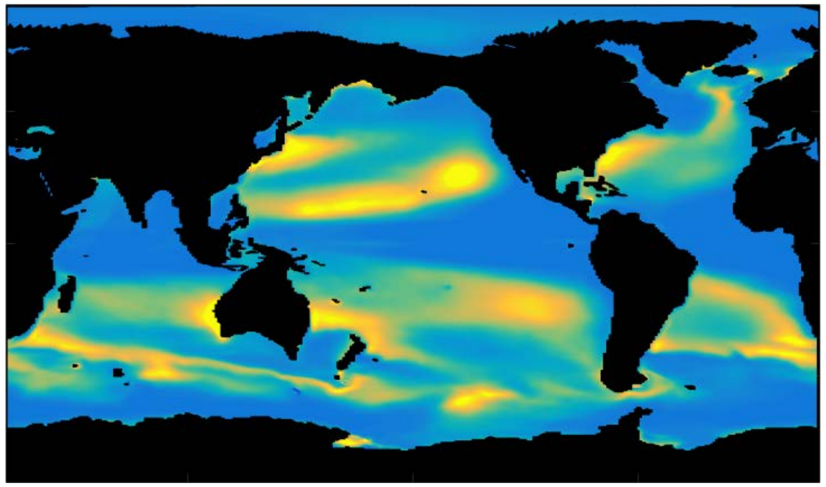
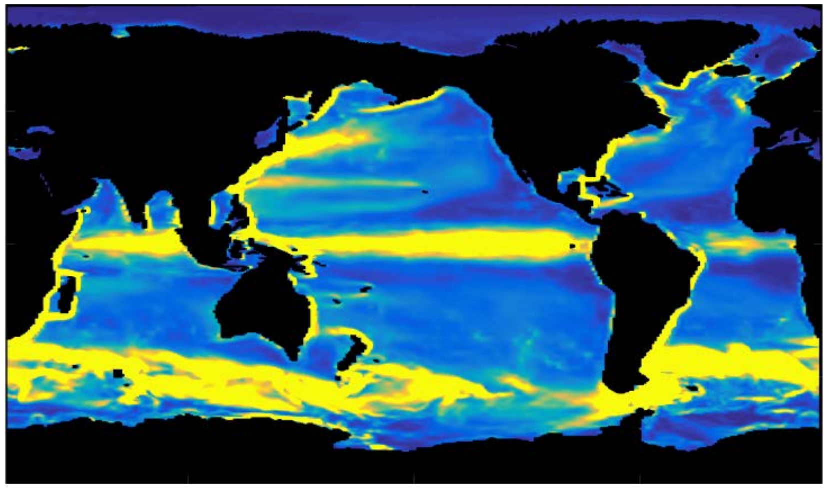
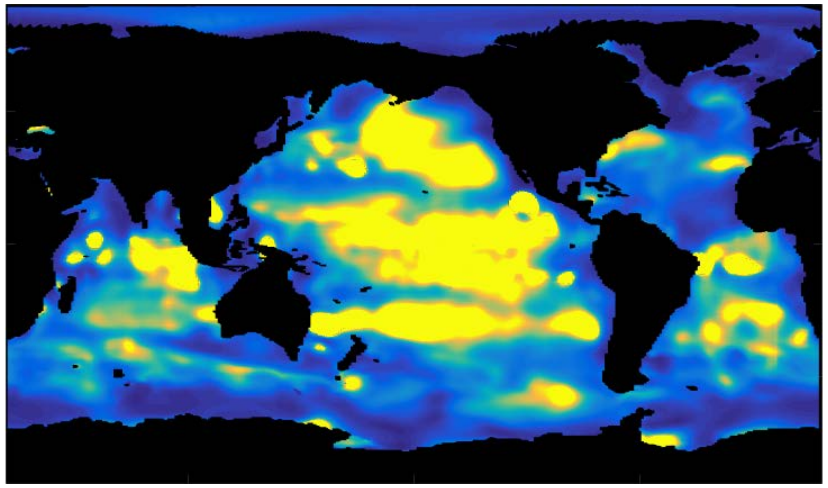
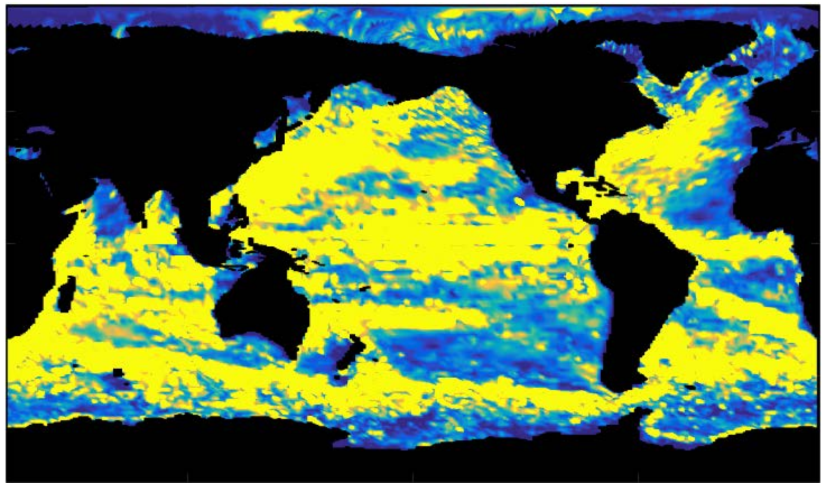






Anisotropy in Mesoscale Eddy Transport



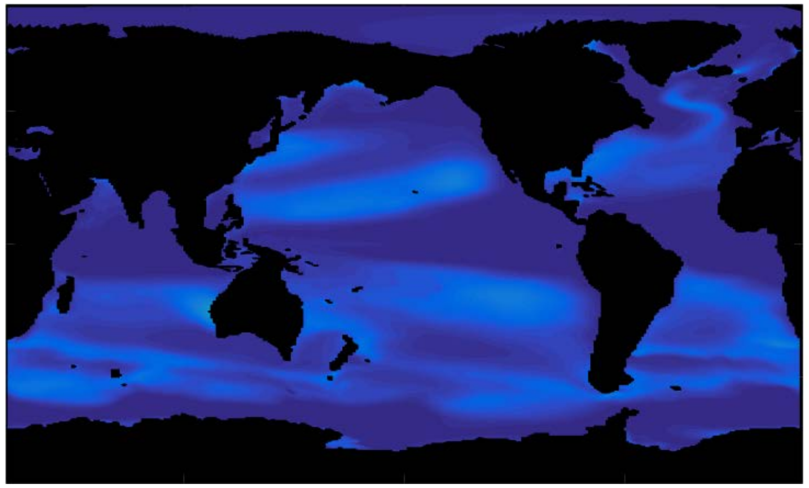
Scott J. Reckinger

Baylor Fox-Kemper

Gokhan Danabasoglu

Scott Bachman

Frank Bryan



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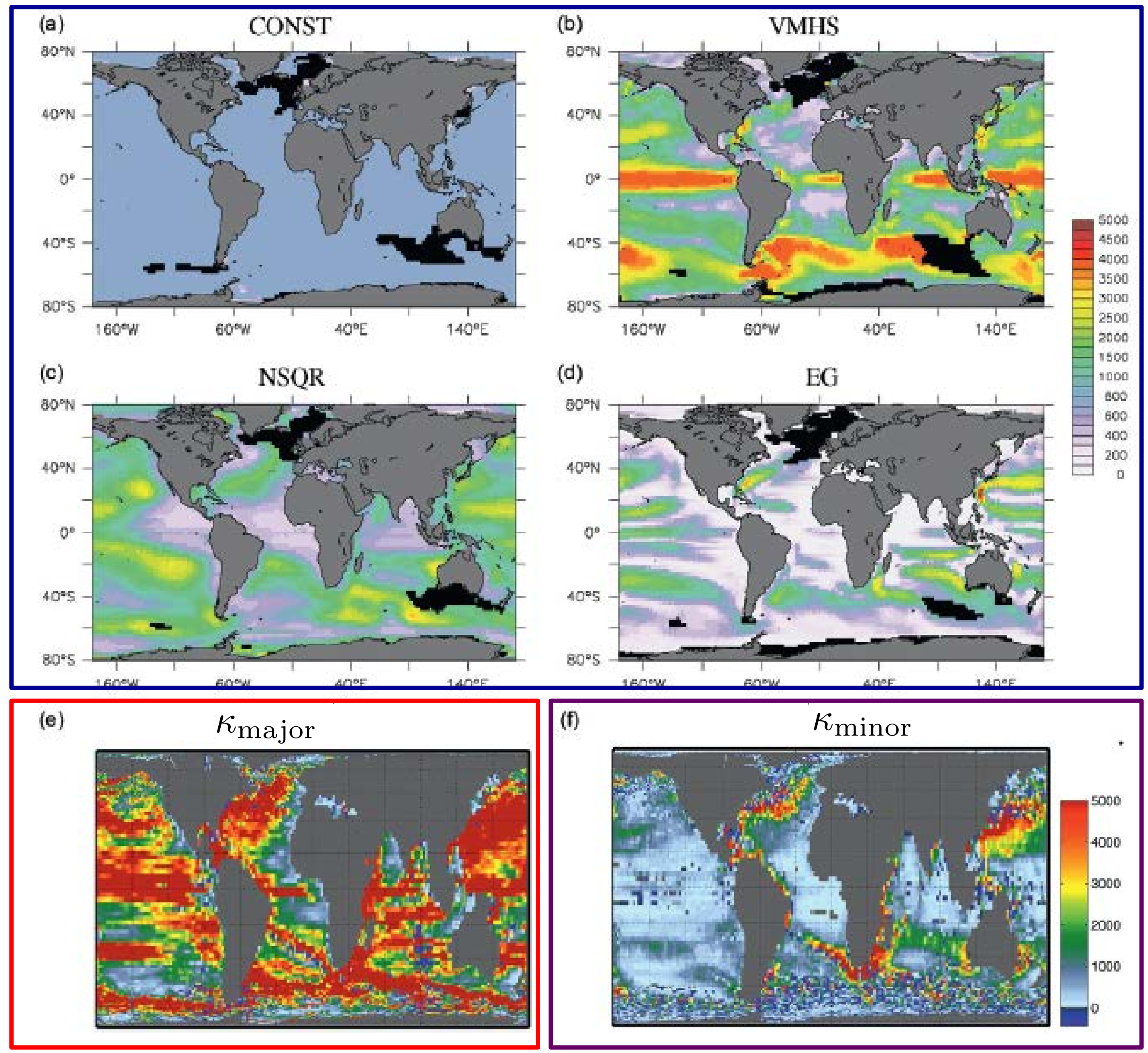
CESM Workshop
June 18th, 2015
Breckenridge, CO

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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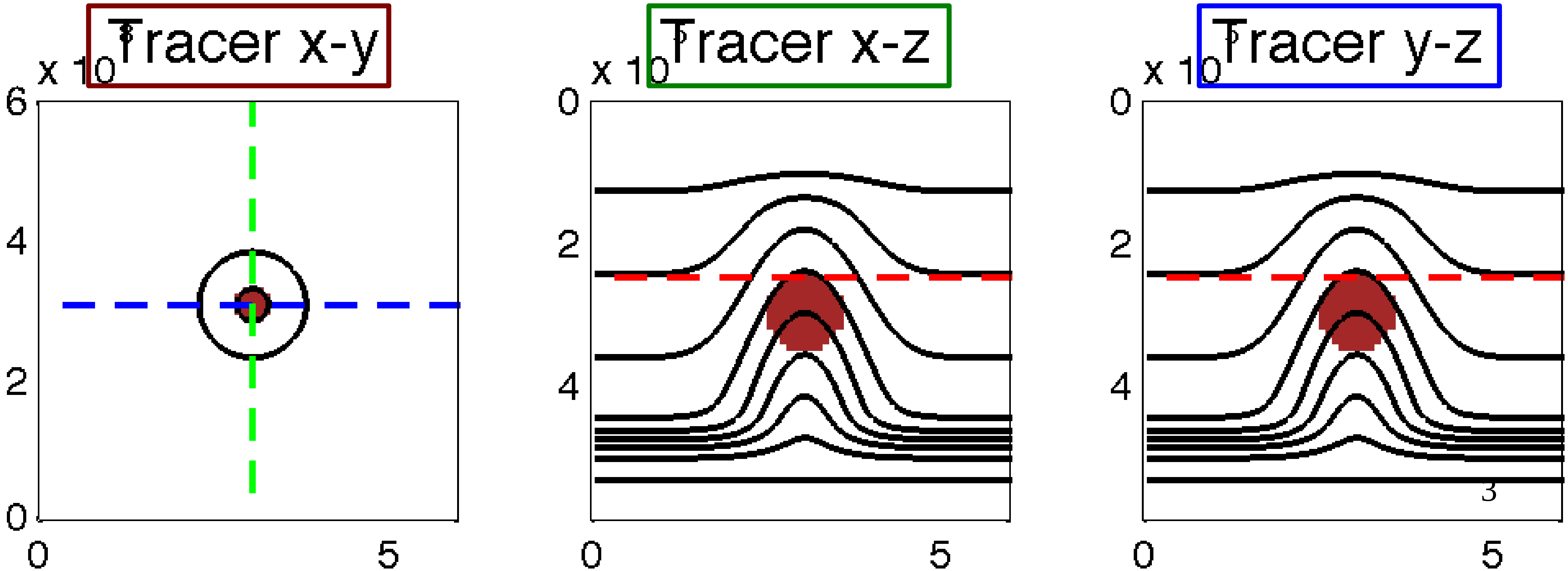
Mesoscale Eddy Parameterization

- Baroclinic instability drives eddies through a conversion of available potential energy to kinetic energy
- Eddies anisotropically…

diffuse along isopycnals | flatten isopycnal slopes

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

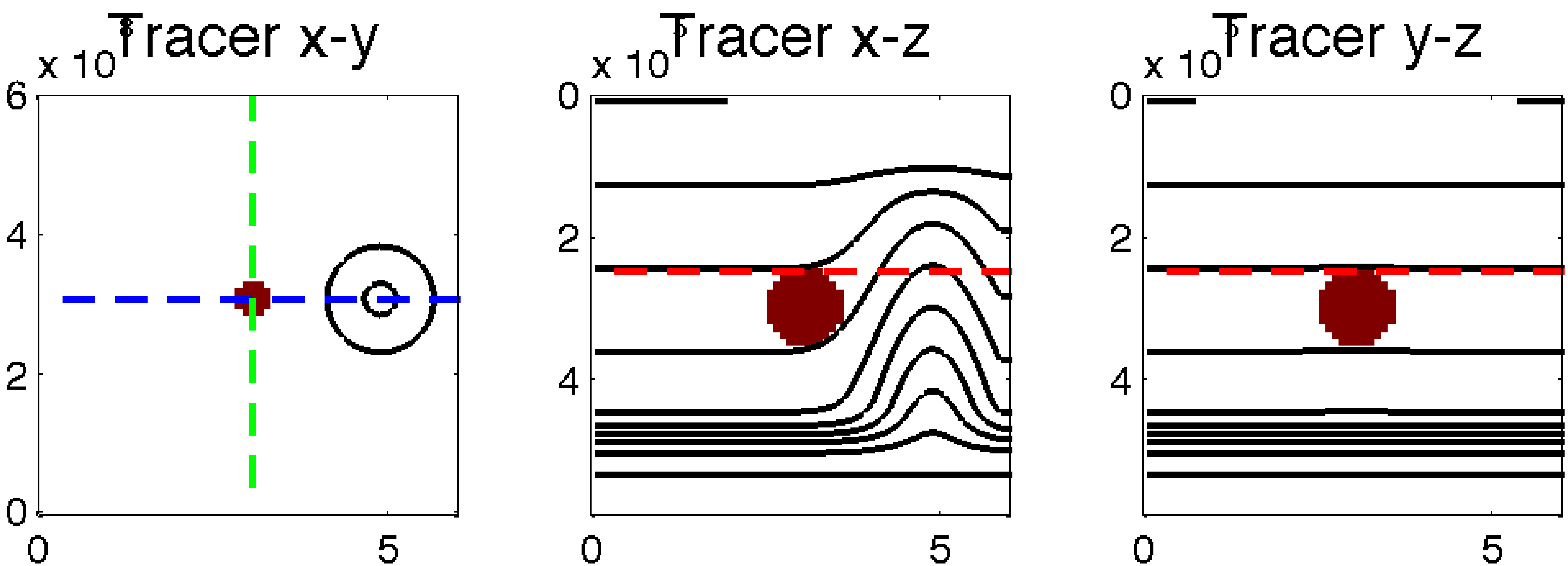


Anisotropic GM/Redi

- Parameterize anisotropic transport mechanisms in the ocean:

