Update on Ocean Model Developments and Simulations towards CESM2

- Updated CESM2 Timeline
- Completed
  - ✓ Barotropic solver enhancements
  - ✓ Sea Surface Diurnal Cycling (SSDC) parameterization (in coupler)
  - ✓ Community ocean Vertical Mixing (CVMix) framework
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  - ➢ Langmuir mixing parameterization & WaveWatch III
  - ➢ Robert – Asselin time filter
  - ➢ Enhanced mesoscale eddy diffusivities at depth
  - ➢ Specification of mesoscale eddy diffusivities via steering level approach
  - ➢ Tidal mixing parameterizations
  - ➢ Anisotropic mesoscale eddy diffusivities (Scott Reckinger)
  - ➢ Estuary parameterization (Frank Bryan / Yuheng Tseng)

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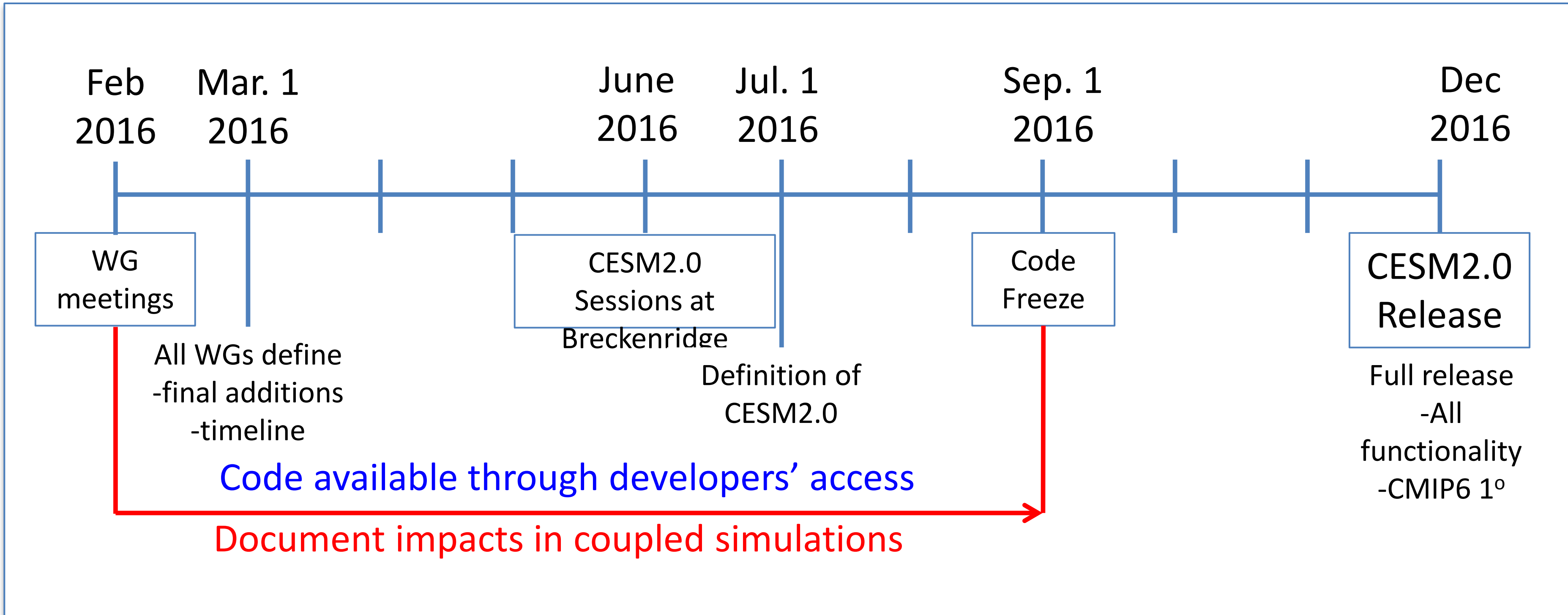
Proposed revised timeline



Pending approval by the SSC

OMWG Overarching Development Themes:

- Addressing persistent model biases (including related to BCG) via inclusion of new (missing) physics as well as improvements of existing parameterizations
- Advancing our modeling capabilities via model (numerical) improvements

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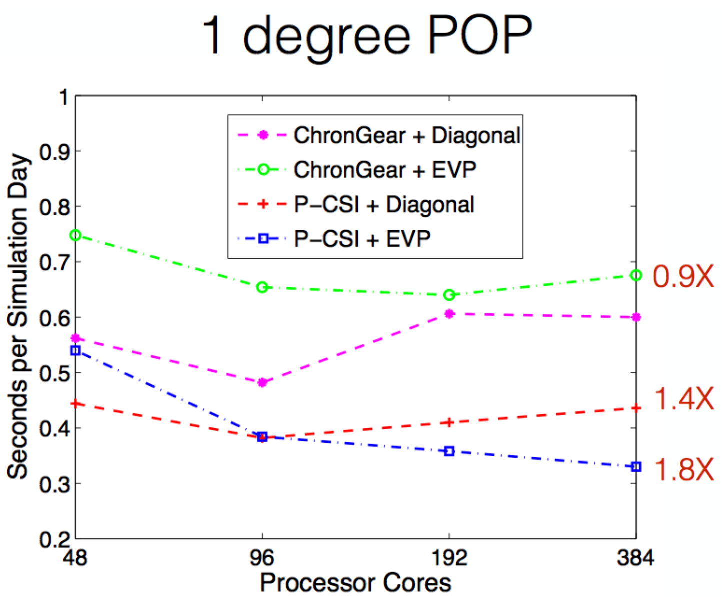
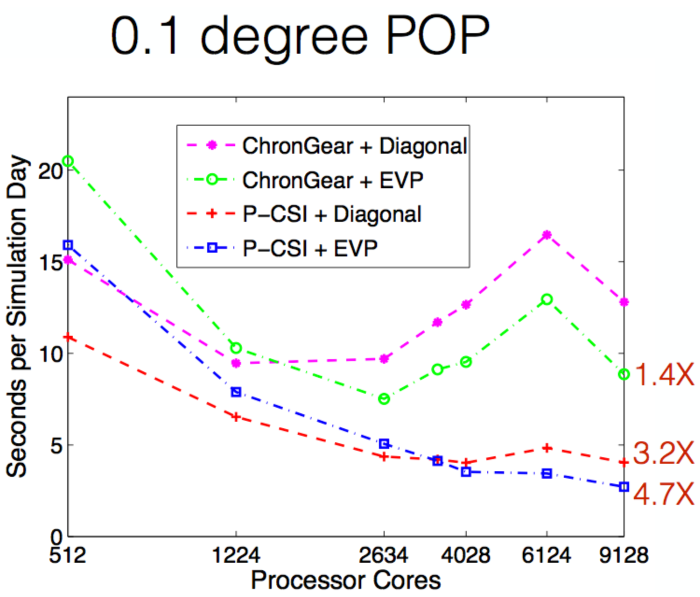
Barotropic Solver Enhancements
(A Scalable Barotropic Solver)

Hu & Huang
Tsinghua University, China

Tseng, Baker, Bryan, & Dennis
NCAR

Replacement of Preconditioned Chronopoulos-Gear (ChronGear) Solver with Preconditioned Stiefel Iteration (P-CSI) Solver which requires no global reductions





On Yellowstone; EVP: Error Vector Propagation Preconditioning

Sea Surface Diurnal Cycling (SSDC) Parameterization

Large & Caron

NCAR

- Parameterization for diurnal cycling of temperature, salinity, and velocity
- Flux calculations make use of T_{bulk} and T_{skin}, rather then T_f (default)
- Fluxes are calculated and accumulated at the coupling frequency of the atmospheric model

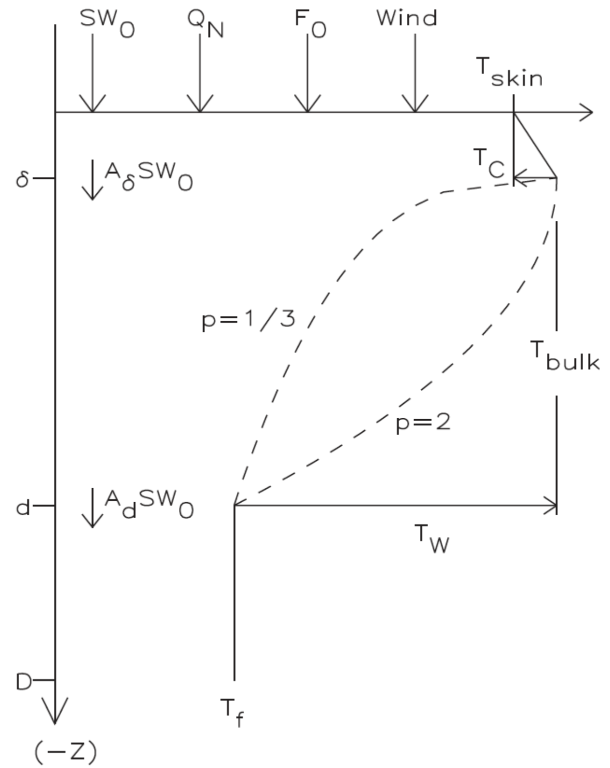


Figure 1. Schematic of diurnal warming of the near-surface ocean. Inputs to SSDC from the atmosphere, SW_0, Q_N, F_0, and wind stress, and from the ocean T_f and A_{-z} are defined in the text, as are the outputs, T_C, T_W, T_{skin}, and T_{bulk}. The dashed curves show equation (6) for p = 1/3 and p = 2. With the latter, more heat is required to warm T_W a given amount and there is a larger gradient, and hence cooling flux, at $-z = d$.

Community ocean Vertical Mixing (CVMix) Framework

Levy, Danabasoglu, & Large

NCAR

Griffies, Adcroft, & Hallberg

GFDL

Ringler & Jacobsen

LANL

Community ocean Vertical Mixing (CVMix) Framework

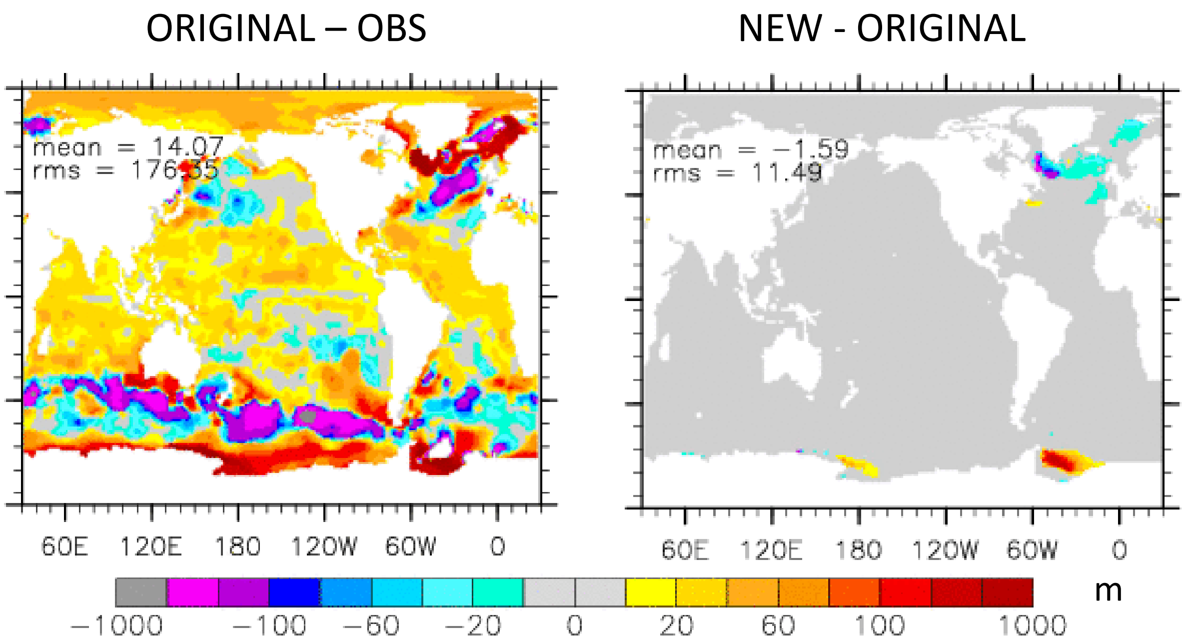
- CVMix is a software package that aims to provide transparent, robust, flexible, well-documented, and shared Fortran source codes for use in parameterizing vertical mixing processes in ocean models.
- The project is focused on developing modular software for a consensus of first-order closures that return a vertical diffusivity, viscosity, and a non-local transport, with each variable dependent on prognostic model fields.
- CVMix modules are used in POP2, MPAS-O, and MOM6.
- In POP2, K-Profile Parameterization (KPP) is enabled via CVMix
- CVMix is available via github – not an official release.

Change in Surface Layer Thickness in KPP

Original: model first layer thickness

New: 10% of the boundary layer depth

Winter-Mean Mixed Layer Depth



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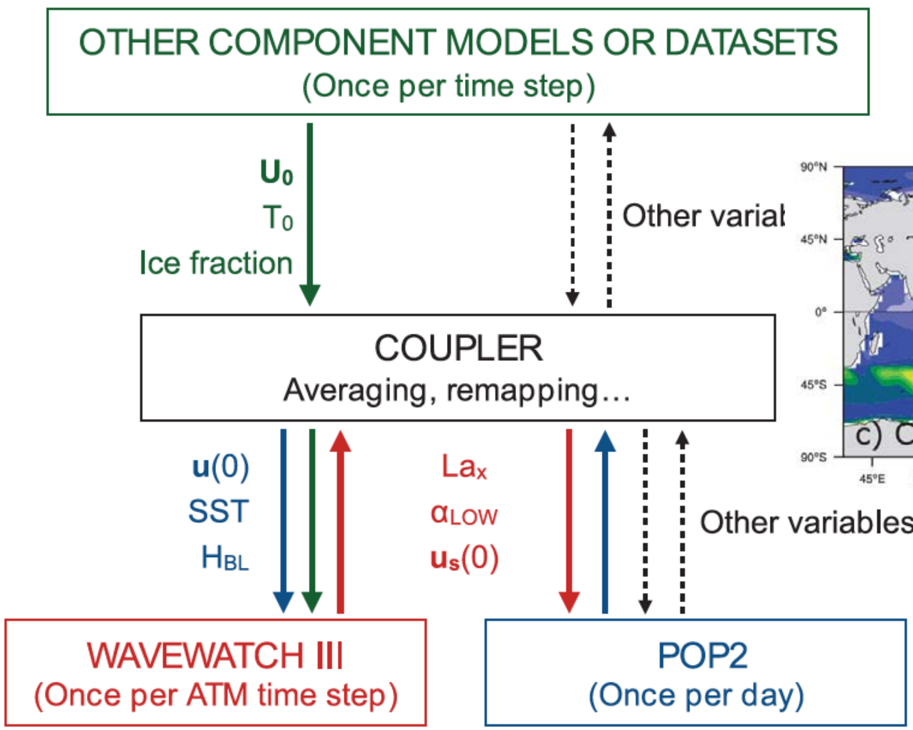
Langmuir Mixing Parameterization & WaveWatch III

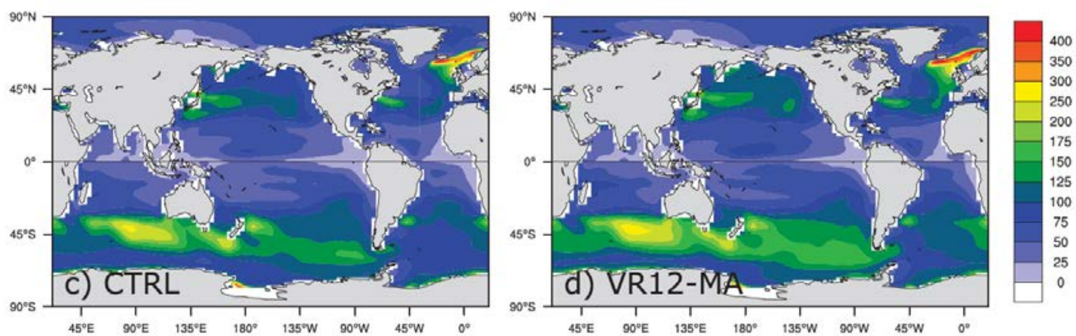
Li, Webb, & Fox-Kemper
Brown University

Craig, Danabasoglu, Large, & Vertenstein
NCAR

Enhanced mixing within the oceanic boundary layer through Langmuir turbulence



Winter Mixed Layer Depth (m)

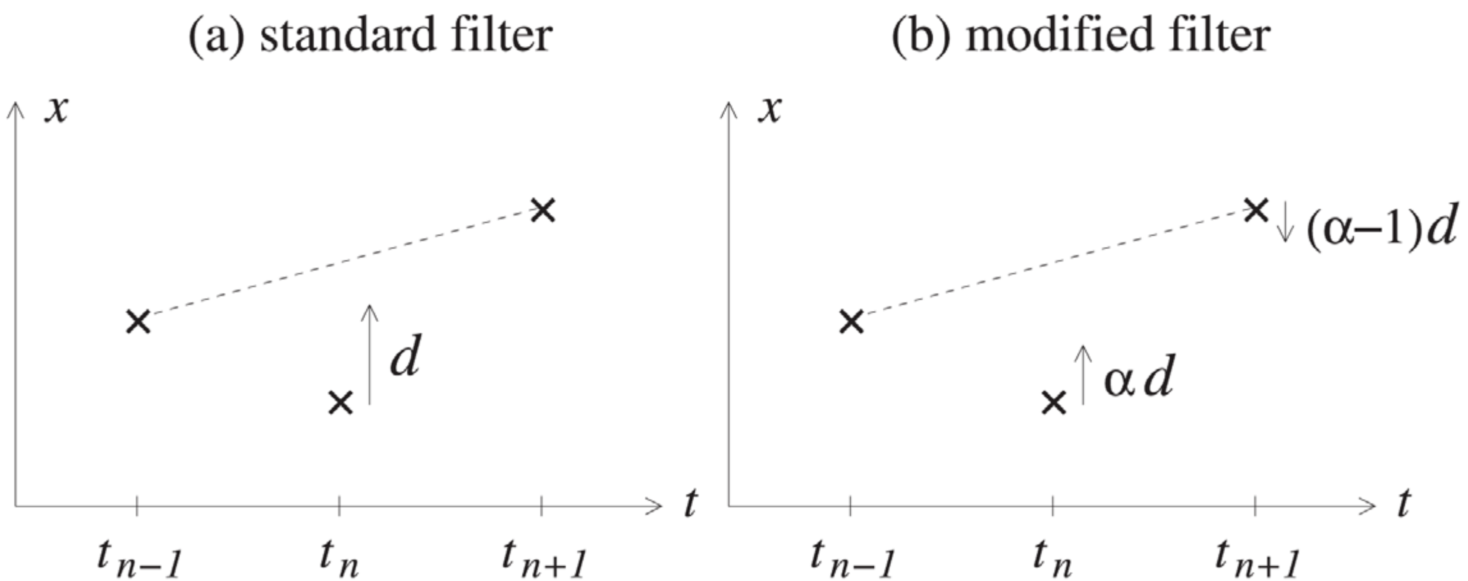


Coupled T31x3

“Conservative” Robert – Asselin Time Filter (RAF)

Norton & Danabasoglu
NCAR

Follows Williams (2009) and MOM4 approach …..



$$d = (\nu/2)(x_{n-1} - 2x_n + x_{n+1})$$

Conservative when α=0.5, but it becomes unconditionally unstable!

Modified RAF has been implemented (relatively straightforward)

Interactions between the filtering method and the rest of the model turned out to be more complicated than anticipated and required significant efforts to diagnose and correct.

Additional modifications include changes in the basic flow of POP2; in budget calculations; and in the overflow parameterization to restore exact restarts.

To maintain conservation:

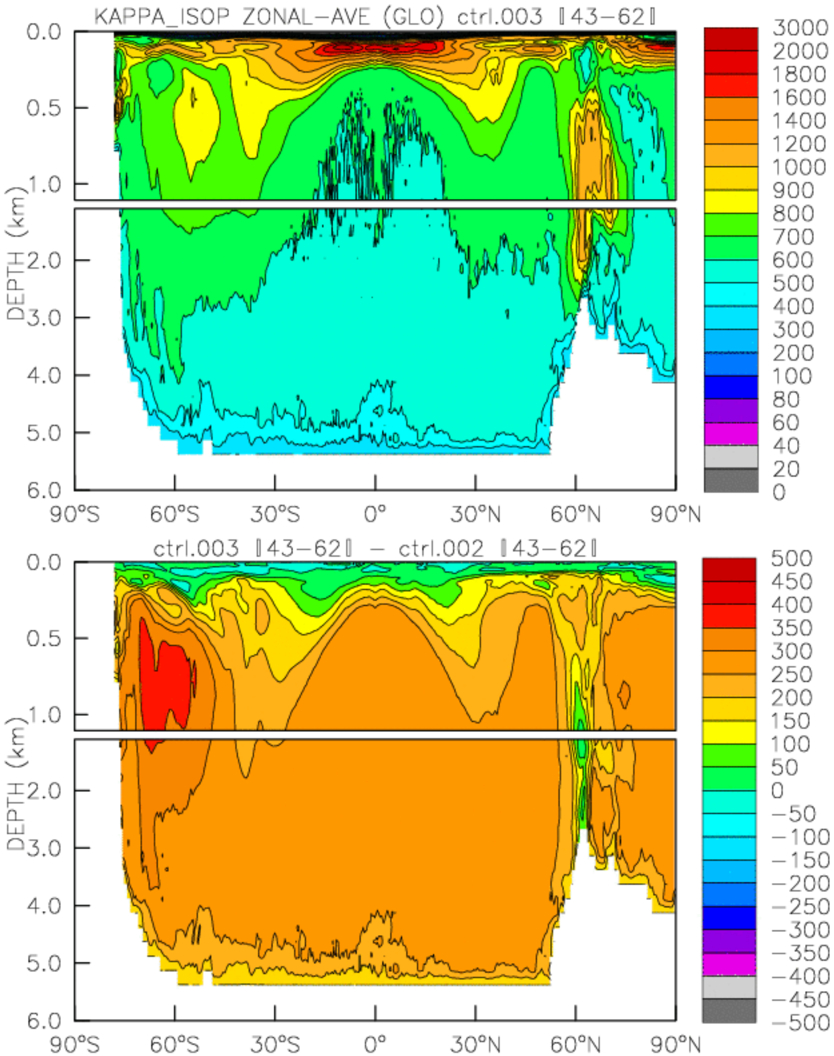
$$C^*(x,y,z) = C(x,y,z) + \alpha\, d(x,y,z) - \langle \alpha\, d \rangle(z)$$

Issues include “global” nature of the correction term as well as treatment of passive tracers.

