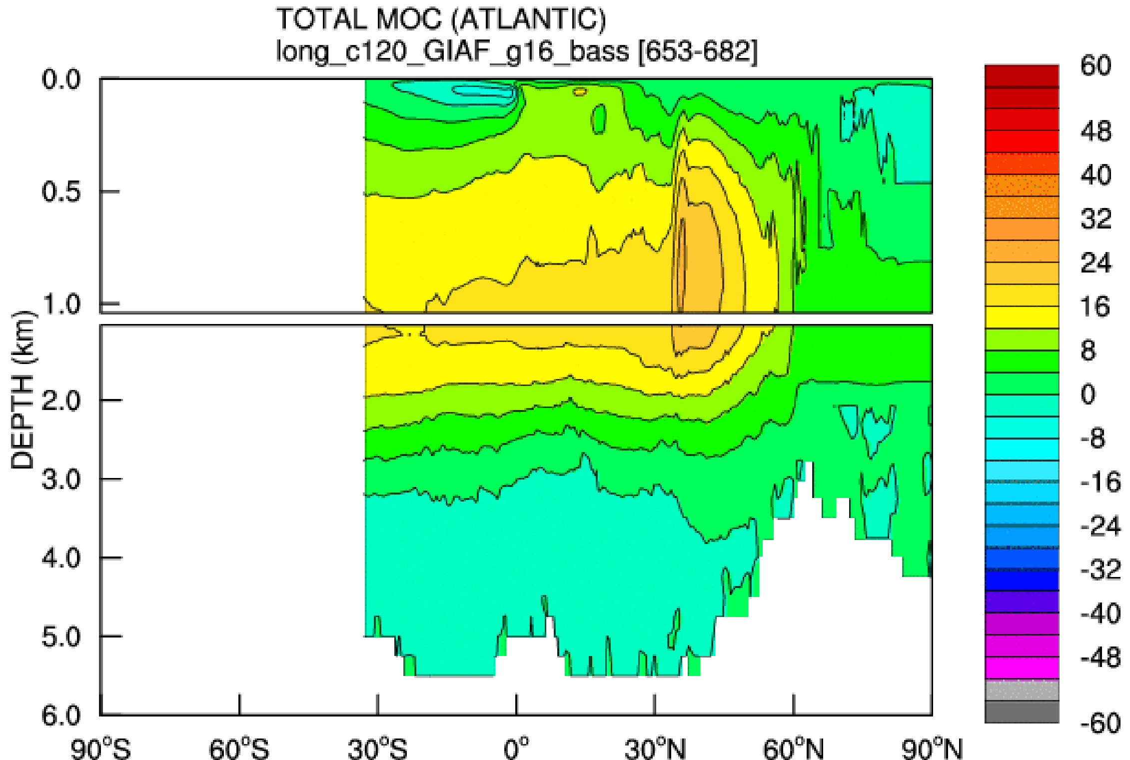
(A)MOC Sensitivity to Anisotropy

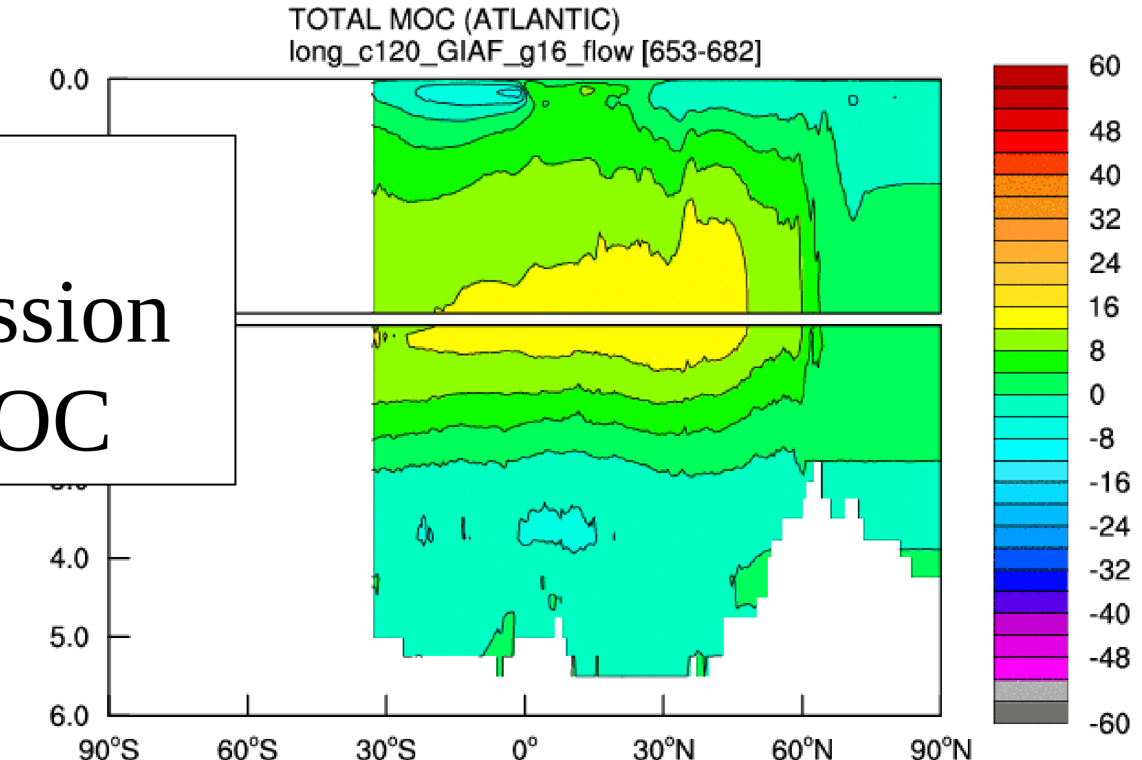
N^2 isotropic

Anisotropic: ratio=5