$\kappa \Rightarrow$

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

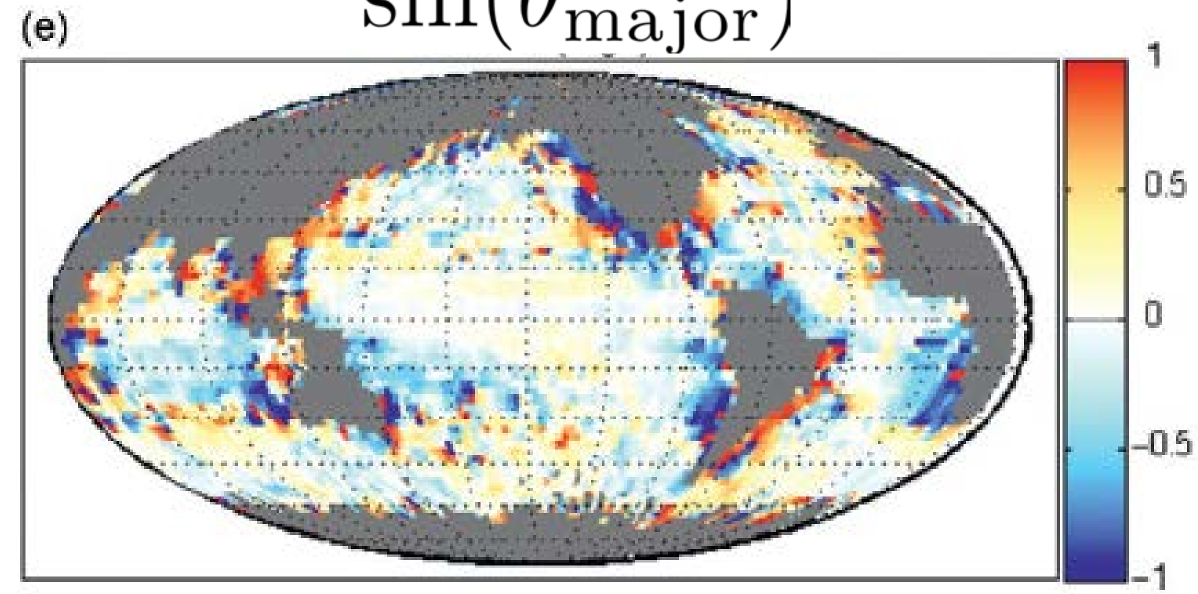


Drifter Observation Diffusivity Tensor

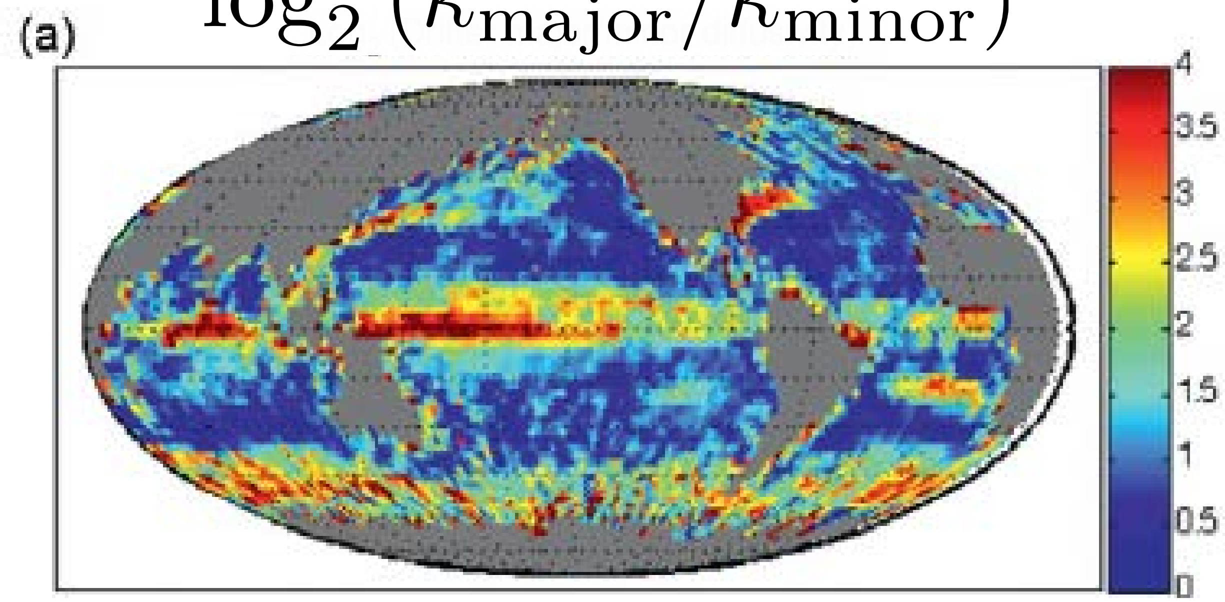
- Principal axis alignment
  - Major axis **aligned zonally** away from boundary currents
  - Major axis **aligned with the flow** near boundary currents

- $\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}}$
  - **> 16** in equatorial region
  - 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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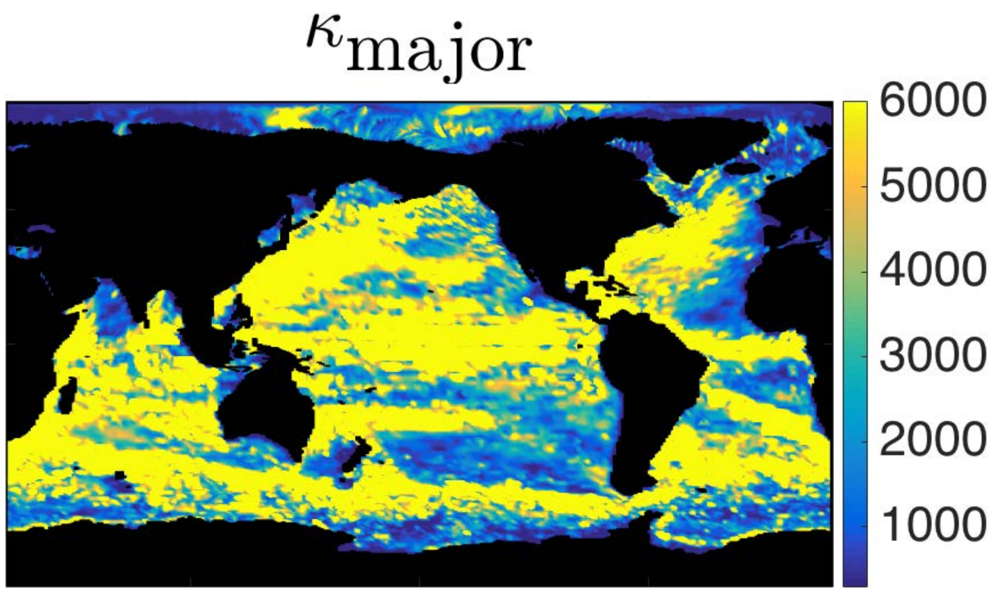
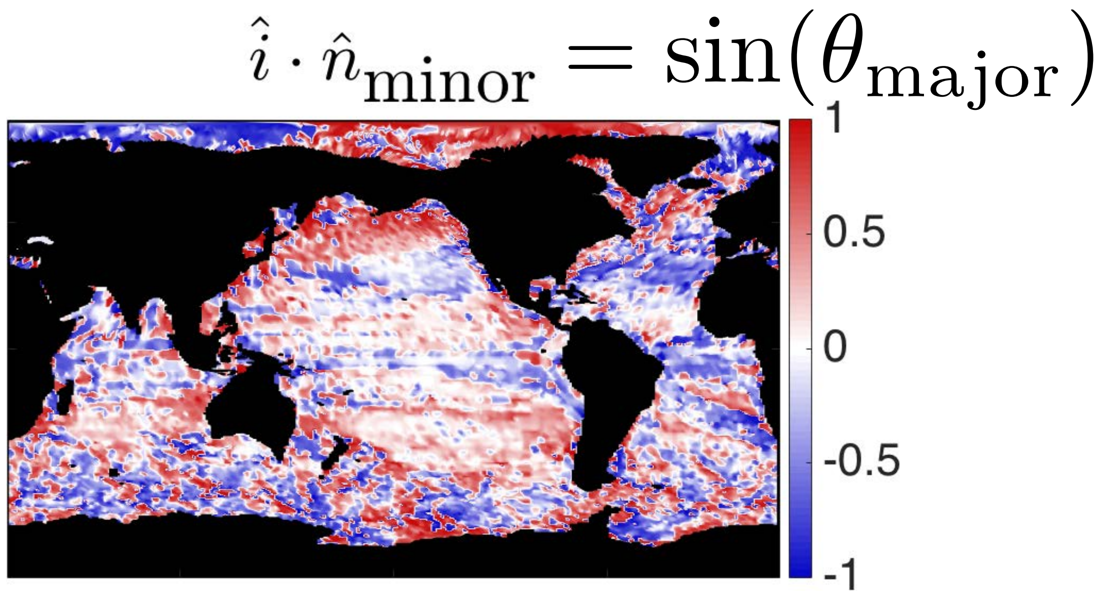
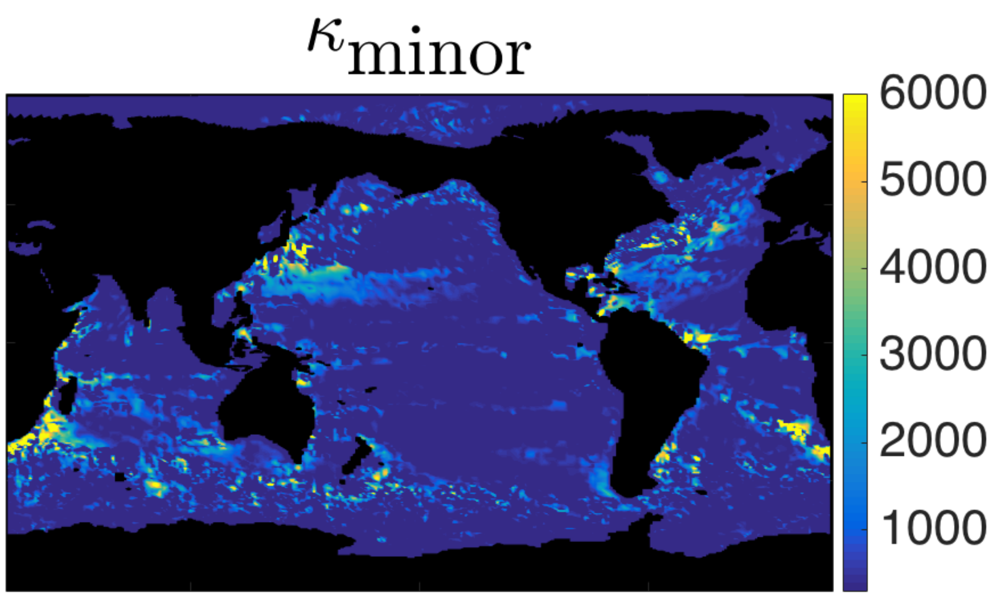
Hi-res Diagnosed Tensor







- 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)

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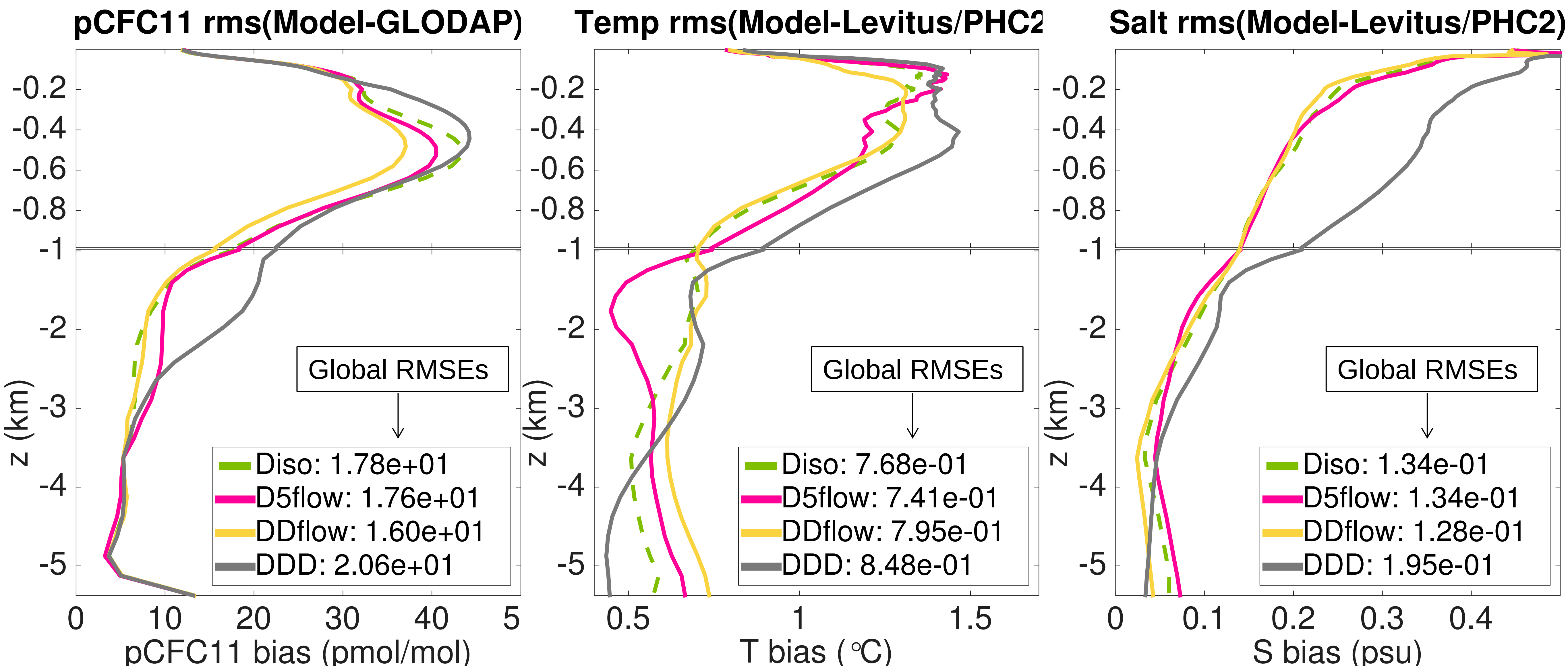
*Bachman & Fox-Kemper (2013)

*Fox-Kemper et al (2013)

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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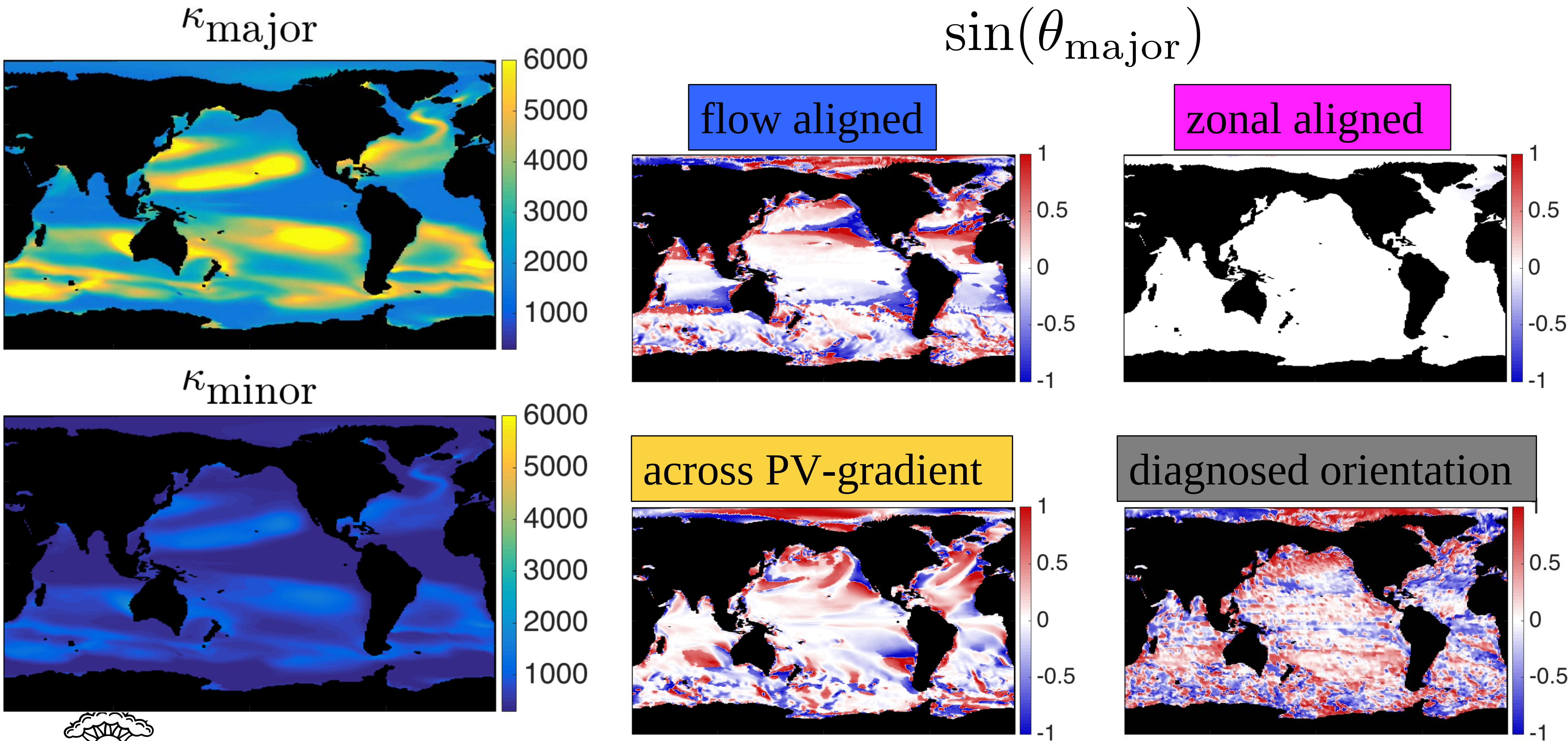
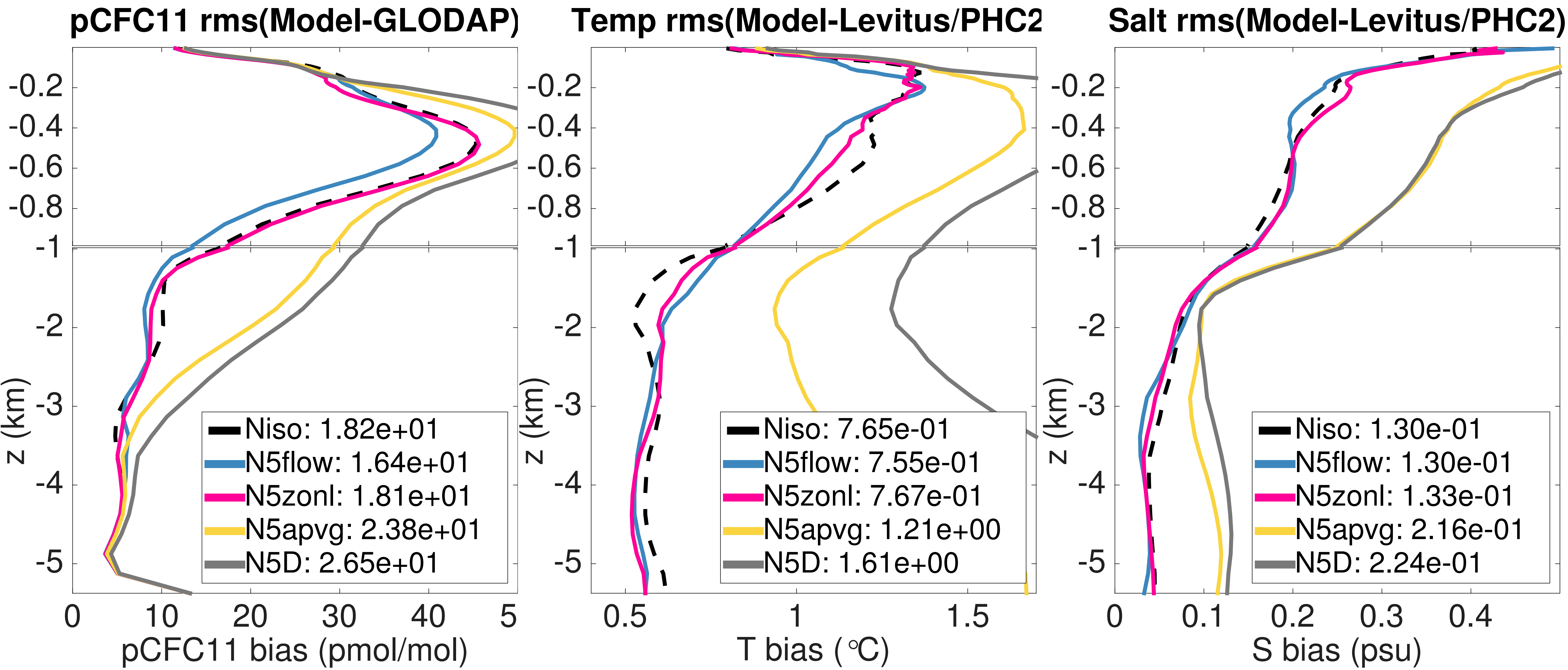
Major Axis Alignment Study