Enhanced Mesoscale Eddy Diffusivities at Depth

Long, Lindsay, Truesdale, & Danabasoglu
NCAR

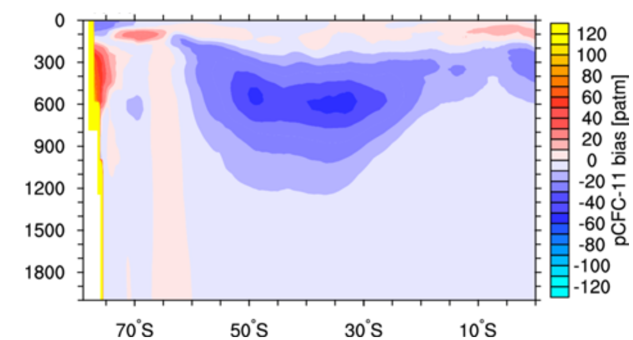
Zonal-Mean Eddy Diffusivity



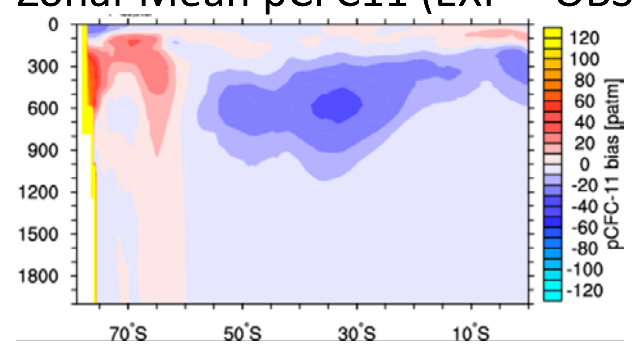
Upper-ocean max = 3000 m^2 s^{-1}

Deep minimum: 300 -> 600 m^2 s^{-1}

Zonal-Mean pCFC11 (CONT – OBS)

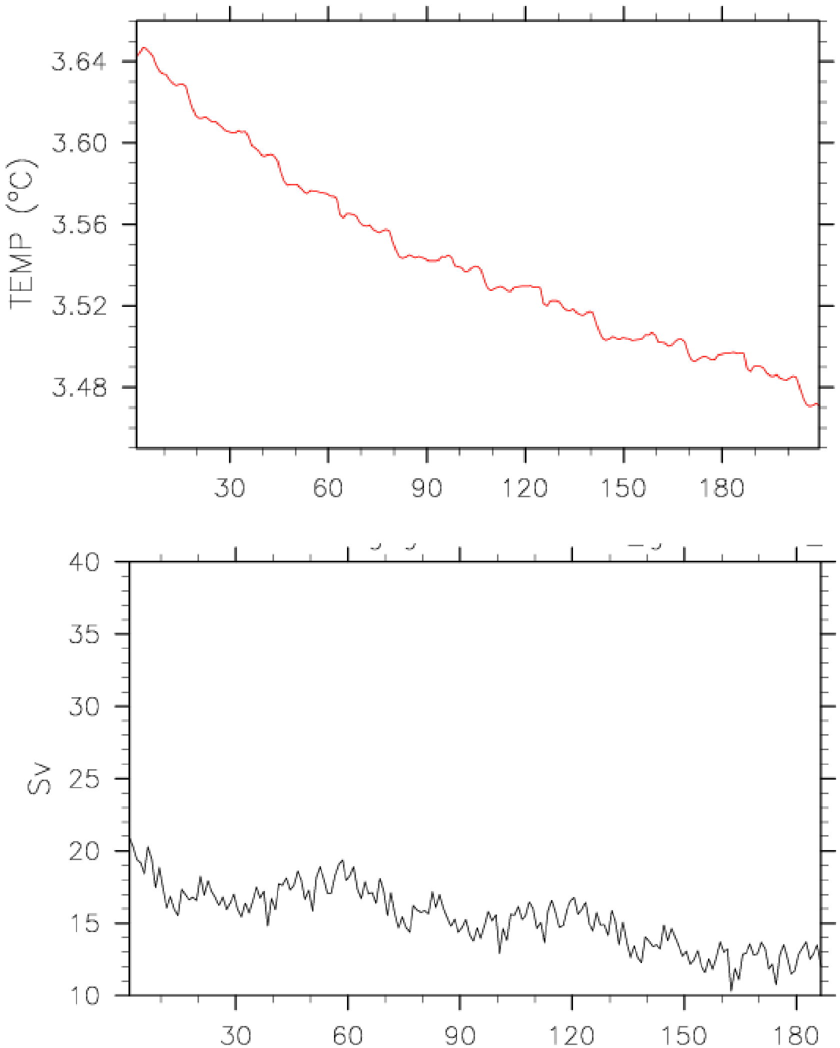


Zonal-Mean pCFC11 (EXP – OBS)

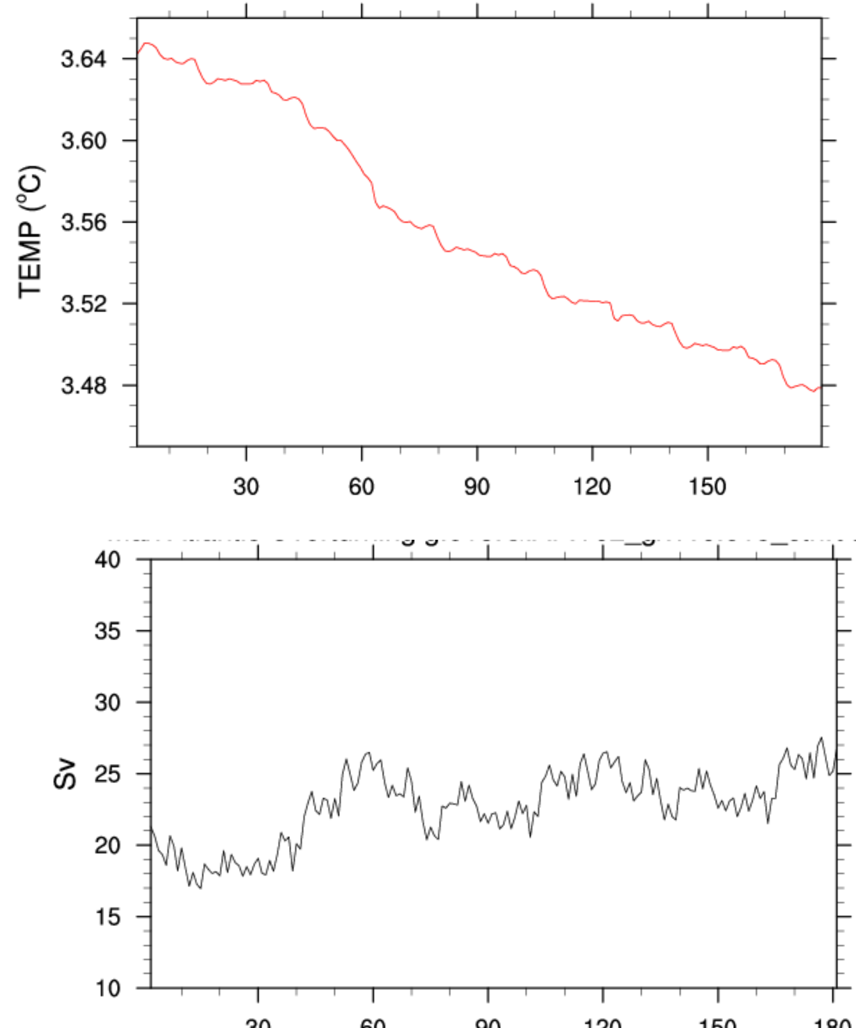


Time Series of Global-Mean Temperature and Maximum AMOC Transport

Enhancement in both isopycnal and thickness diffusivities



Enhancement in only isopycnal diffusivity



From forced ocean – sea-ice coupled simulations

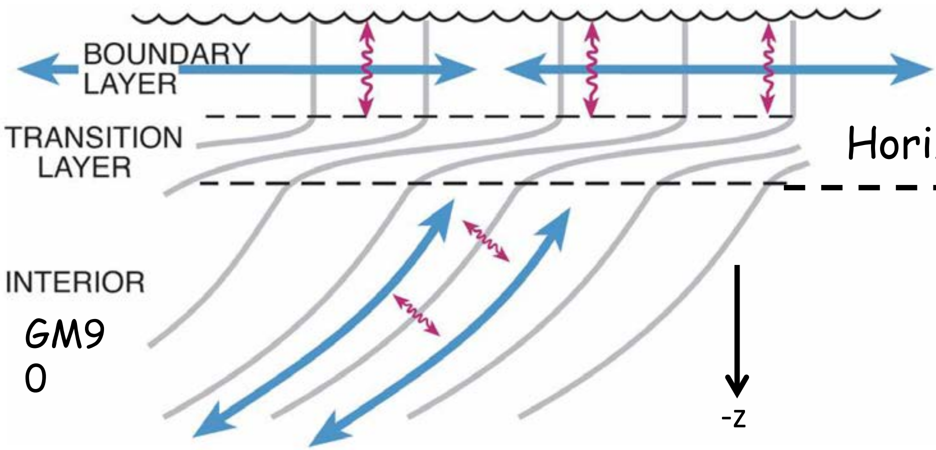
Specification of Mesoscale Eddy Diffusivities via Steering Level Approach

Truesdale & Danabasoglu
NCAR

Marshall
MIT

Current Specification of Isopycnal and Thickness Diffusivities

Near-Surface Eddy Flux Parameterization & Variations in the Vertical



Diffusivities	$K = K_{REF} \, (N^2 / N^2_{REF})$
Horizontal	$(N^2/N^2_{REF}) = 1$; K_{REF}
Horizontal/Isopycnal	
Isopycnal	$N_{min} <= (N^2/N^2_{REF}) <= 1$

N: Local buoyancy frequency;

N_{REF}: Reference buoyancy frequency just below the transition layer;

K_{REF}: Constant reference value of K within the surface diabatic region (= 3000 $m^2 \, s^{-1}$ in x1);

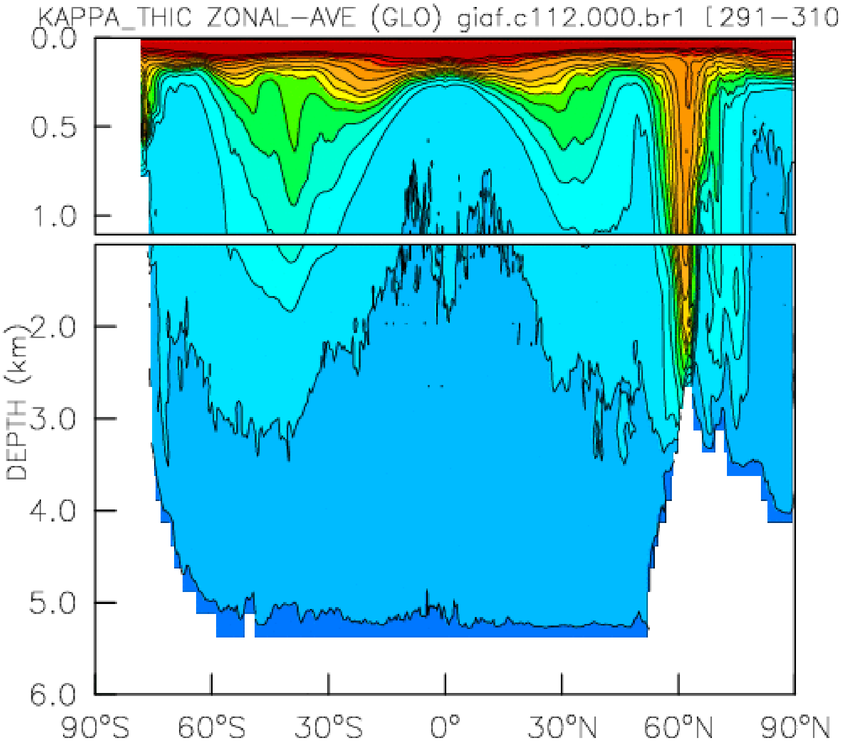
N_{min} (=0.1): a lower limit;

Isopycnal and thickness diffusivities are the same.

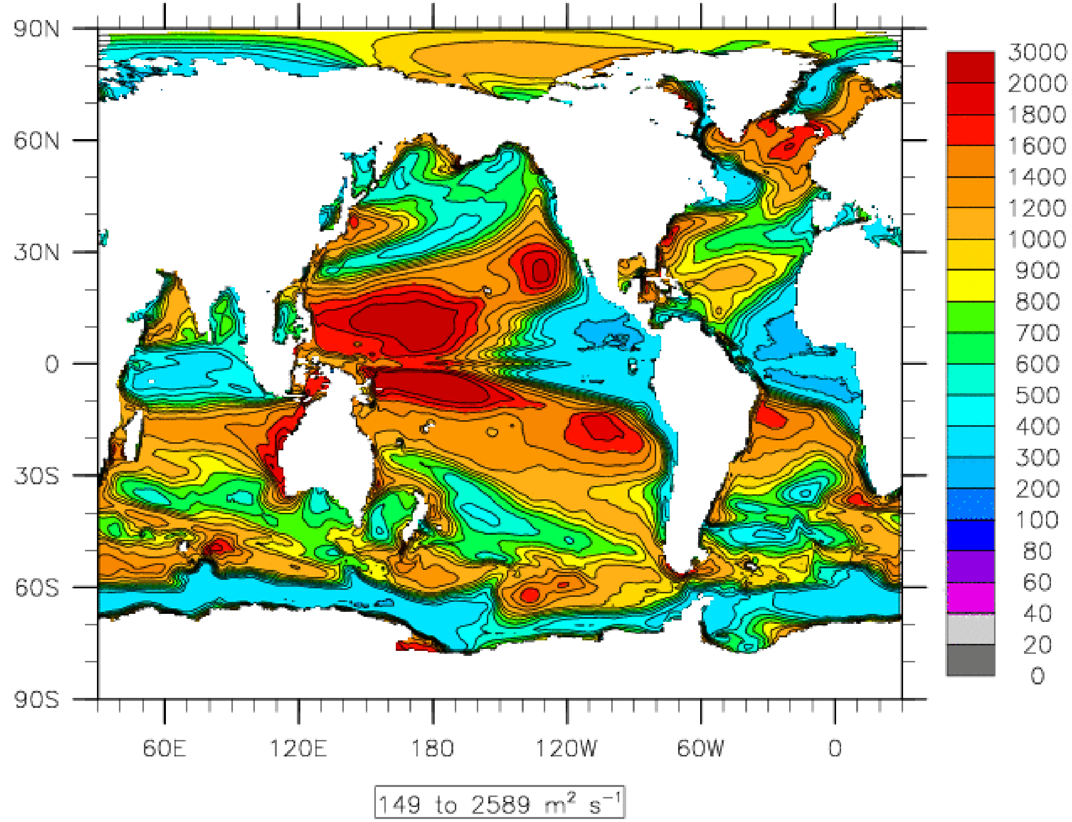
Ferrari et al. (2008, J. Climate); Danabasoglu et al. (2008, J. Climate);
Ferreira & Marshall (2005, JPO); Danabasoglu & Marshall (2007, Ocean Modelling)

Diffusivity Distributions

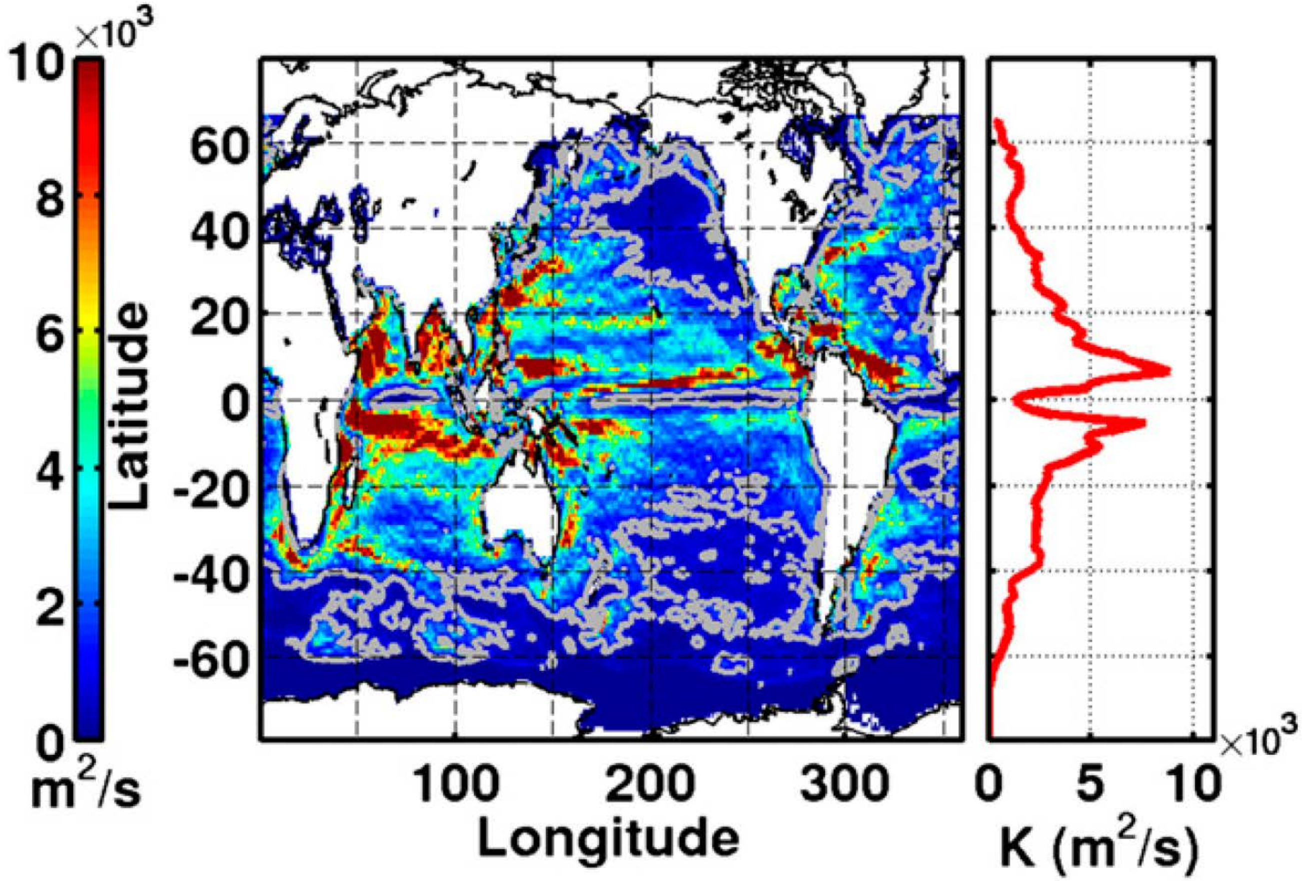
Global Zonal Average



At 200 m Depth



An Estimate of (Cross-Stream) Surface Diffusivity



Based on advection of numerical tracers with the geostrophic velocity obtained from altimetry.

Abernathey & Marshall (2013, JGR)

Steering Level Arguments

Ferrari & Nikurashin (2010, JPO)

Bates, Tulloch, Marshall, & Ferrari (2014, JPO)

Steering levels: Surfaces / regions at which the propagation speed of mesoscale eddies approach that of the mean flow;

Maximum mixing occurs at the steering levels;

Mixing is strongly suppressed away from the steering levels, e.g., in strong flows where the mean flow and propagation speed of eddies differ significantly;

When the eddies propagate at a speed different from the mean flow, some of the tracer can be advected by the mean flow out of the eddy before it is fully mixed, i.e., there is not enough time for mixing and it is suppressed;

In contrast, when the eddies move with the flow, mixing can be more effective, i.e., no suppression of mixing.

Starting with the mixing length theory,

$$K = u_{rms} L_{mix}$$

where K is diffusivity; u_{rms} is the root-mean-square eddy velocity; and L_{mix} is the mixing length, i.e., a characteristics distance that a fluid parcel travels before being mixed.

After some theory and lots of assumptions (Bates et al. 2014):

G (=5)

$$K = u_{rms} \frac{\Gamma L_{eddy}}{1 + b_1 |\overline{u} - c|^2 / u_{rms}^2 (z=0)}$$

Suppression

L_{eddy} is the eddy length scale; c is the characteristic eddy propagation speed; $\overline{u}$ is the mean zonal velocity.

b_1 = 4 and Γ=0.35 are adjustable parameters.

Using observational data and output from ECCO, Bates et al. (2014) obtained K distributions similar to that of Abernathey & Marshall (2013).

Steering Level Parameterization

Assume that the scaling arguments given by our primary equation is valid at all depths.

Assume that the eddies are propagating as a coherent structure in the vertical: L_{eddy} and c are depth independent.

Mean zonal velocity is the 3D prognostic model velocity.

A vertical structure for u_{rms} is specified simply using N^2/N^2_{REF} as in Ferreira et al. (2005) and Danabasoglu & Marshall (2007).

Isopycnal and thickness diffusivities are the same and isotropic.

$100 \leq K \leq 10000$ m^2 s^{-1}.

Simulations w/o and w/ steering level (CONTROL and SL, respectively):

- Latest CESM version;
- Ocean – sea-ice hindcast simulations forced with the CORE-II inter-annually varying data sets for the 1948-2009 period;
- 310-year integrations, corresponding to 5 forcing cycles;
- last 20-year means are presented (except for SL-related fields).