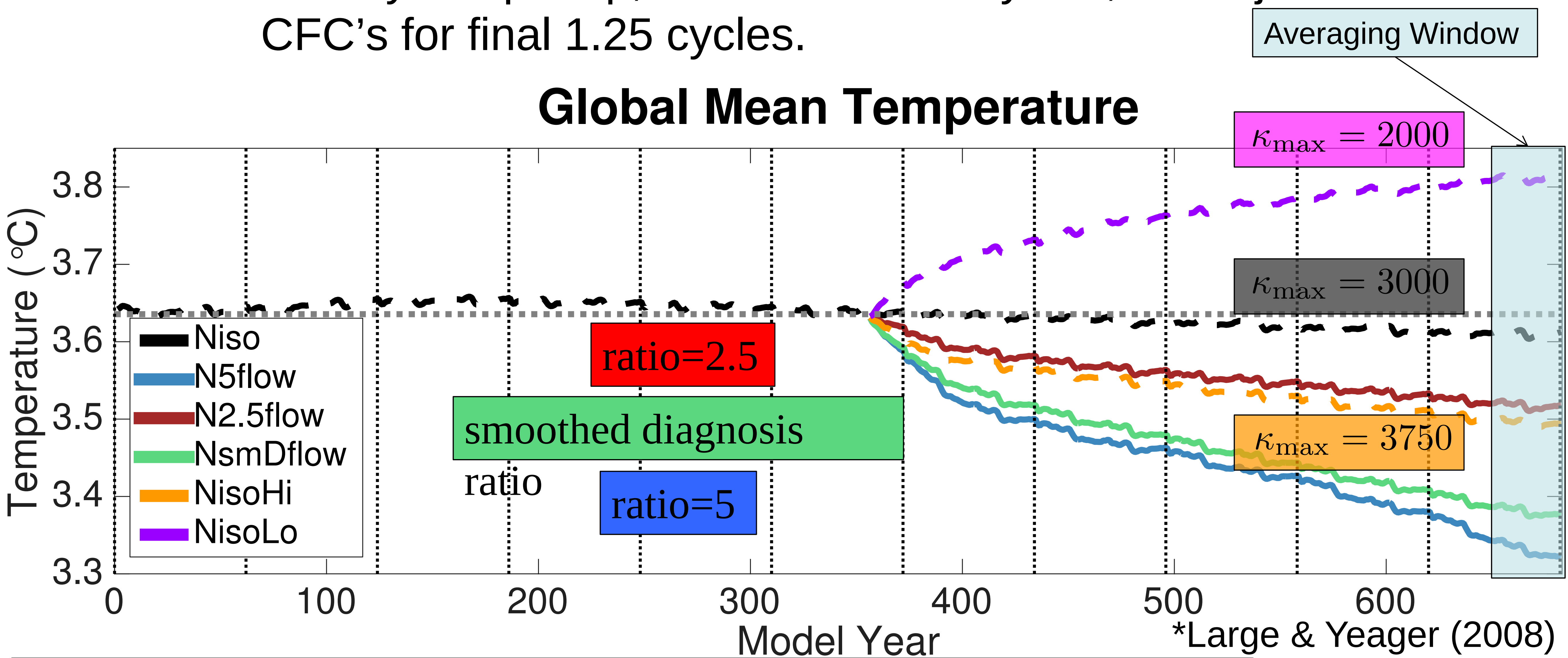




Strong suppression of AMOC

Summary of Numerical Experiments

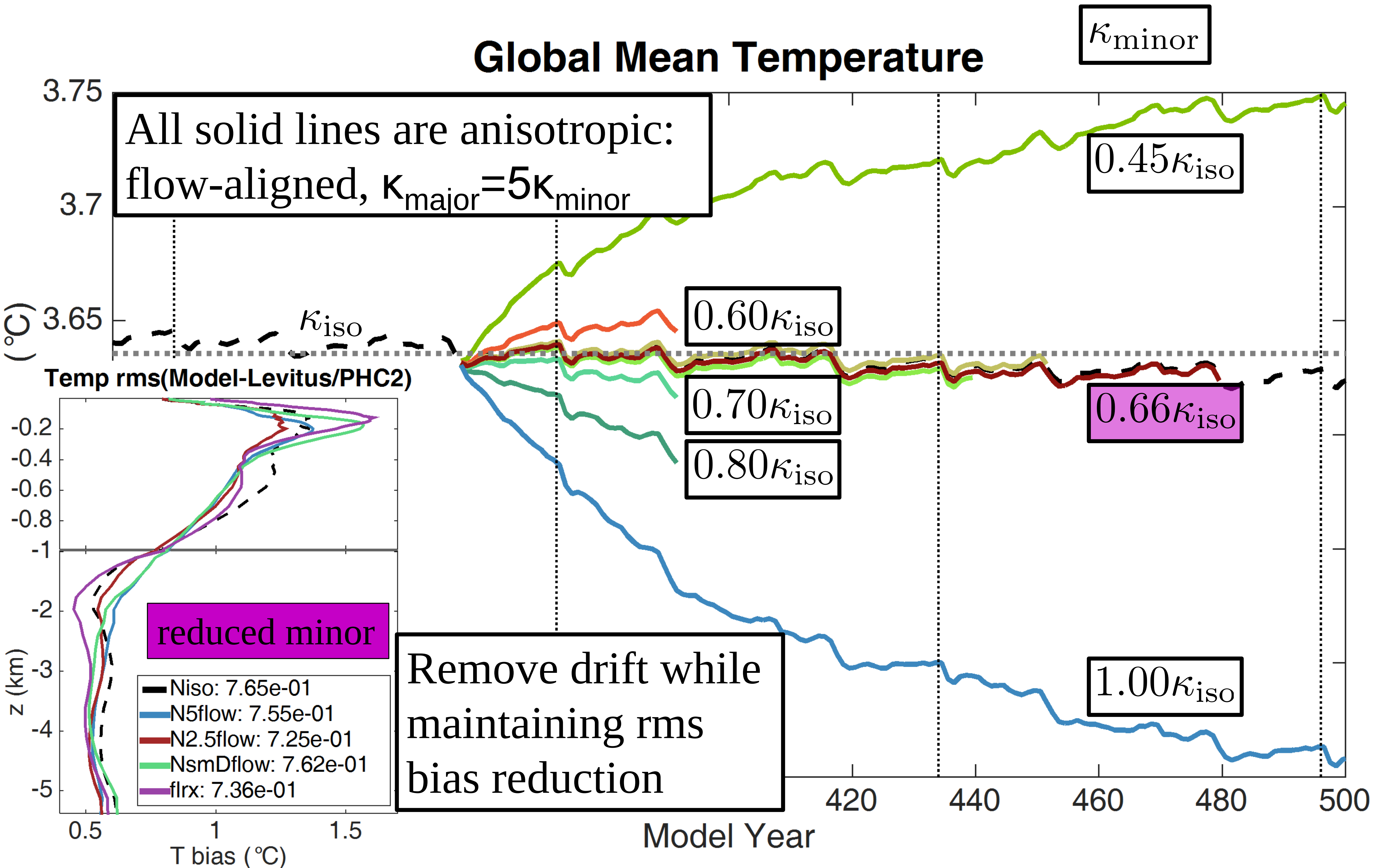
- Community Earth System Model (CESM1.2)
  - CORE 62-year interannual forcing (GIAF compset)*
  - 1° resolution (gx1v6 grid)
  - 5.75 cycle spin-up, branch for 5.25 cycles, and inject CFC's for final 1.25 cycles.