- 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!

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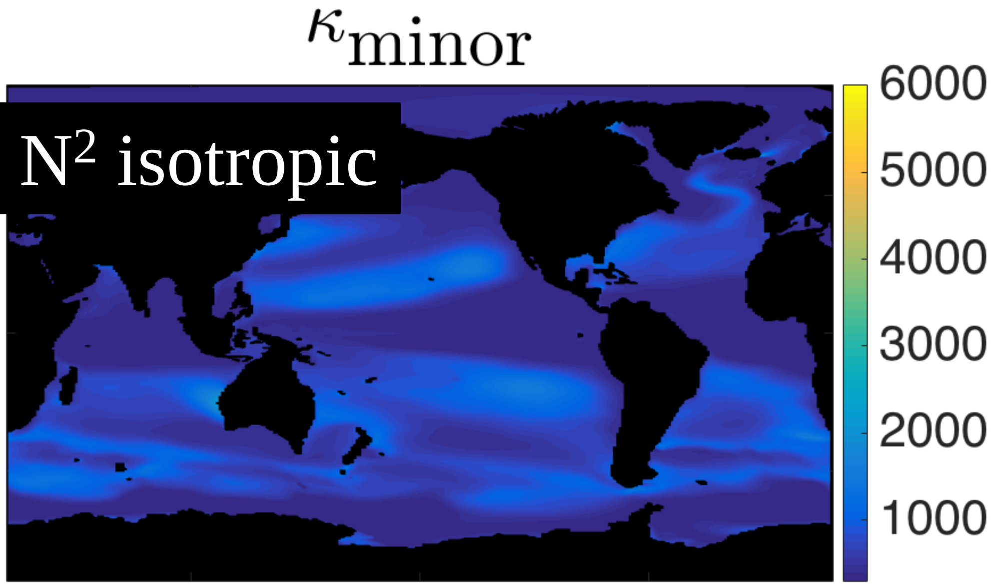
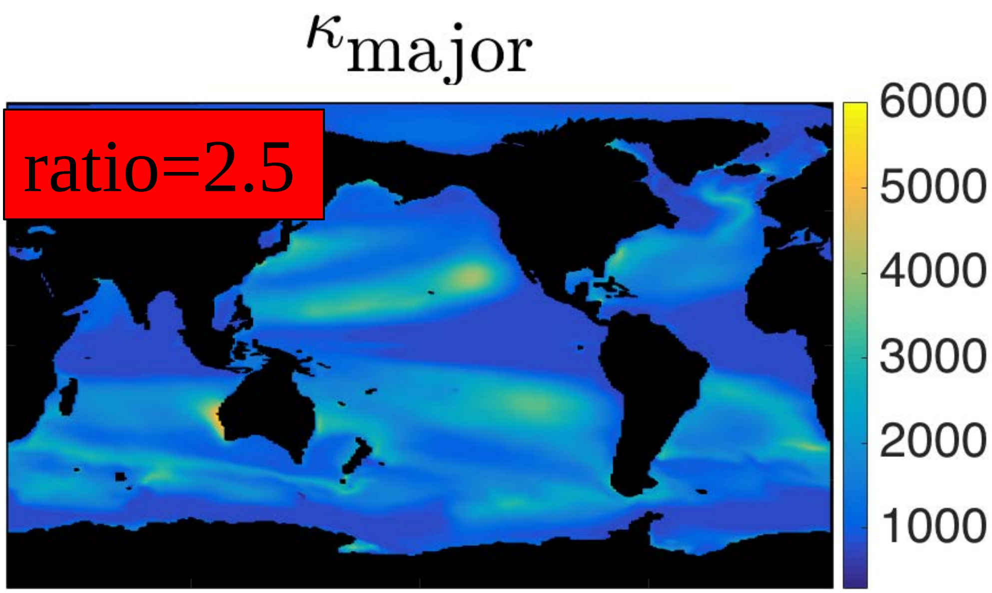
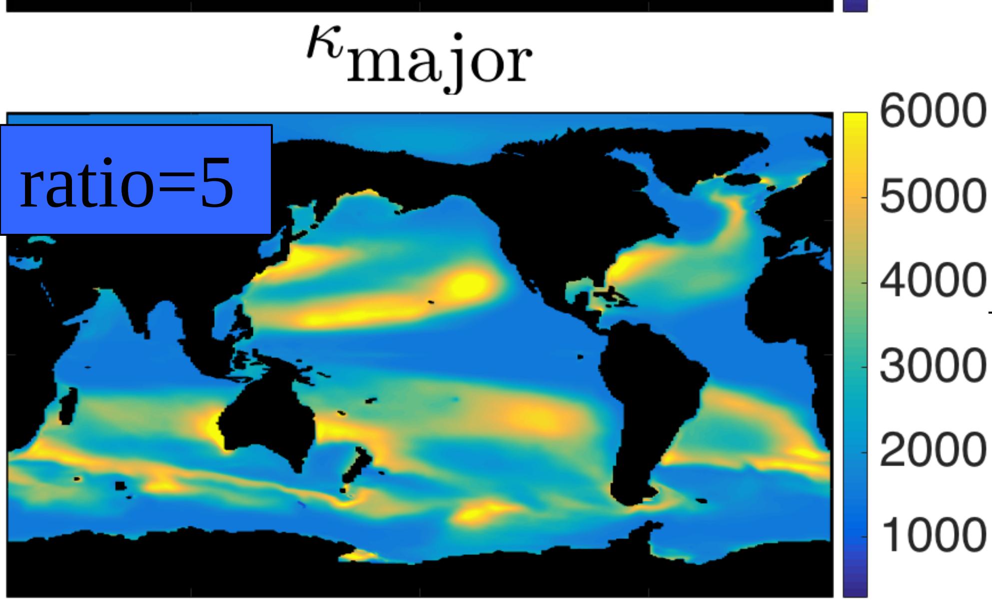
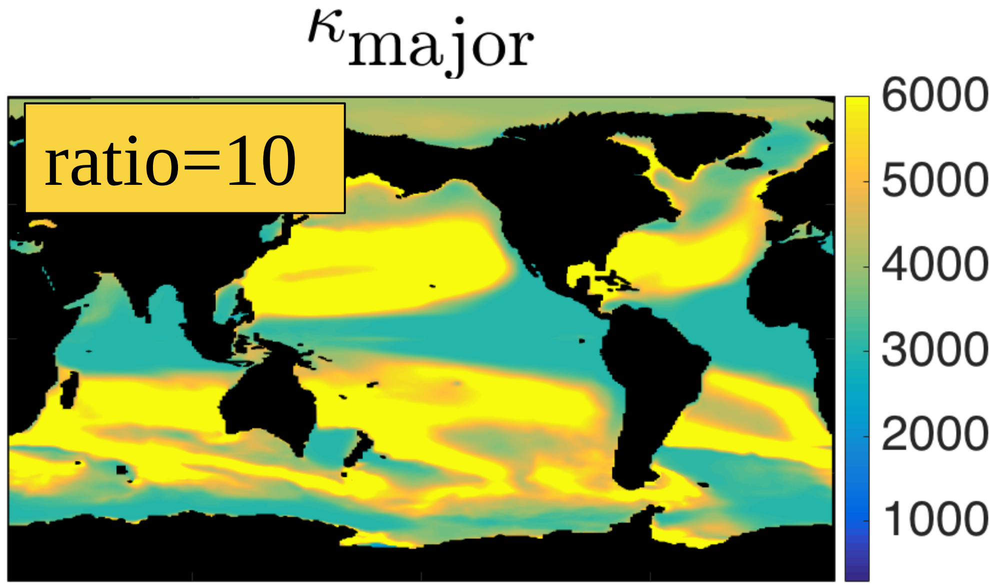
Diffusivity Ratio Study

