Anisotropic Eddy Transport of the Mesoscale

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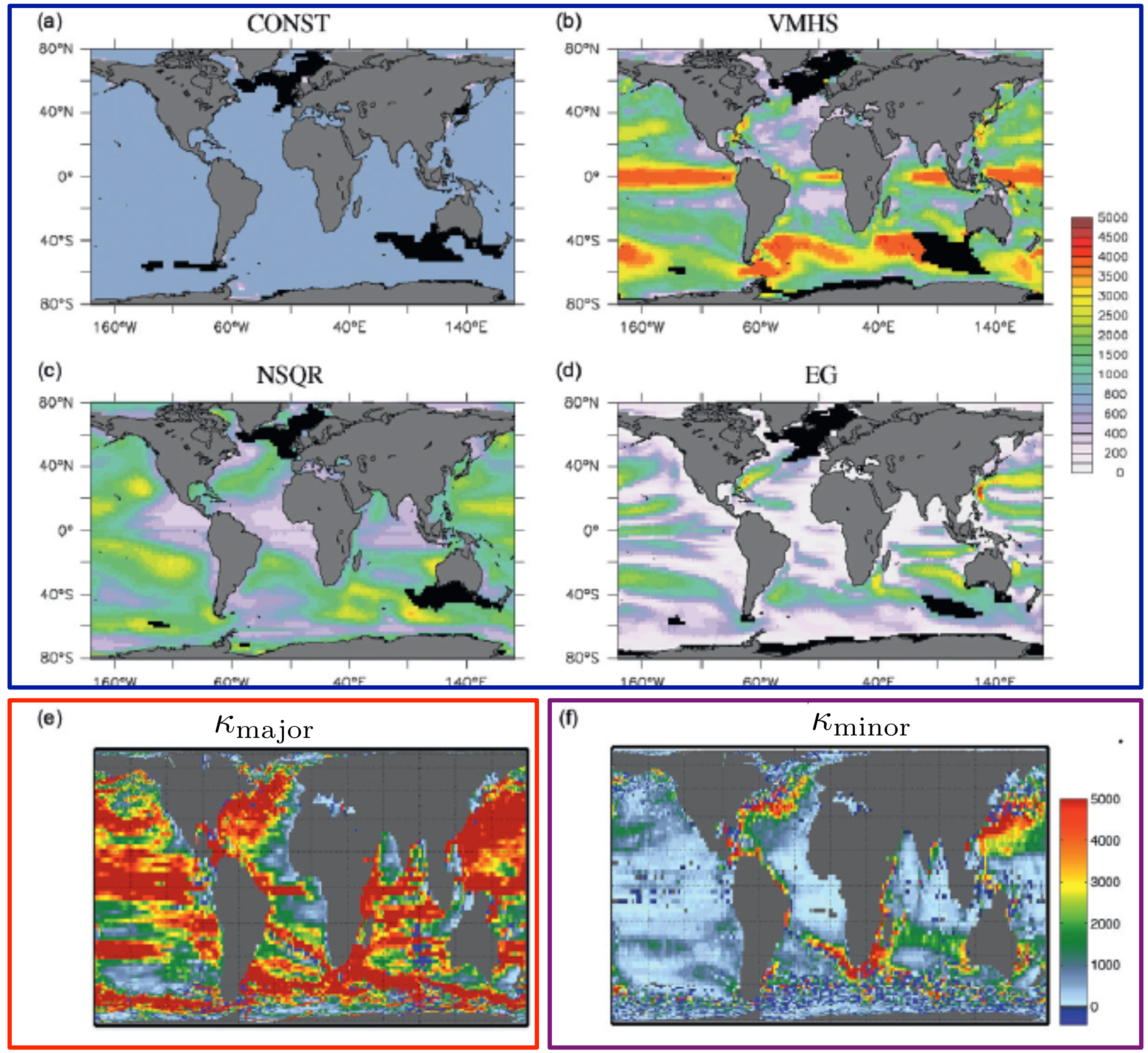
Mesoscale Eddy Parameterization

- 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

- 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

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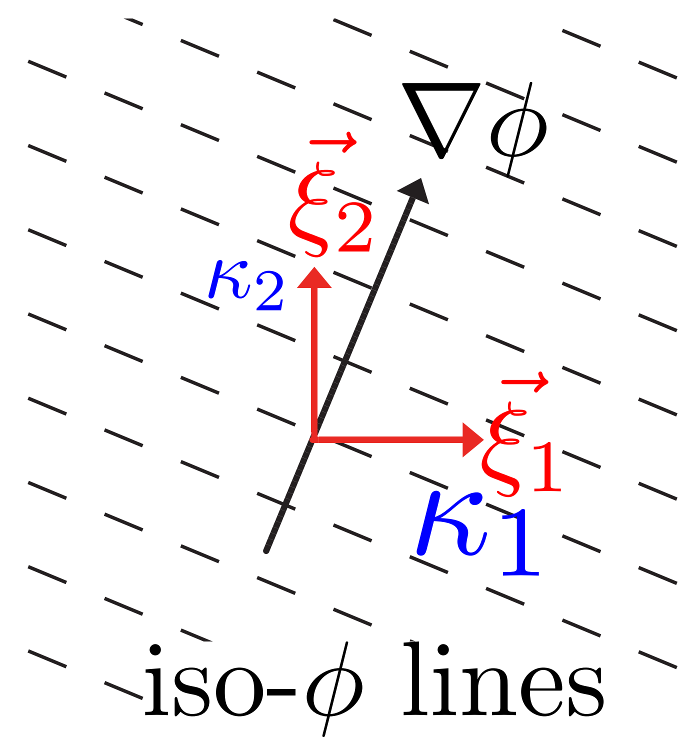
Anisotropic Gent-McWilliams/Redi

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

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



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

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

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

$$\bar{\bar{A}} = \begin{pmatrix} 0 & 0 & -\bar{\bar{K}}_H \cdot \vec{S} \\ 0 & 0 & \\ \vec{S} \cdot \bar{\bar{K}}_H & & 0 \end{pmatrix}$$

*Smith & Gent (2004)

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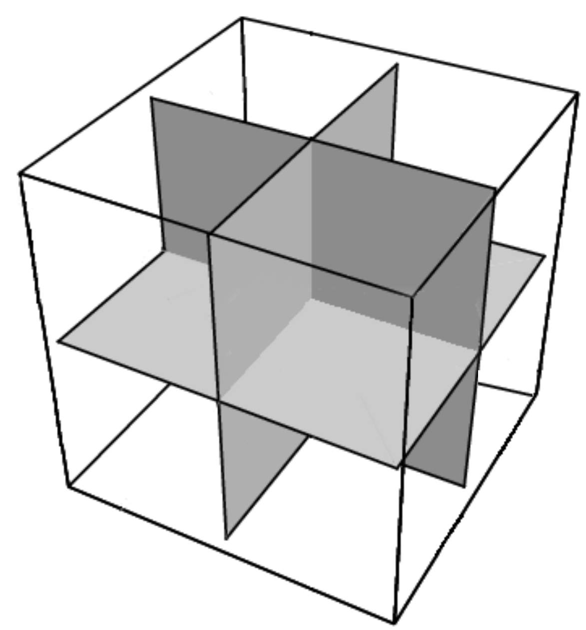
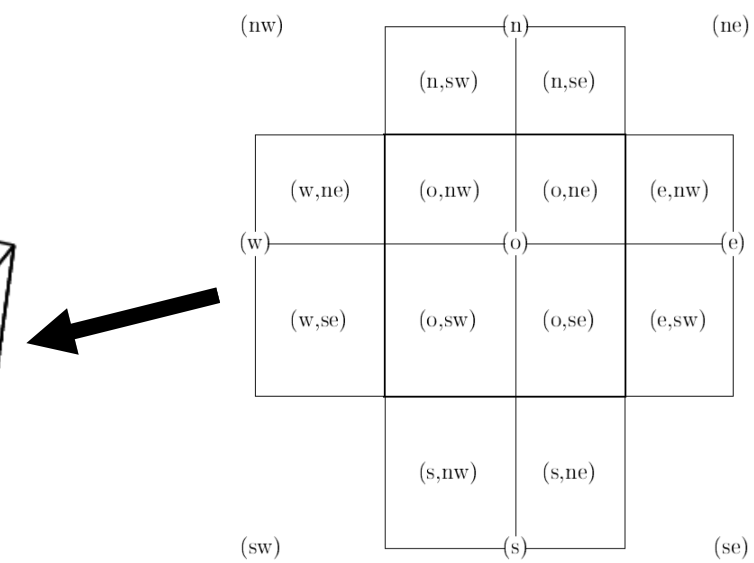
Discretization of the Anisotropic Operator

- 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)

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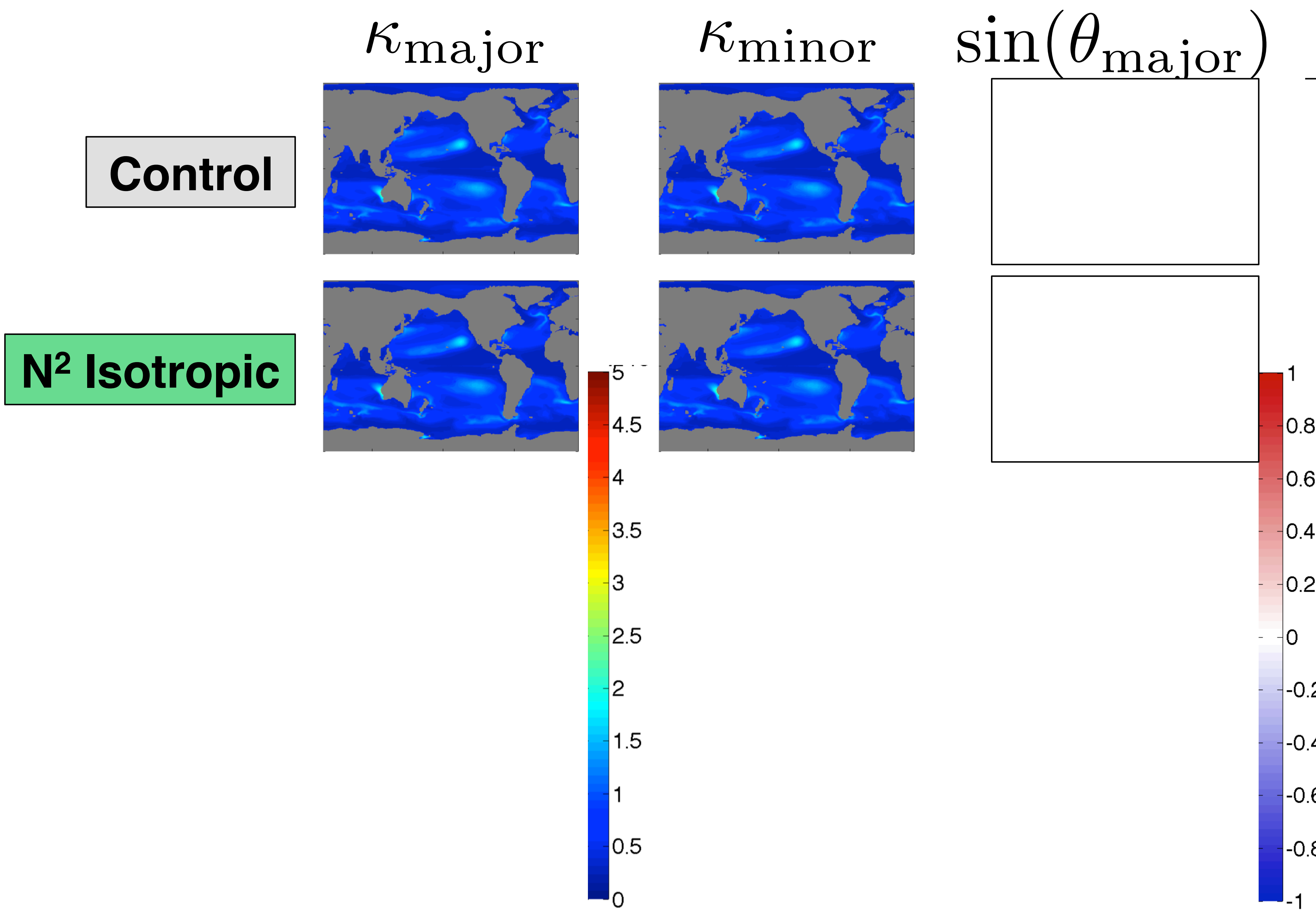
Summary of Numerical Experiments