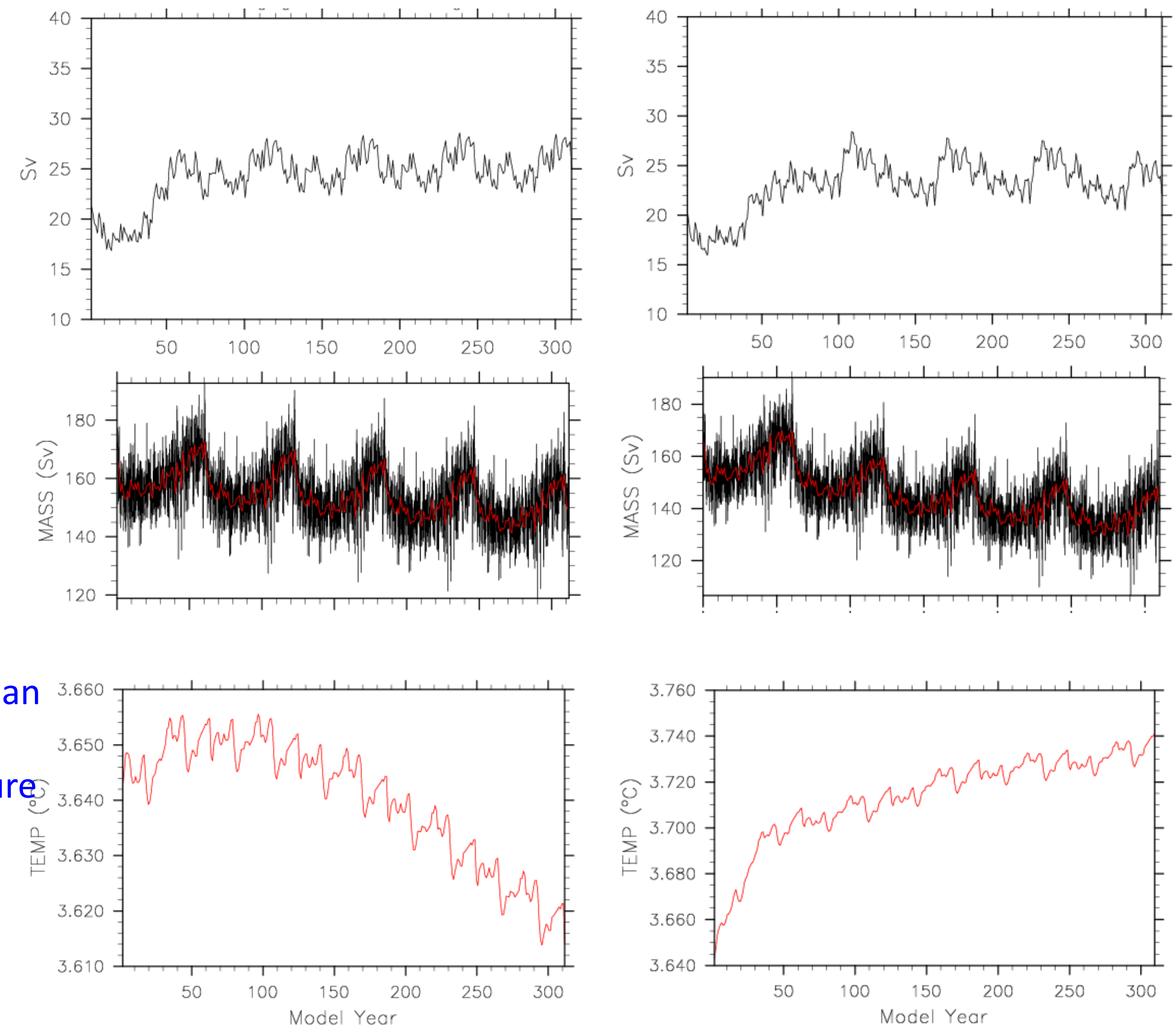
Time Series

CONTROL | SL

AMOC max

ACC at Drake

Global-mean potential temperature

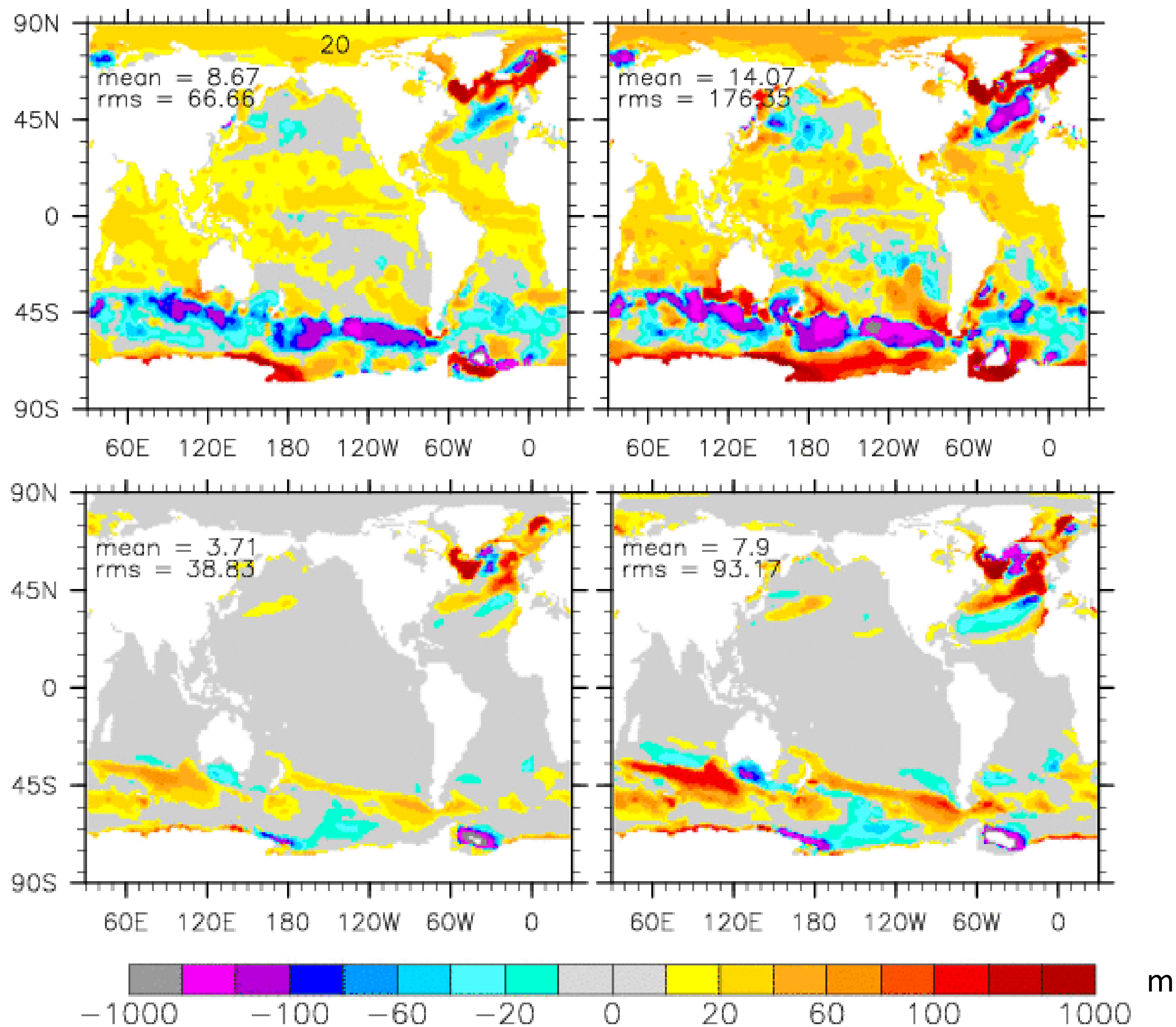


Mixed Layer Depth

Annual-Mean | Winter-Mean

CONTROL - OBS

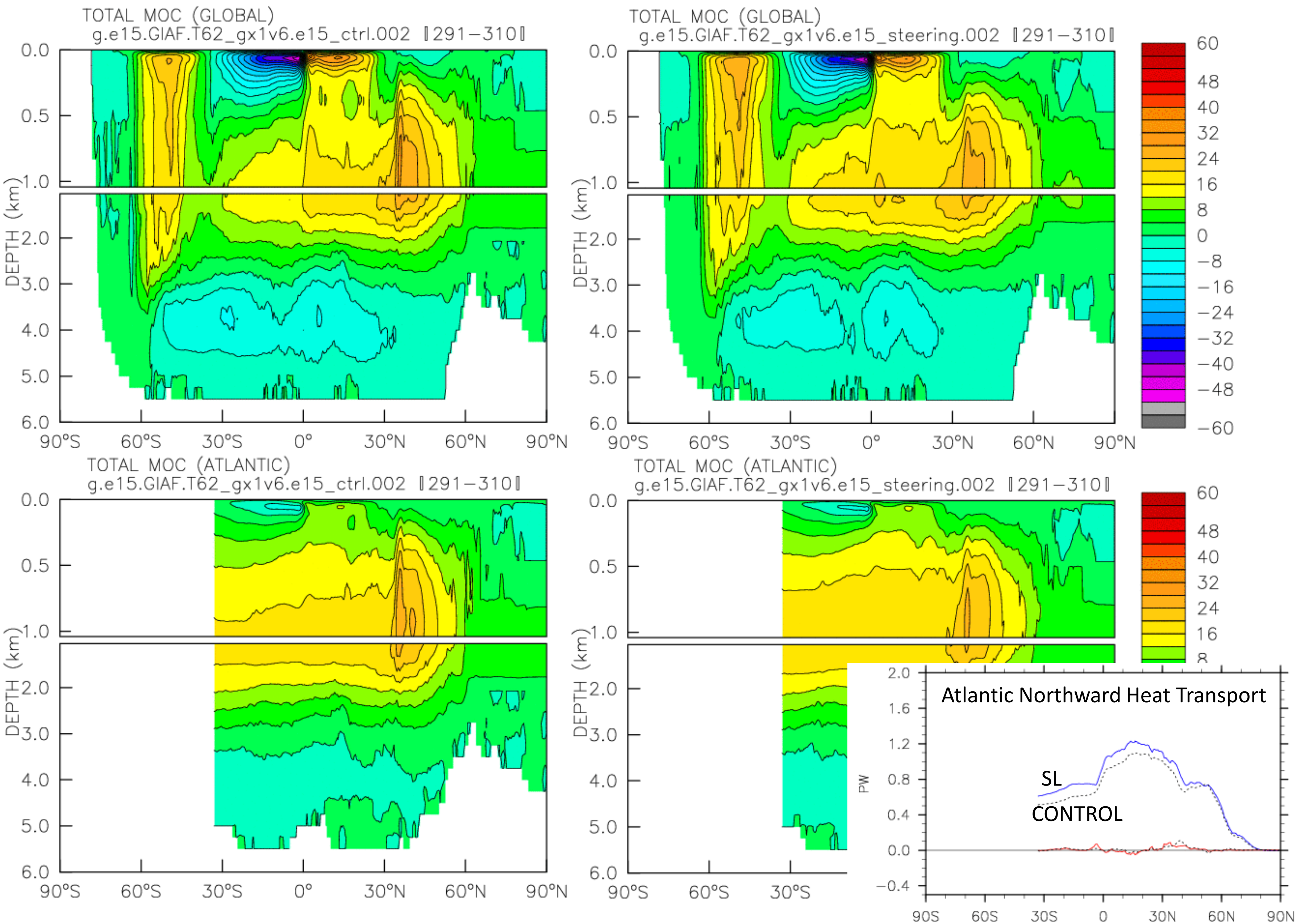
SL - CONTROL



Meridional Overturning Circulation (Sv)

CONTROL

SL

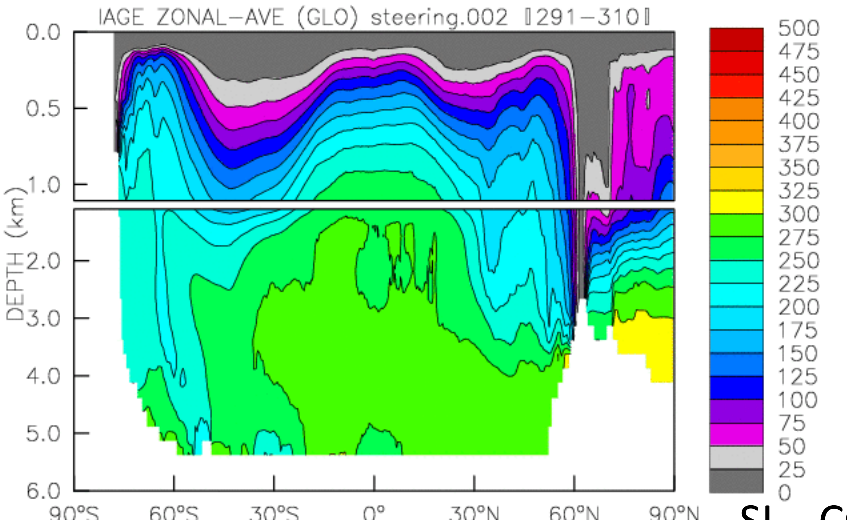


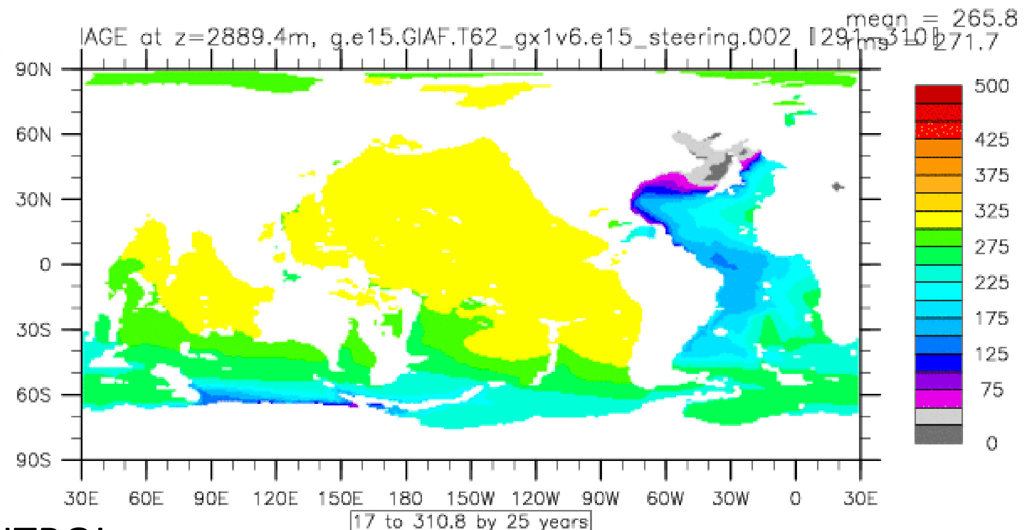
Ideal Age (yr)

Global Zonal-Mean

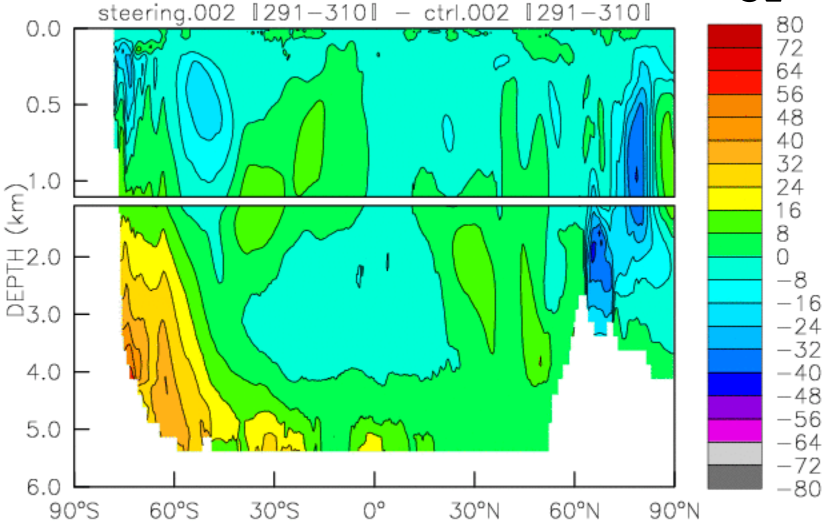
At 2900-m Depth

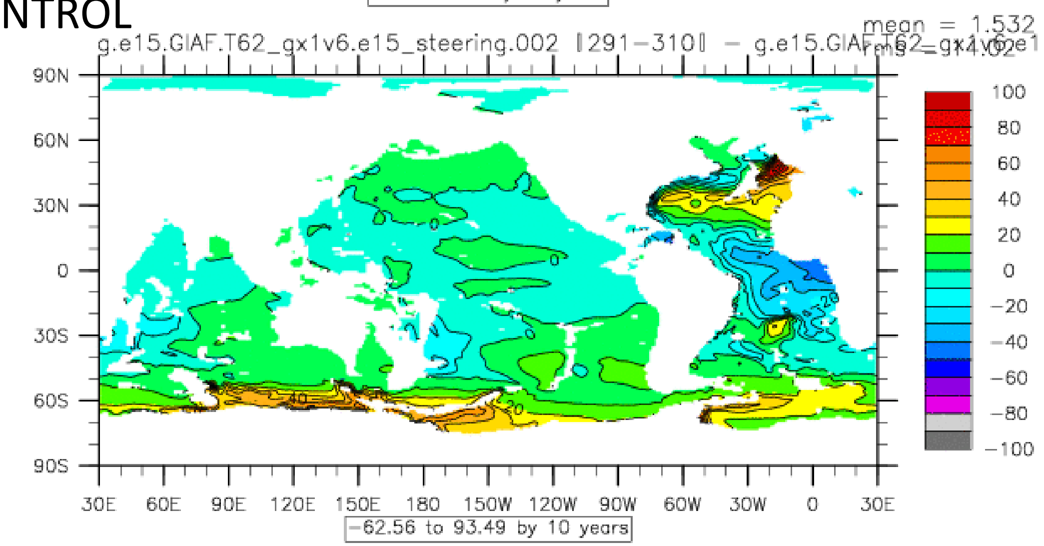
SL



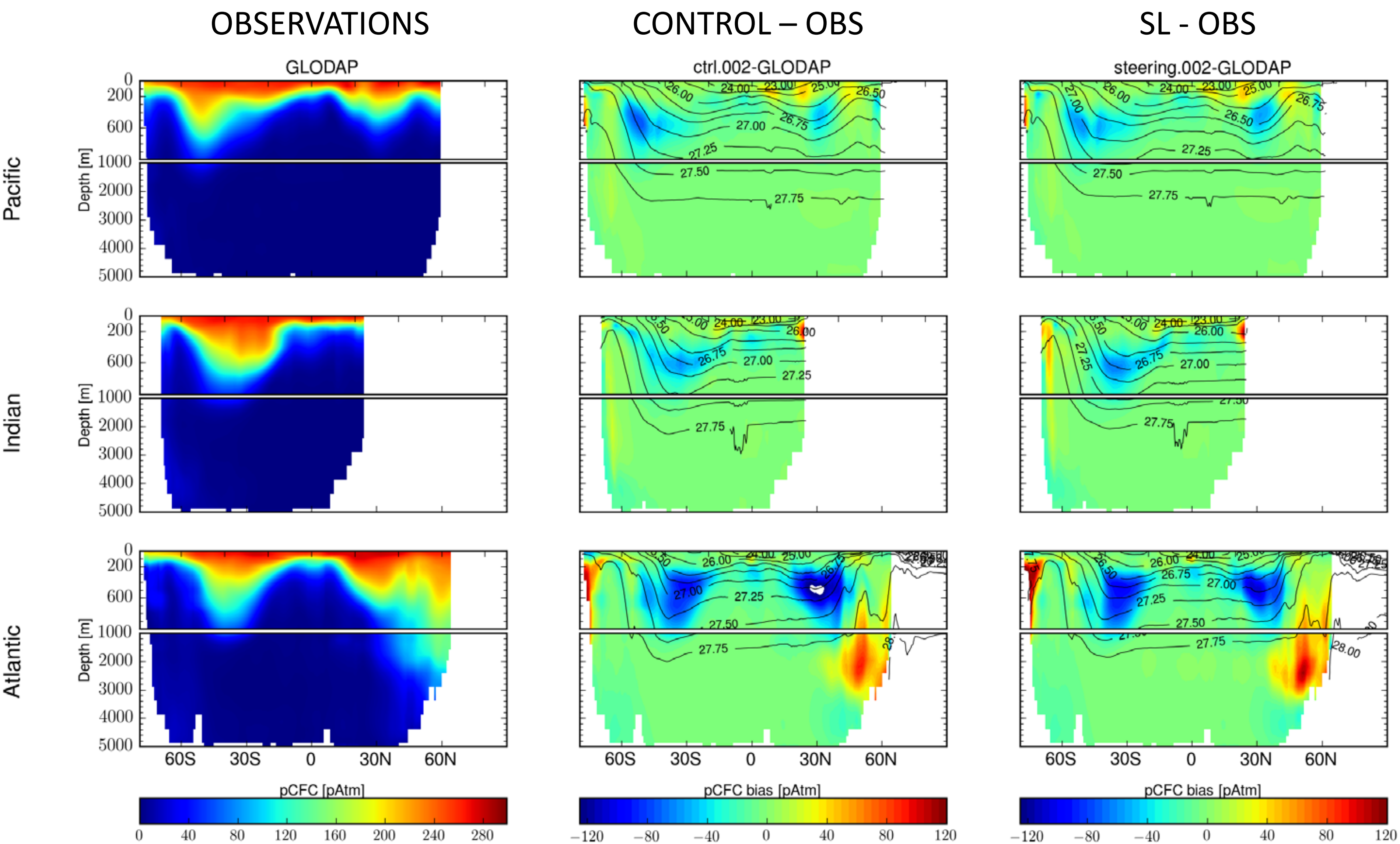


SL - CONTROL





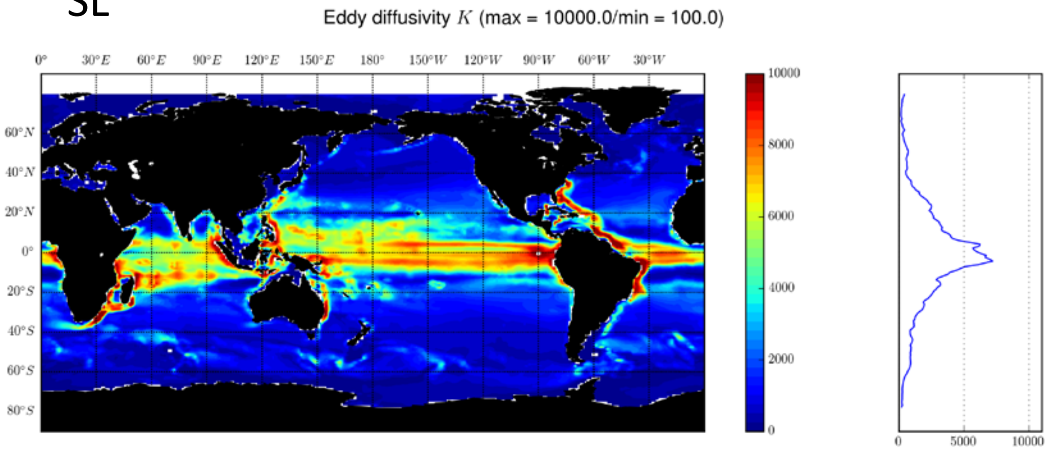
pCFC11



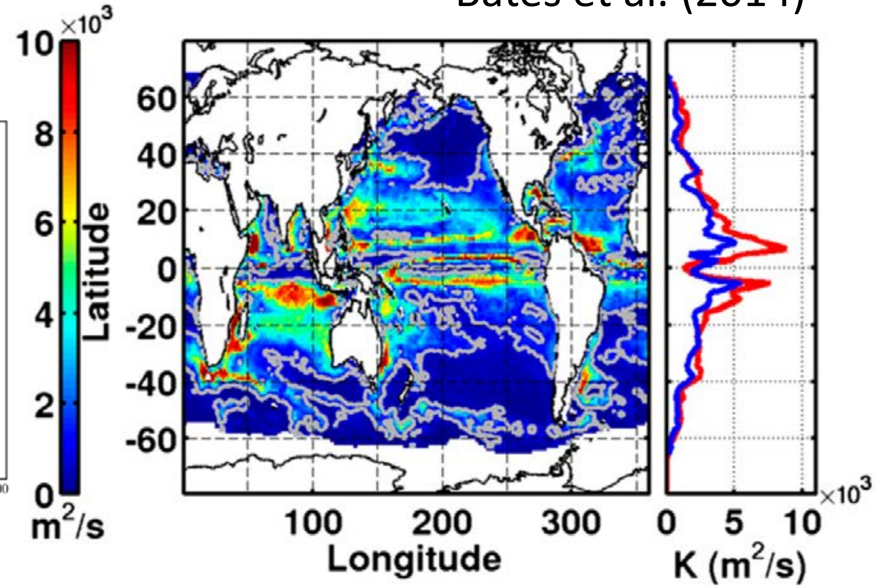
OBSERVATIONS
CONTROL – OBS
SL - OBS
GLODAP
ctrl.002-GLODAP
steering.002-GLODAP
Pacific
Indian
Atlantic
Depth [m]
0
200
600
1000
2000
3000
4000
5000
60S
30S
0
30N
60N
pCFC [pAtm]
0
40
80
120
160
200
240
280
pCFC bias [pAtm]
−120
−80
−40
0
40
80
120