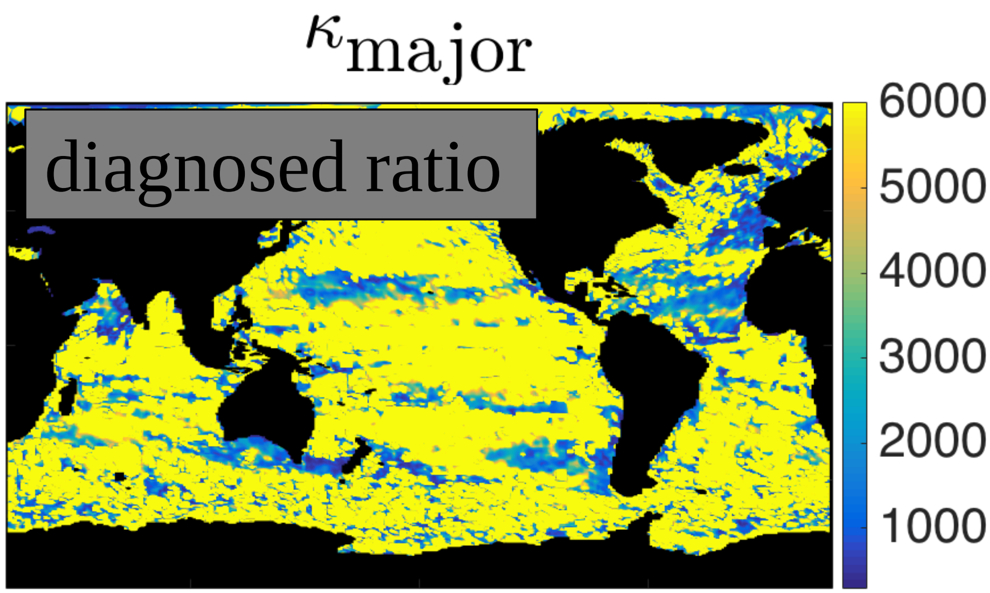


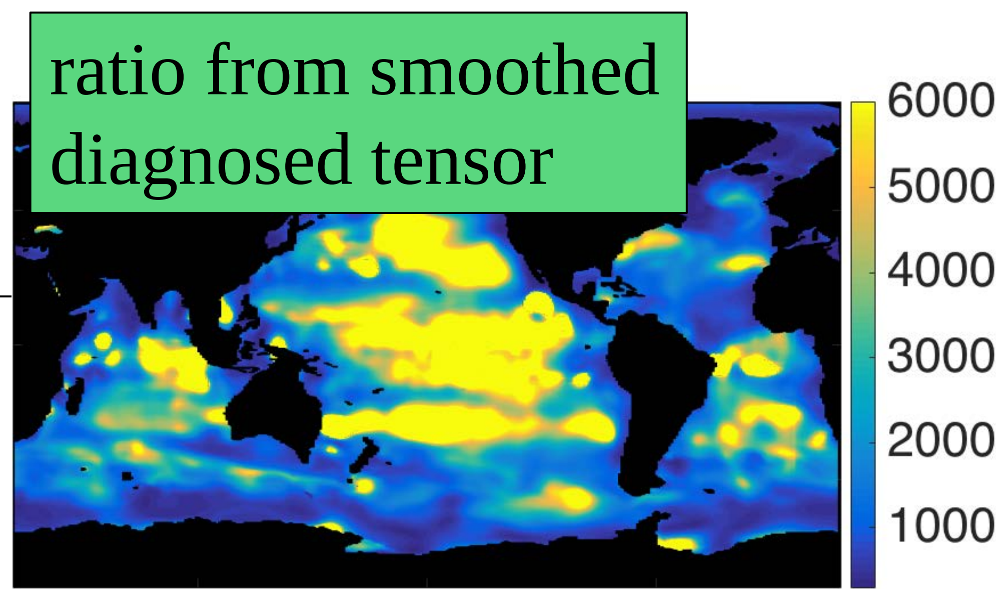




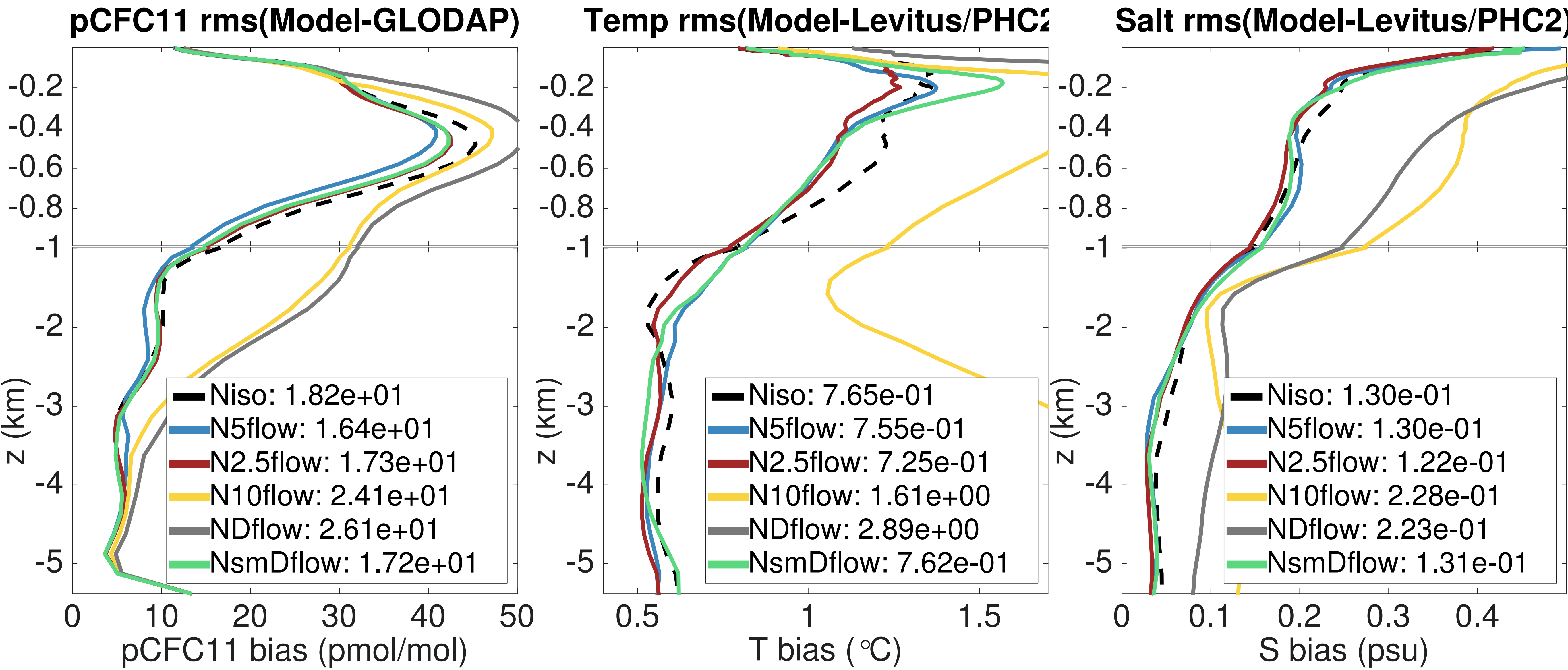
- N^2 param. for minor, flow-aligned







Diffusivity Ratio Study



N^2 isotropic | ratio=5 | ratio=2.5 | ratio=10 | diagnosed | smoothed diagnosis

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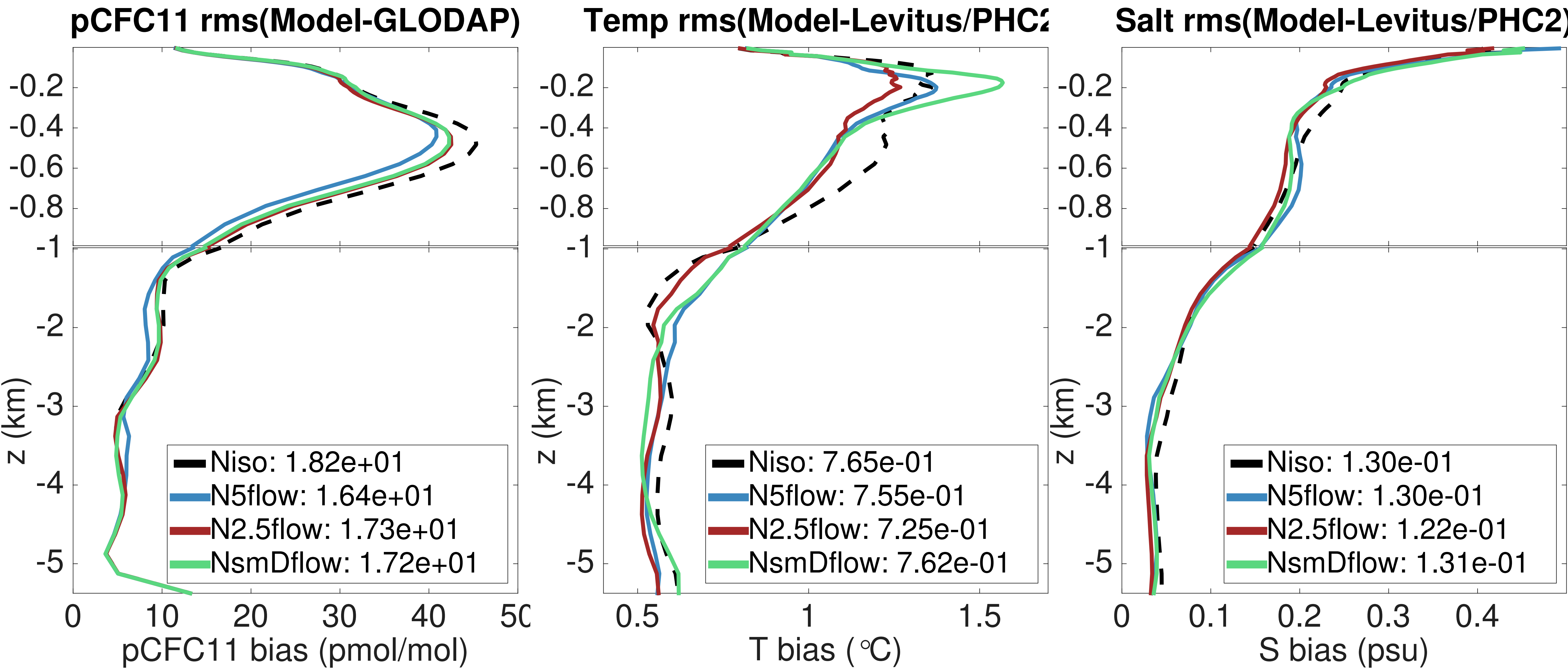
High diffusivity ratios introduce drastic biases likely due to suppression of deep water formation & AMOC shutdown

Parameter Sensitivity Results



N^2 isotropic | ratio=5 | ratio=2.5 | smoothed diagnosis

Flow alignment required, less sensitive to major/minor diffusivity

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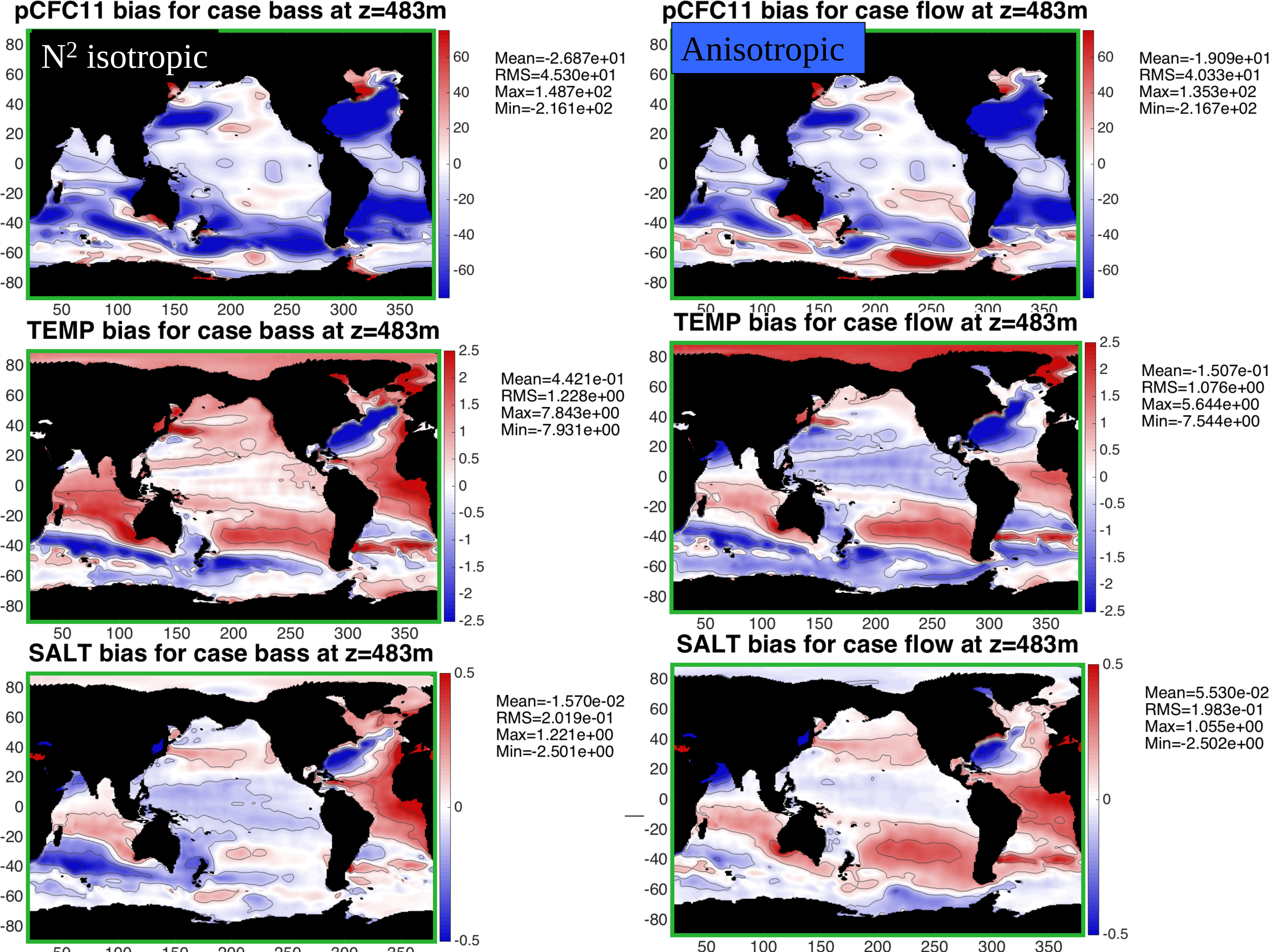
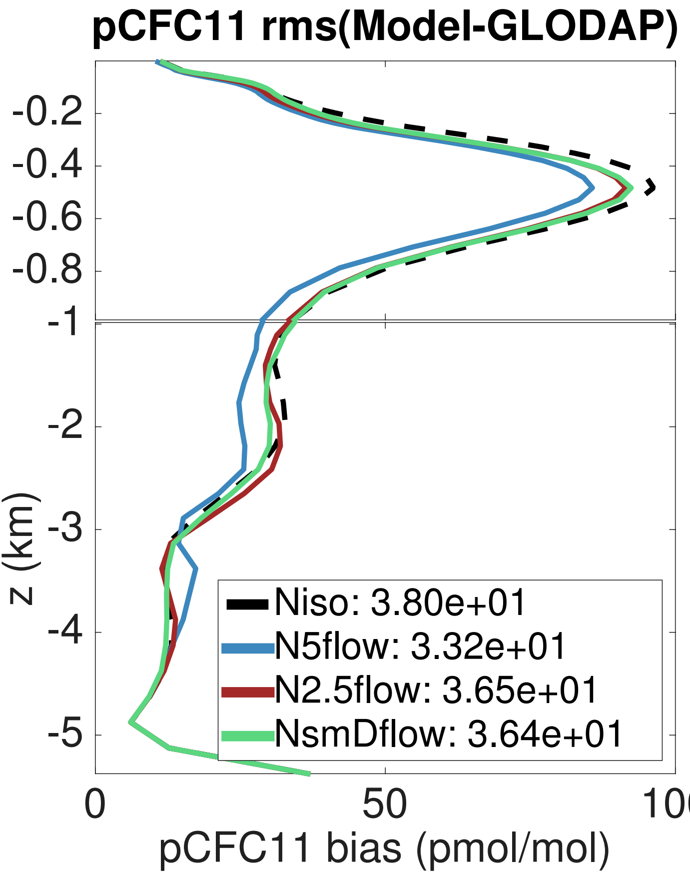
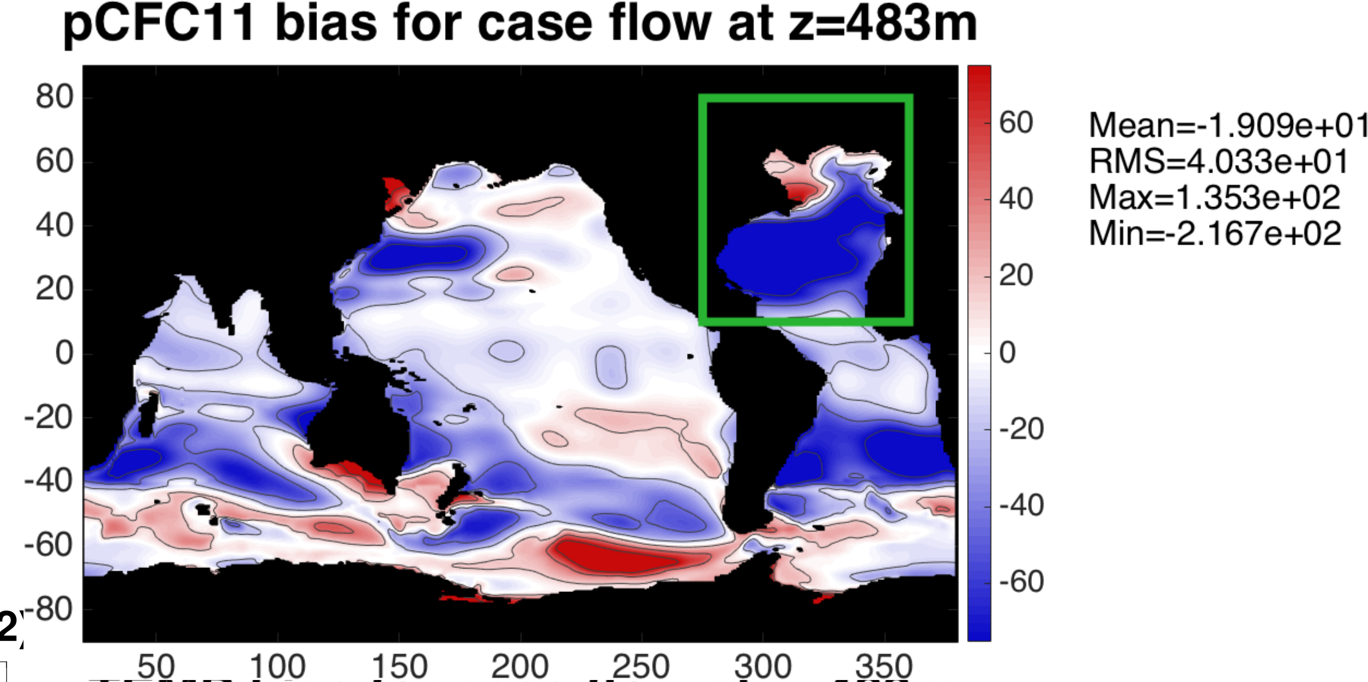
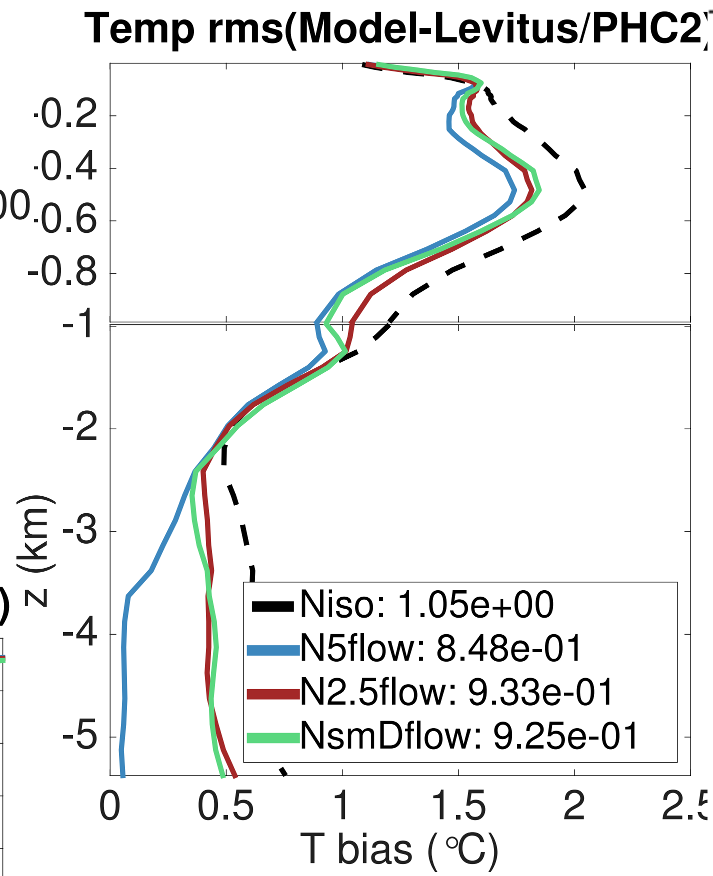


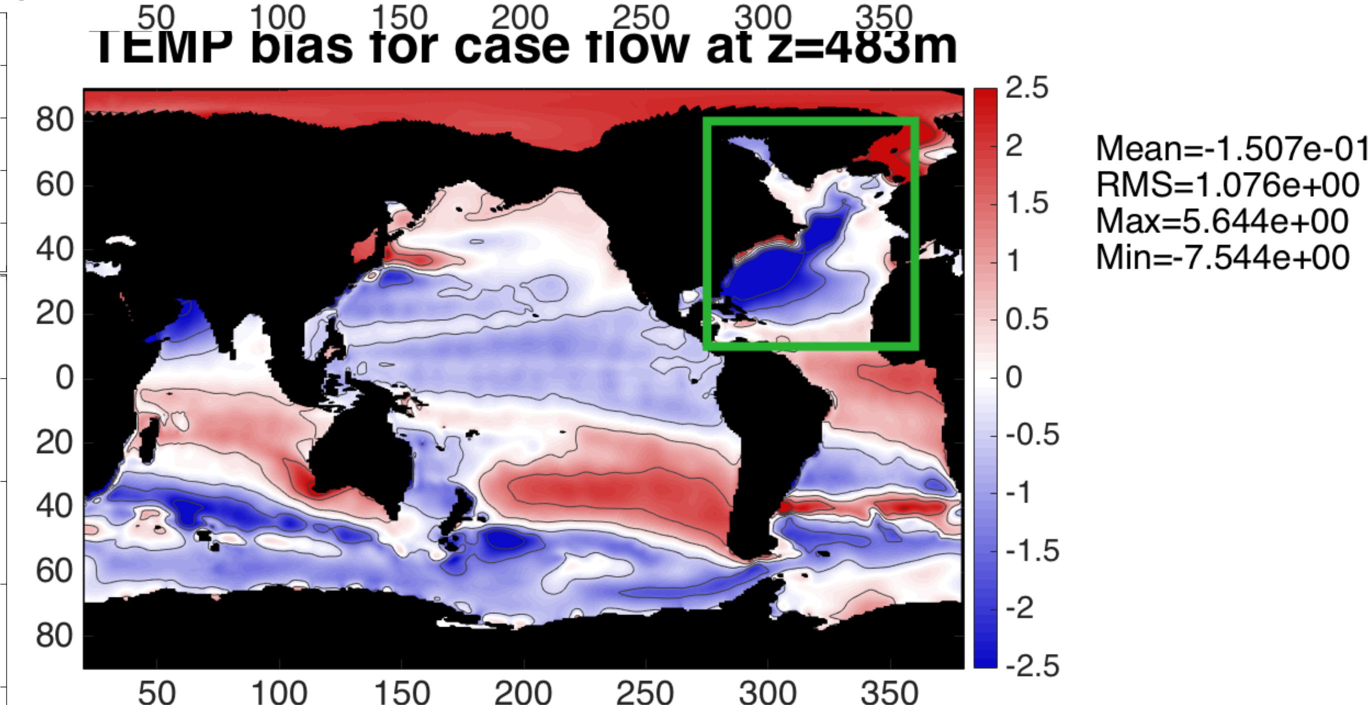
pCFC11 bias for case bass at z=483m
N^2 isotropic
Mean=-2.687e+01
RMS=4.530e+01
Max=1.487e+02
Min=-2.161e+02
pCFC11 bias for case flow at z=483m
Anisotropic
Mean=-1.909e+01
RMS=4.033e+01
Max=1.353e+02
Min=-2.167e+02
TEMP bias for case bass at z=483m
Mean=4.421e-01
RMS=1.228e+00
Max=7.843e+00
Min=-7.931e+00
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