κ_{minor}

$\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}}$

alignment

N^2

1

$\sim$

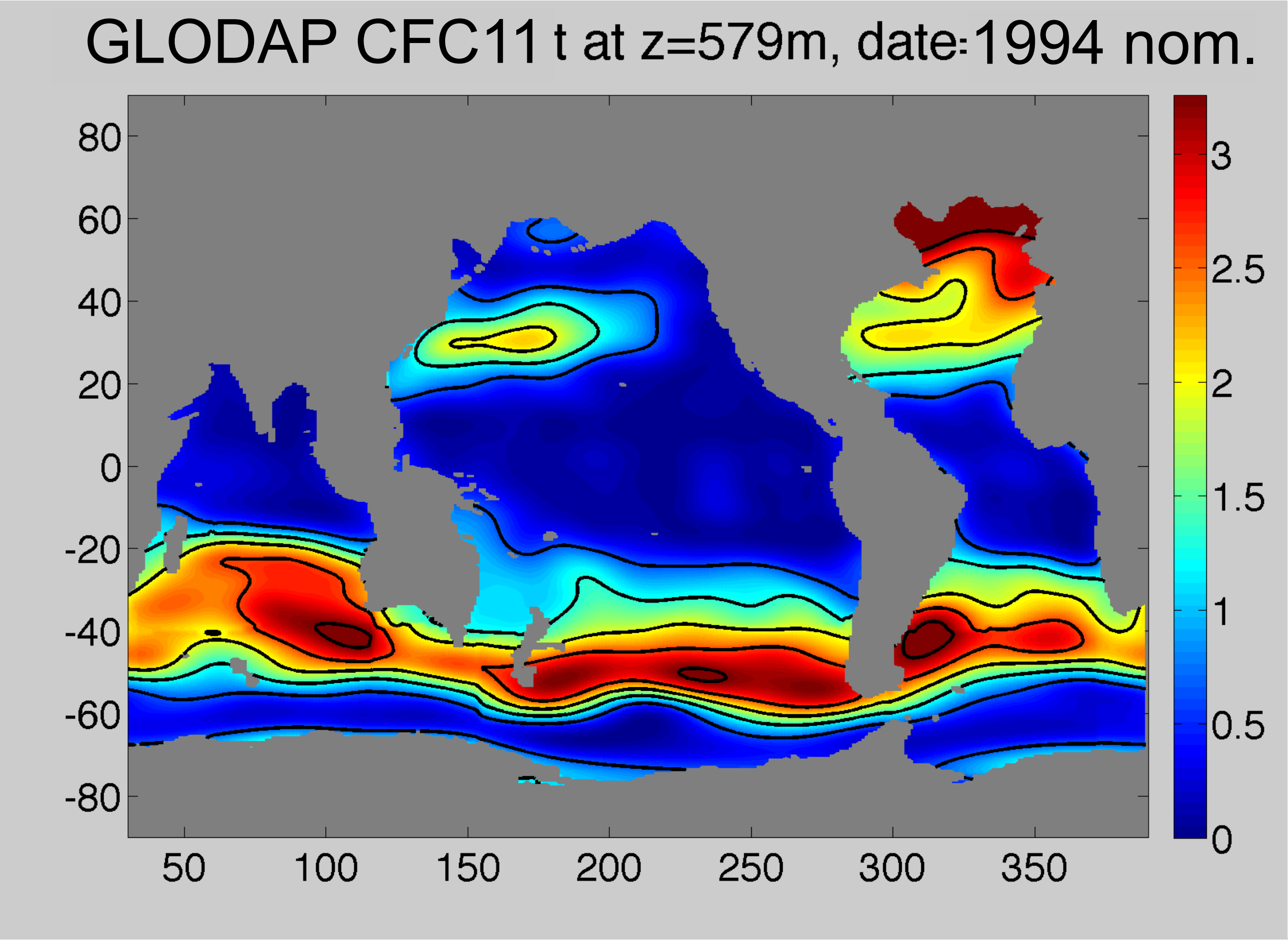
N^2

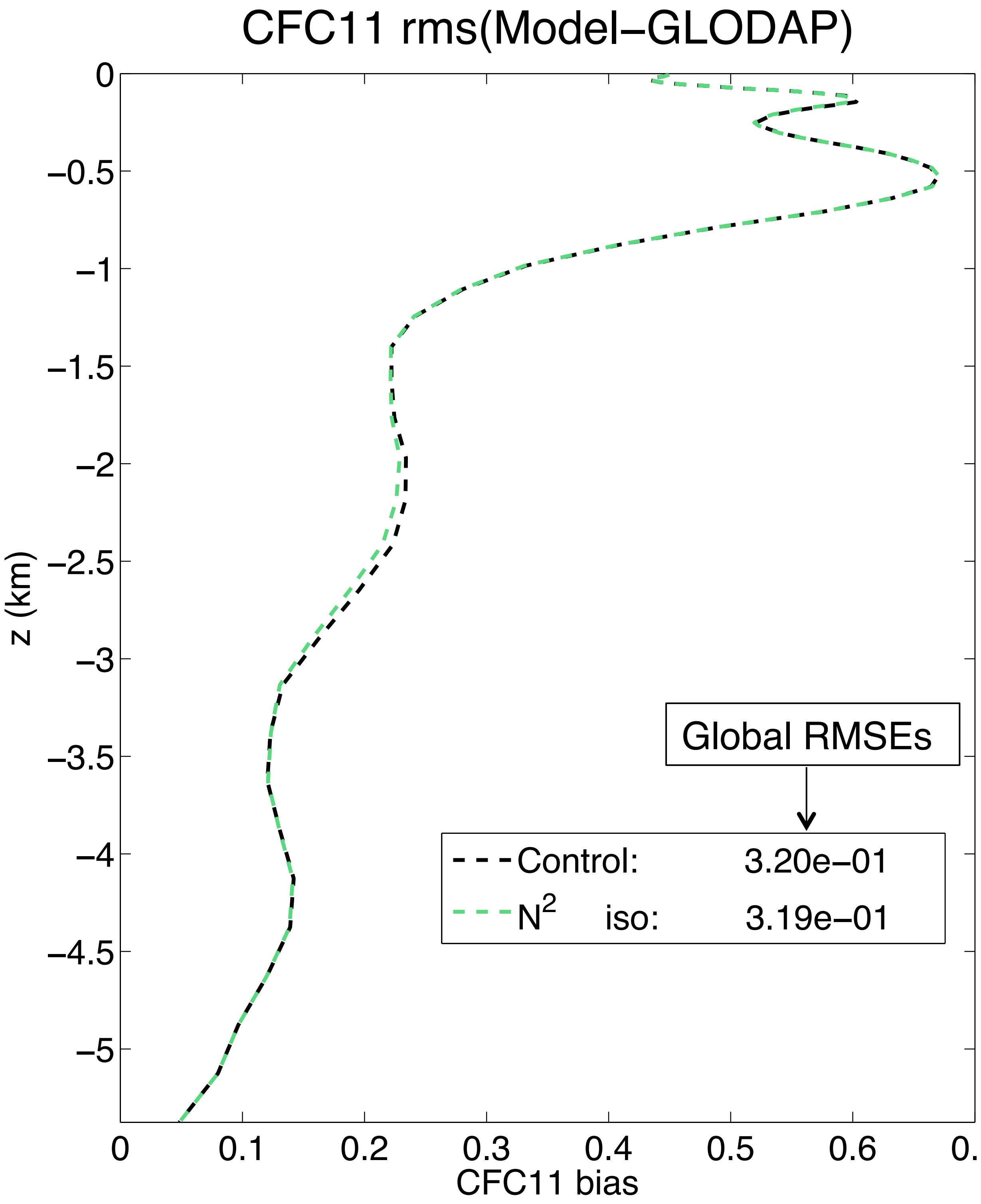
1

$\sim$

CFCs – Control vs. New

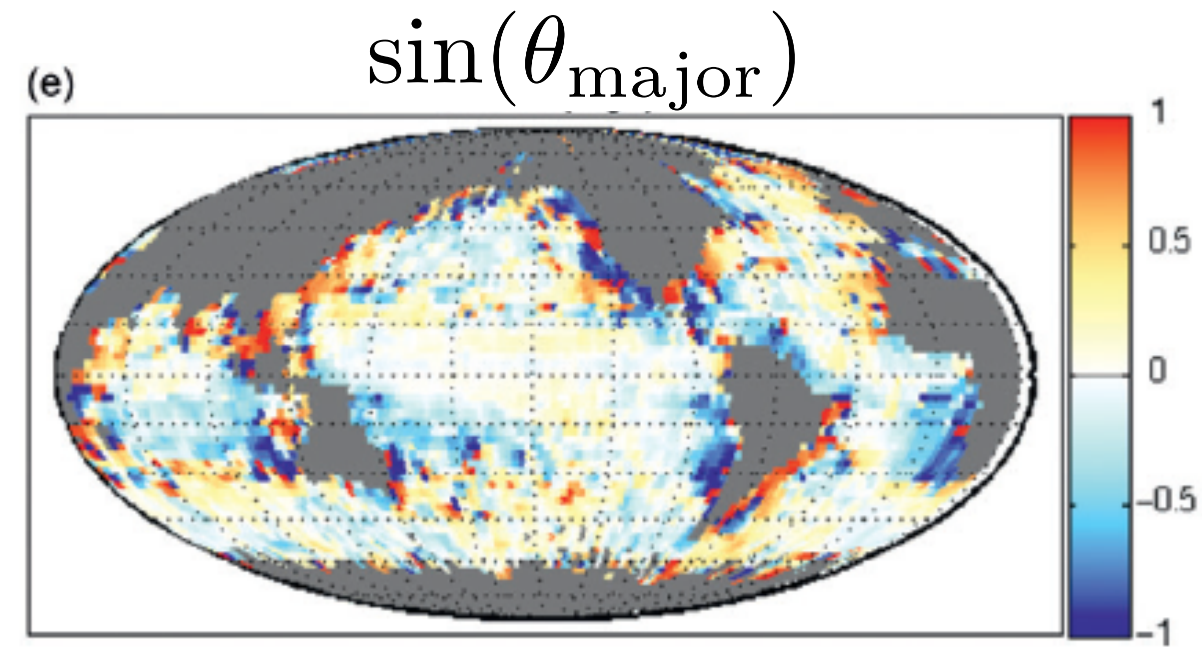
- Small differences due to minor change in transition layer physics treatment