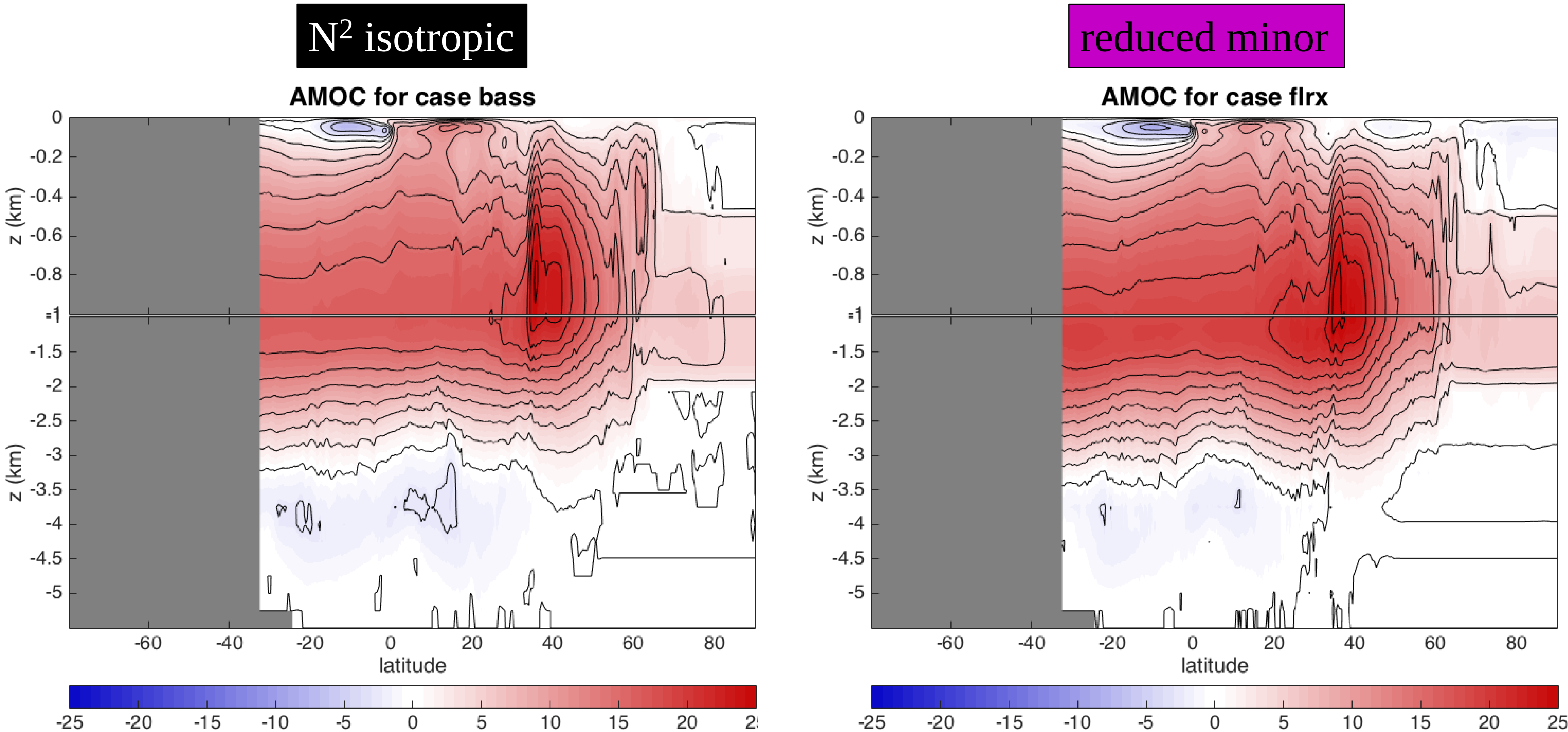
*Large & Yeager (2008)