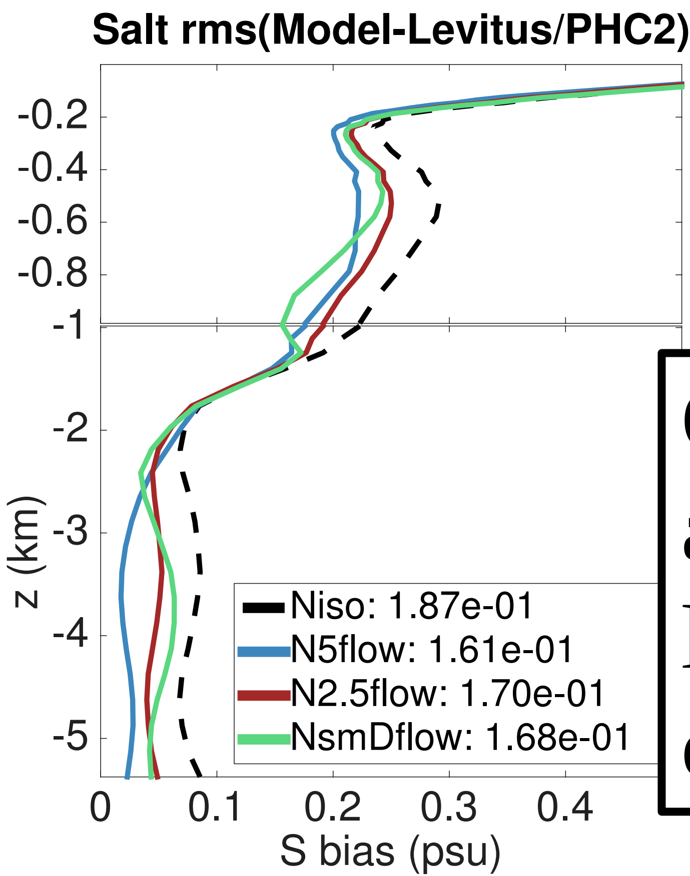


Large bias reductions due to anisotropy in the North Atlantic

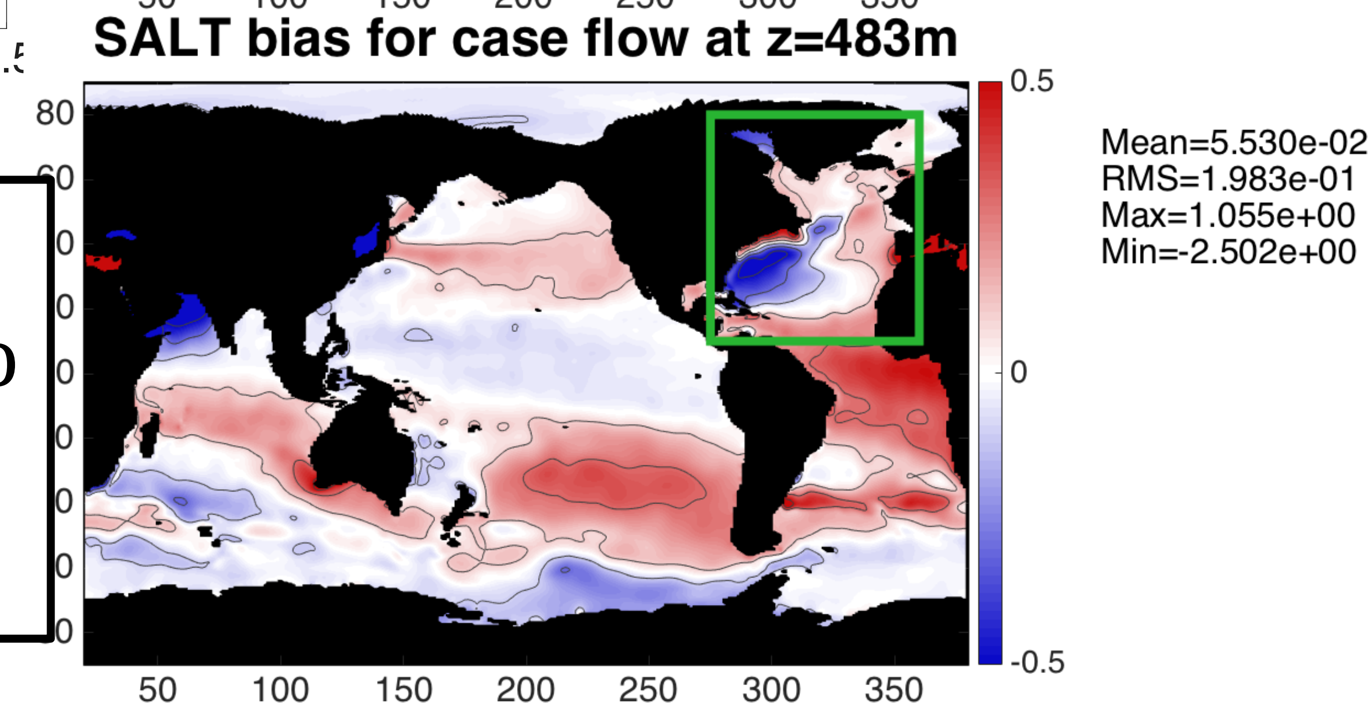


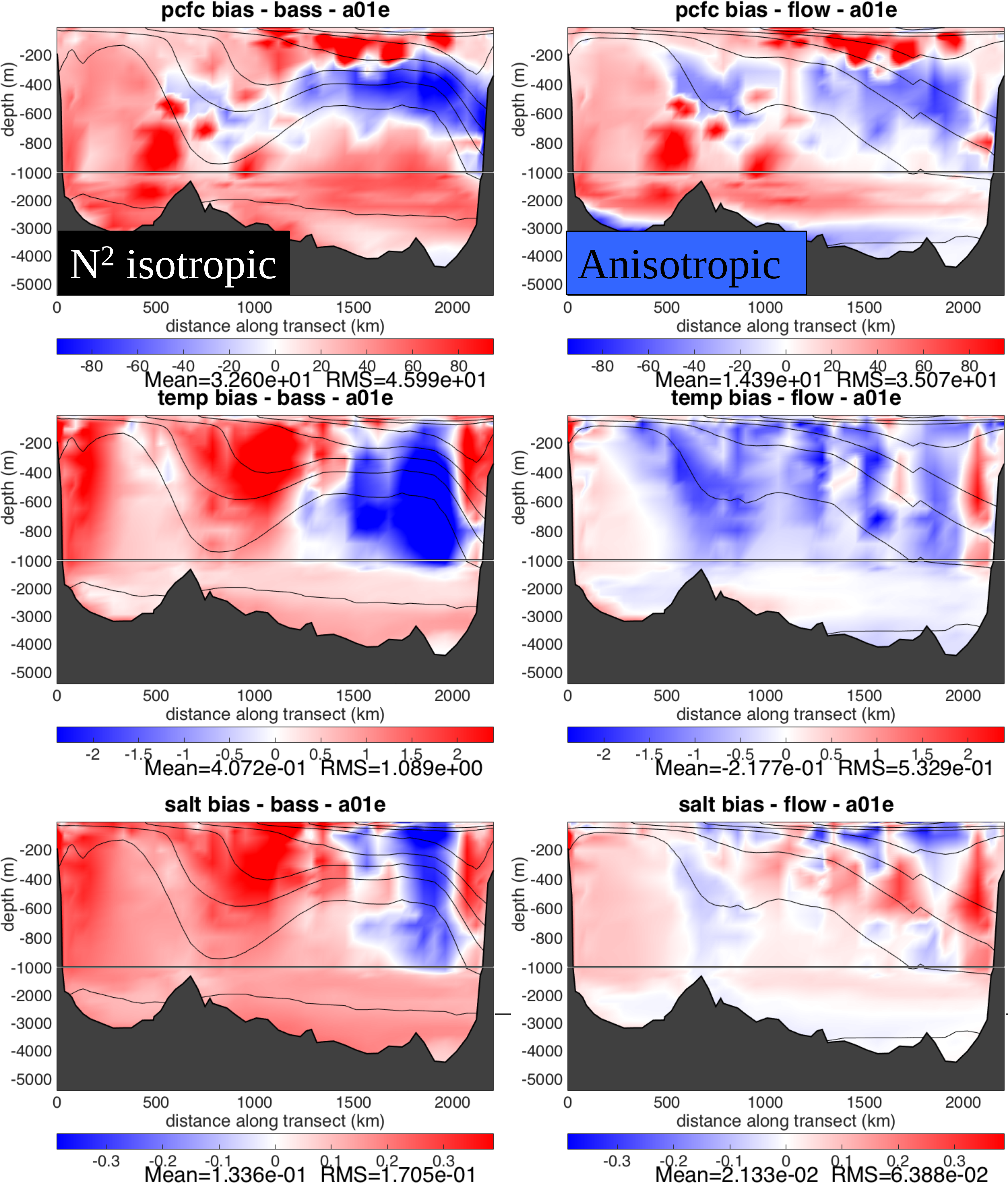




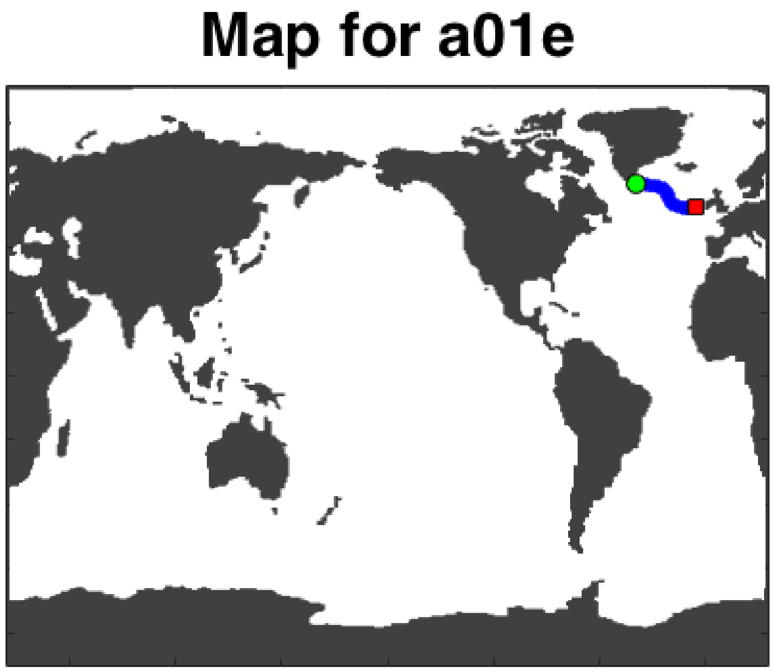


Overaggressive anisotropy can also lead to a shutdown of AMOC



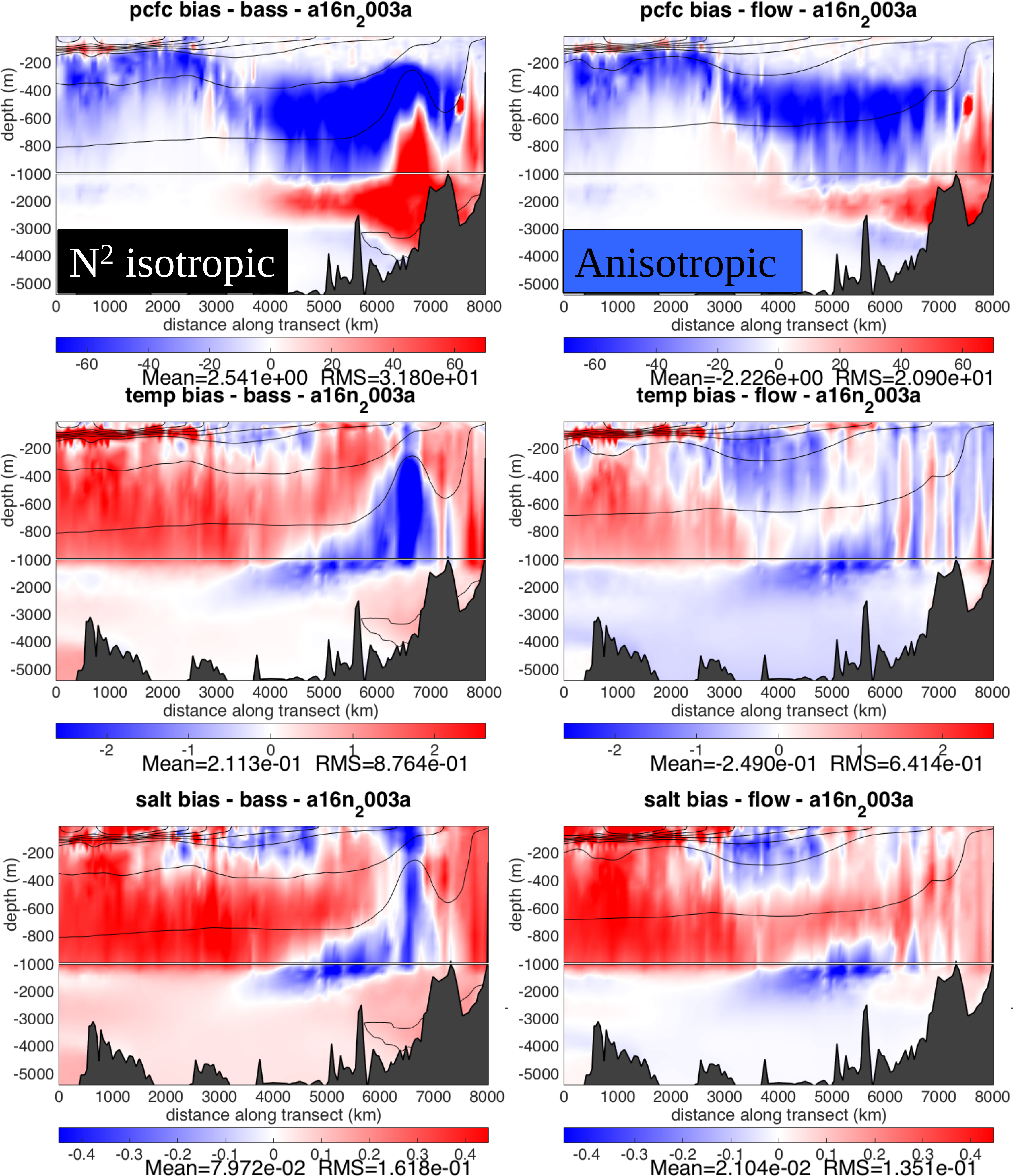


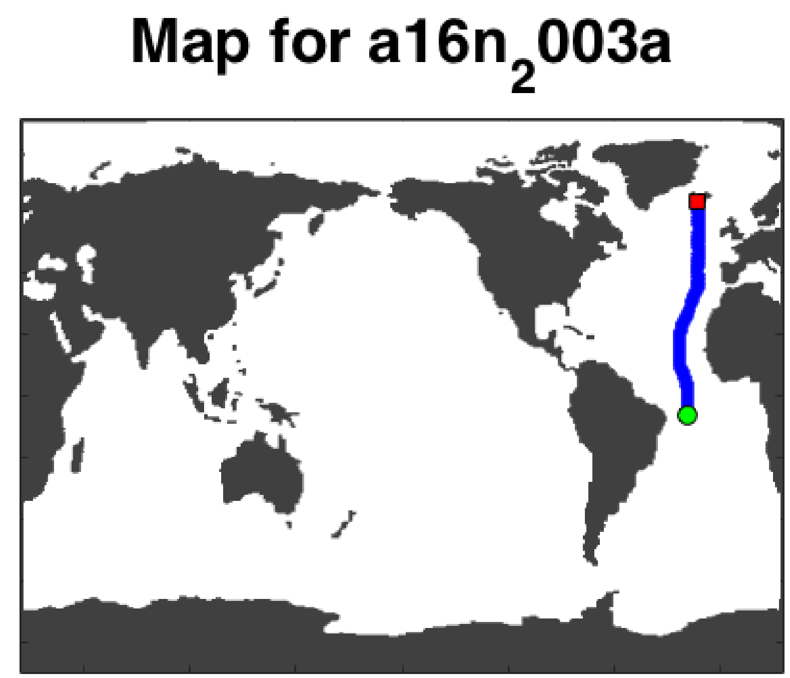
Along WOCE Transect



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

Along WOCE Transect

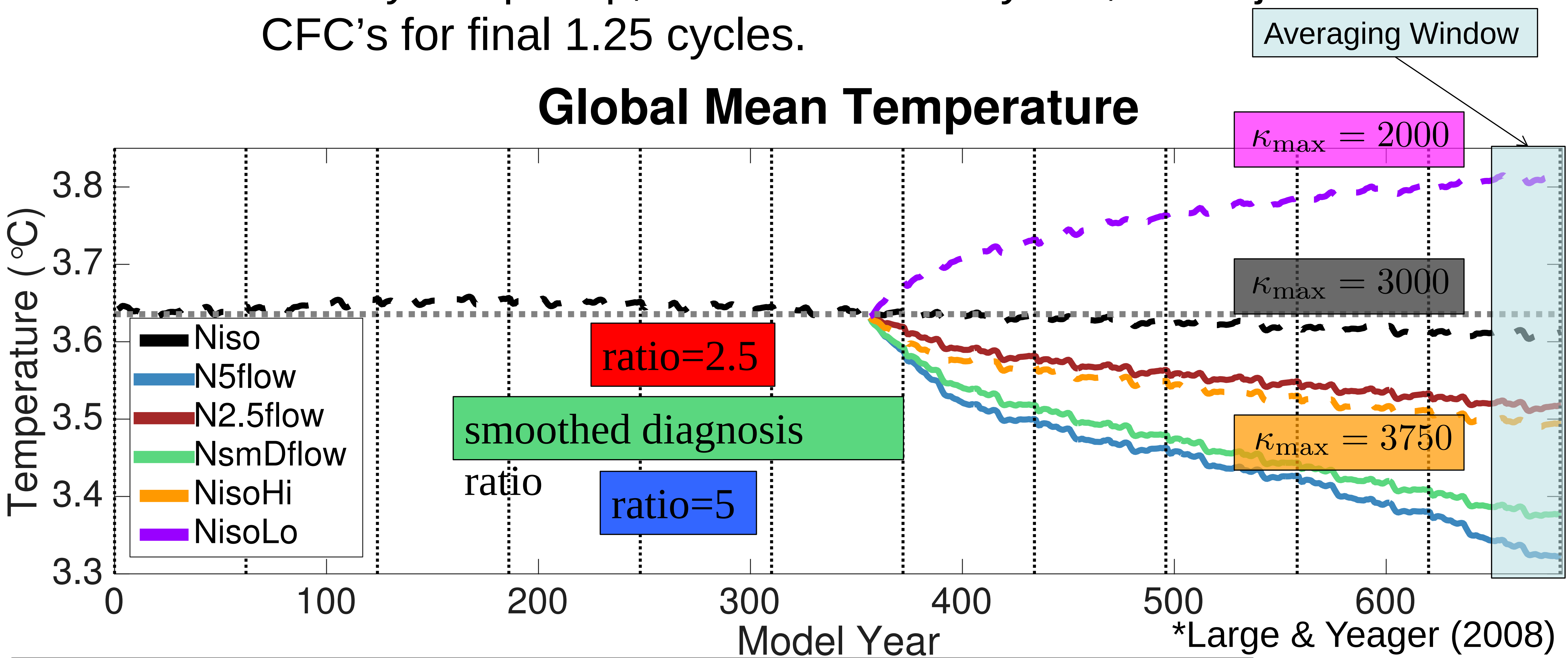




Anisotropy also reduces biases in equatorial Atlantic

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.