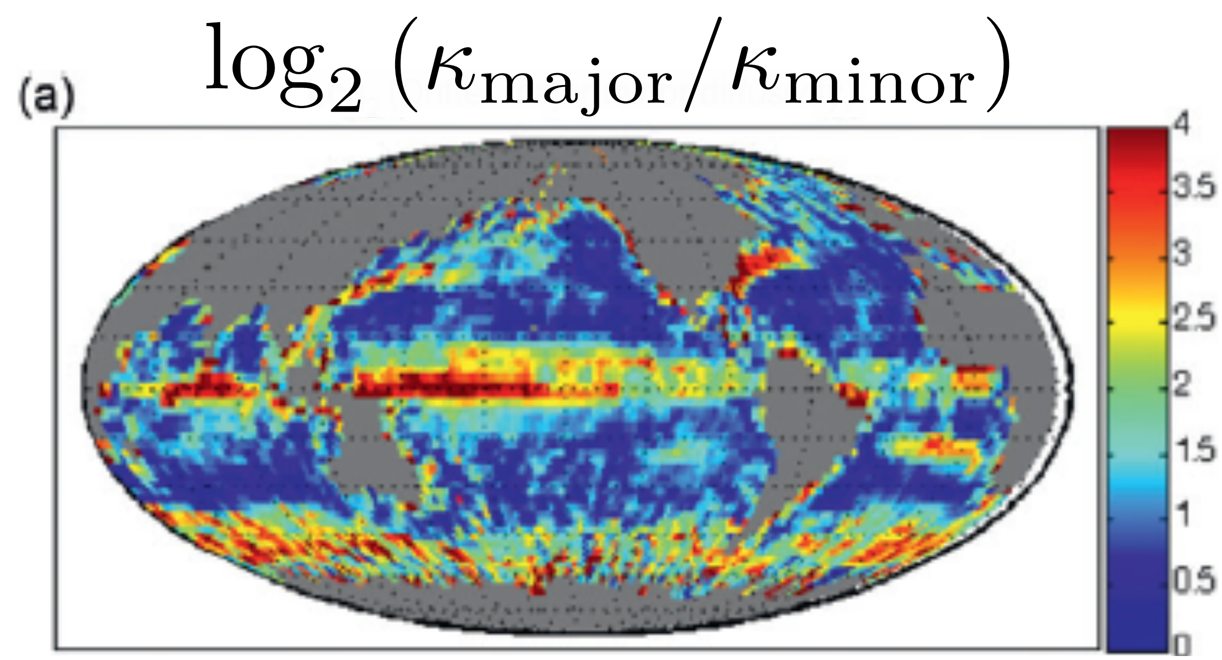




Drifter Observation Diffusivity Tensor

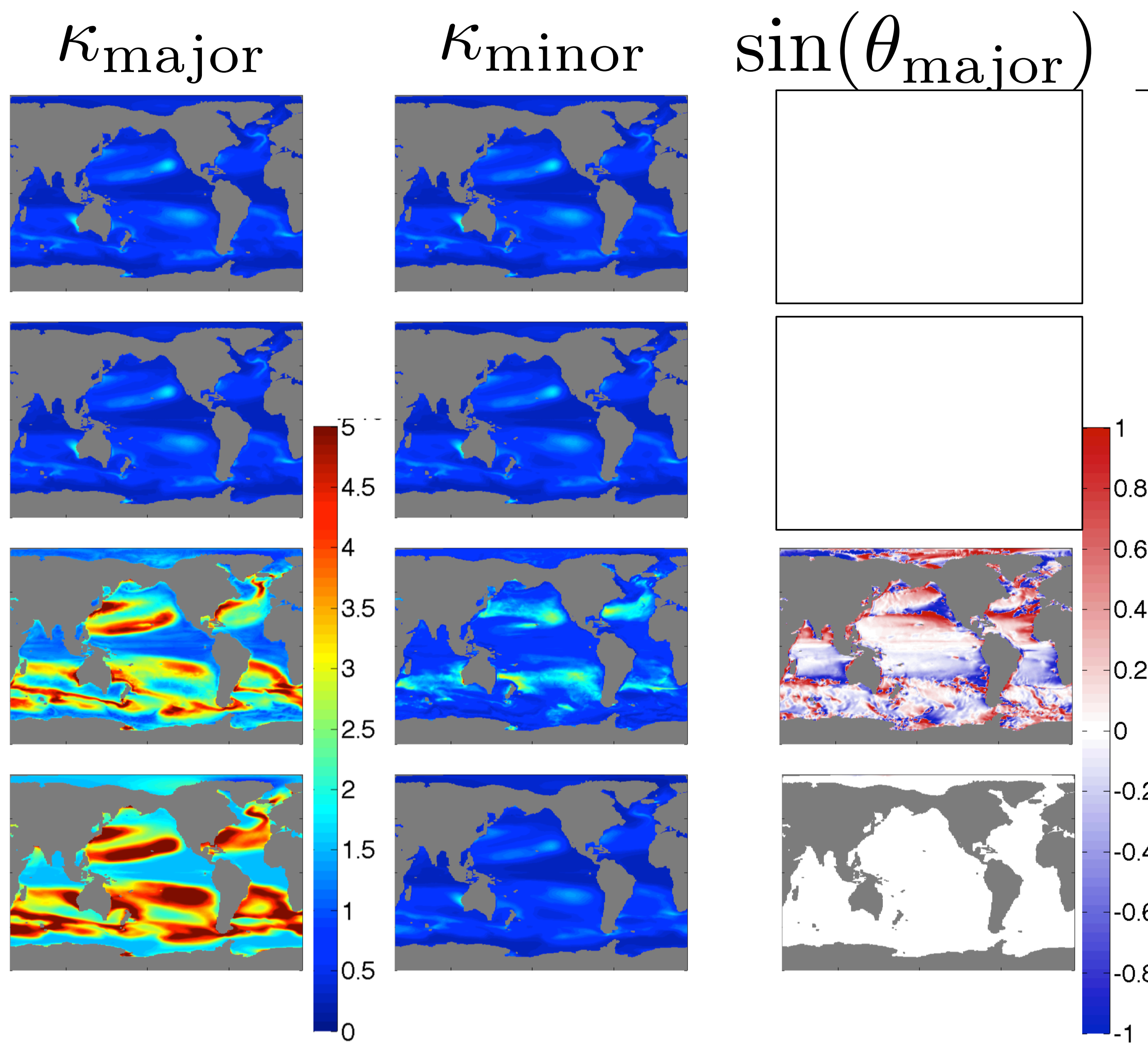
- Principal axis alignment
  - Major axis **aligned zonally** away from boundary currents
  - Major axis **aligned with the flow** near boundary currents
- $\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}}$
  - **> 16** in tropical regions
  - Typical ratio is **≈ 5**





*Bachman & Fox-Kemper (2013)
*Fox-Kemper et al (2013)