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

Minor Diffusivity Reduction



Minor Diffusivity Reduction



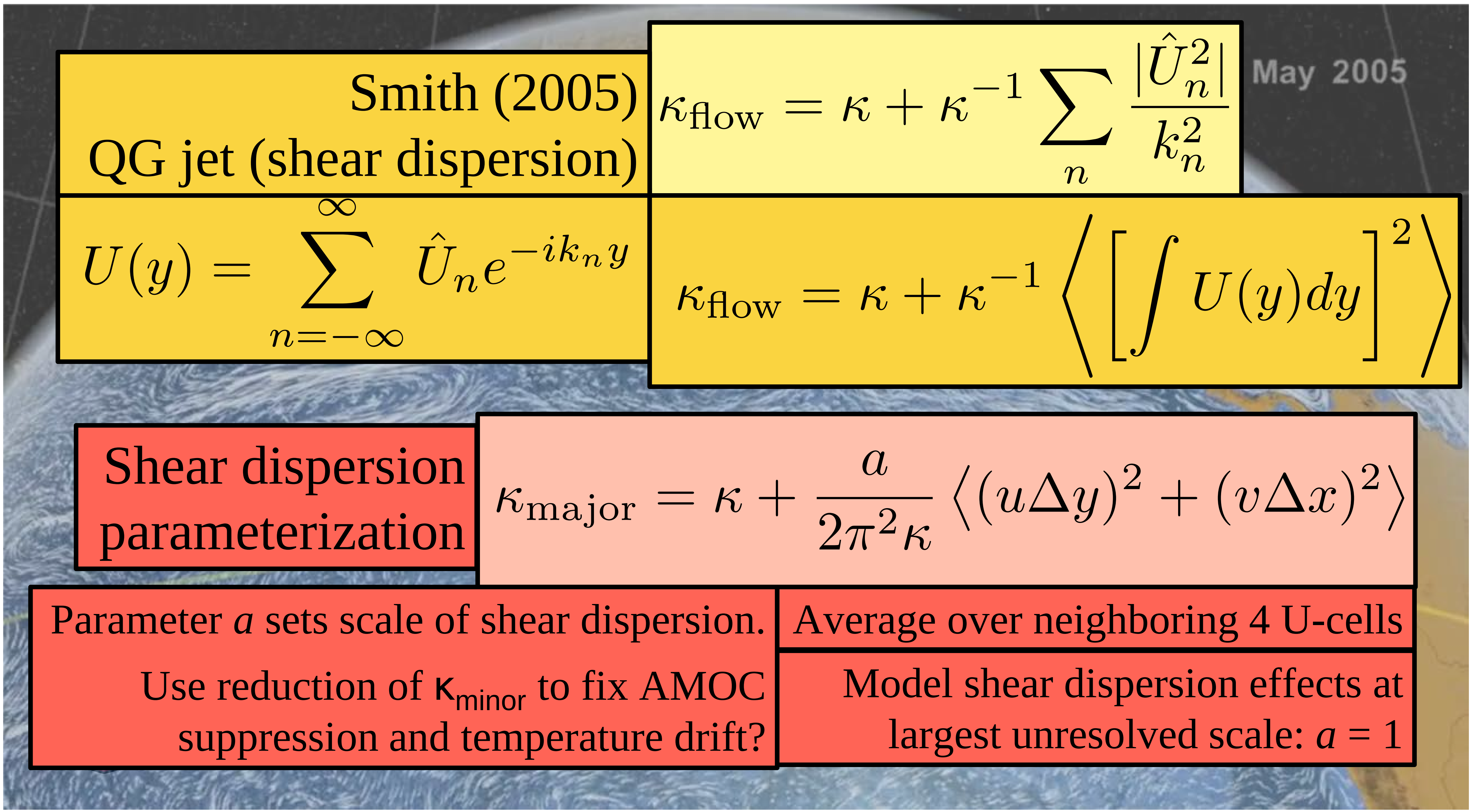
Slight increase in AMOC

Shear Dispersion Parameterization

Taylor (1953) pipe flow

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

κ = background diffusivity



Smith (2005) QG jet (shear dispersion)

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

$$U(y) = \sum_{n=-\infty}^{\infty} \hat{U}_n e^{-ik_n y}$$

$$\kappa_{\text{flow}} = \kappa + \kappa^{-1} \left\langle \left[\int U(y) dy \right]^2 \right\rangle$$

Shear dispersion parameterization

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

Parameter *a* sets scale of shear dispersion.

Use reduction of κ_{minor} to fix AMOC suppression and temperature drift?

Average over neighboring 4 U-cells

Model shear dispersion effects at largest unresolved scale: *a* = 1

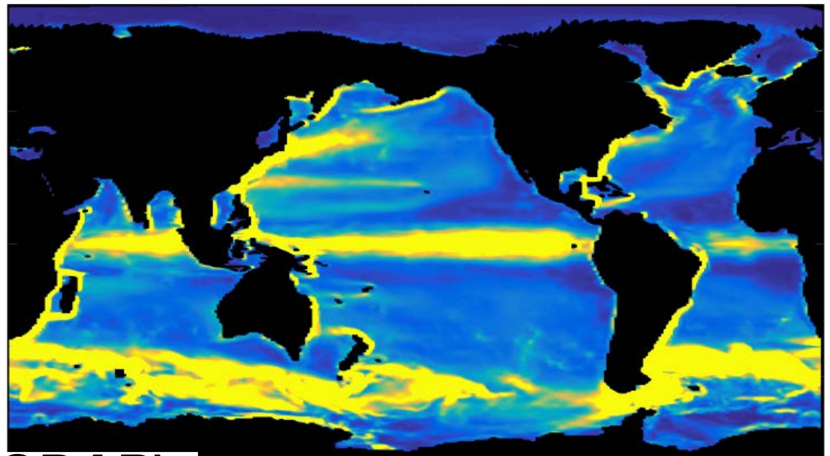
Shear Dispersion Parameterization

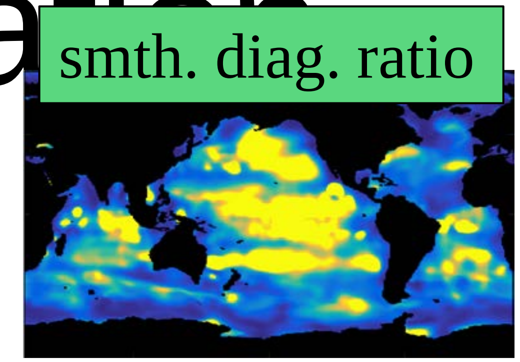
$$\kappa_{\text{major}} = \kappa + \frac{a}{2\pi^2\kappa}\left\langle (u\Delta y)^2 + (v\Delta x)^2 \right\rangle$$