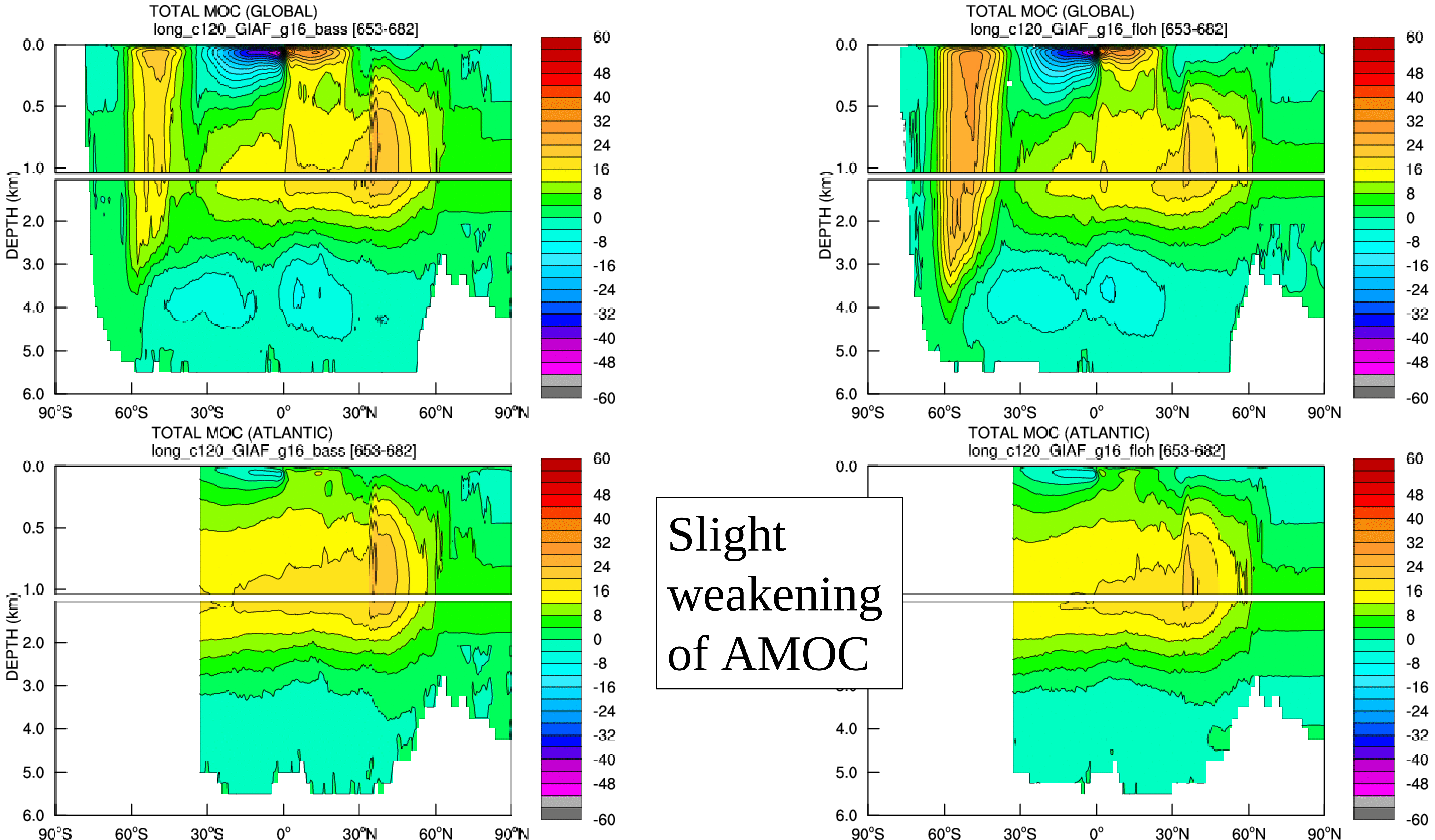
*Large & Yeager (2008)