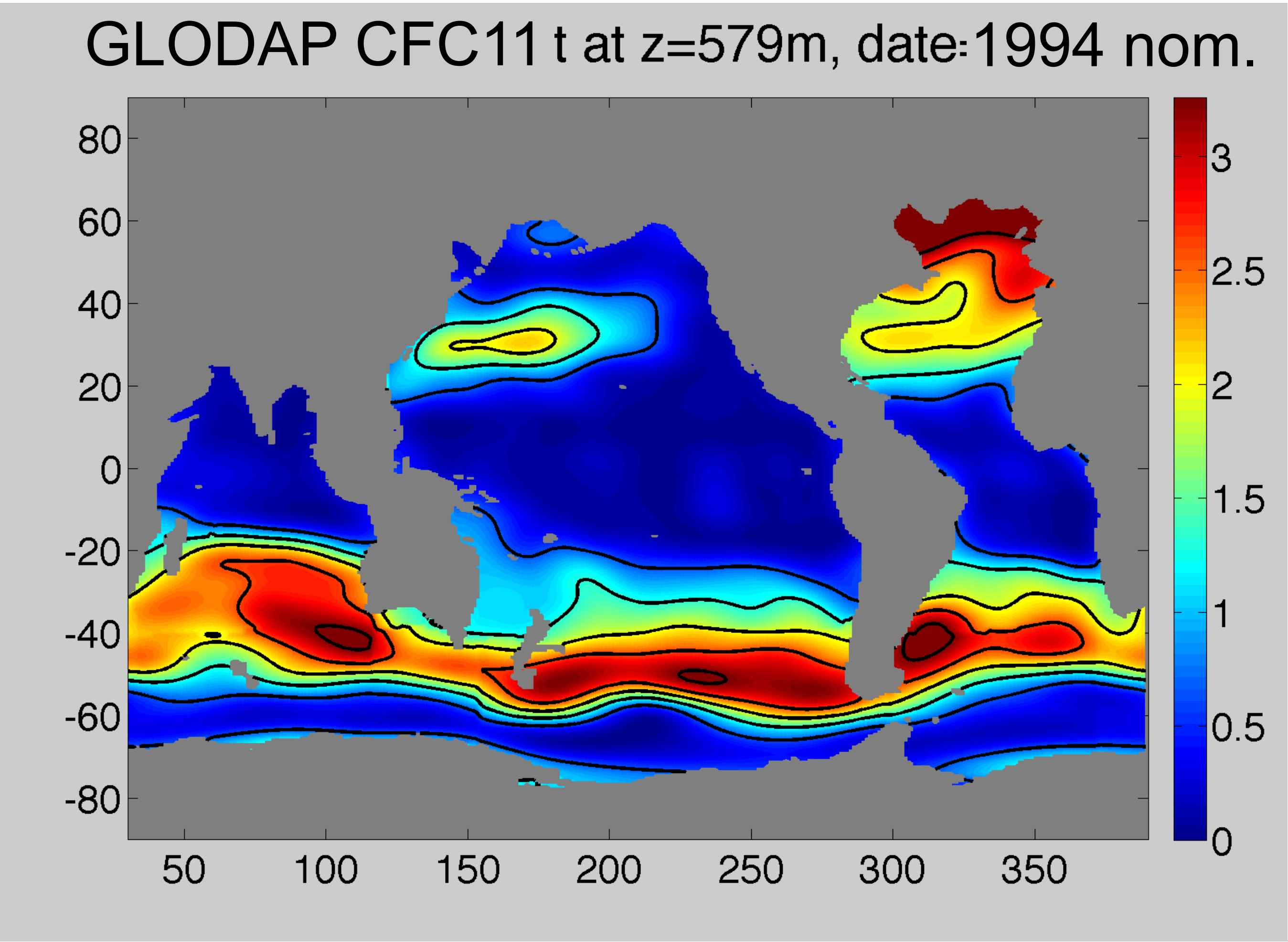
Summary of Numerical Experiments

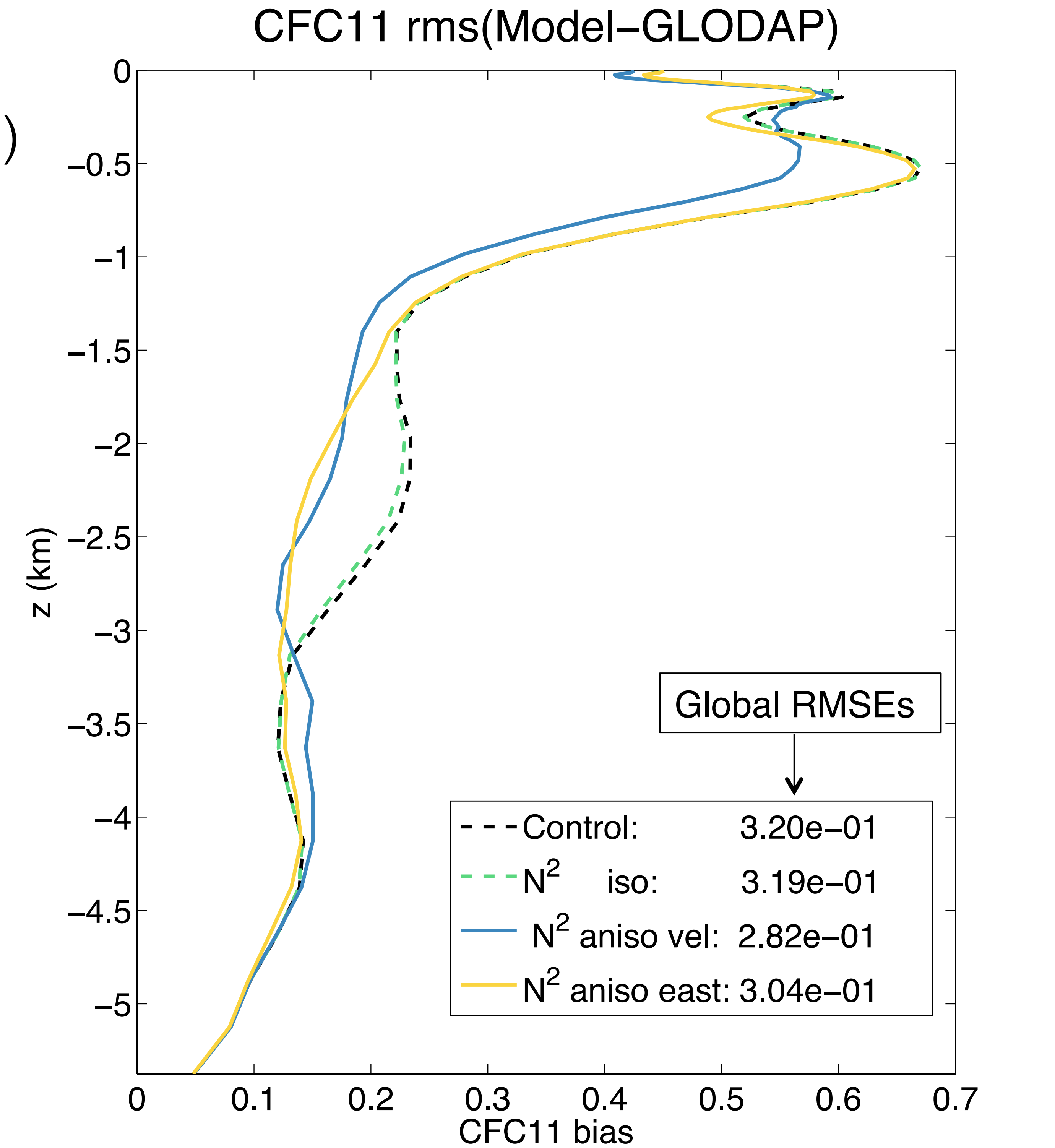


	κ_{minor}	$\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}}$	alignment
Control	N^2	1	$\sim$
N² Isotropic	N^2	1	$\sim$
N² Anisotropic Velocity	N^2	5	with flow
N² Anisotropic East	N^2	5	zonally

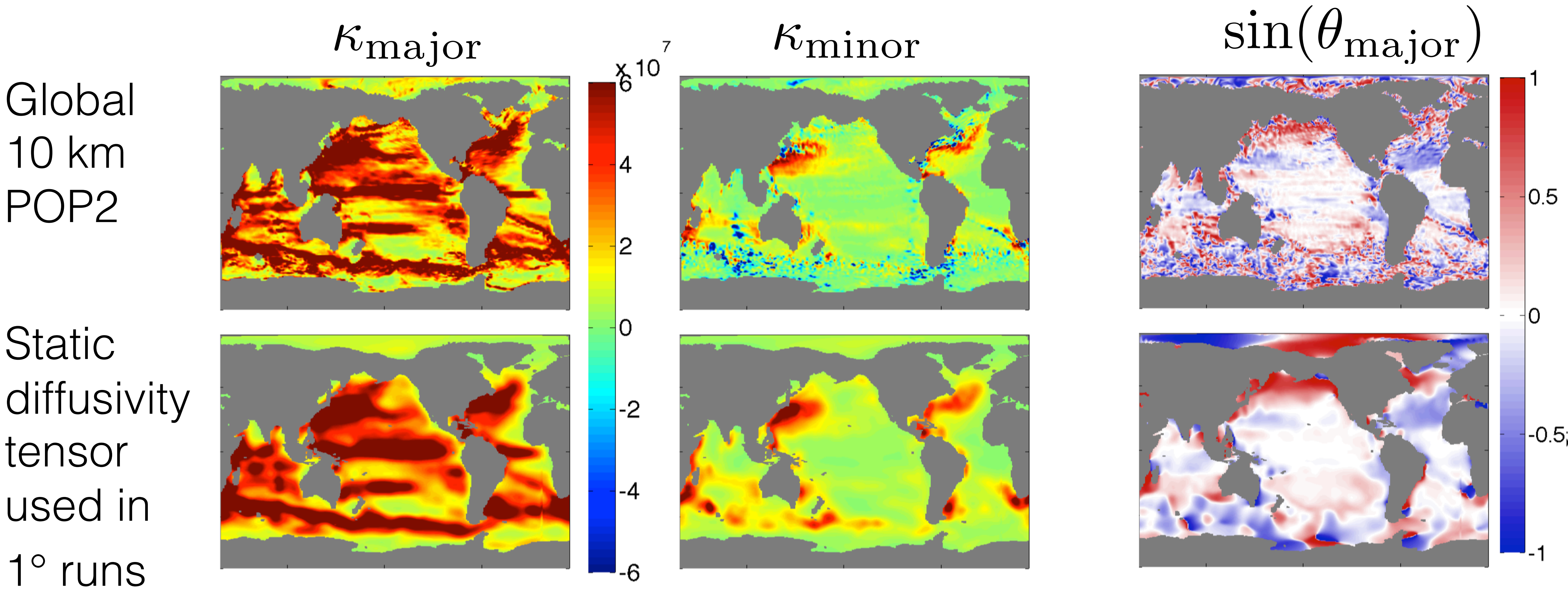
CFCs – N^2 Anisotropic

- Flow-aligned case (vel):
  - Large bias reduction (0-3 km)
  - Better ventilation
- Zonal-aligned case (east):
  - Follows or beats iso. case





Diagnosed Tensor from Hi-Res Model*



Requirements: smoothing, positive diffusivities, CFL restrictions

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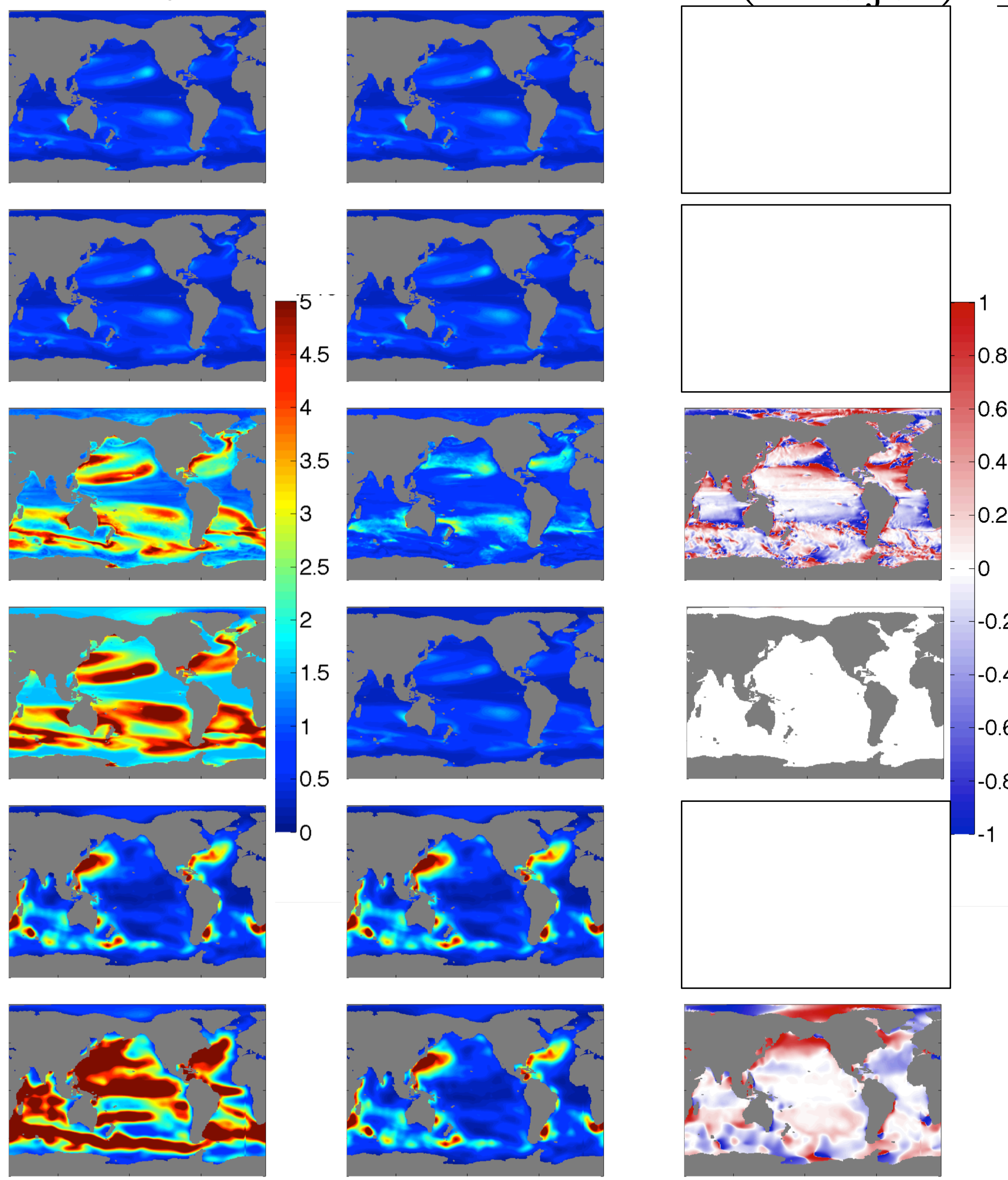
*Bachman & Fox-Kemper (2013)
*Fox-Kemper et al (2013)