Eddy Diffusivities at (Near) Surface

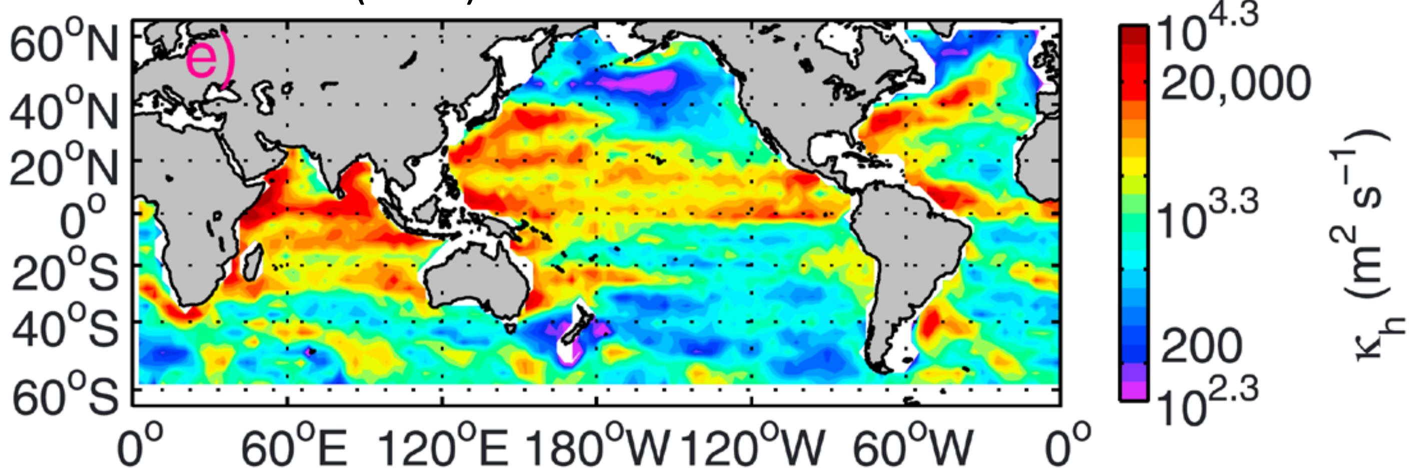
SL



Bates et al. (2014)



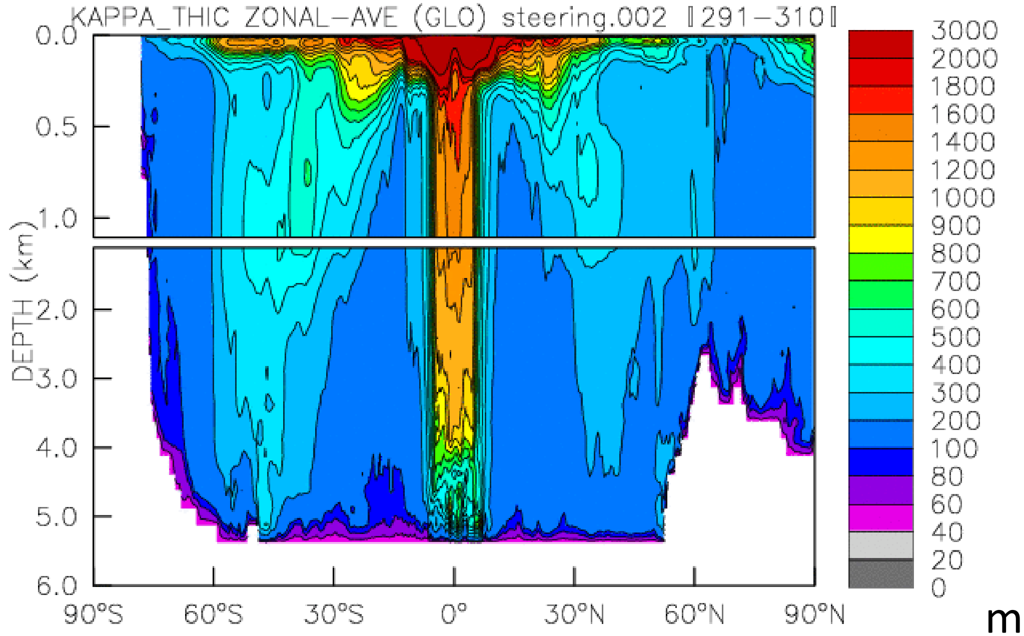
Cole et al. (2015)



at base of winter mixed layer

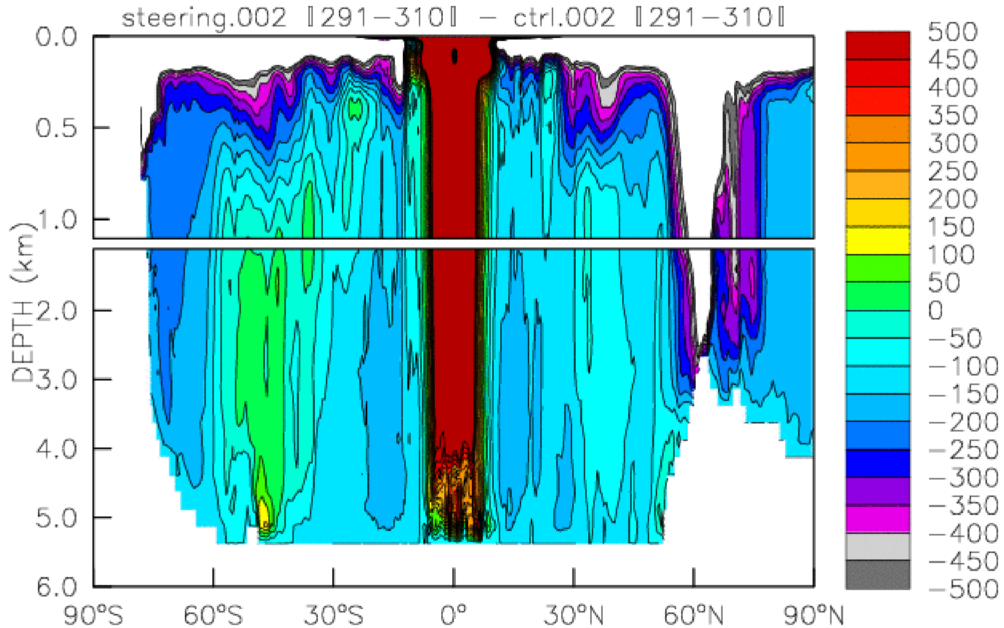
Global Zonal-Mean Eddy Diffusivities

SL



$m^2\ s^{-1}$

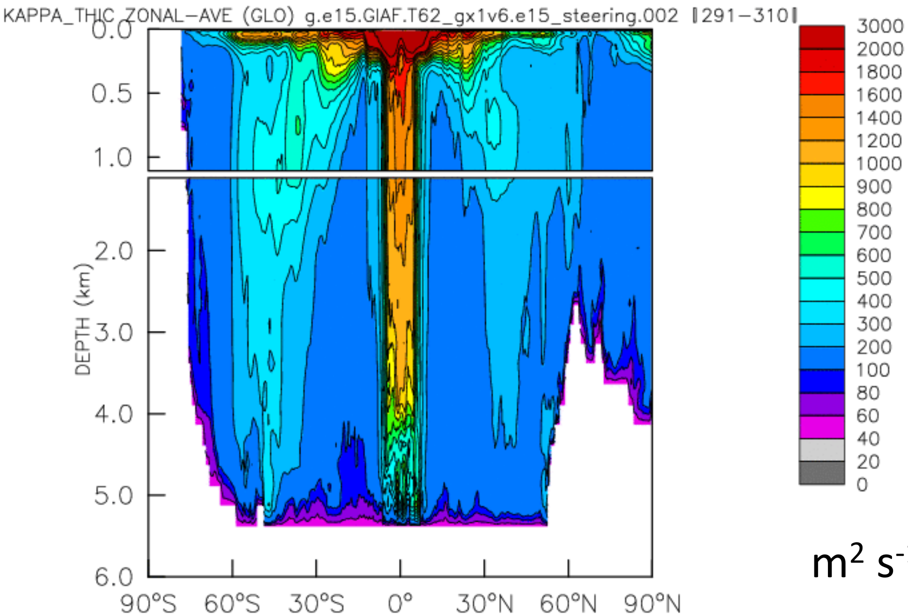
SL - CONTROL



Zonal-Mean Eddy Diffusivities

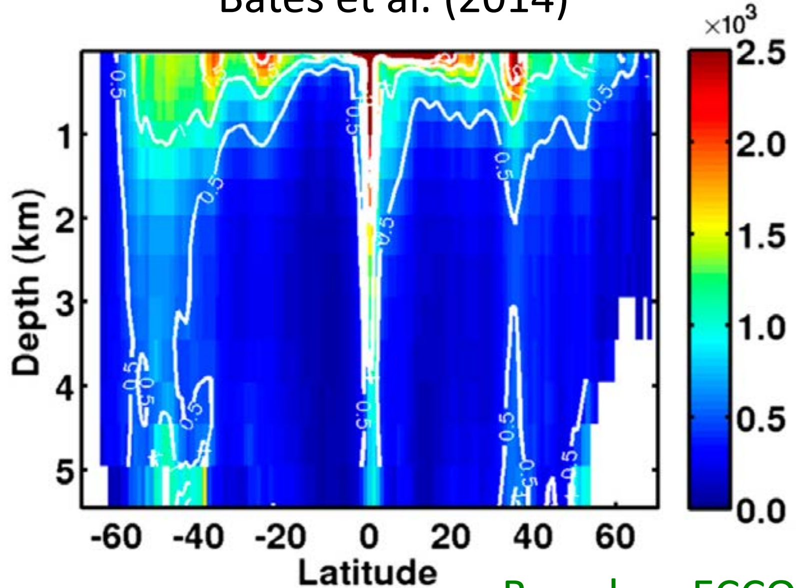
SL

Global



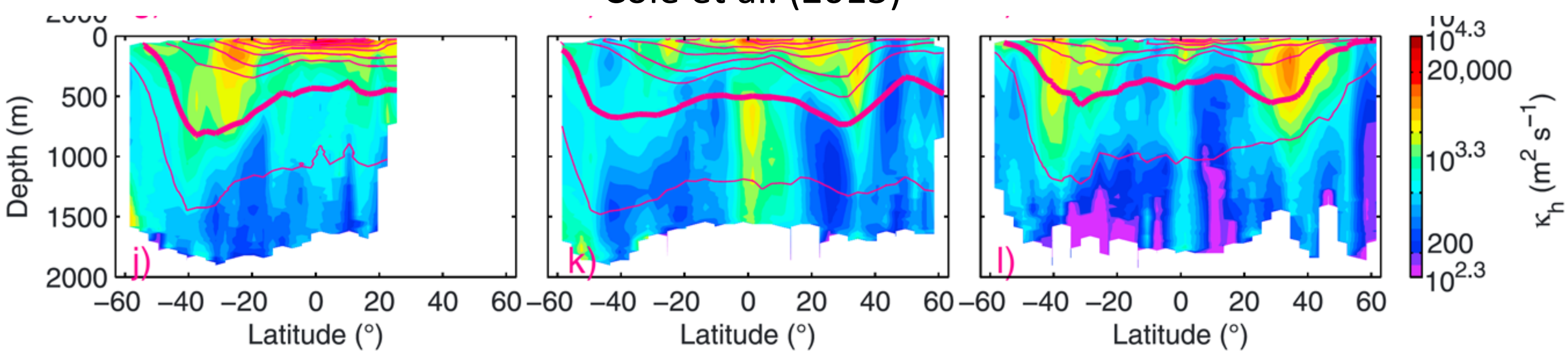
$m^2\ s^{-1}$

Bates et al. (2014)



Based on ECCO

Cole et al. (2015)



INDIAN

PACIFIC

ATLANTIC

Summary

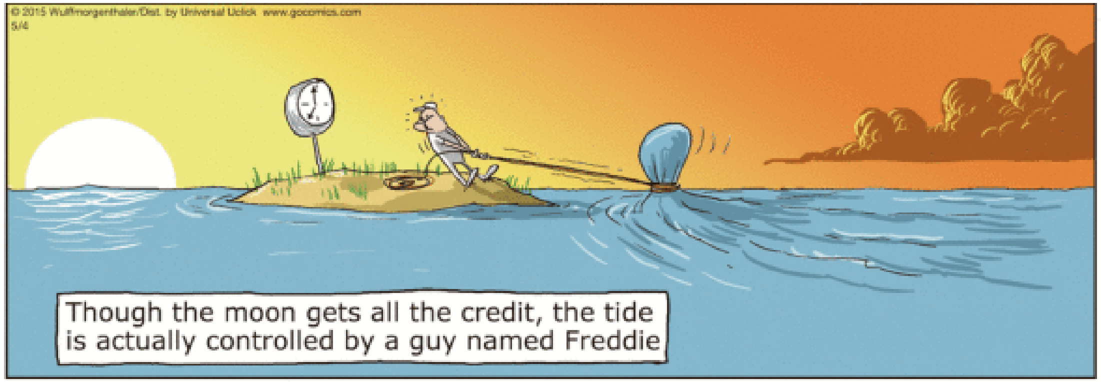
- A specification for mesoscale eddy diffusivities based on steering level approach has been implemented in the CESM ocean component
- Results are mixed both from physics and BGC perspectives
- There appears to be little sensitivity of model solutions to some details of parameterization choices, e.g., various limits and parameter values
- Evolving model state appears to exert strong control on the suppression factor, and hence the resulting K
- Additional sensitivity experiments will be performed considering use of SL approach only for the isopycnal diffusivities; using observed phase speed; obtaining eddy length scales using observed phase speed; etc.

Tidal Mixing Parameterizations

Norton & Danabasoglu
NCAR

Schmittner & Ullman
Oregon State University

Climate Process Team on Internal Wave Mixing



Existing Formulation in POP2 (The Default Parameterization)

[based on Jayne & St. Laurent (2001, GRL); St. Laurent et al. (2002, GRL); Simmons et al. (2004, Ocean Modelling)]

Vertical diffusivity due to background and tidal mixing:

$$k_v = k_{\mathrm{bg}} + \frac{\Gamma \varepsilon}{N^2}$$

where *N*: buoyancy frequency,

Γ (=0.2): canonical mixing efficiency of turbulence.

$$\varepsilon = \frac{q E(x, y) F(z, H)}{\rho}$$

where q (=1/3): local dissipation efficiency,

ρ: density,

E: energy flux out of the barotropic tide,

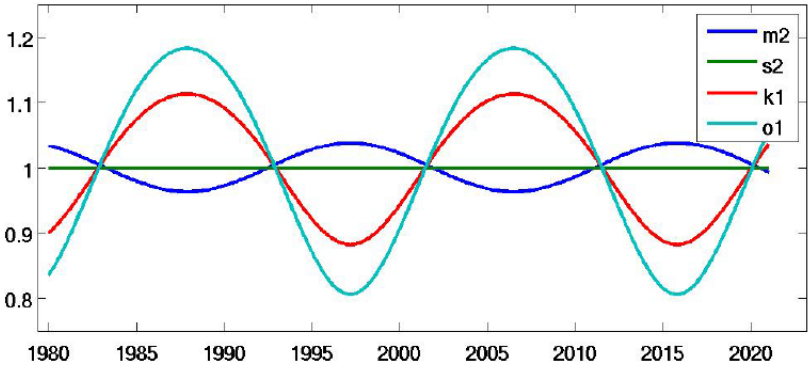
F: vertical distribution (decay) function

$$F(z, H) = \frac{e^{-(H-z)/\zeta}}{\zeta(1 - e^{-H/\zeta})}$$

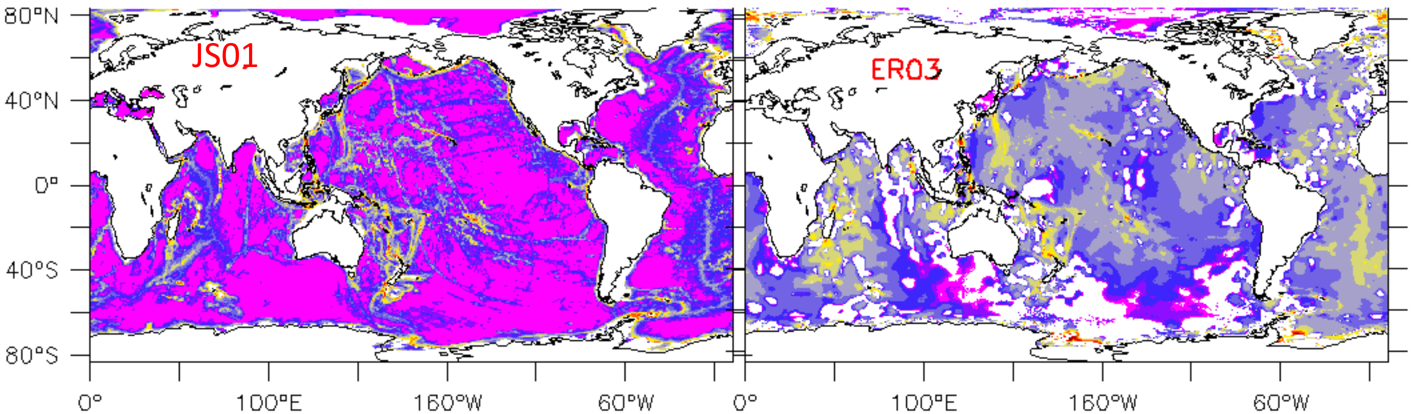
with ζ = 500 m

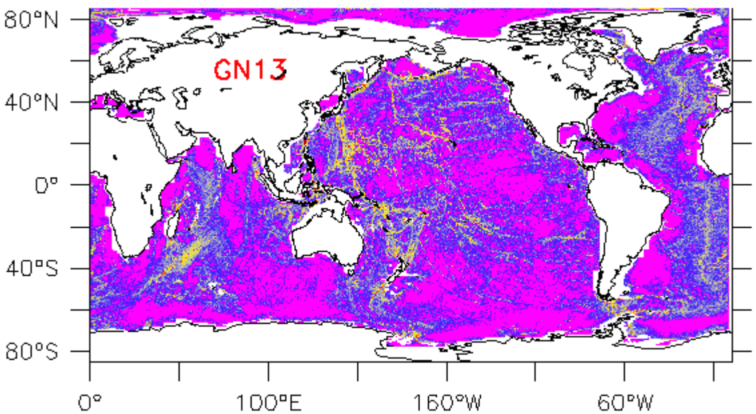
New Tidal Mixing Parameterizations / Approaches Implemented in POP2

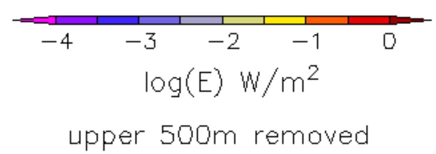
- New dissipation energy flux fields from the barotropic tides from Egbert & Ray (2003; EG03) and Green & Nycander (2013; GN13) – current default is based on Jayne & St. Laurent (2001; JS01),
- Effects of subgrid-scale bathymetry in the energy flux field, following Schmittner & Egbert (2014; SE14),
- Separation of semi-diurnal and diurnal tides with different local dissipation efficiency, following SE14,
- Algebraic decay of dissipation energy, following Polzin (2009) à la Melet et al. (2013),
- Incorporation of the 18.6-year Lunar Nodal Cycle (LNC)