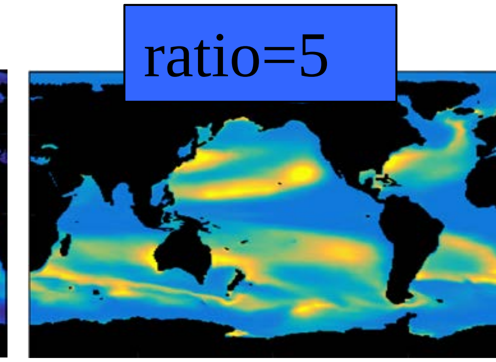
shear dispersion

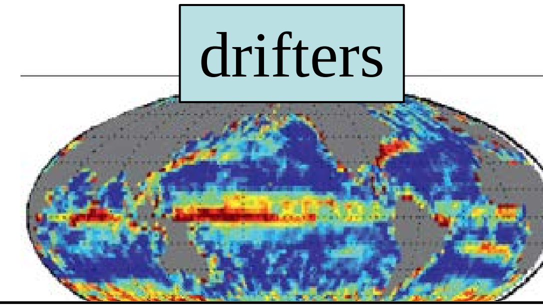
$(a = \pi^2)$

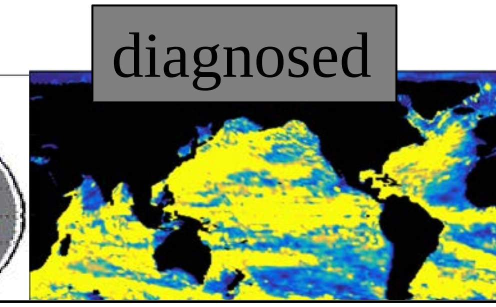
Shear dispersion scale too high!