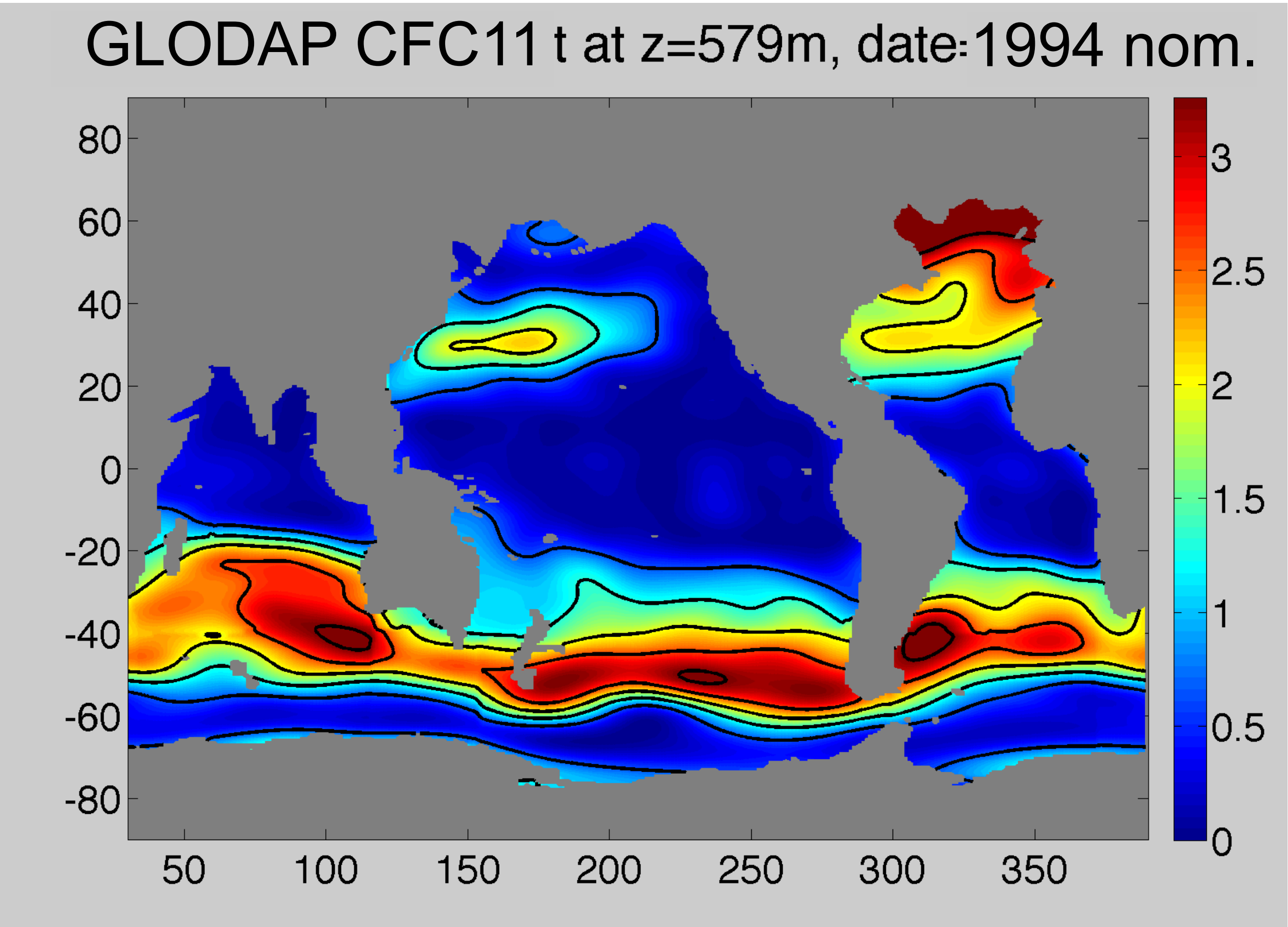
Summary of Numerical Experiments

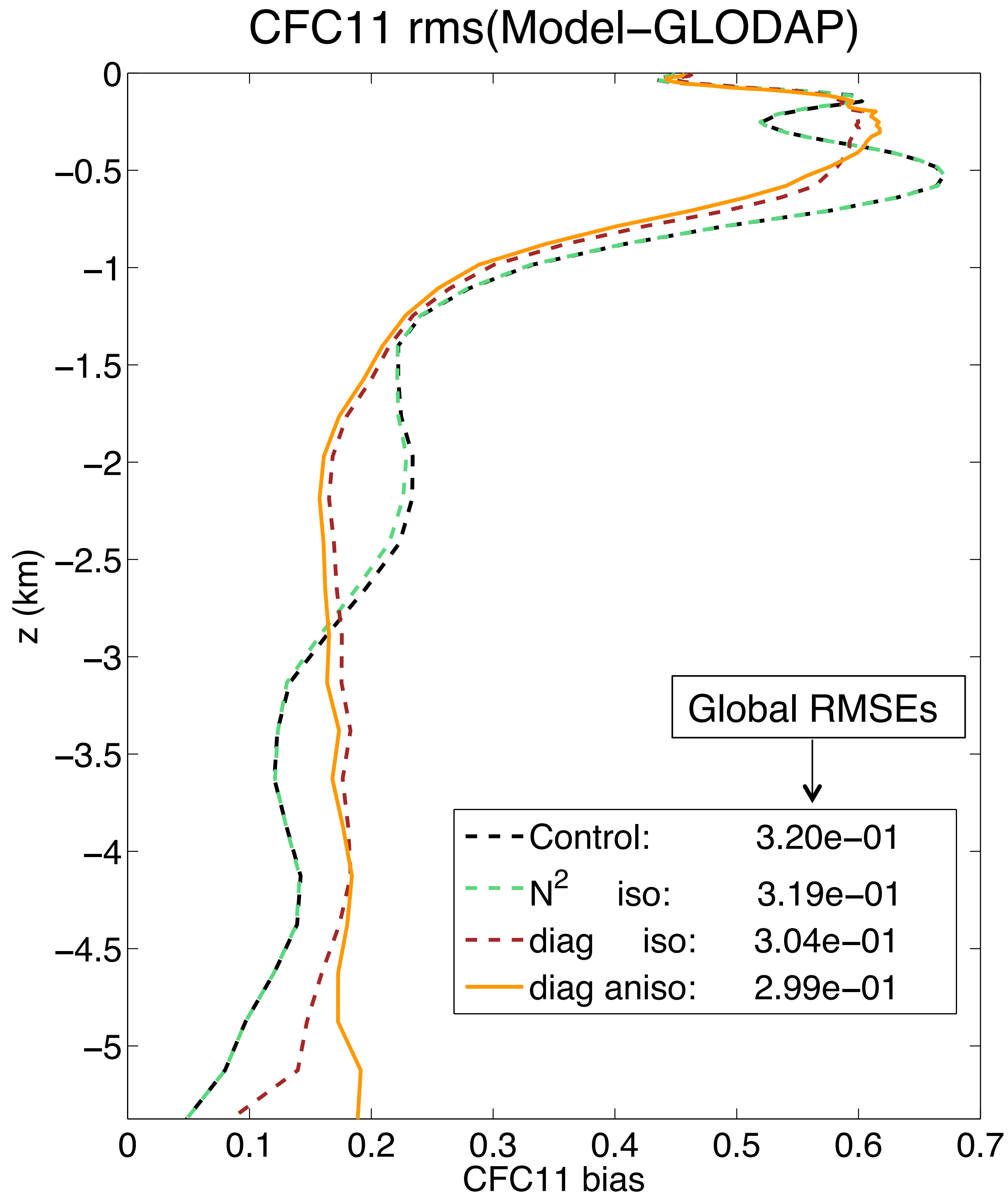


Experiment	κ_{major}	κ_{minor}	$\sin(\theta_{major})$	κ_{minor}	$\kappa_{major}/\kappa_{minor}$	alignment
Control				N^2	1	$\sim$
N^2 Isotropic				N^2	1	$\sim$
N^2 Anisotropic Velocity				N^2	5	with flow
N^2 Anisotropic East				N^2	5	zonally
Diagnosed Isotropic				diagnosed	1	$\sim$
Diagnosed Anisotropic				diagnosed	diagnosed	diagnosed

CFCs – Diagnosed Tensor

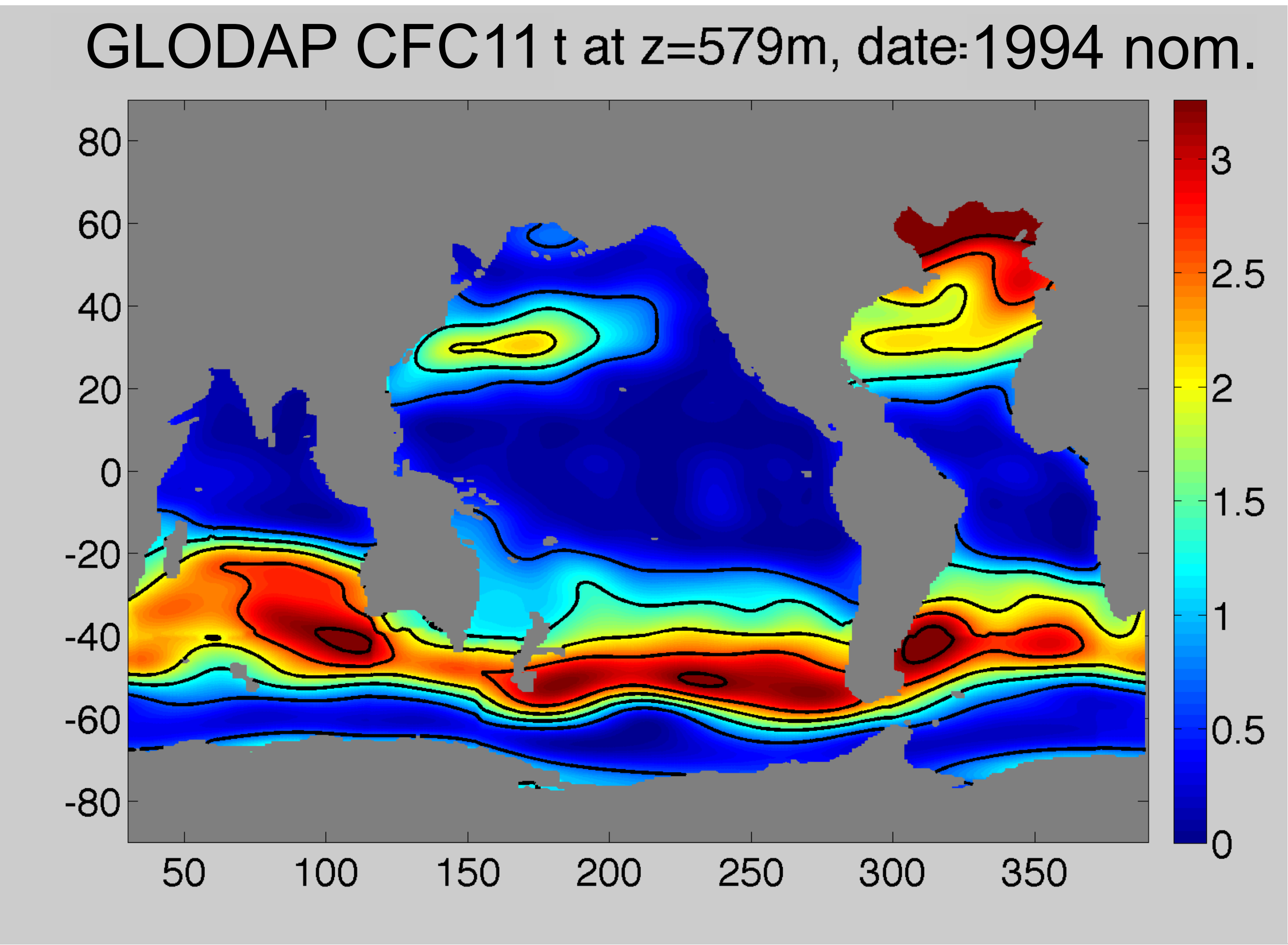
- Diagnosed diffusivities lead to bias reduction
- Anisotropic case slightly beats isotropic
- Anisotropy required for higher mixing without large errors