Dissipation Energy Flux from the Barotropic Tides







JS01: Estimated using a barotropic tide model with parameterized internal wave drag; 8 tidal constituents

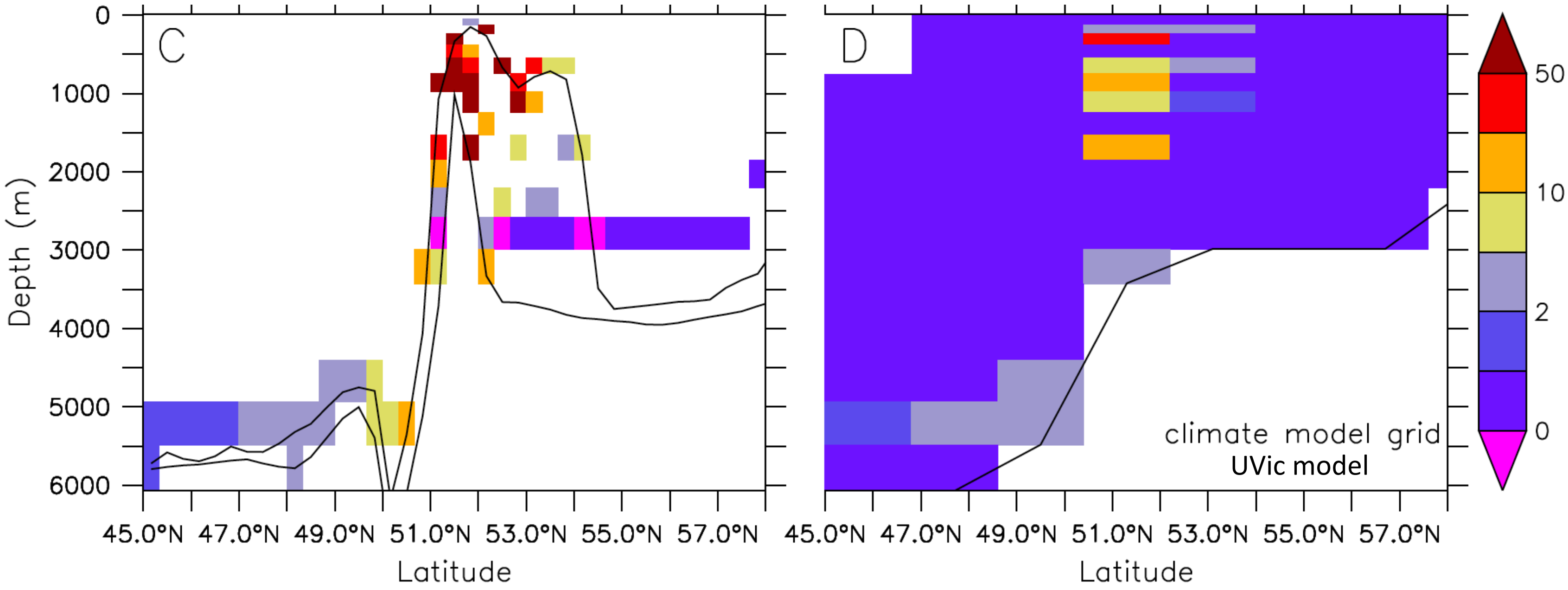
ER03: Estimated from assimilation of satellite altimetry data into a hydrodynamic model; 4 tidal constituents

GN13:Estimated using a high-resolution (1/8° x 1.8°) barotropic tide model with parameterized internal wave drag; 4 tidal constituents

Subgrid-Scale Bathymetry

An example using the Aleutian Islands chain

Energy flux from the K1 barotropic tide (10^{-3} W m^{-2})



Schmittner & Egbert (2014)

Tidal Constituents (TCs)

Four TCs:

- Semi-diurnal lunar and solar tides, M2 and S2, respectively, with q = 1/3,
- Diurnal tides K1 and O1 with q = 1 polewards of 30^{o} latitude

$$\varepsilon = \frac{1}{\rho} \sum_{z' > z}^{H} \sum_{\mathrm{TC}} q_{\mathrm{TC}} E_{\mathrm{TC}}(x, y, z') F(z, z')$$

Algebraic Decay of Dissipation Energy

Polzin (2009) à la Melet et al. (2013)

Static vs time-varying dissipation energy:

$$E(x,y,t) = (1/2)\ \rho_0\ N_b(t)\ \lambda\ h^2\ U^2$$

where

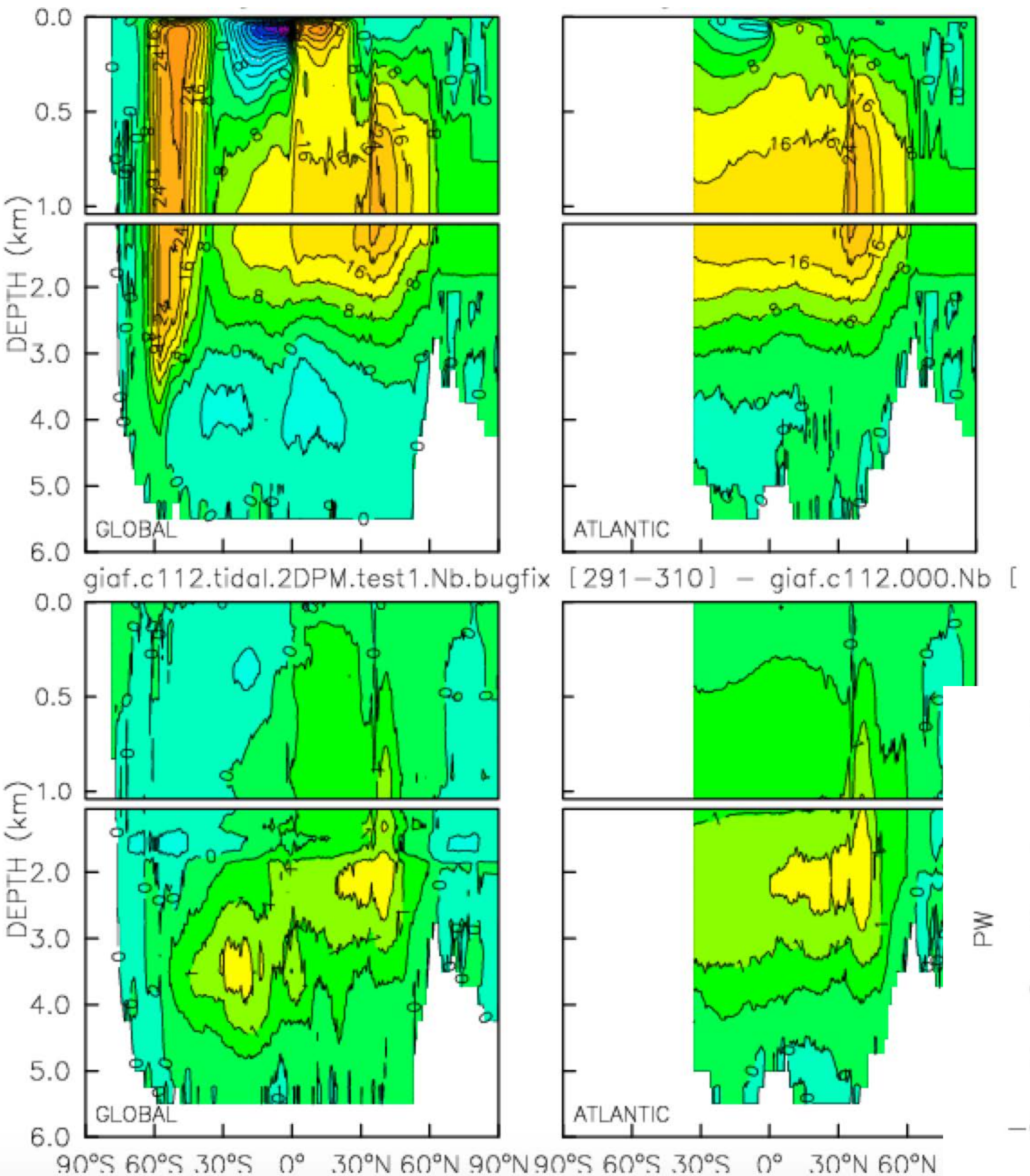
- ρ_0: reference density
- N_b: buoyancy frequency along the seafloor
- λ: wavenumber scale for topographic roughness
- h: amplitude scale for topographic roughness
- U^2: barotropic tide variance

Model Simulations

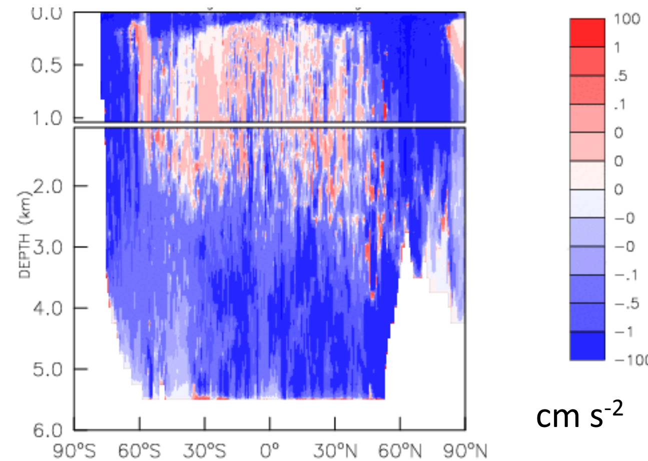
- Ocean – sea-ice coupled simulations forced with the Coordinated Ocean – ice Reference Experiments inter-annually varying atmospheric data sets (aka, CORE-II simulations);
- 62- to 310-year experiments corresponding to one to five repeat cycles of the 1948-2009 forcing period;
- More than 30 experiments;
- No fully-coupled simulations yet!

Algebraic Minus Exponential Vertical Decay Experiment

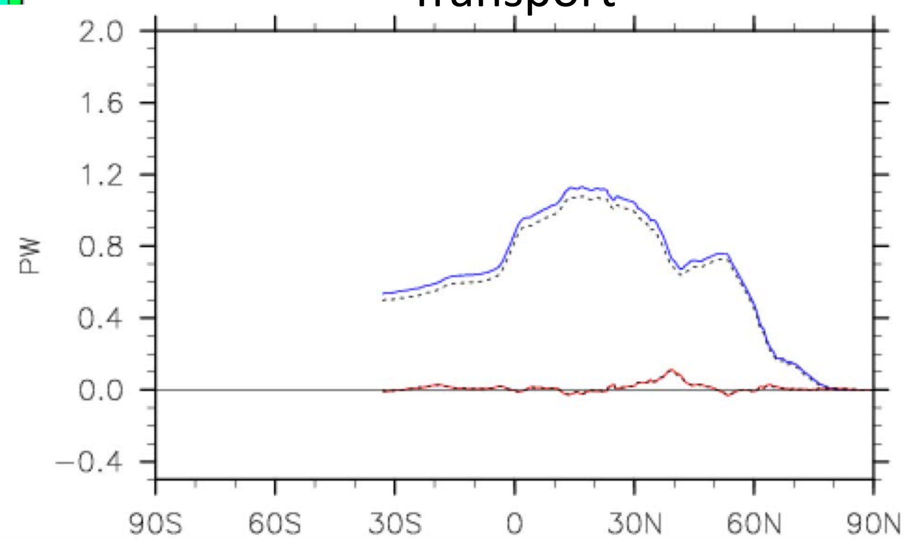
Global and Atlantic MOC (Sv)

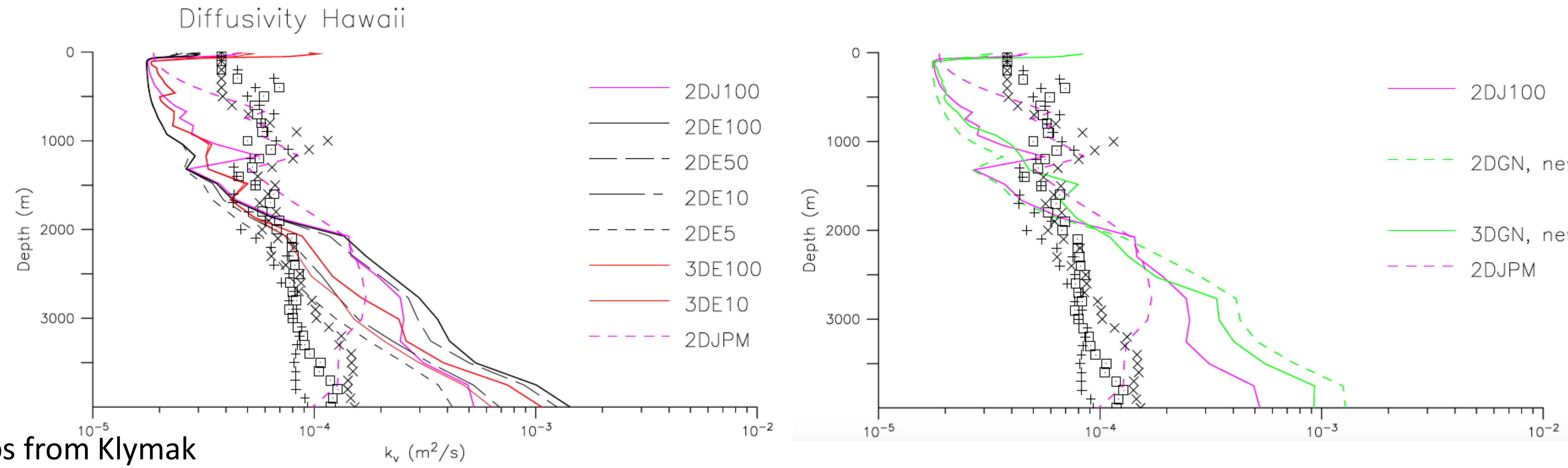


Global and zonally-averaged k_v

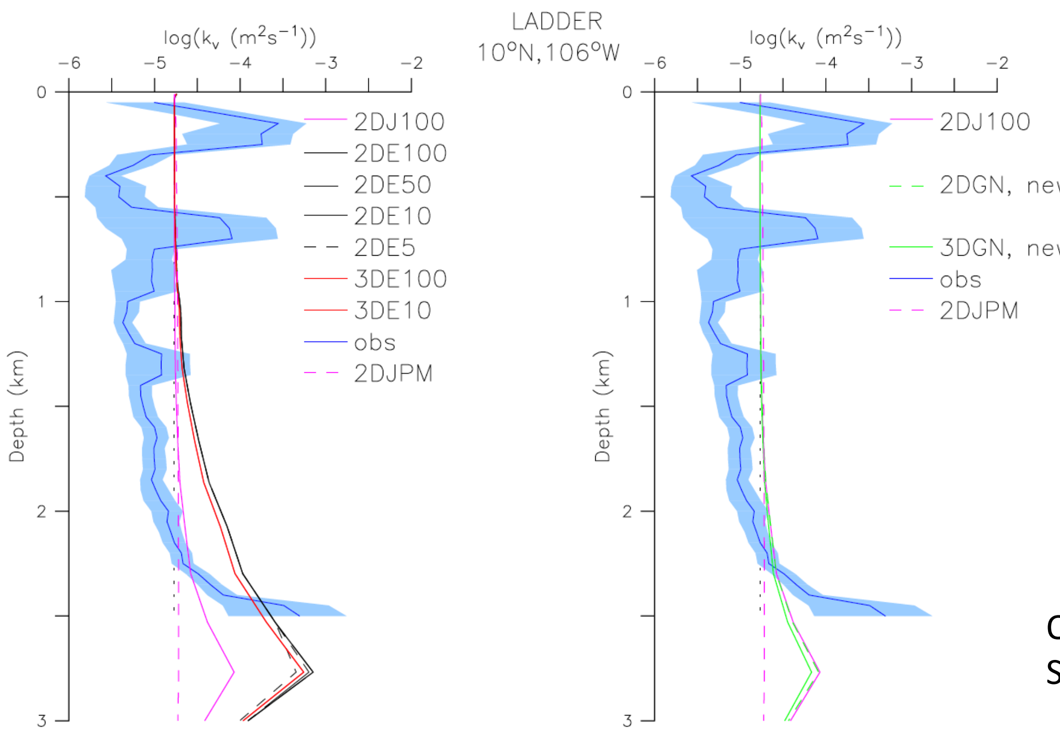


Atlantic Northward Heat Transport



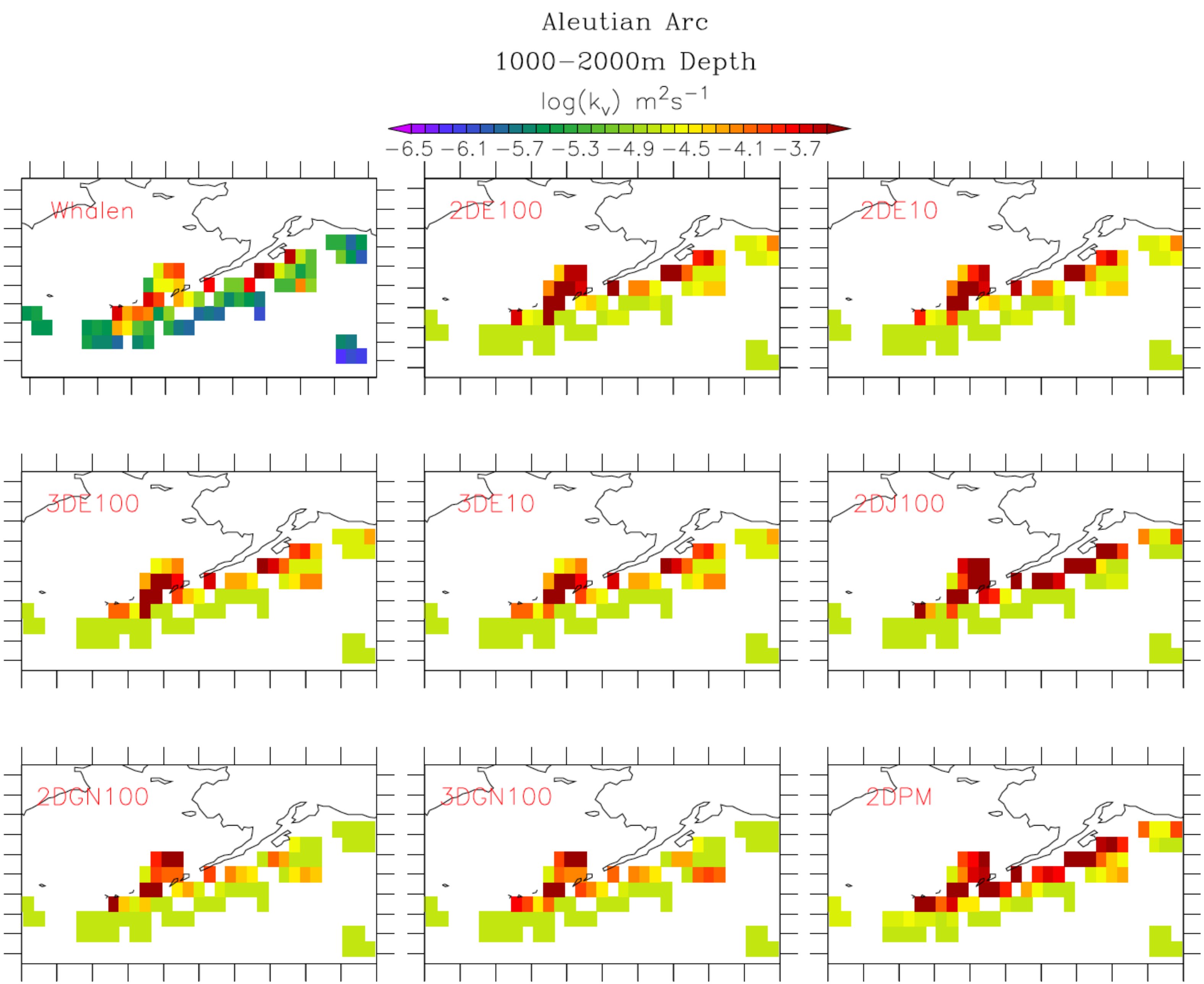


Obs from Klymak et al. (2006)



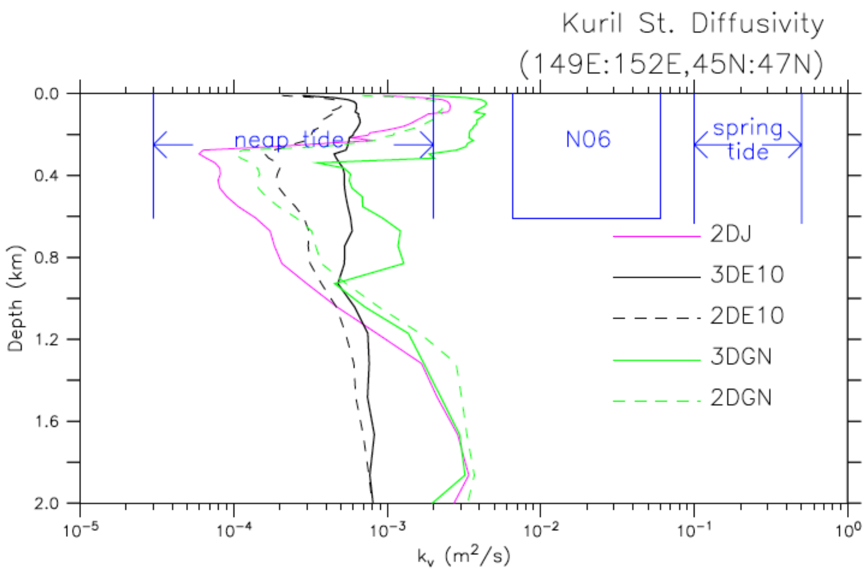
Tropical Eastern Pacific

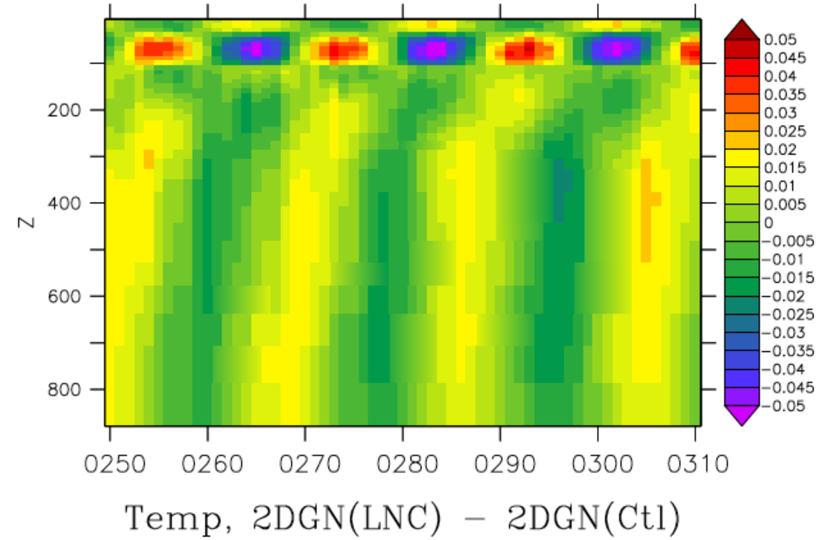
Obs from Thurnherr & St. Laurent (2011)