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

(A)MOC Sensitivity to Anisotropy

N^2 isotropic

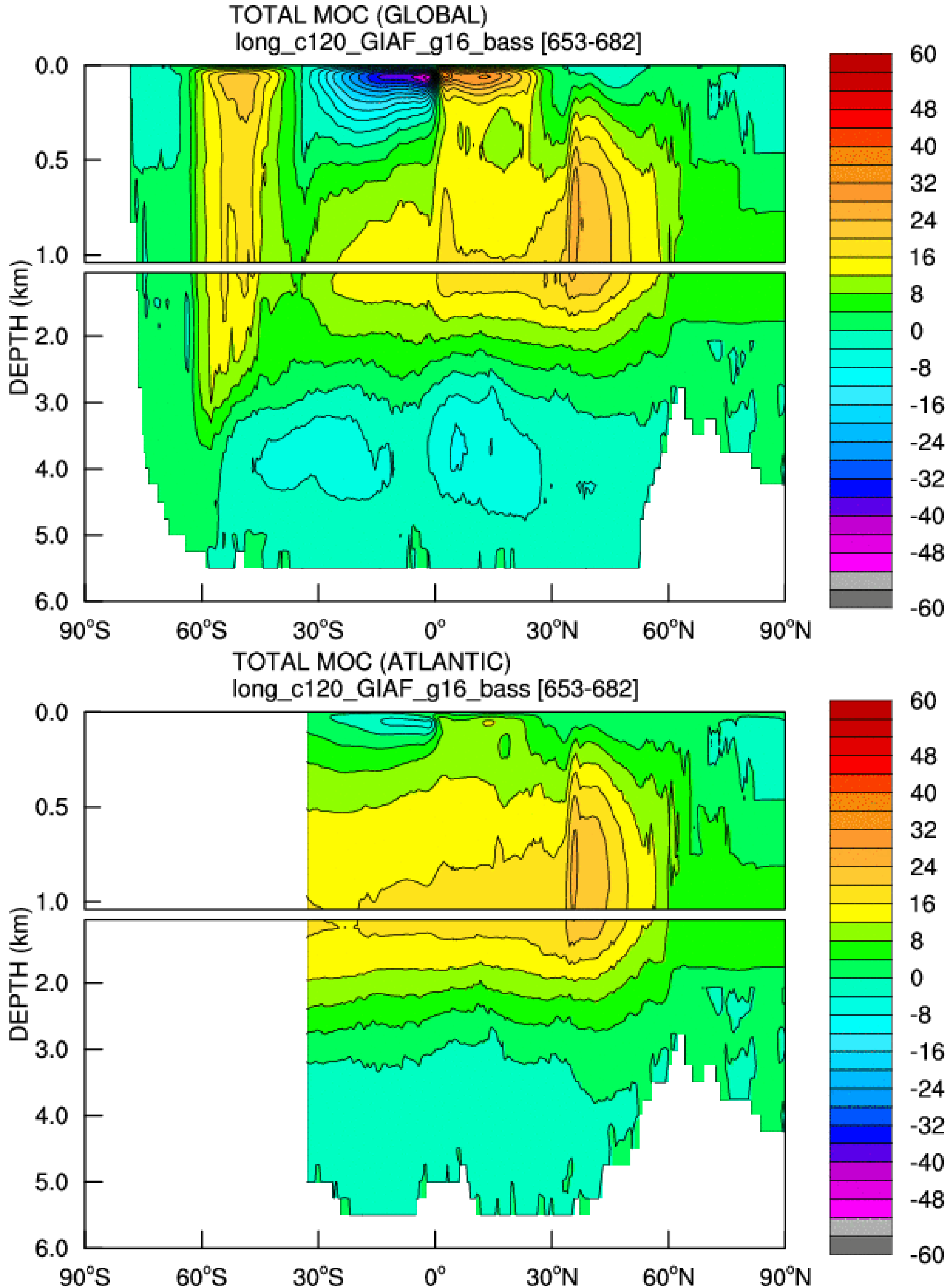
Anisotropic: ratio=2.5



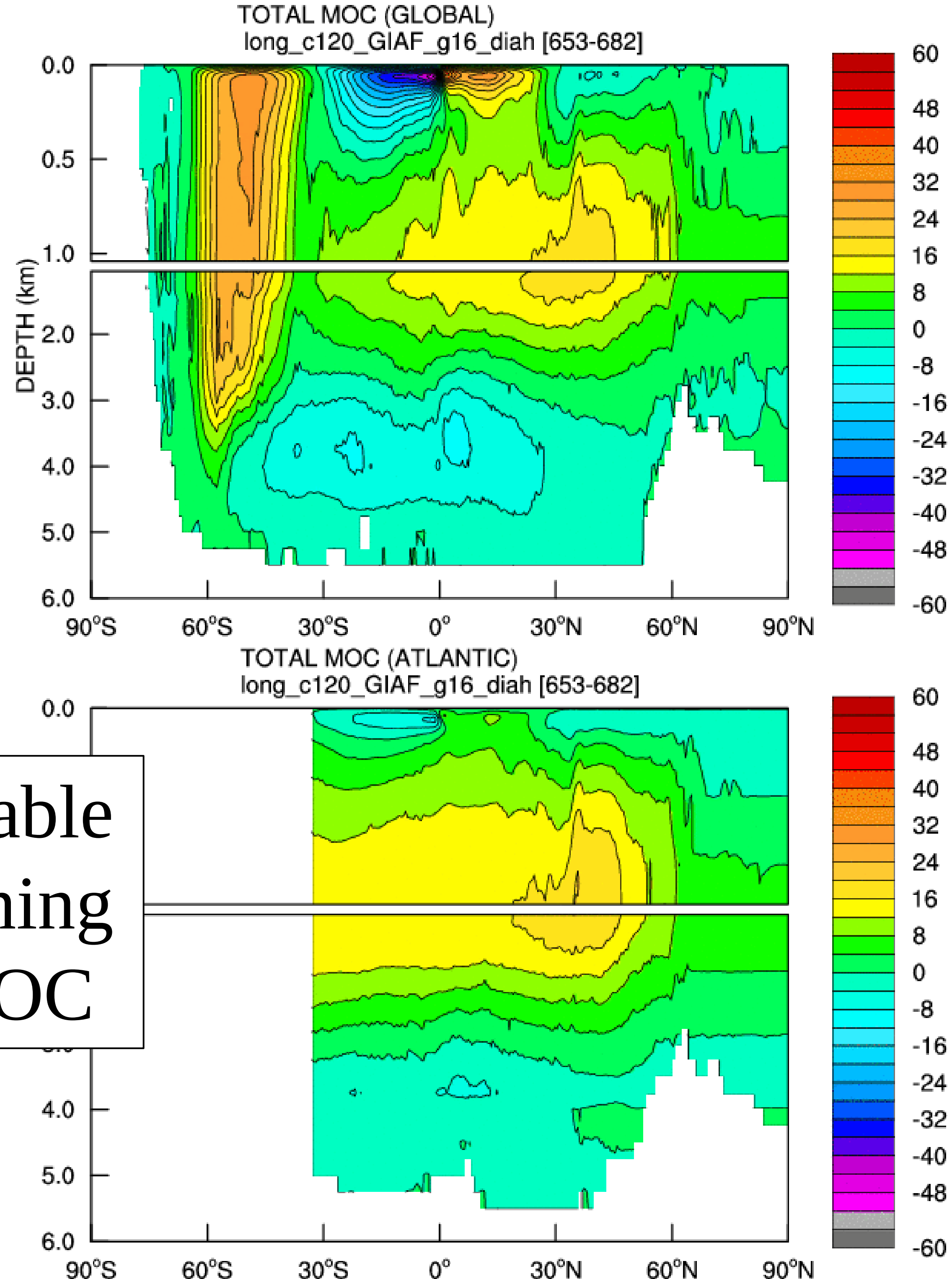
Slight weakening of AMOC

(A)MOC Sensitivity to Anisotropy

N^2 isotropic



Anisotropic: smoothed diag. ratio

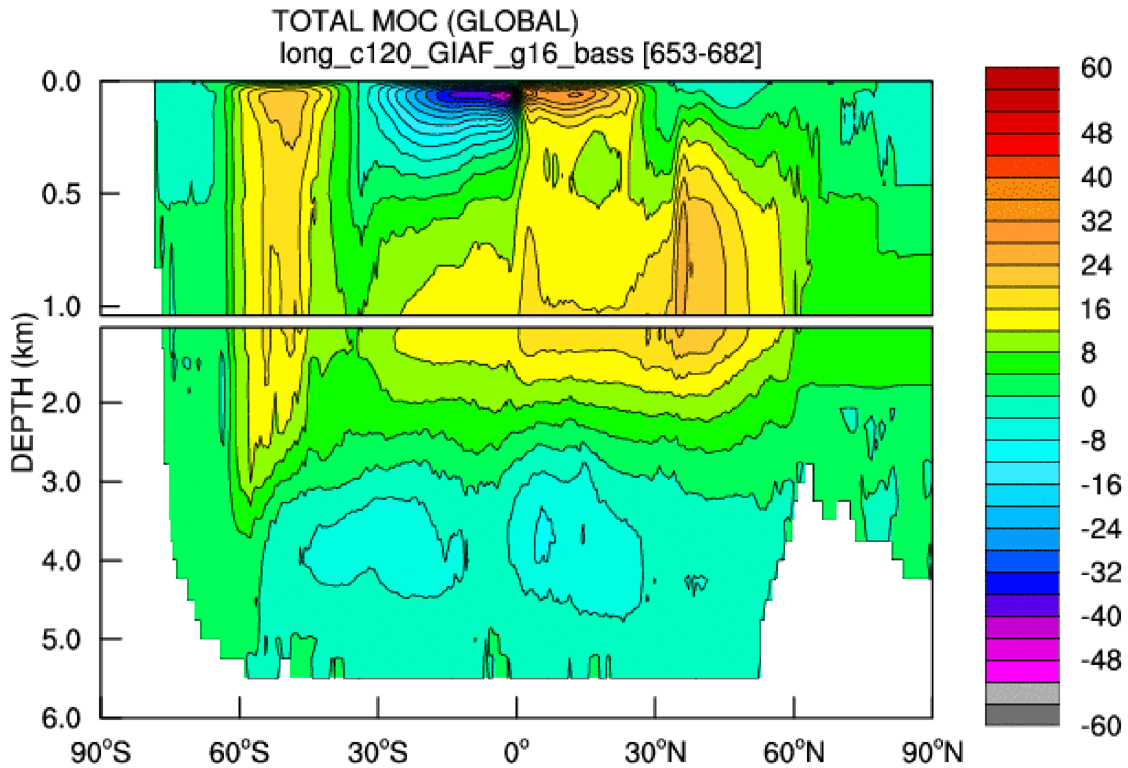


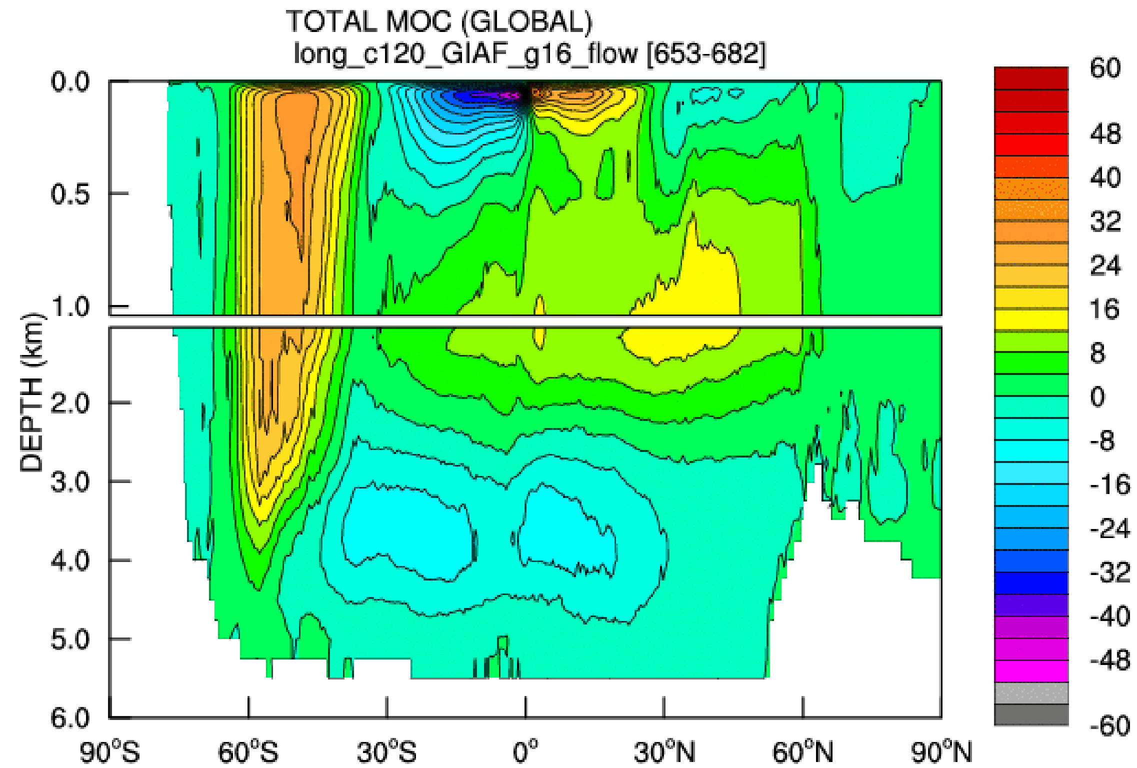
Noticeable weakening of AMOC

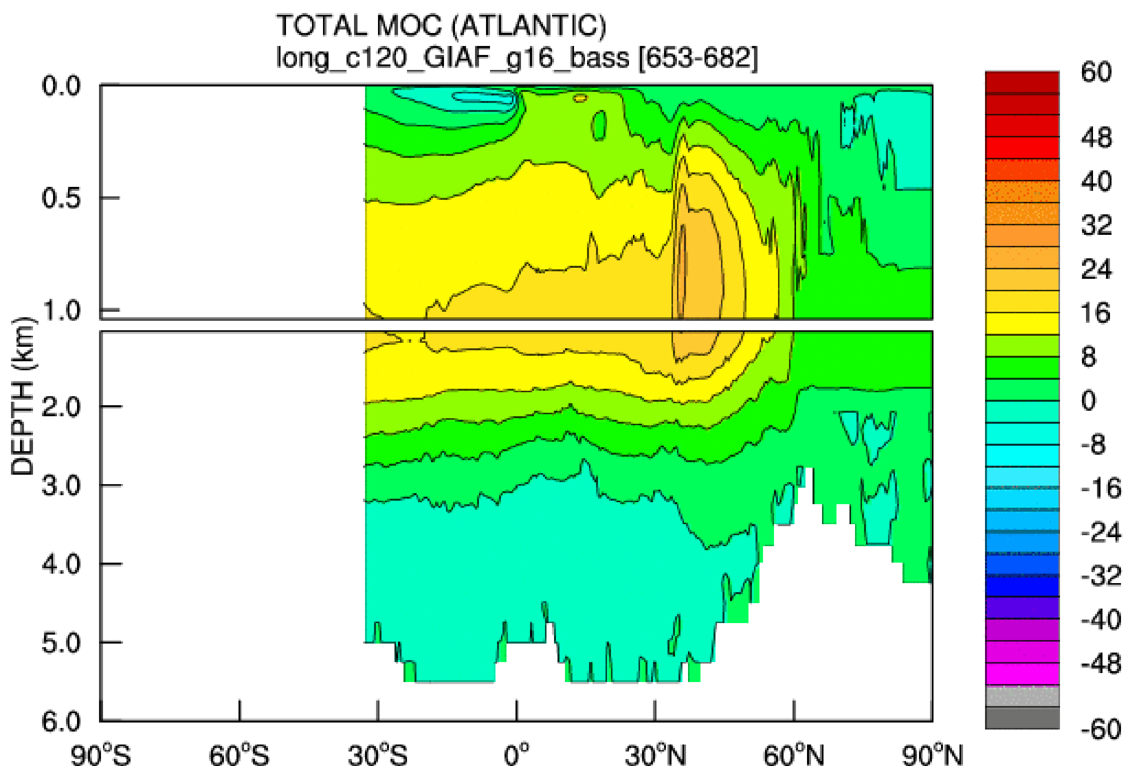
(A)MOC Sensitivity to Anisotropy

N^2 isotropic

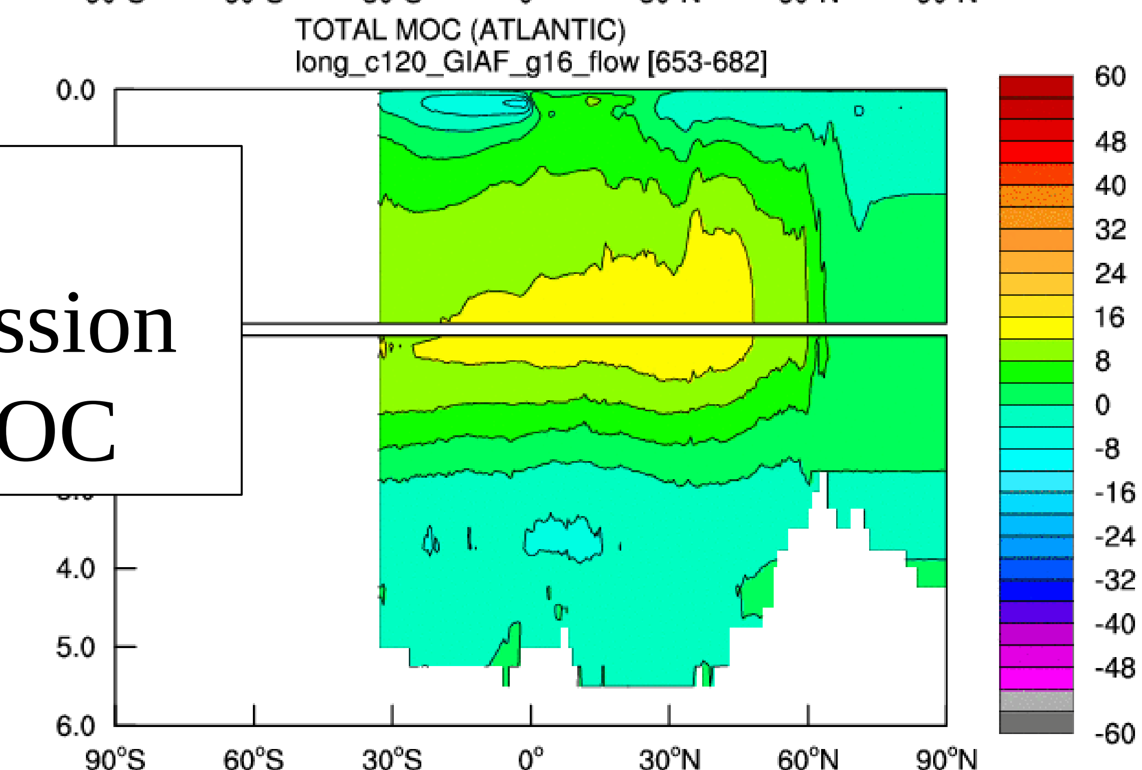
Anisotropic: ratio=5





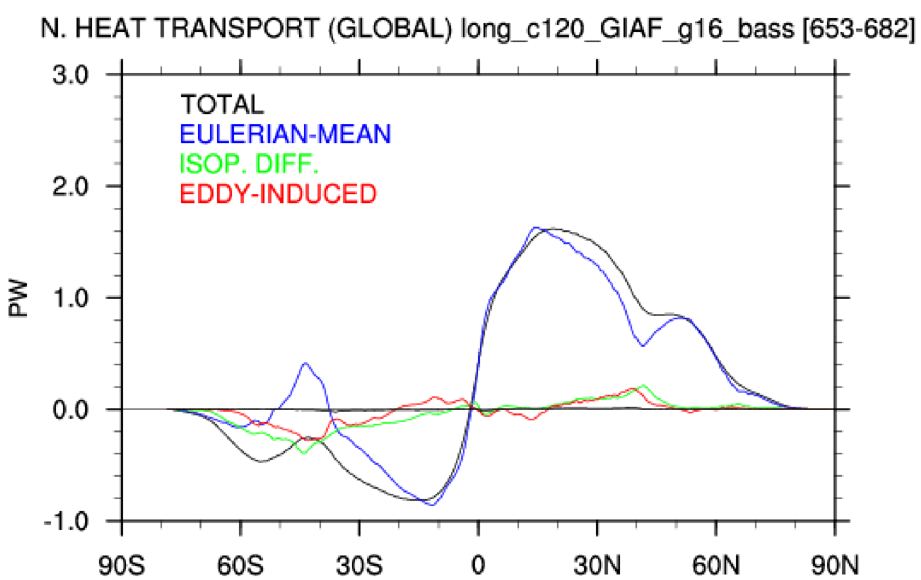


Strong suppression of AMOC



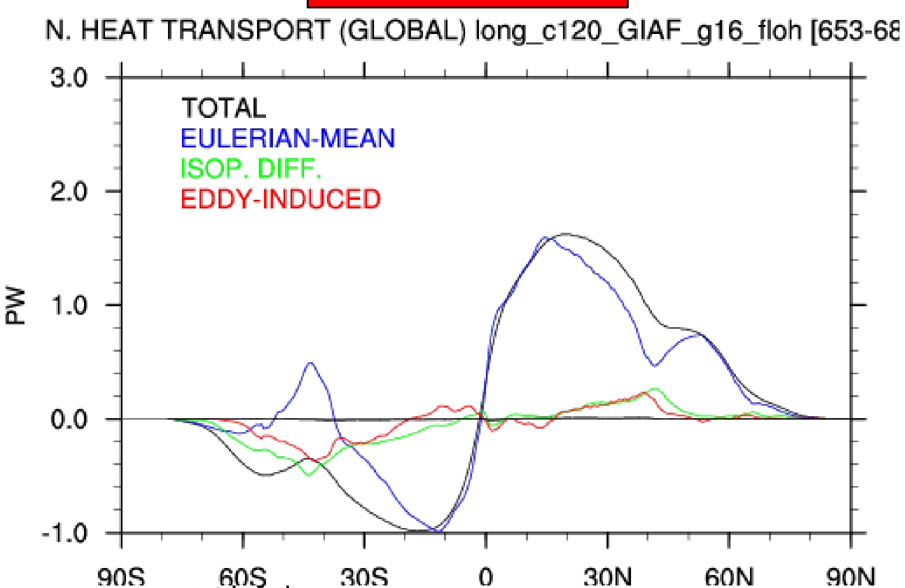
Meridional Heat Transport

N^2 isotropic

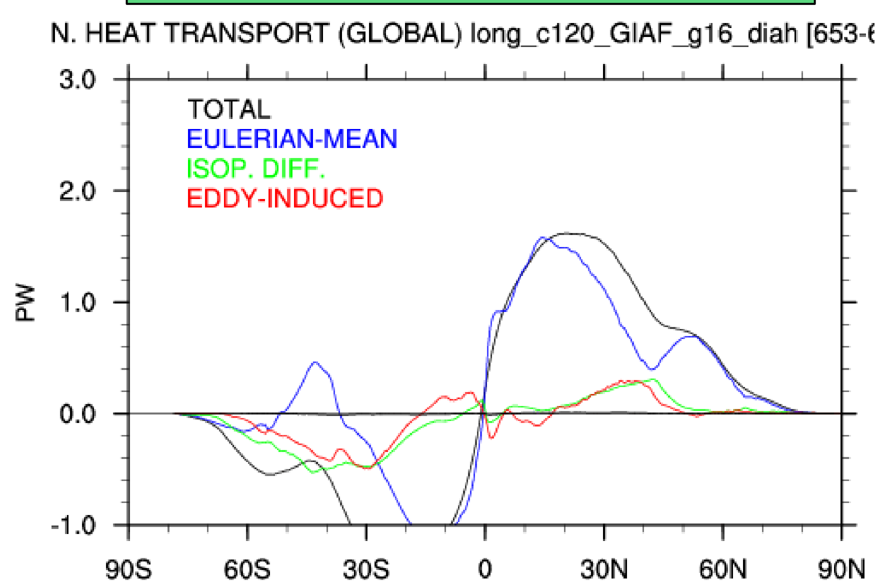


- No noticeable effect in Northern Hemisphere
- Increased transport in Southern Hemisphere