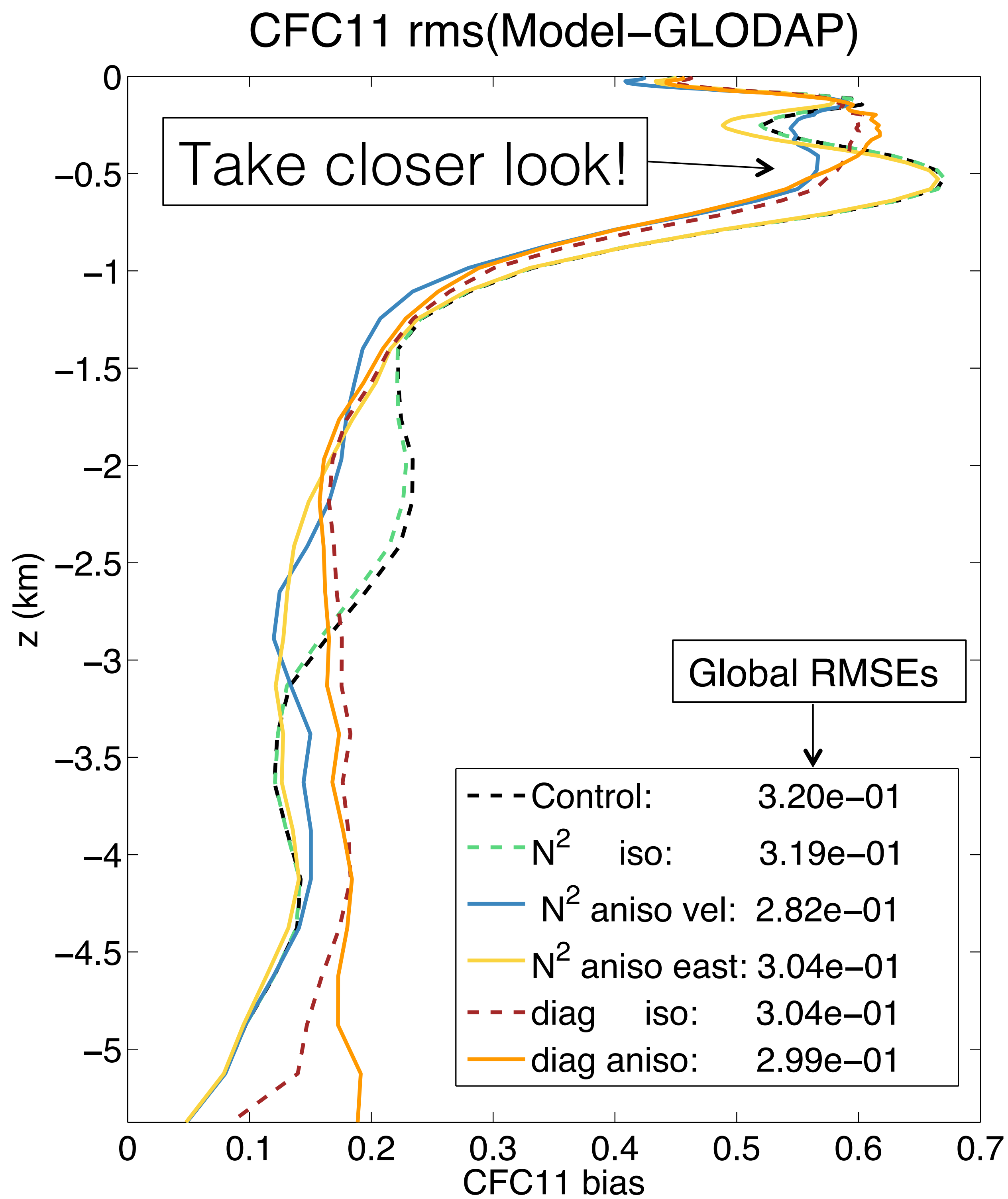




CFCs – All Cases

- Anisotropy improves ventilation
- Aligning major diffusivity axis with the flow leads to largest bias reduction

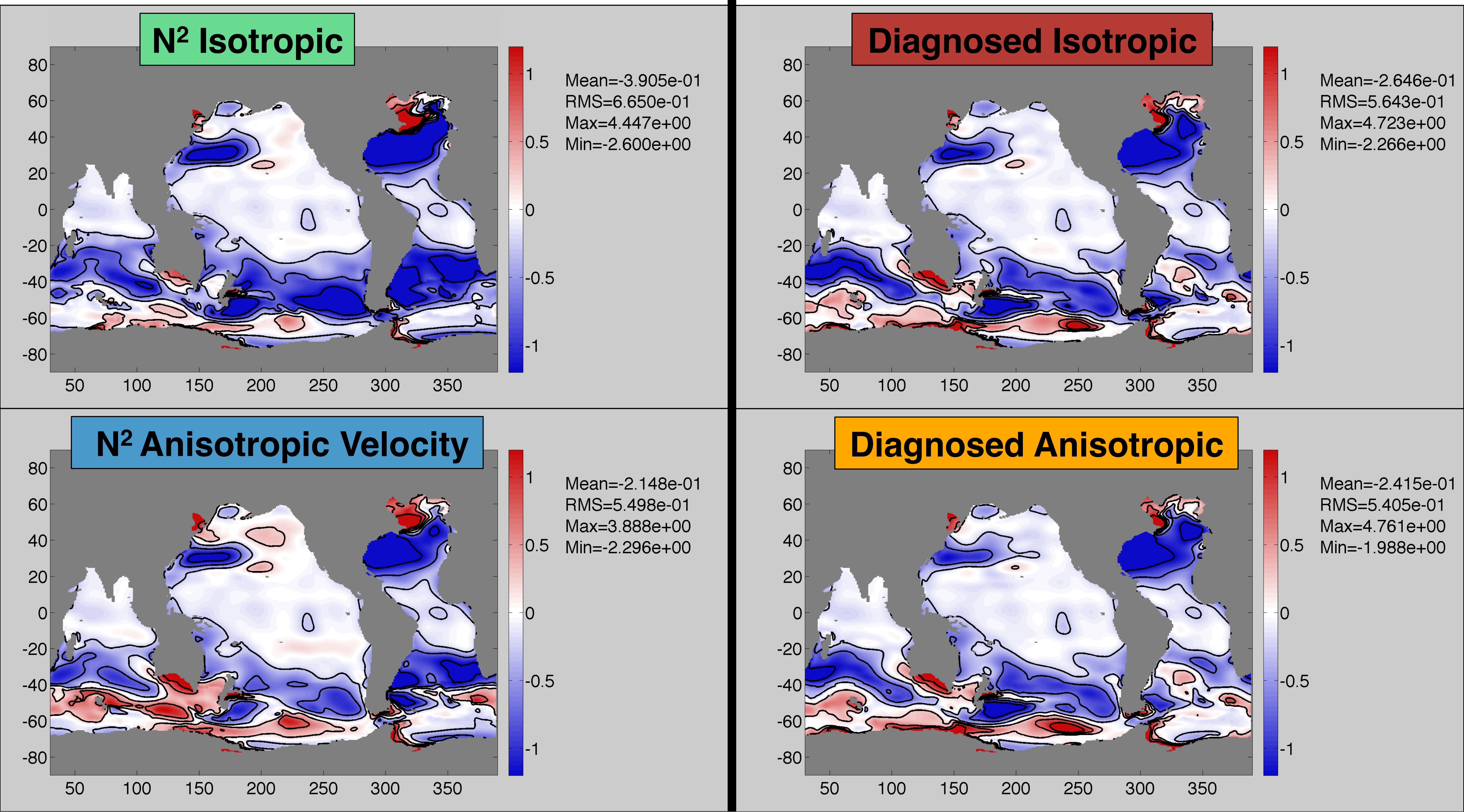




CFC11 Bias at z=579m

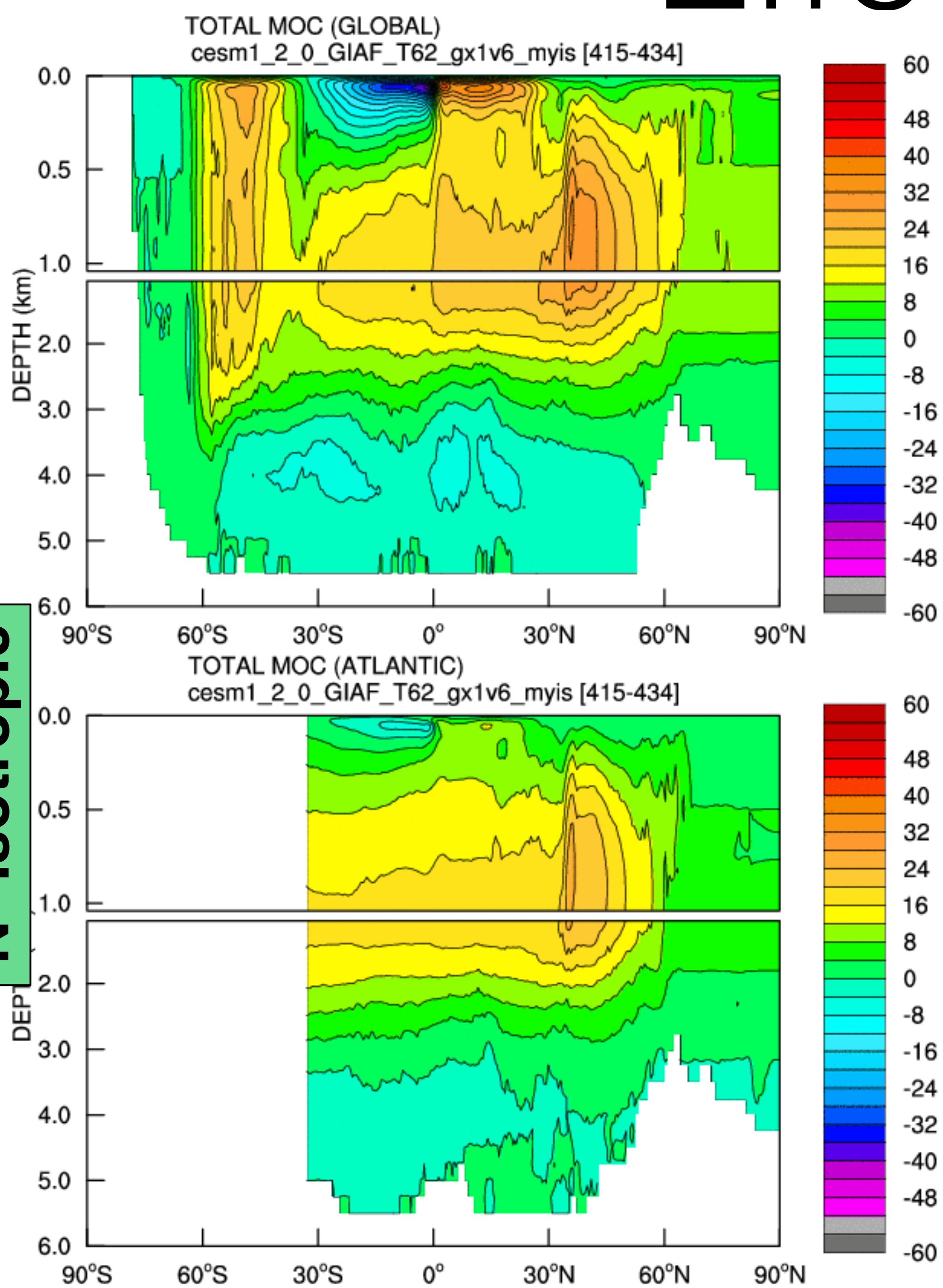
Anisotropy leads to **large** increase in ventilation
(Kuroshio & Gulf Stream extensions, Southern Ocean)