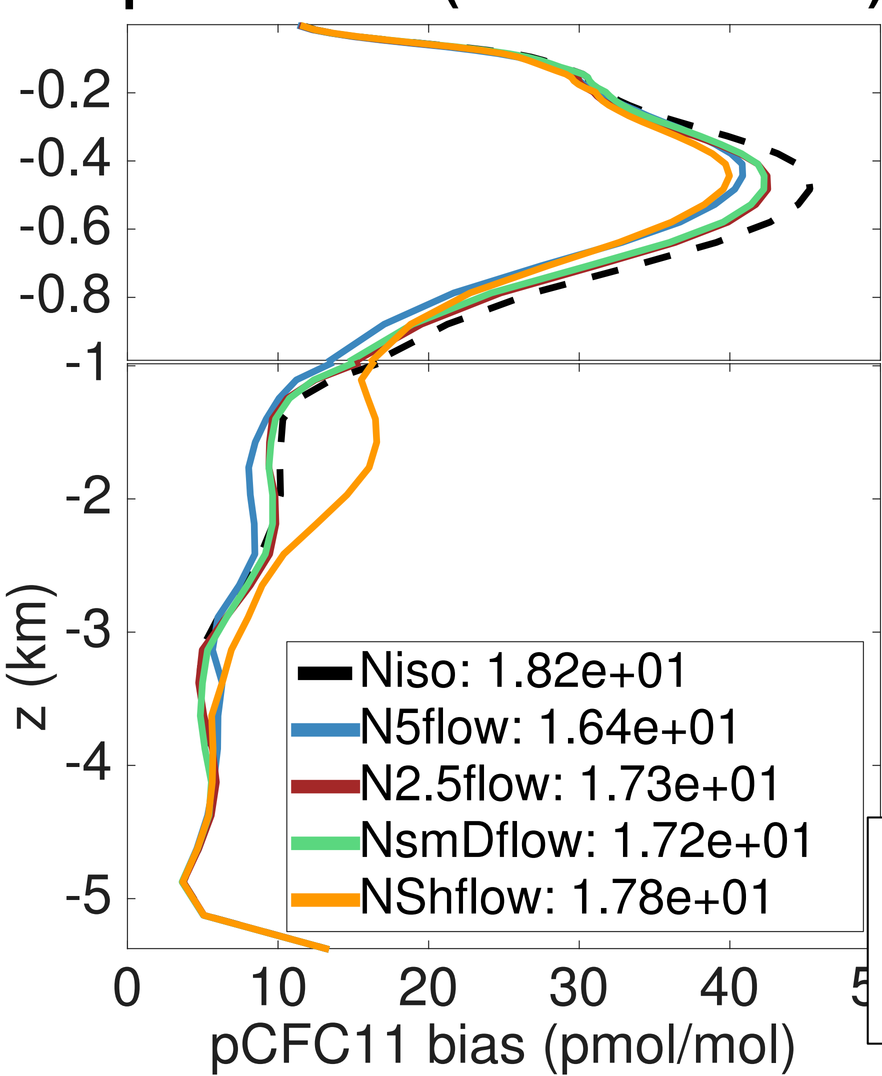








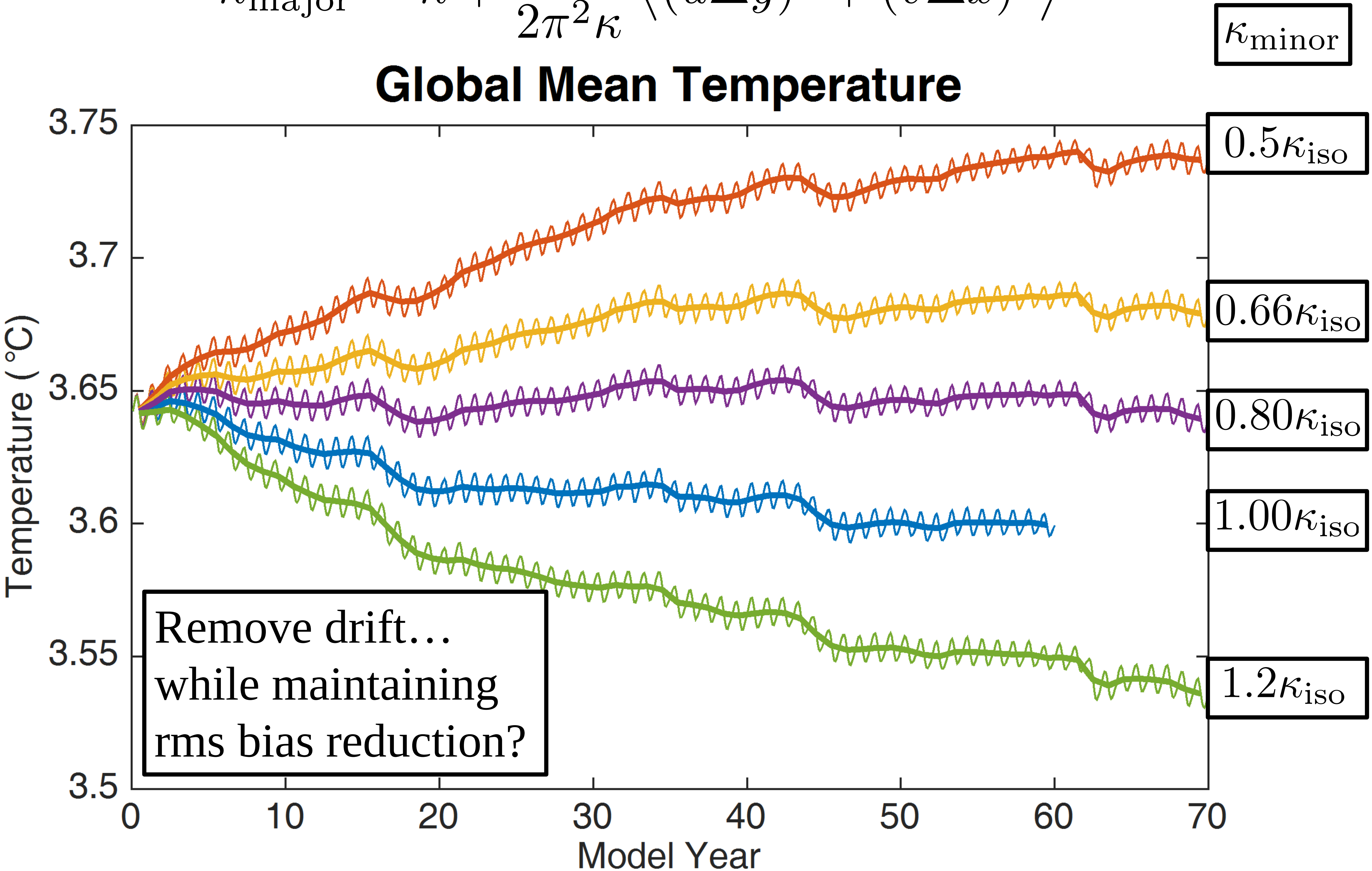




pCFC bias reduction; strong diffusion in Lab Sea prevents deep water formation & AMOC weakening

Minor Diffusivity Reduction – Shear Dispersion

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



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 (a and κ_{minor}) must be tested for centuries-long run
- Better background diffusivity, κ? Minor suppression κ_{minor}?