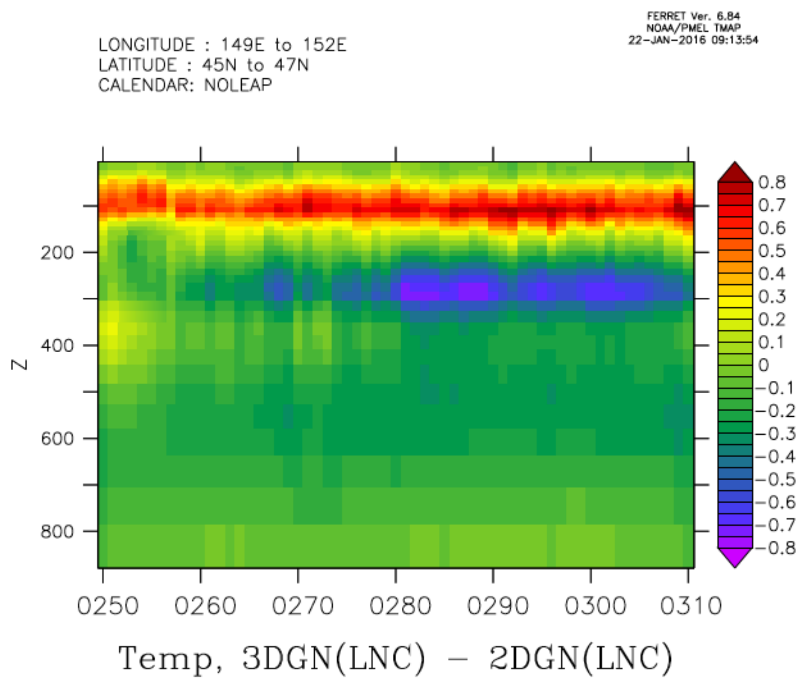


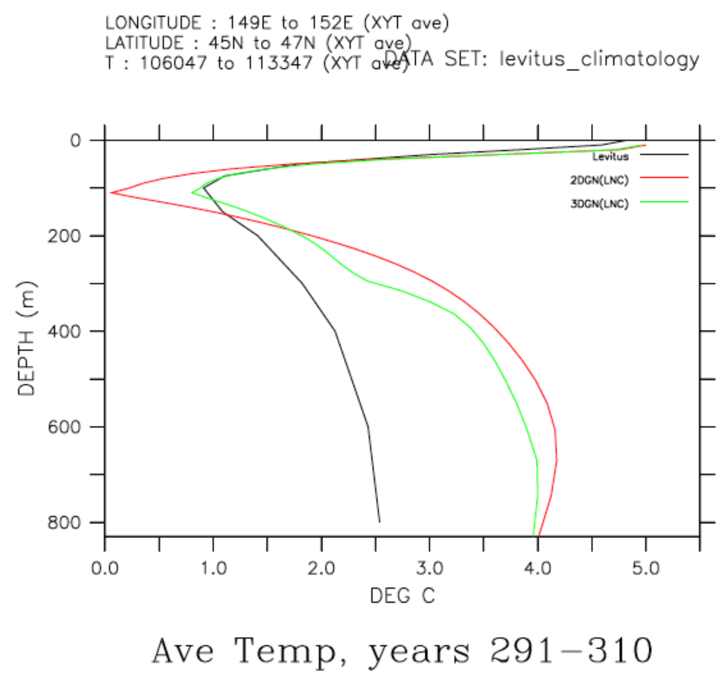
Updated from Whalen et al. (2012)

LNC and Kuril Strait









Summary and Plans

- Impacts of the new tidal mixing parameterizations / approaches on the solutions from forced ocean – sea-ice hindcast simulations appear to be rather small in many metrics of climate interest, including BGC fields;
- Fully-coupled simulations are being performed to assess climate impacts of some select approaches;
- Infrastructure developed for tidal mixing needs to be brought into the CVMix framework.

Steering Level Parameterization

Eddy length scale L_{eddy}:

$$L_{eddy} = \min(L_R, L_{\mathrm{Re}q})$$

Where L_R and L_{Req} are the Rossby deformation radius given by

$$L_R = \frac{c_R}{|f|} \qquad L_{\mathrm{Re}q} = \sqrt{\frac{c_R}{2\beta}}$$

f is the Coriolis parameter; β is its latitudinal variation; and c_R is the first baroclinic wave speed calculated following Chelton et al. (1998).

Zonal mean flow: Instantaneous velocity in the grid zonal direction

Steering Level Parameterization

Eddy propagation speed *c*:

$$c = -\beta L_{eddy}^2$$

Long Rossby wave speed assumption from Tulloch et al. (2009, JGR);
$|c| \leq 20$ cm s^{-1}

Eddy velocity u_{rms}:

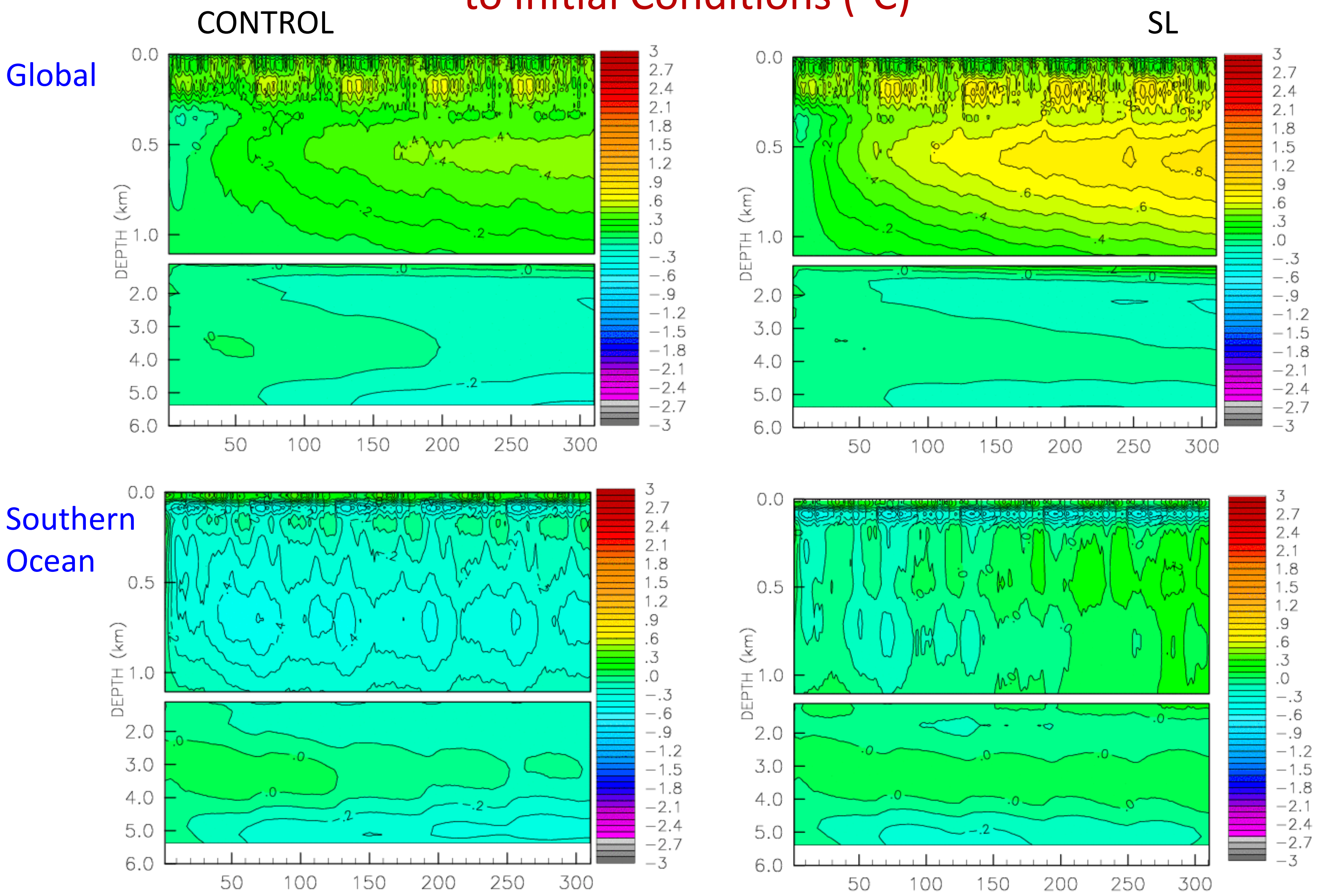
$$u_{rms} = \alpha \sigma L_{eddy}$$

Where α (=4) is a scaling parameter and σ is the Eady growth rate given by

$$\sigma = \frac{1}{L_z} \int_z \frac{f}{\sqrt{Ri}} dz = \frac{1}{L_z} \int_z \frac{M^2}{N} dz$$

M is the horizontal buoyancy gradient; *Ri* is a Richardson number; and vertical average is calculated for the 100 – 2000 m depth range.

Time Series of Horizontal-Mean Potential Temperature Relative to Initial Conditions (^oC)



Zonal-Mean Distributions Based on Data from Argo and ECCO2

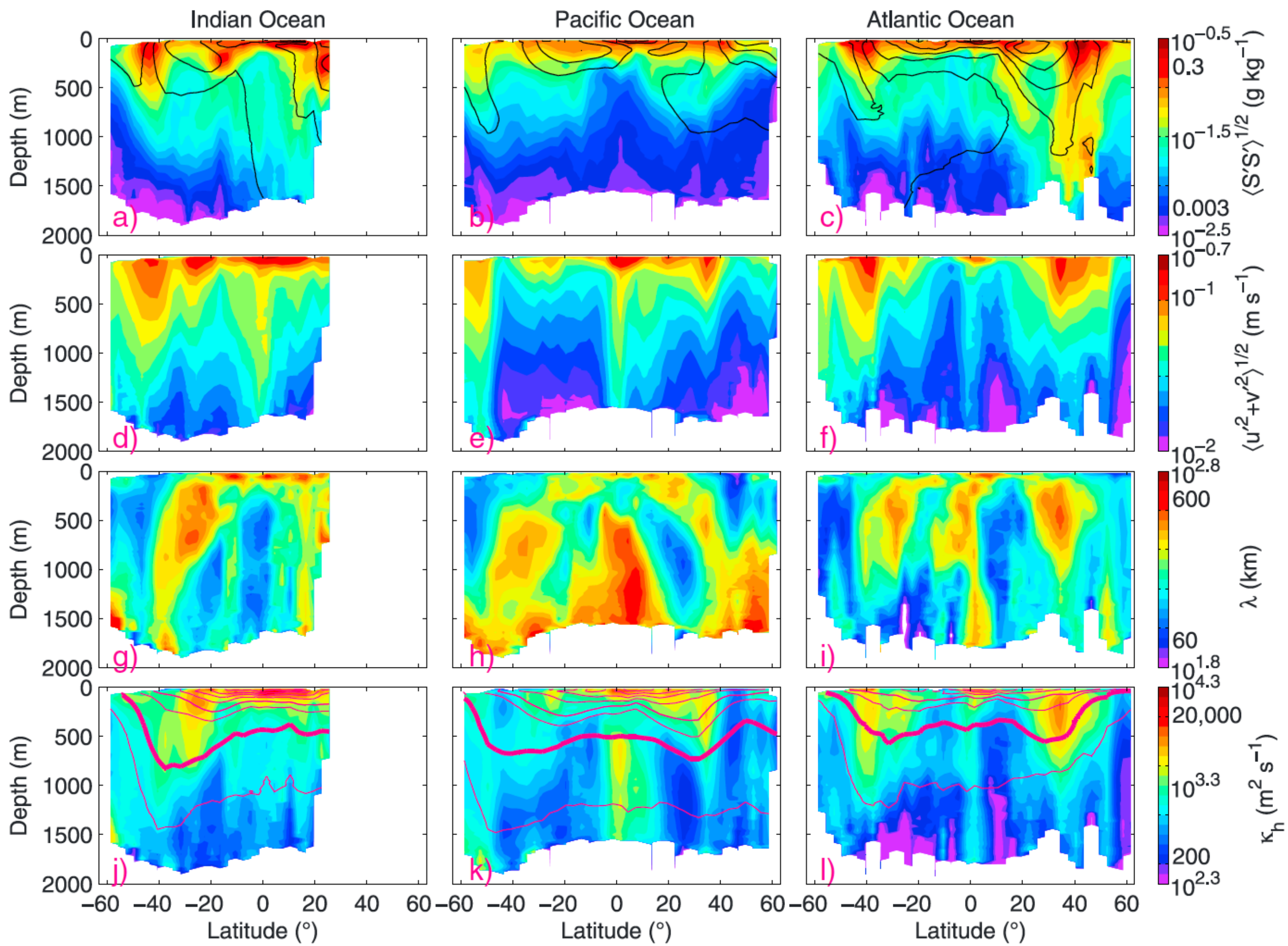


Figure 4. Zonally averaged (a–c) salinity standard deviation with average salinity (black contours), (d–f) ECCO2 velocity fluctuations, (g–i) mixing length, and (j–l) horizontal diffusivity with average density (magenta contours; 27.0 kg m^{-3} in bold) in the (a, d, g, and j) Indian Ocean, (b, e, h, and k) Pacific Ocean, and (c, f, i, and l) Atlantic Ocean.

Cole et al. (2015)

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL063827

Key Points:
- Salinity anomalies on density surfaces are used to investigate eddy stirring
- Mixing length and horizontal diffusivity are estimated in the upper 2000 m
- Horizontal diffusivity varies by more than two orders of magnitude

Correspondence to:
S. T. Cole,
scole@whoi.edu

Citation:
Cole, S. T., C. Wortham, E. Kunze, and W. B. Owens (2015), Eddy stirring and horizontal diffusivity from Argo float observations: Geographic and depth variability, *Geophys. Res. Lett.*, *42*, doi:10.1002/2015GL063827.

Eddy stirring and horizontal diffusivity from Argo float observations: Geographic and depth variability

Sylvia T. Cole[1], Cimarron Wortham[2], Eric Kunze[3], and W. Brechner Owens[1]

[1]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA, [2]Applied Physics Laboratory, University of Washington, Seattle, Washington, USA, [3]Northwest Research Associates, Redmond, Washington, USA

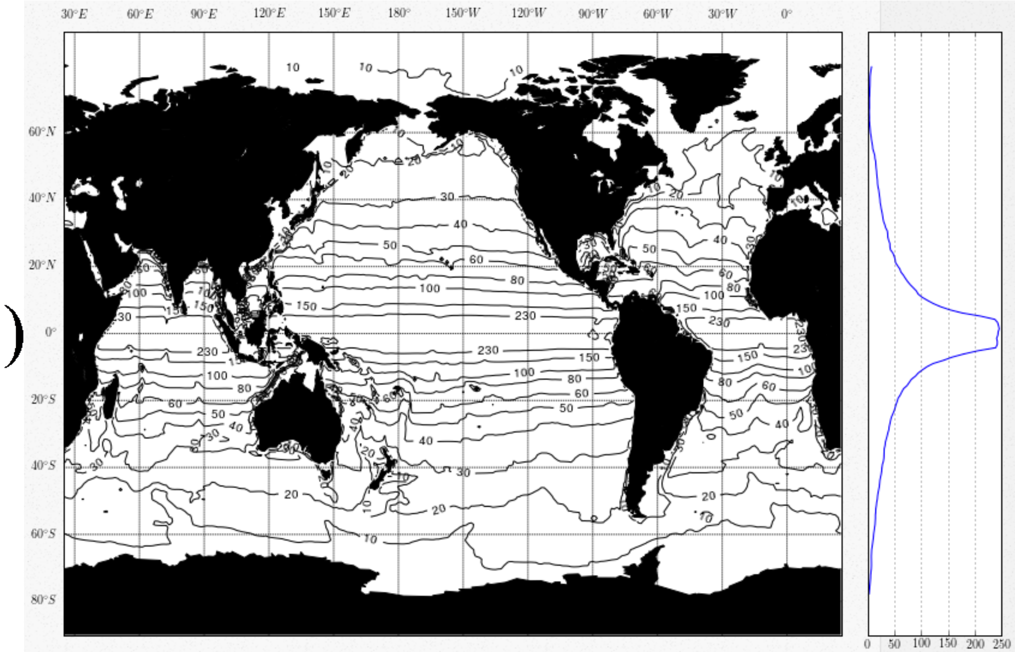
Abstract Stirring along isopycnals is a significant factor in determining the distribution of tracers within the ocean. Salinity anomalies on density surfaces from Argo float profiles are used to investigate horizontal stirring and estimate eddy mixing lengths. Eddy mixing length and velocity fluctuations from the ECCO2 global state estimate are used to estimate horizontal diffusivity at a 300 km scale in the upper 2000 m with near-global coverage. Diffusivity varies by over two orders of magnitude with latitude, longitude, and depth. In all basins, diffusivity is elevated in zonal bands corresponding to strong current regions, including western boundary current extension regions, the Antarctic Circumpolar Current, and equatorial current systems. The estimated mixing lengths and diffusivities provide an observationally based data set that can be used to test and constrain predictions and parameterizations of eddy stirring.

$$\lambda = \langle S'S' \rangle^{\frac{1}{2}} / \langle \, | \nabla \{ S \} | \, \rangle$$

$$\kappa_h = c_0 \lambda u_{rms}$$

Eddy Length Scale

$$L_{eddy} = \min(L_R, L_{\mathrm{Req}})$$



km

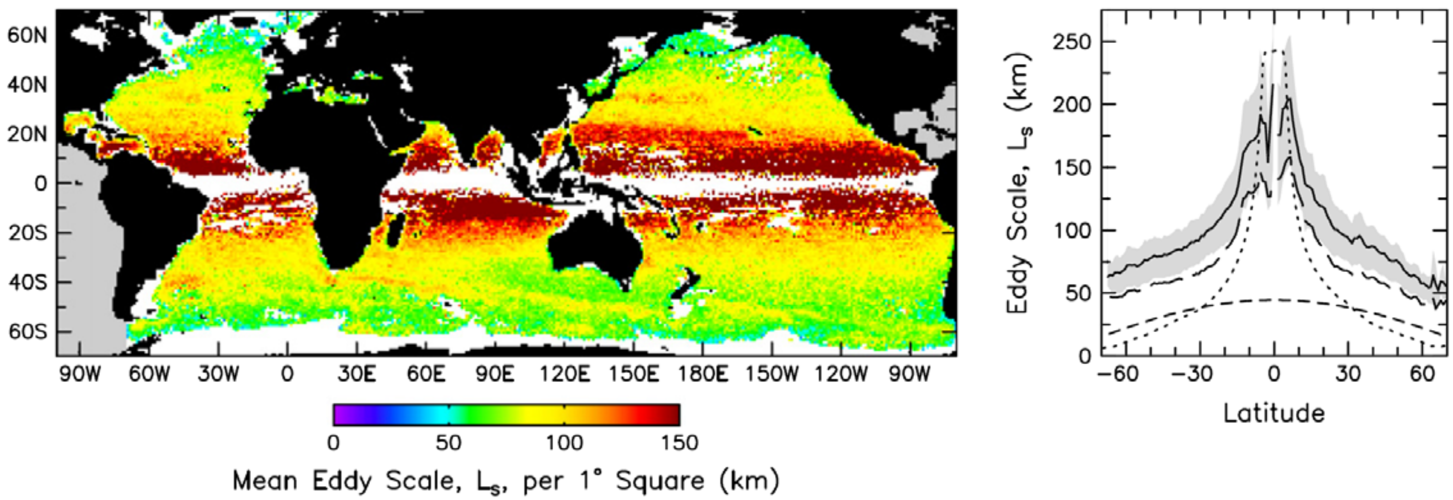


Fig. 12. Map of the average speed-based radius scale L_s for eddies with lifetimes $\geqslant$16 weeks (left) for each 1° × 1° region. The right panel shows meridional profiles of the average (solid line) and the interquartile range of the distribution of L_s (gray shading) in 1° latitude bins. The long dashed line is the meridional profile of the average of the e-folding scale L_e of a Gaussian approximation of each eddy (see Appendix B.3). The short dashed line represents the 0.4° feature resolution limitation of the SSH fields of the AVISO Reference Series for the zonal direction (see Appendix A.3) and the dotted line is the meridional profile of the average Rossby radius of deformation from Chelton et al. (1998).