Anisotropy leads to **slight** increase in ventilation
(Kuroshio & Gulf Stream extensions, Southern Ocean)

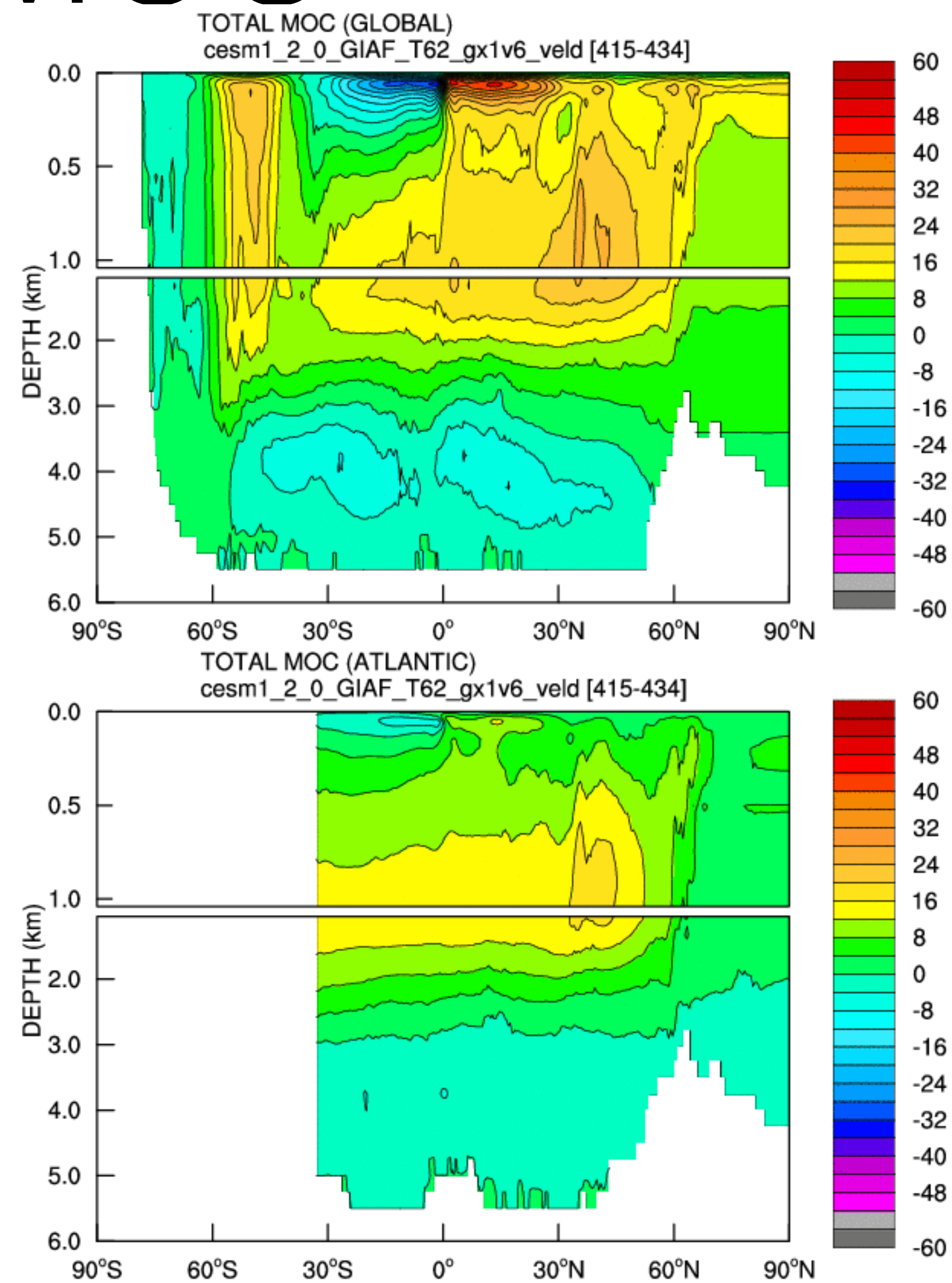


Effects on MOC

N² Isotropic



Stronger diffusion along flow **weakens*** and **expands** the MOC, **closing nearer to surface**



N² Anisotropic Velocity

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

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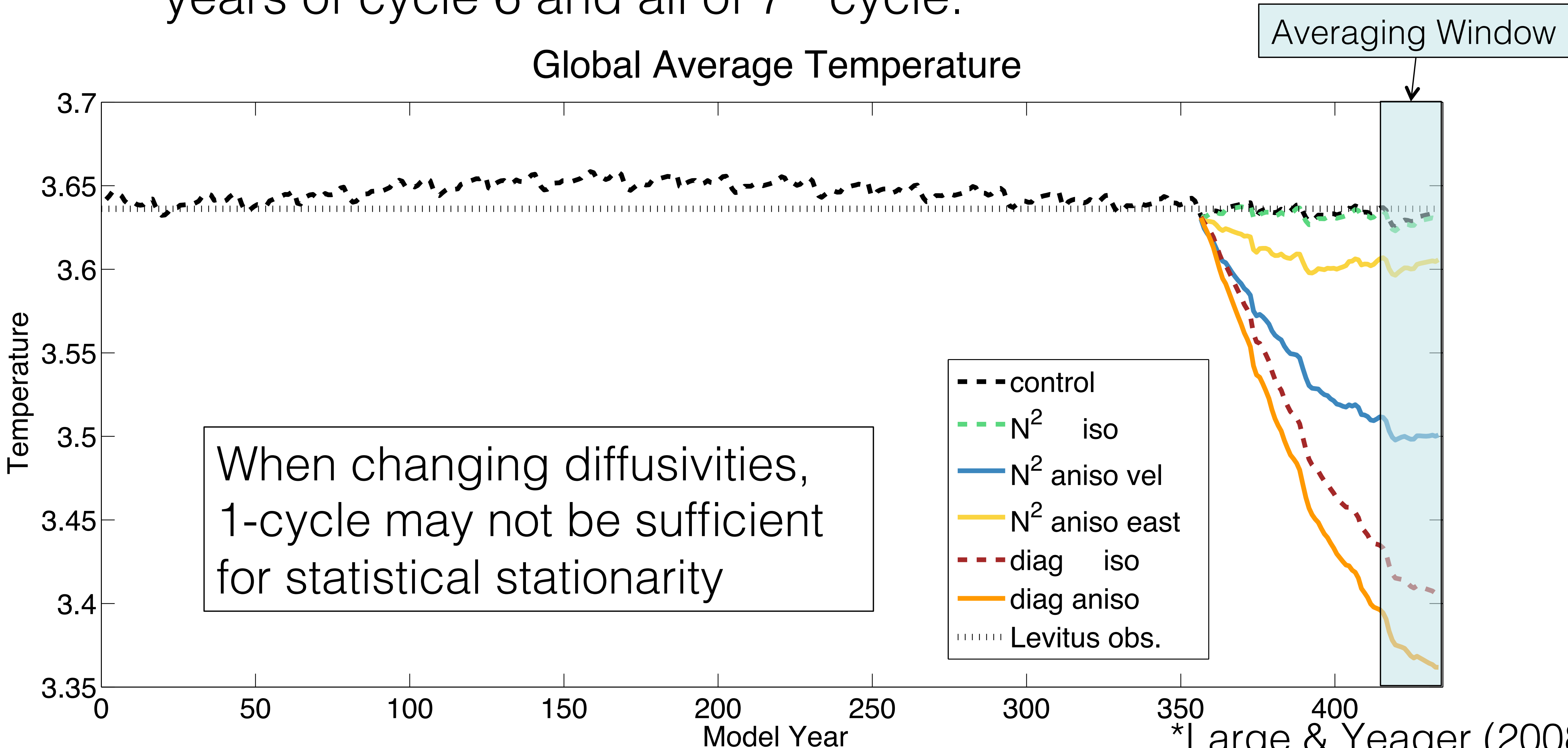
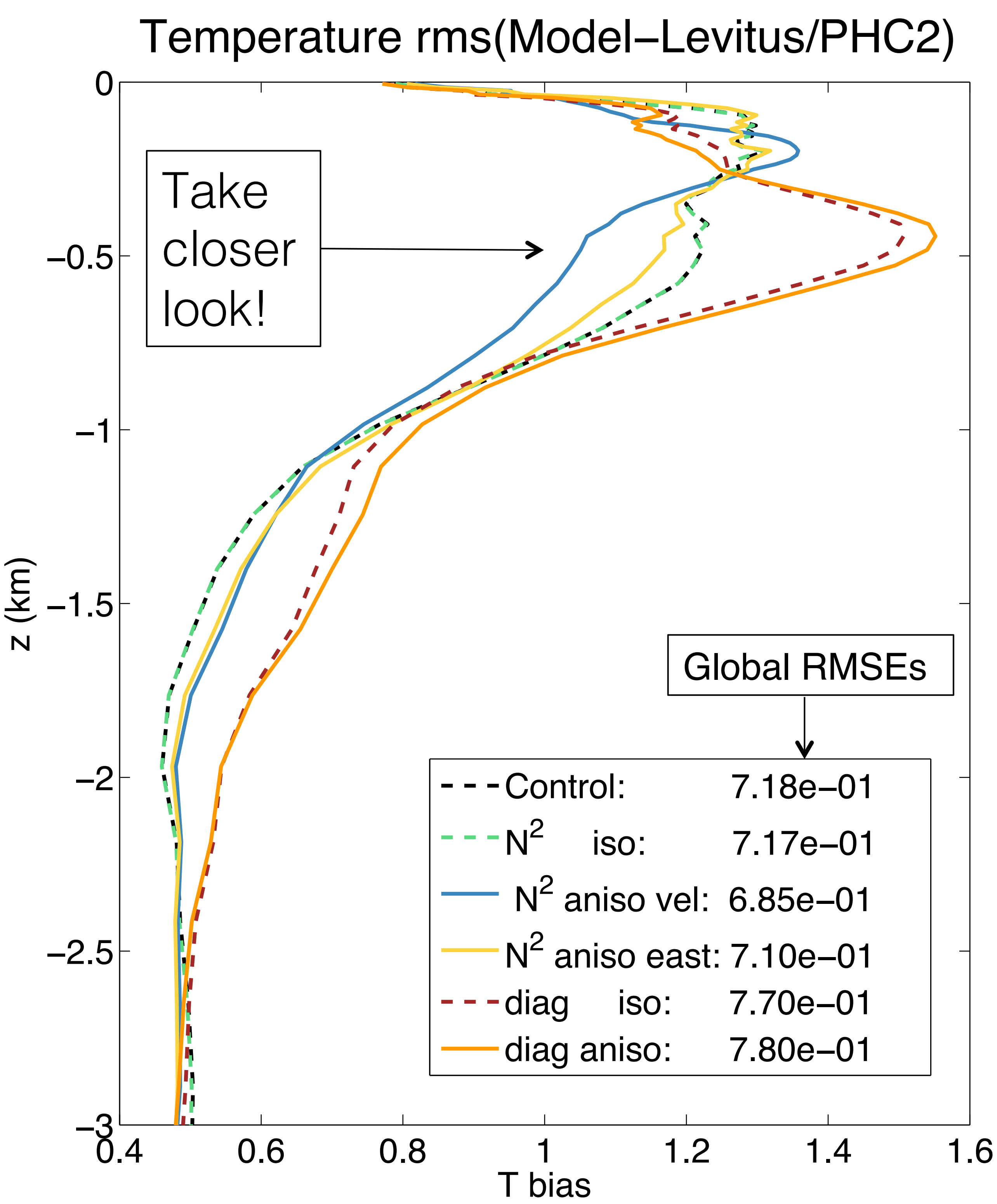
Summary of Numerical Experiments