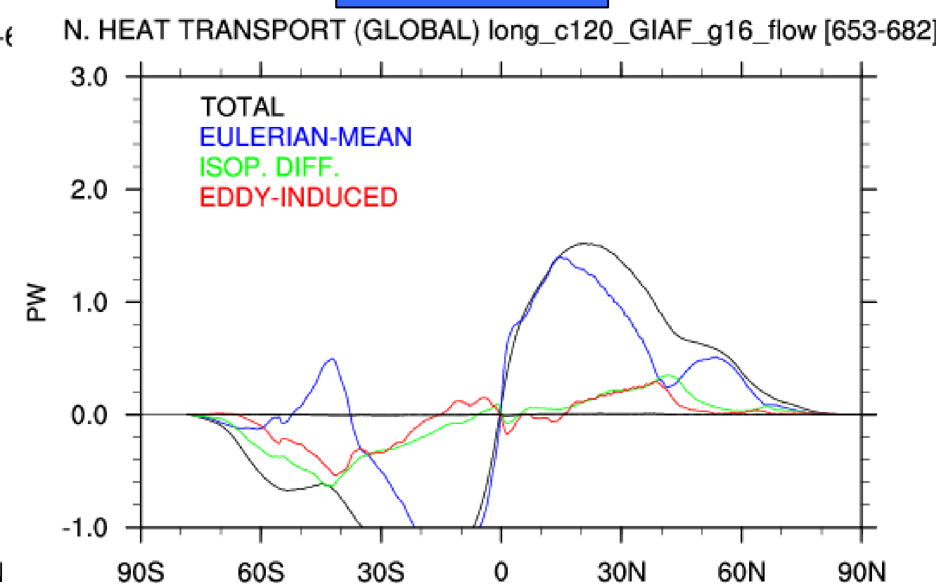
ratio=2.5



smoothed diag. ratio



ratio=5



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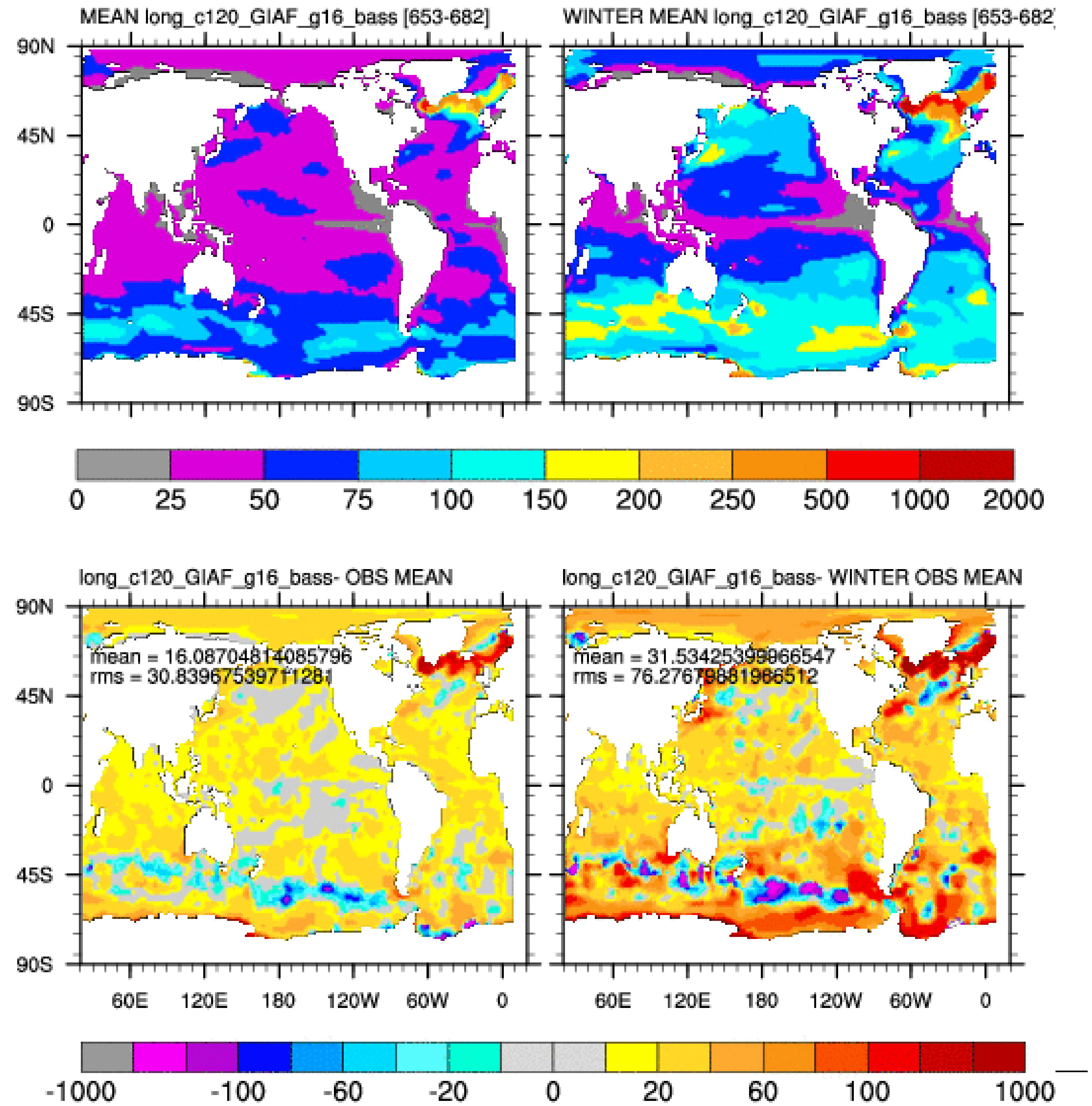
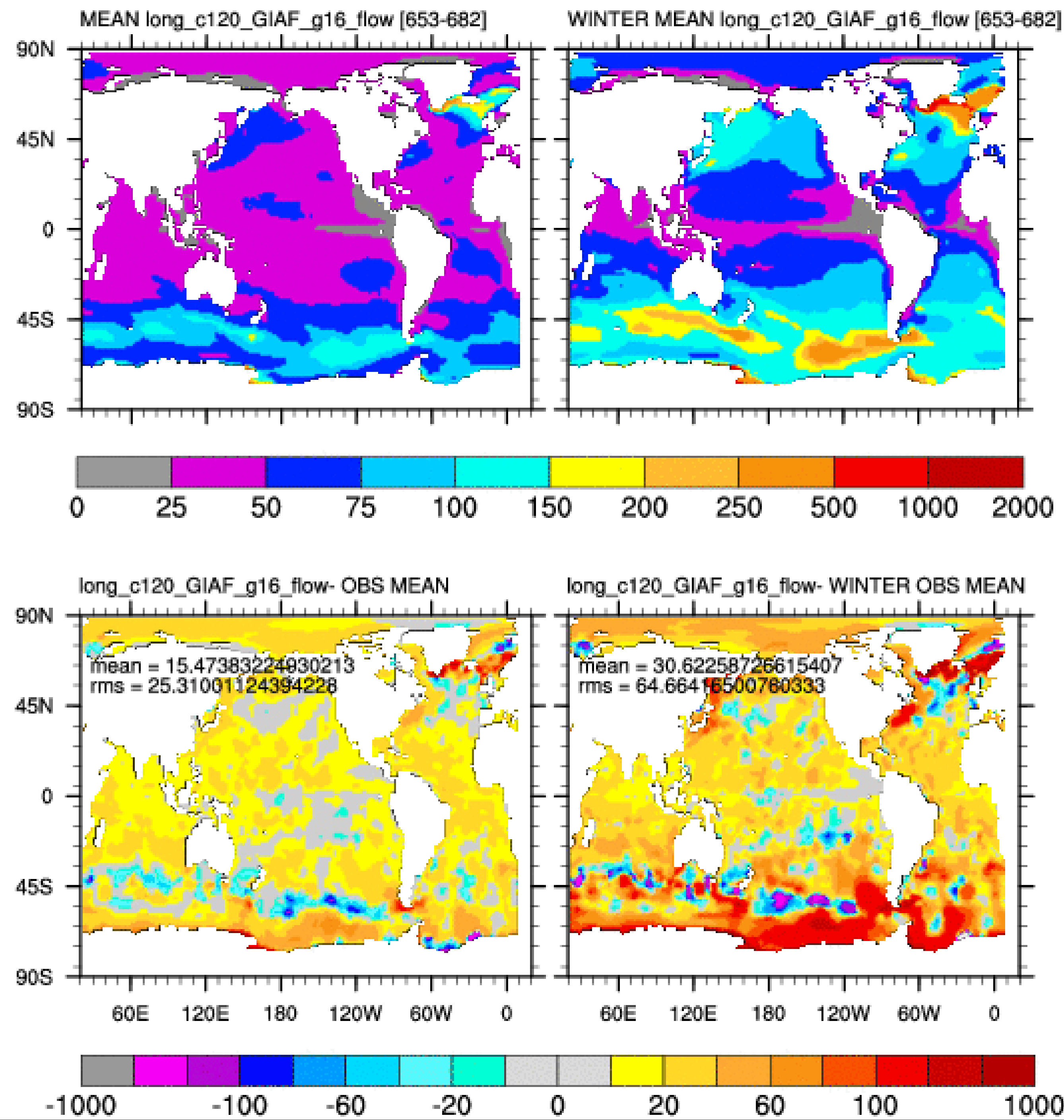
Mixed Layer Depth

N² isotropic



Anisotropic: ratio=5

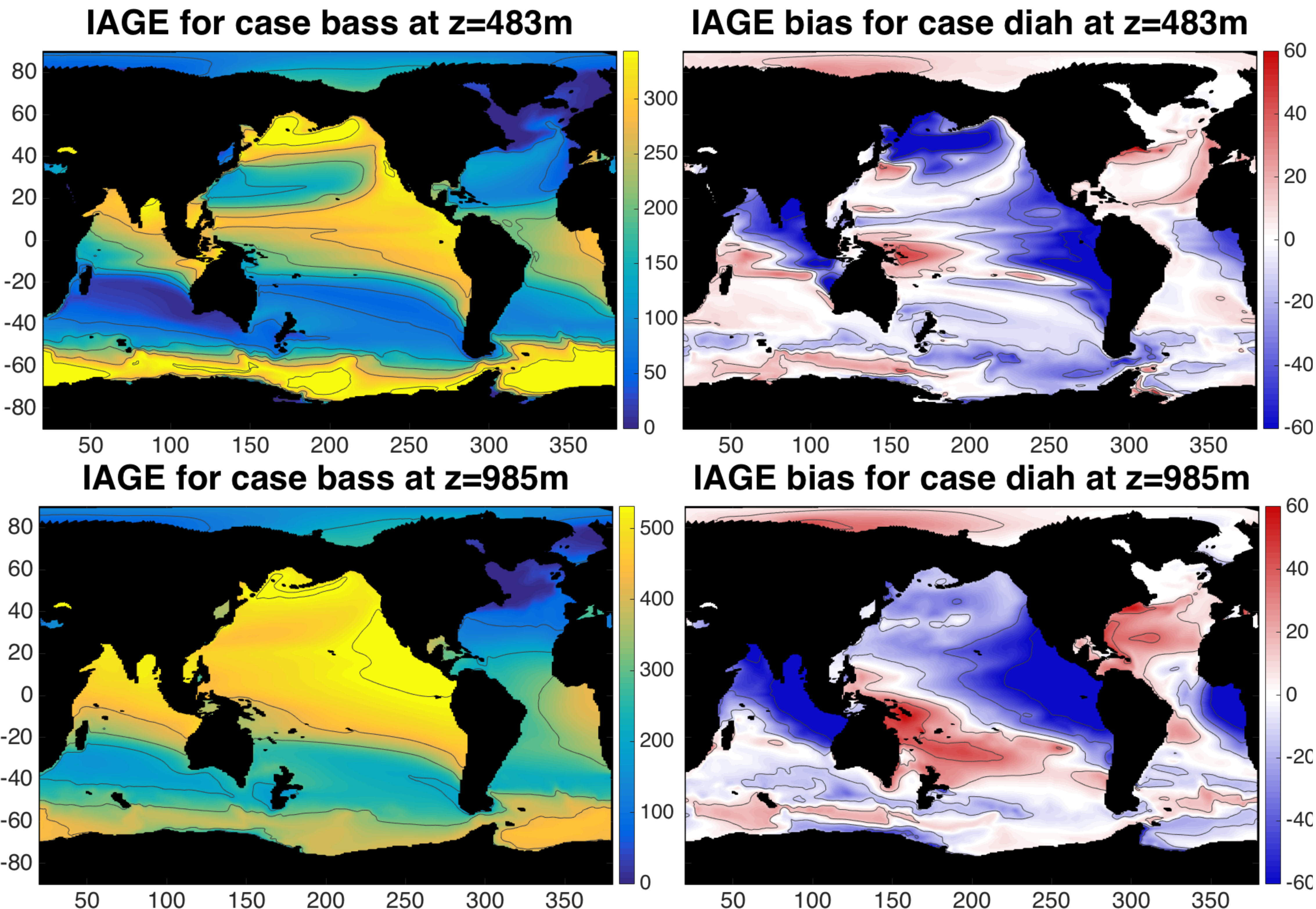


Anisotropy deepens MLD in Southern Ocean, shallows MLD in North Atlantic, and reduces winter mean rms bias by 15% (annual by 18%)

Ideal Age and Oxygen Minimum Zones

N^2 isotropic

smth. diag. ratio — N^2 isotropic



blue = younger than cntl

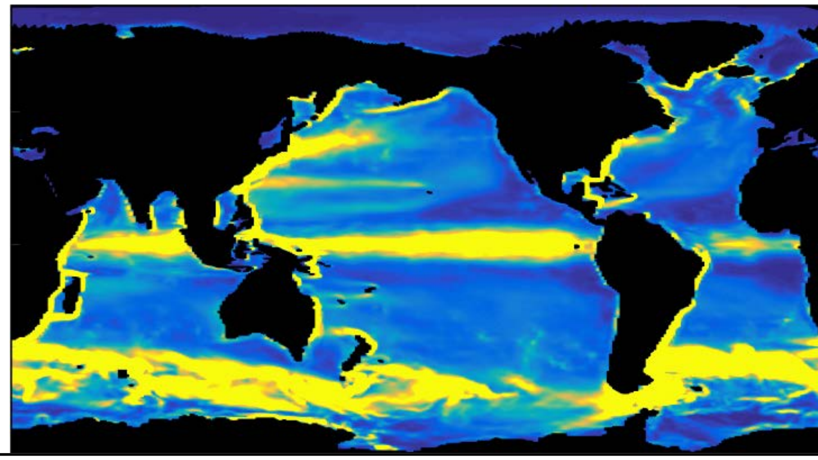
red = older than cntl

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

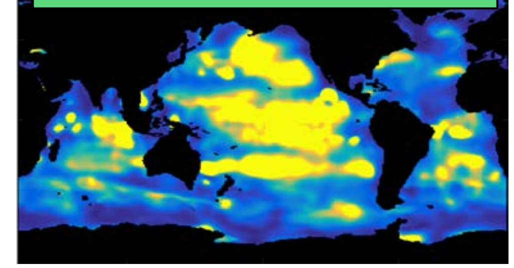
Shear Dispersion Parameterization

$$\kappa_{\mathrm{major}} = \kappa + \kappa^{-1} \left\langle (u\Delta y)^2 + (v\Delta x)^2 \right\rangle$$

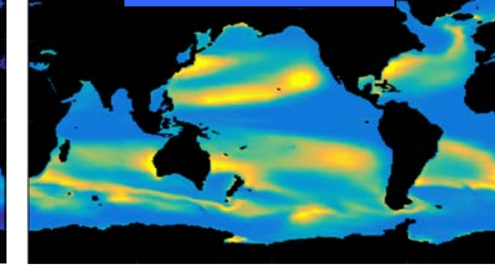
shear dispersion



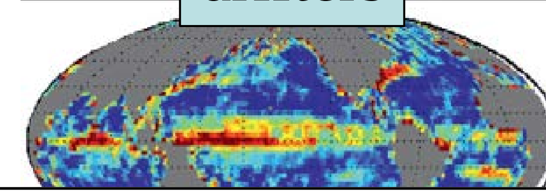
smth. diag. ratio



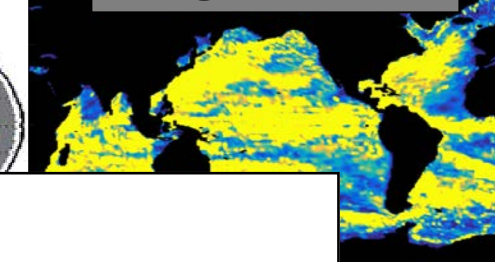
ratio=5



drifters



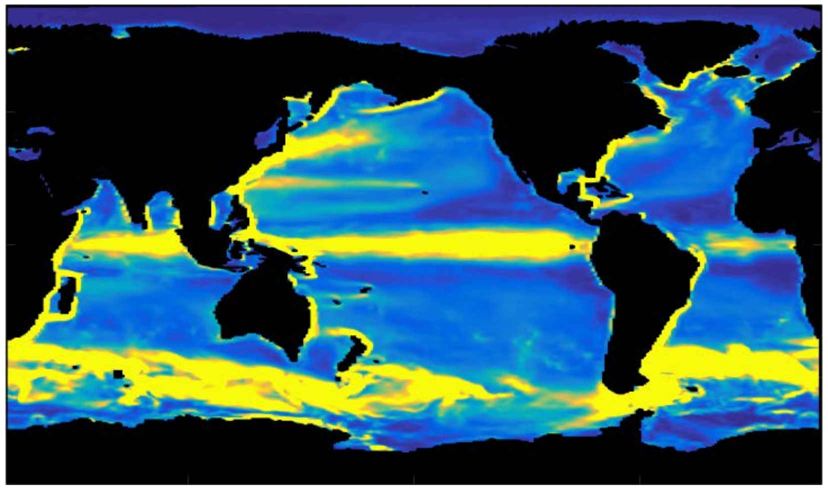
diagnosed

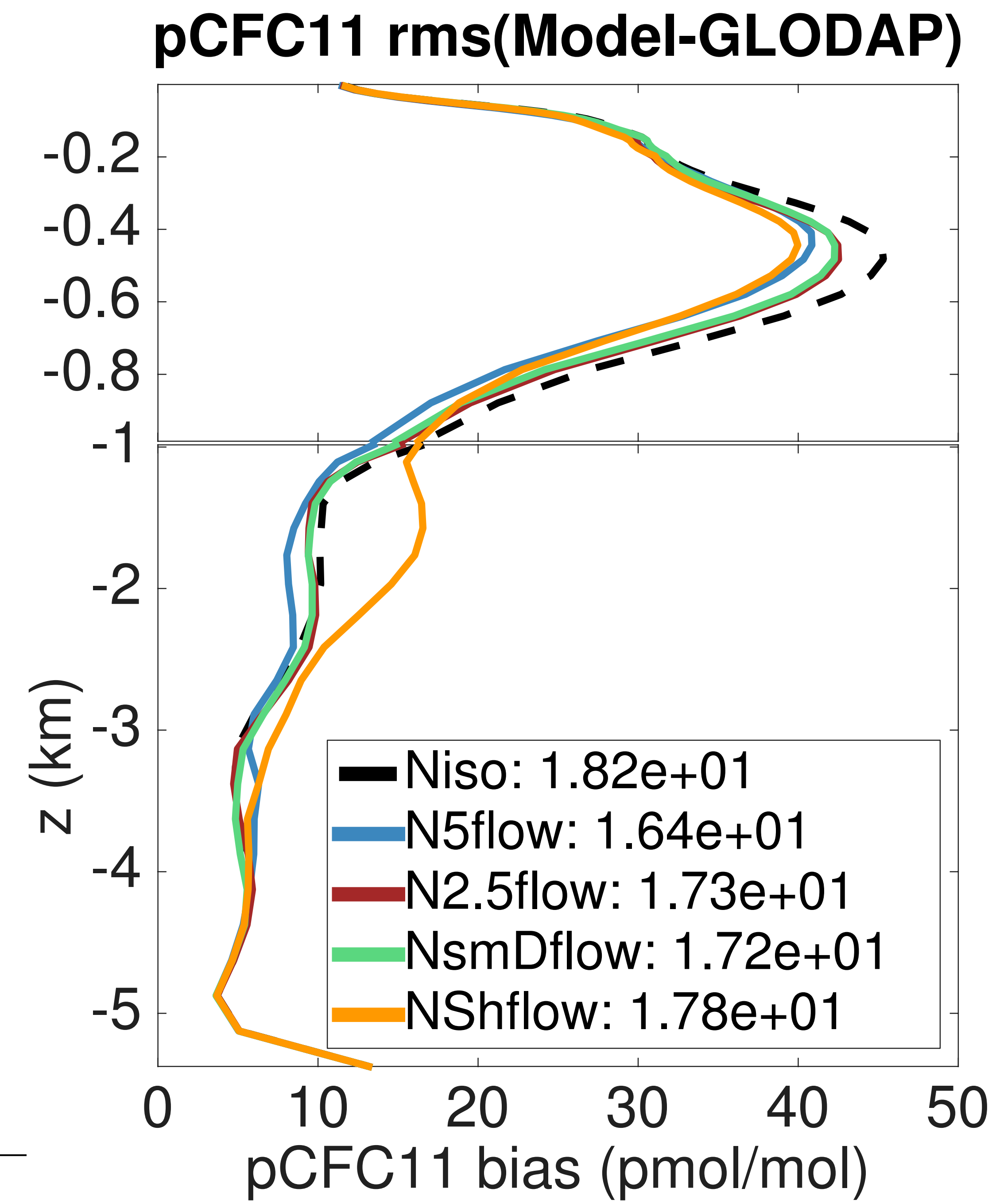


Shear Dispersion Parameterization

$$\kappa_{\mathrm{major}} = \kappa + \kappa^{-1}\left\langle (u\Delta y)^2 + (v\Delta x)^2 \right\rangle$$

shear dispersion





Current version reduces CFC bias, but does not maintain AMOC, likely due to strong shear (strong diffusion) in Labrador Sea, preventing deep water formation

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Conclusions and Future Work

- Sensitivity to anisotropy:
  - Alignment: high sensitivity, **flow-alignment** performs best (CFC, T, & S bias reductions) 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, although large bias reductions in the North Atlantic despite suppression of AMOC and global mean temperature drift.
  - MLD: Southern Ocean deepening, North Atlantic shallowing, rms bias reduction.
- Outstanding issues: across-flow suppression (e.g. steering levels), better “background diffusivity” (than N^2 parameterization), merging with Langmuir mixing, fully-coupled simulations, near-surface transition