Chelton et al. (2011)

Eddy Length Scale

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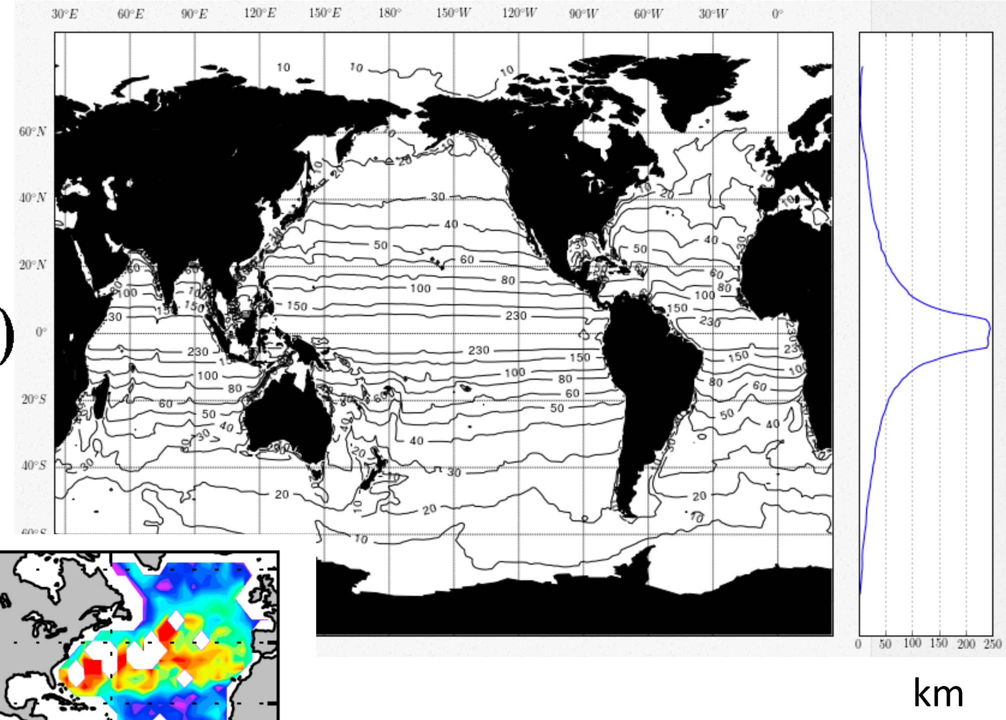
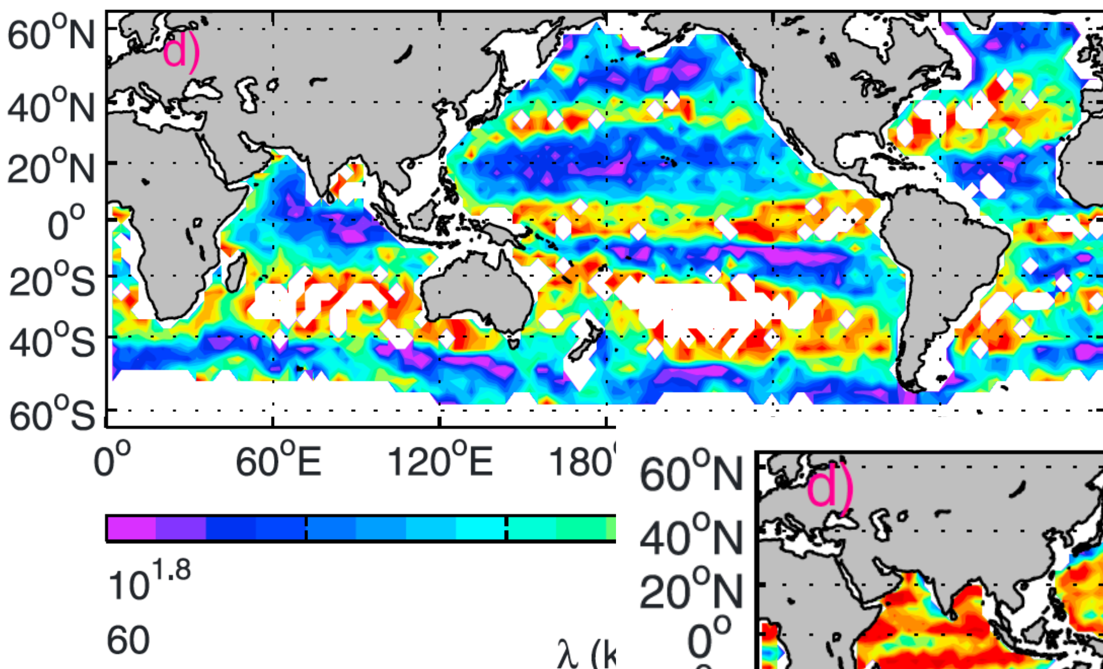
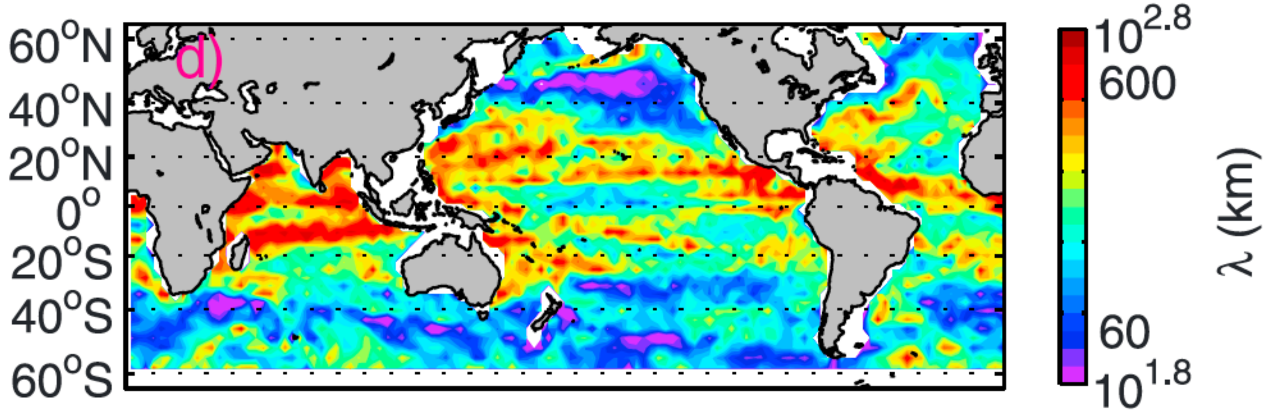


at 27 sigma0 depth



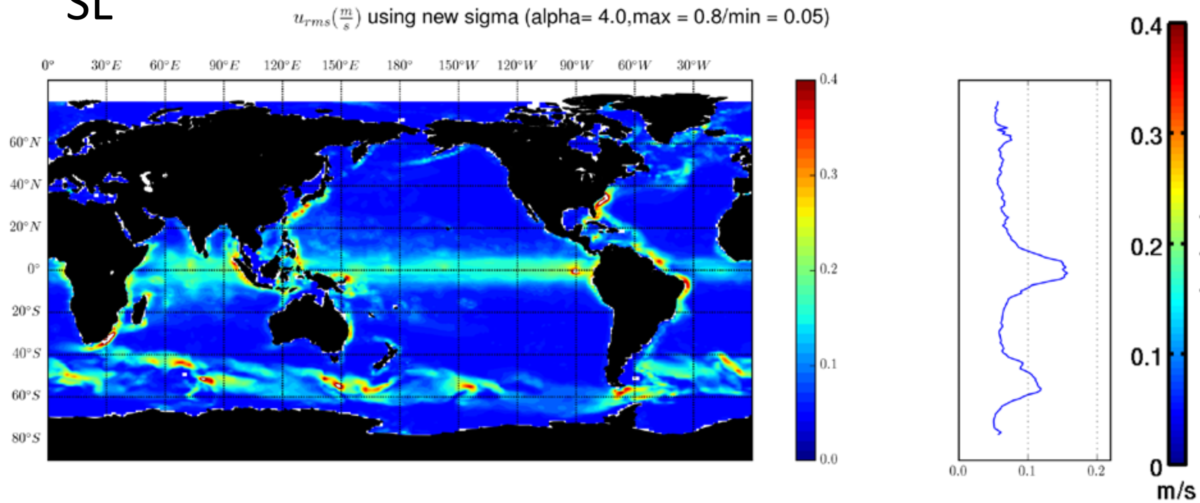
at base of winter mixed layer



Cole et al. (2015)

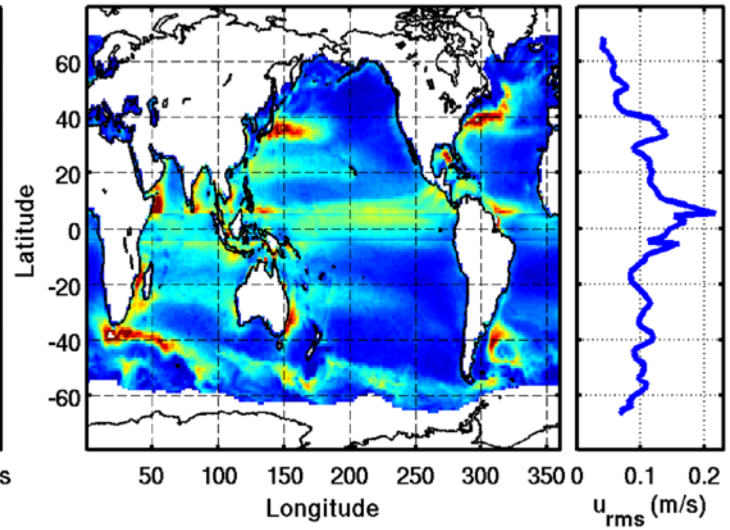
Eddy Velocity u_{rms} at (Near) Surface

SL

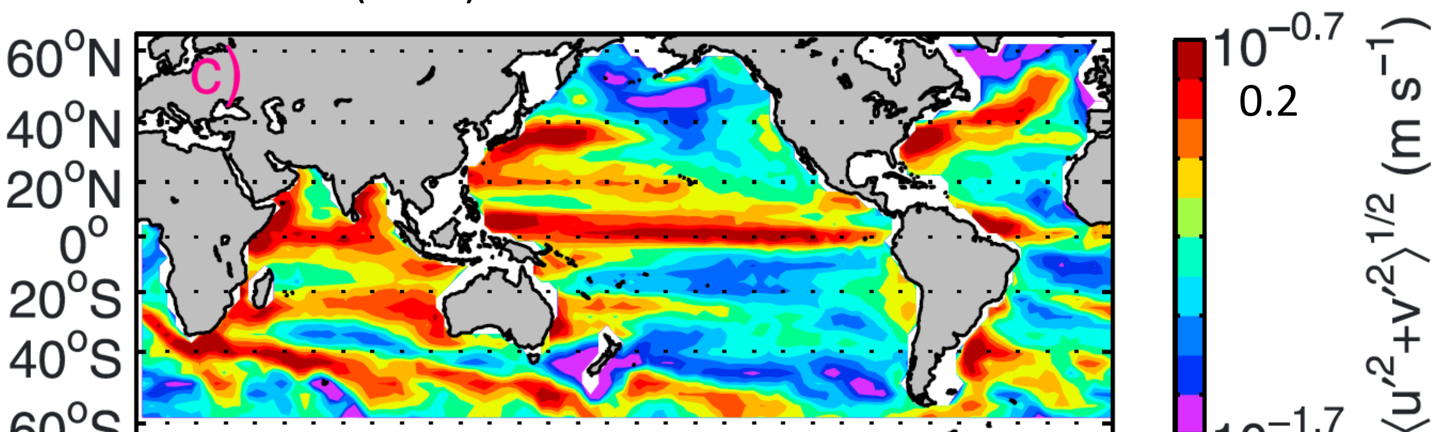


Bates et al. (2014)

Altimeter (AVISO)



Cole et al. (2015)



at base of winter mixed layer

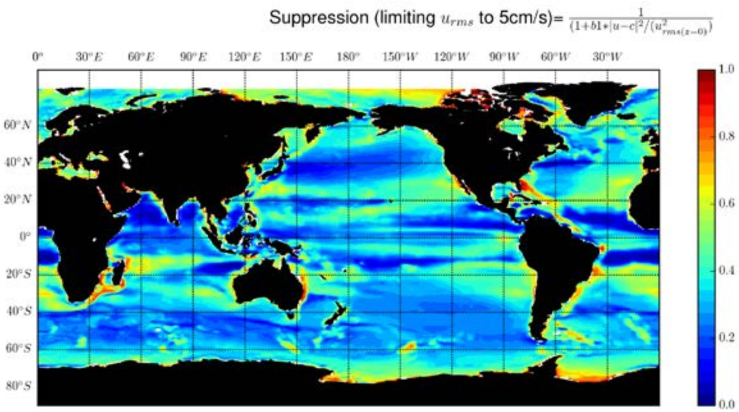
0.02

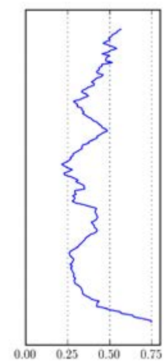
Suppression Factor

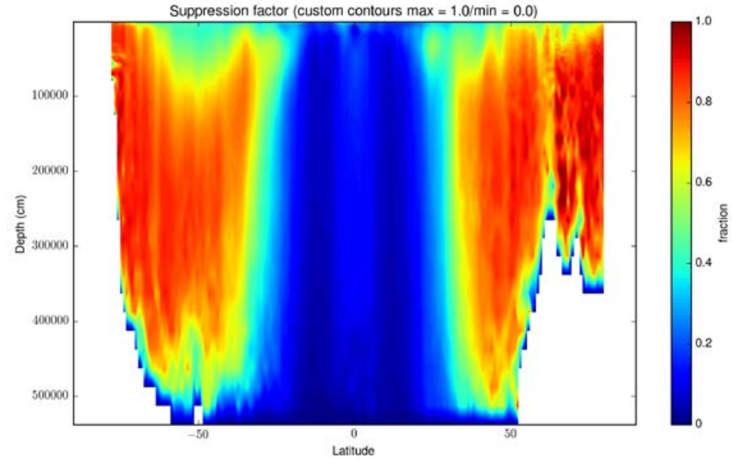
Surface

CESM

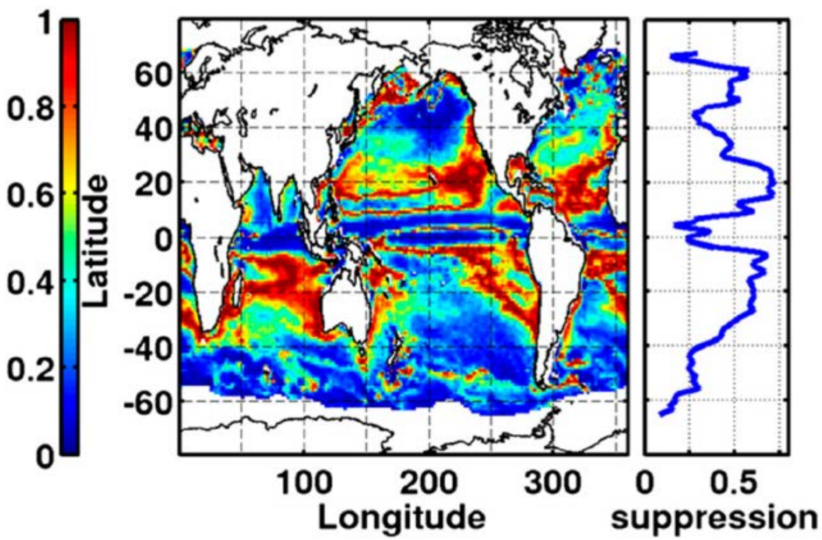
Global Zonal Average

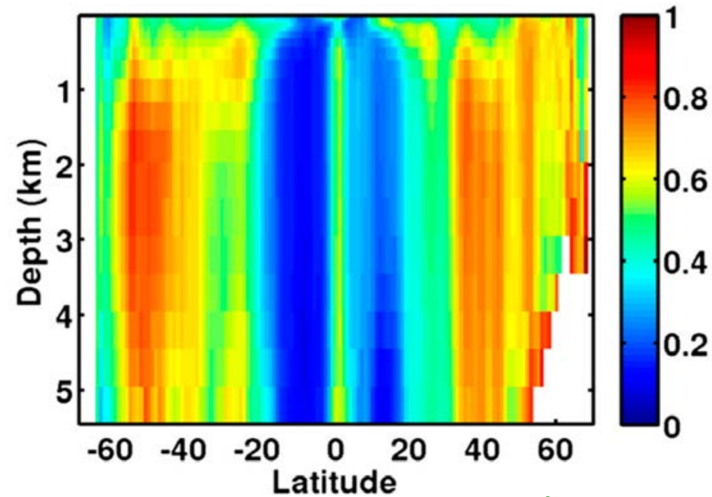






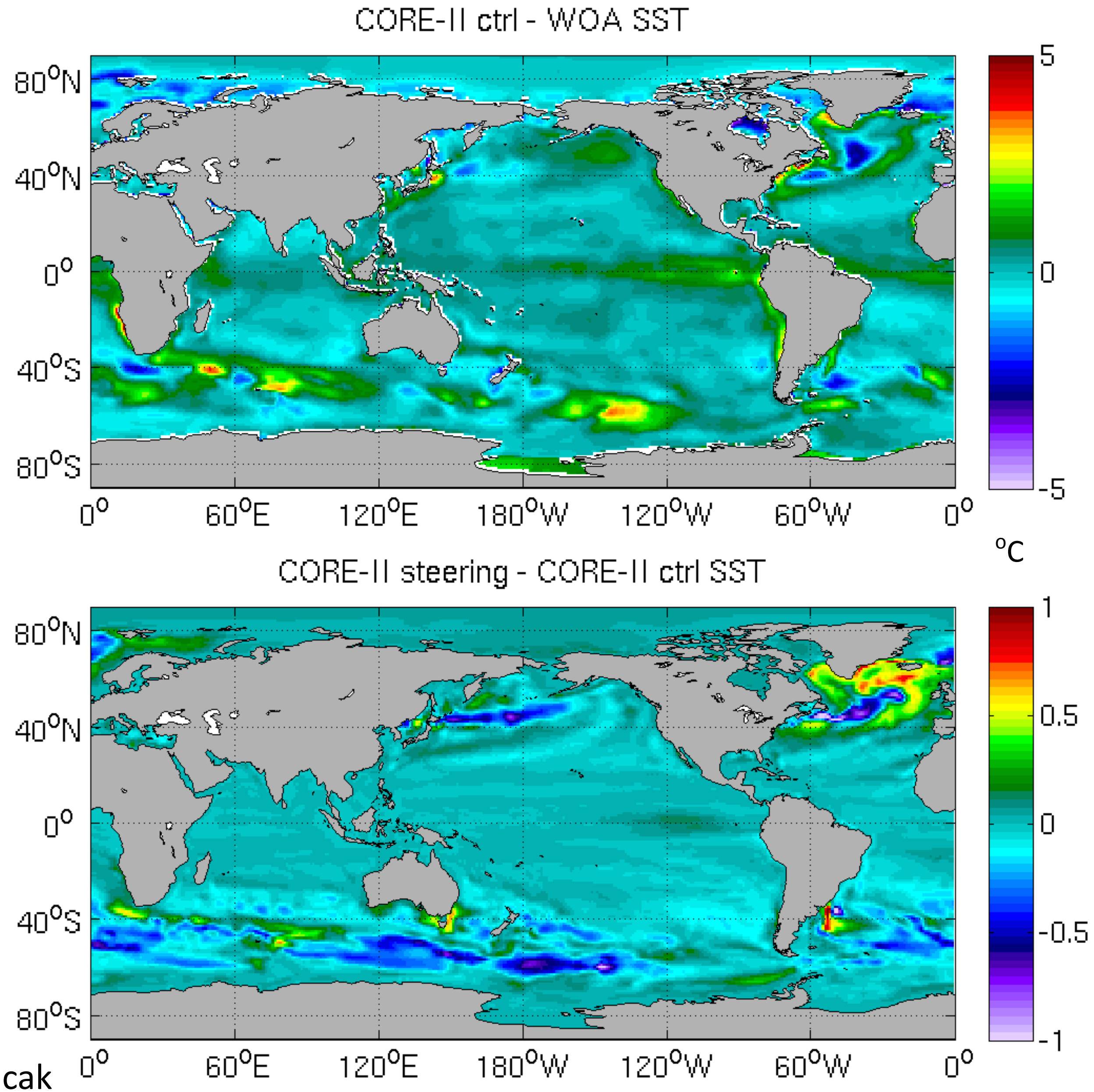
Bates et al. (2014)





Based on ECCO

SSTs from CORE-II Simulations with NorESM



From Mehmet Ilicak

Eddy Length Scale

Bates et al. (2014)

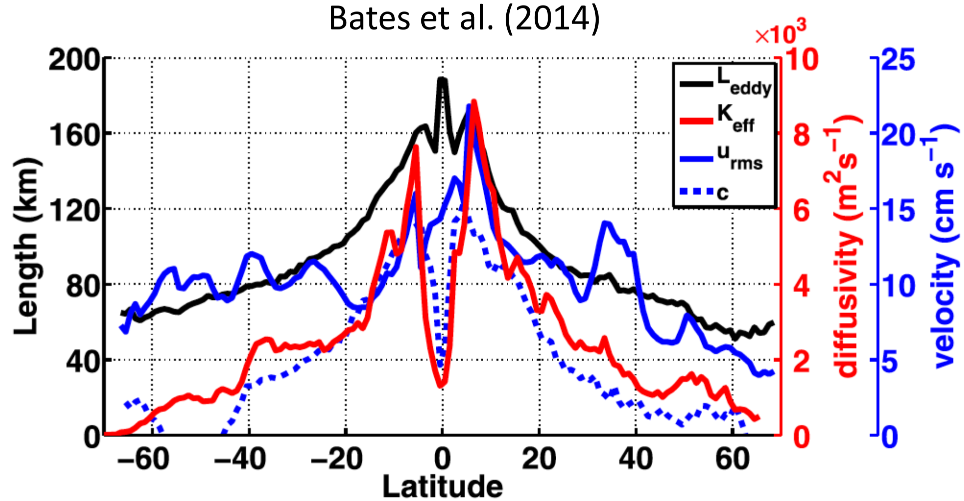
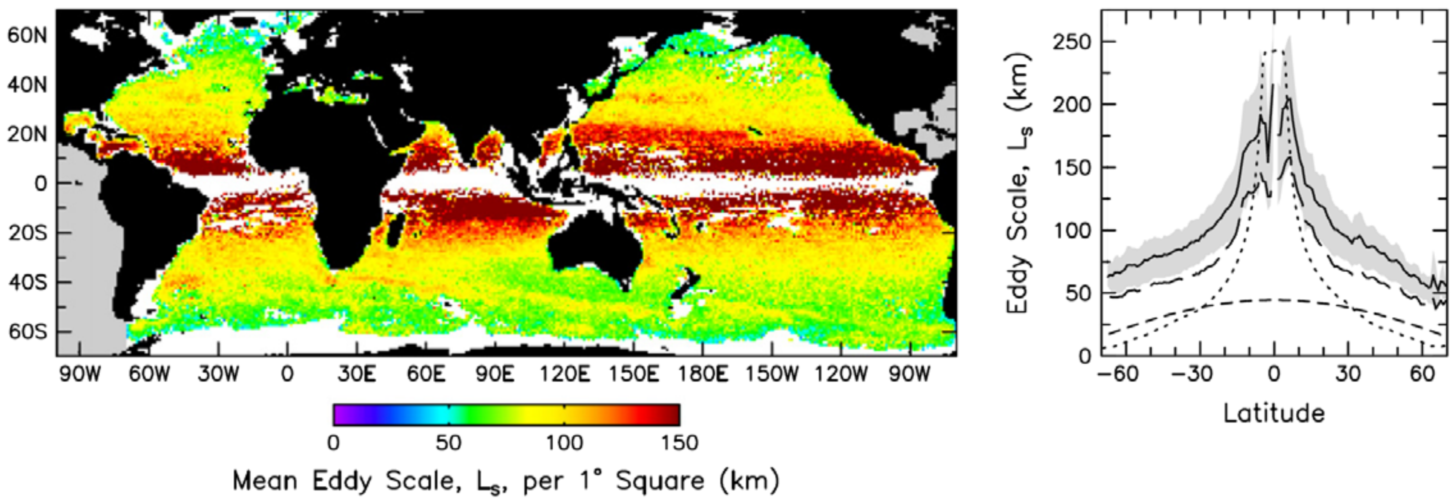


FIG. 3. The zonally averaged diffusivity K_{eff} of Abernathey and Marshall (2013, red), the zonally averaged eddy diameter L_{eddy} (solid black) of Chelton et al. (2011), the AVISO rms velocity u_{rms} (solid blue), and the Hughes westward zonal eddy phase speed c (i.e., westward is positive; dashed blue). The color of the curves corresponds to the color of the vertical axis (black corresponds to length, red corresponds to diffusivity, and blue corresponds to velocity).