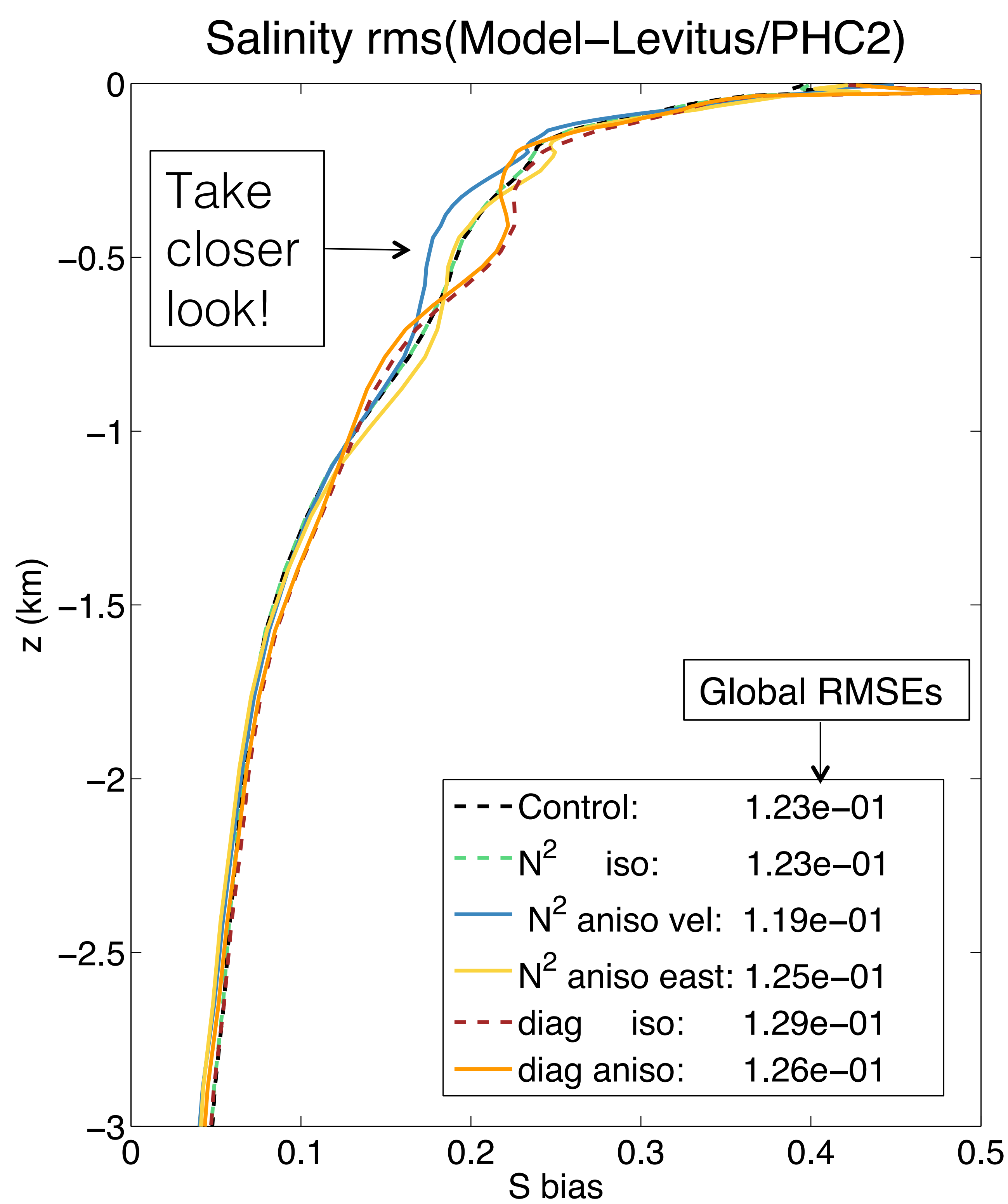
- Community Earth System Model (CESM1.2)
  - CORE 62-year interannual forcing (GIAF compset)*
  - 1° resolution (gx1v6 grid)
  - 5+ cycle spin-up – branch and inject CFC's for final 17 years of cycle 6 and all of 7th cycle.



*Large & Yeager (2008)

Temperature and Salinity

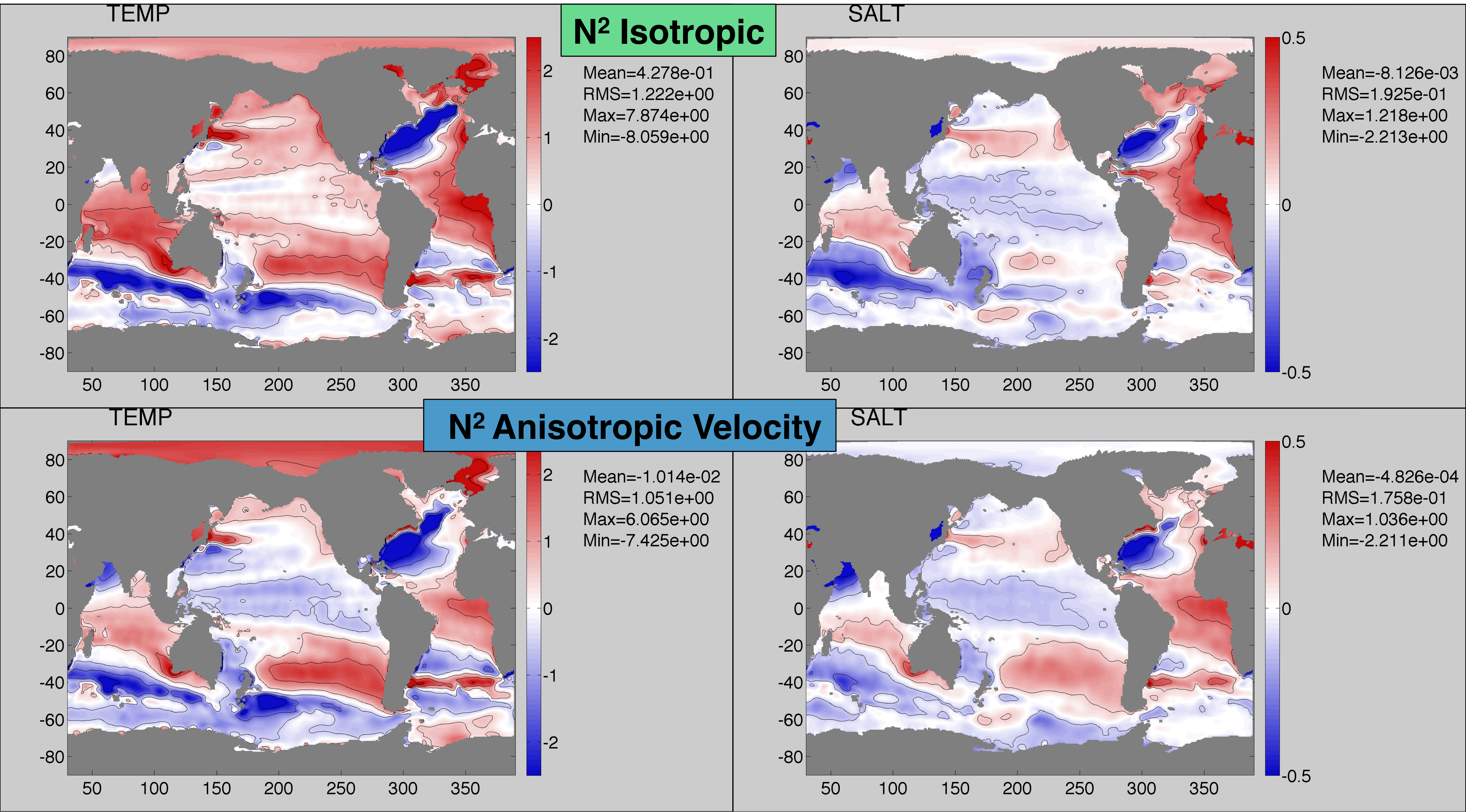




T & S Bias at z=483m

Nearly ubiquitous temperature bias reduction

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



Conclusions and Future Work

- Anisotropic GM/Redi: control the diffusive processes in a way that is **justified theoretically**, **matches observations**, and can be **diagnosed from high resolution simulations**
- Implemented with **PBCs** and accurate **transition layer physics**
- Simple idea, $\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}} = 5$, aligned with flow, **improves biogeochemical tracer ventilation** and **reduces temperature and salinity biases** – Can do even better!
- Short term plans:
  - Longer spin-up after branching with modified diffusivities
  - Use diagnosed diffusivities aligned with flow
  - Align major diffusivity across PV-gradient
  - Diagnosis improvements (restoring timescale corrections)
- Longer term plan: parameterize anisotropic transport mechanisms (Shear dispersion, PV-barriers, etc.)