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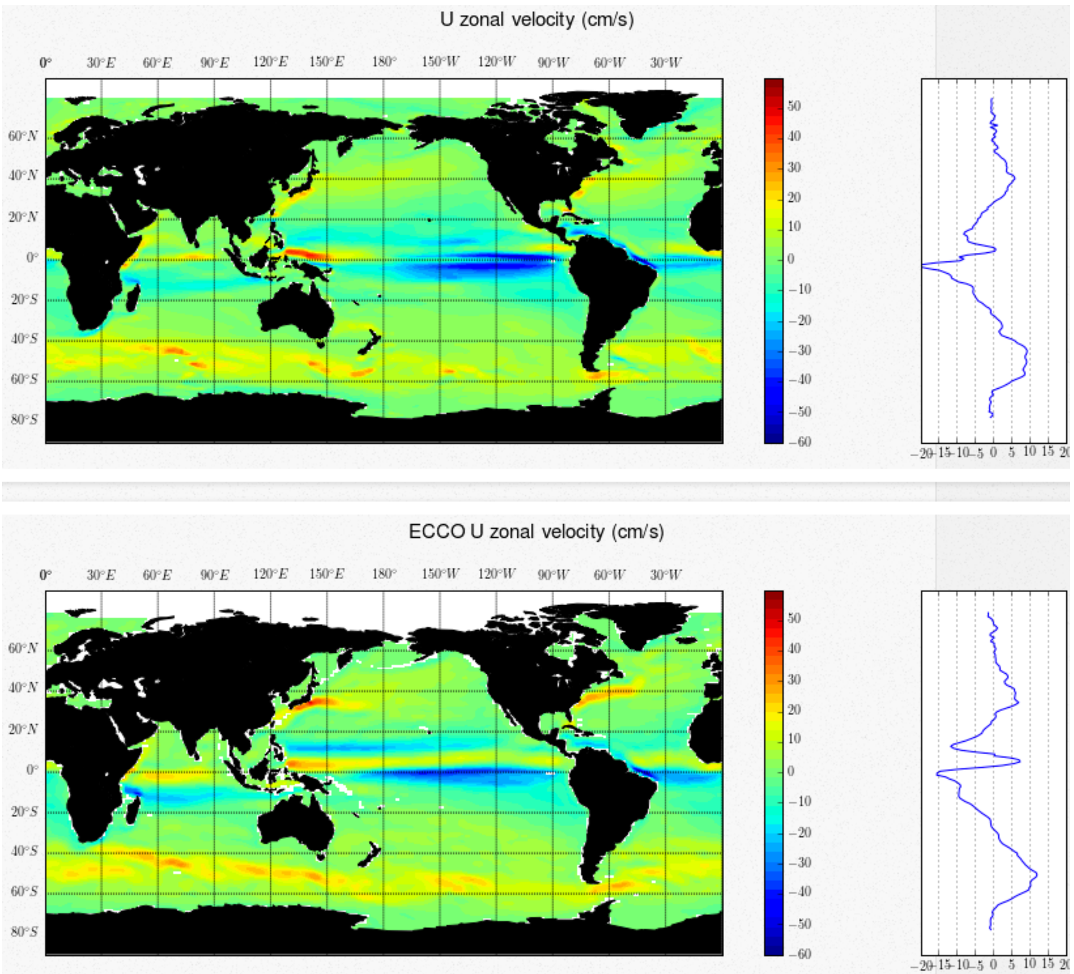
Chelton et al. (2011)

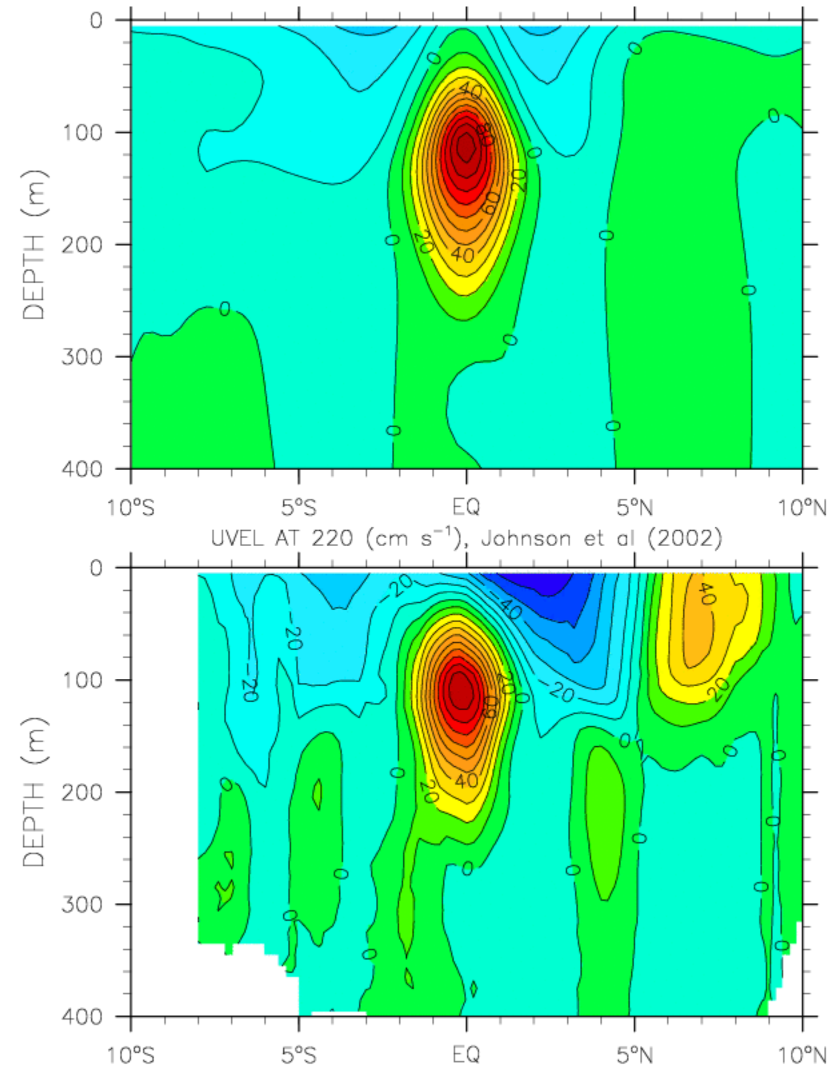
Zonal Mean Flow

Surface

top panels: CESM

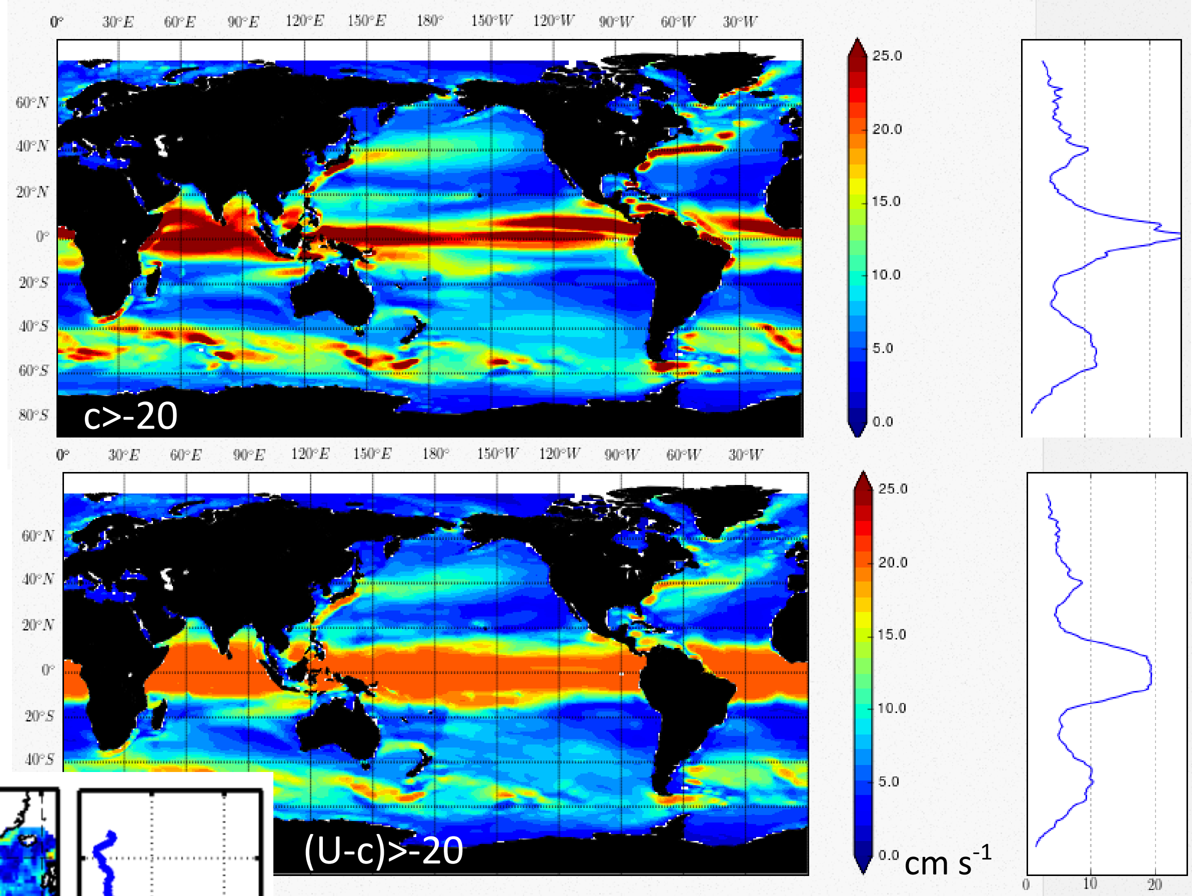
at 220^{o}E

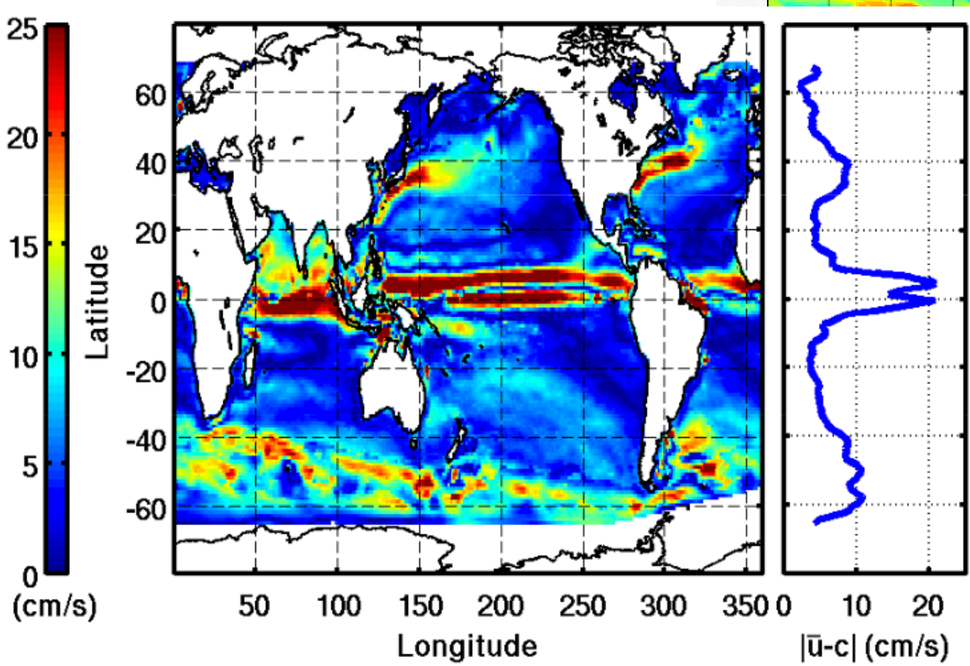




|U-c|

CESM

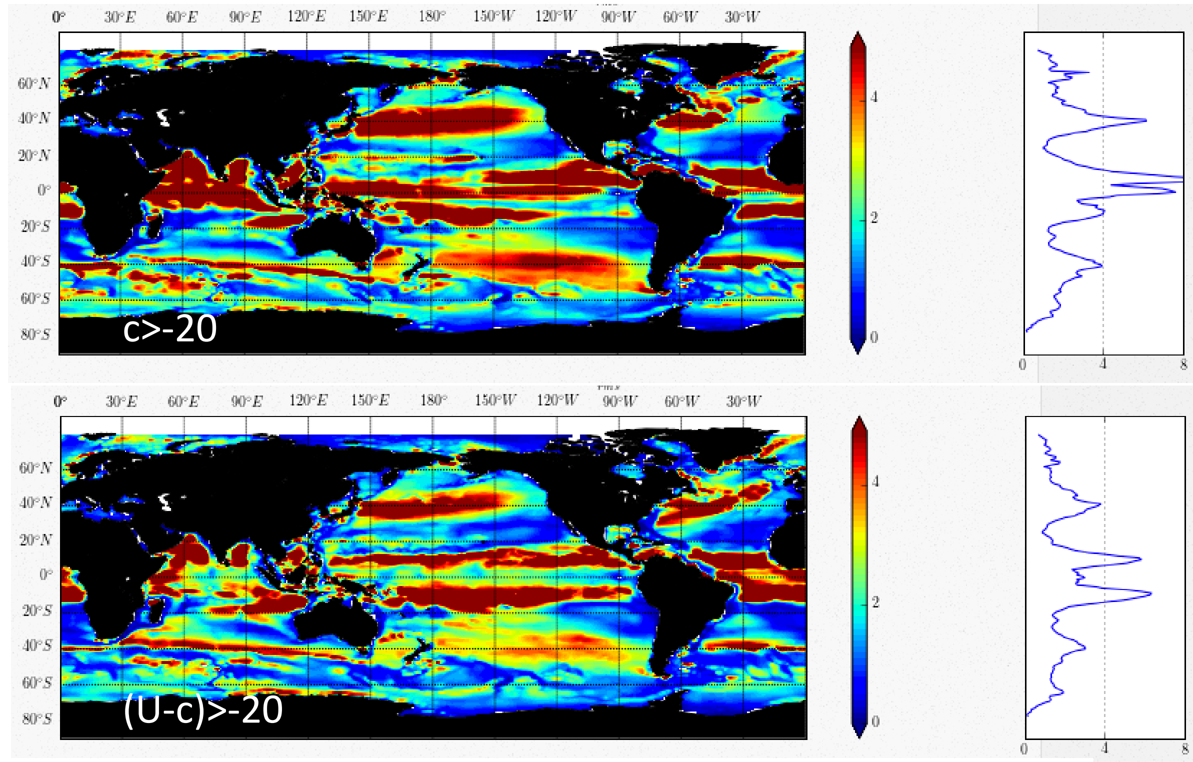


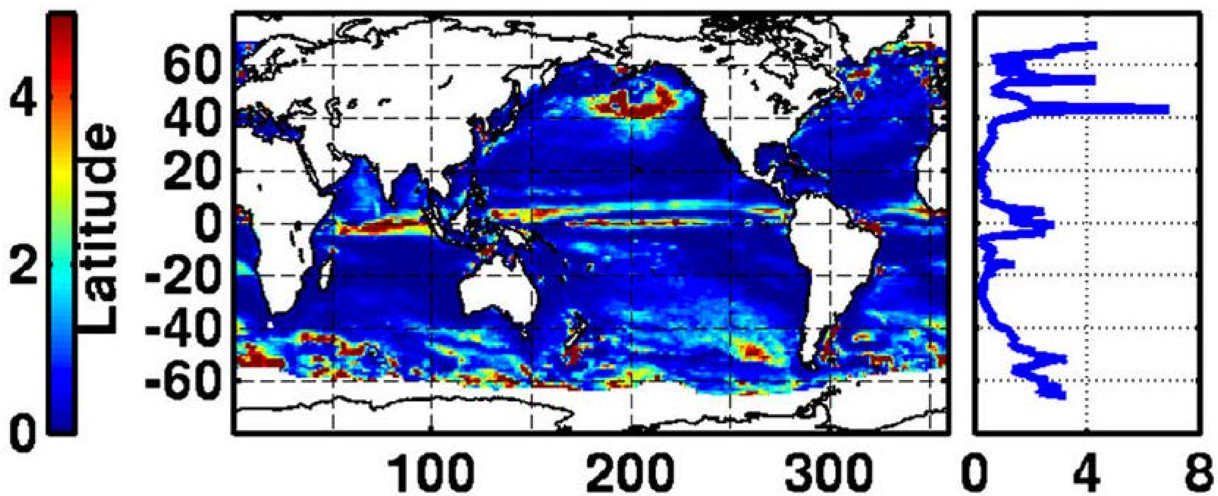


Bates et al. (2014)

$|U-c|^2/(u_{rms})^2$

CESM





Bates et al. (2014)

Mixing Length (and Related) Distributions Based on Data from Argo and ECCO2

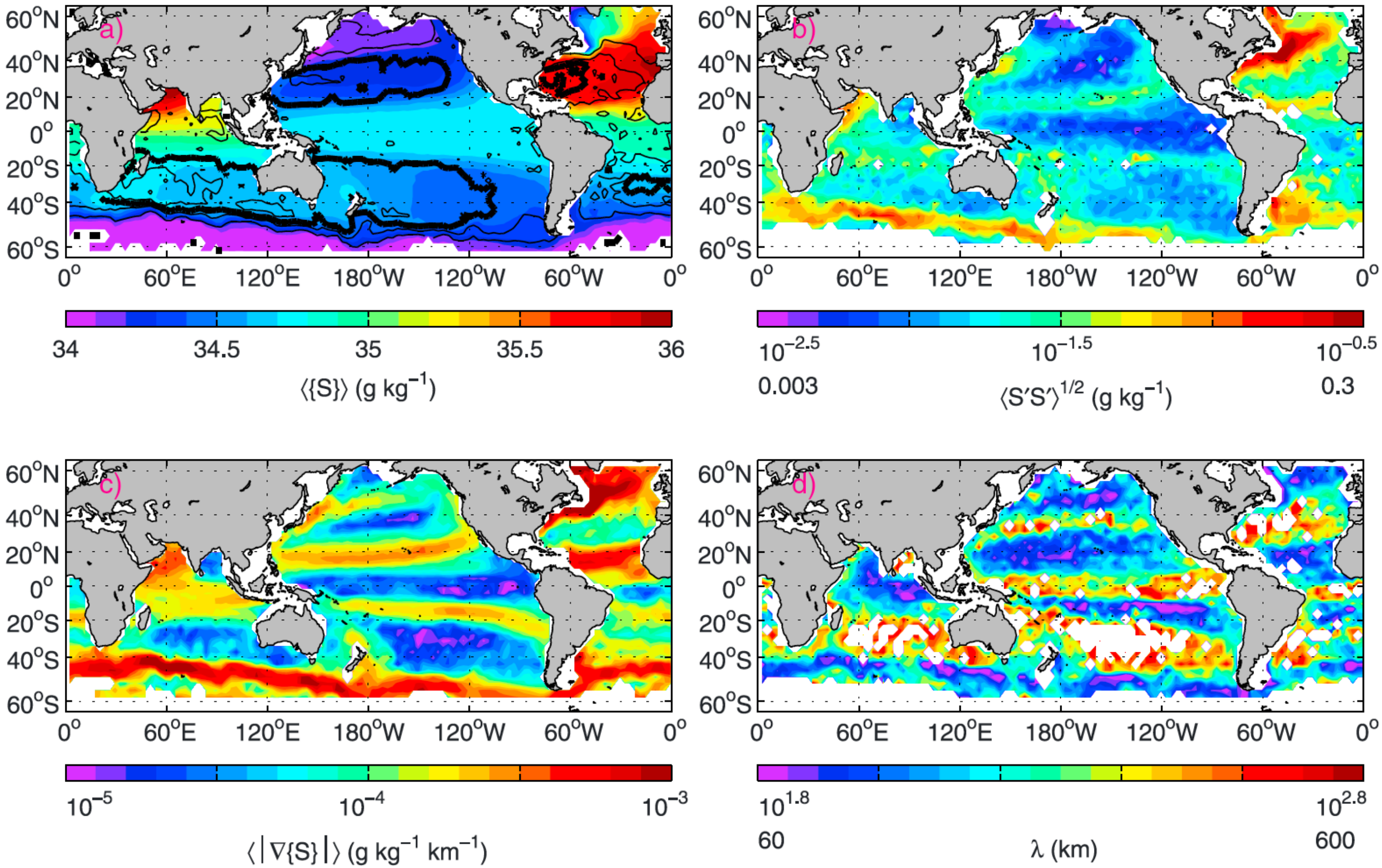
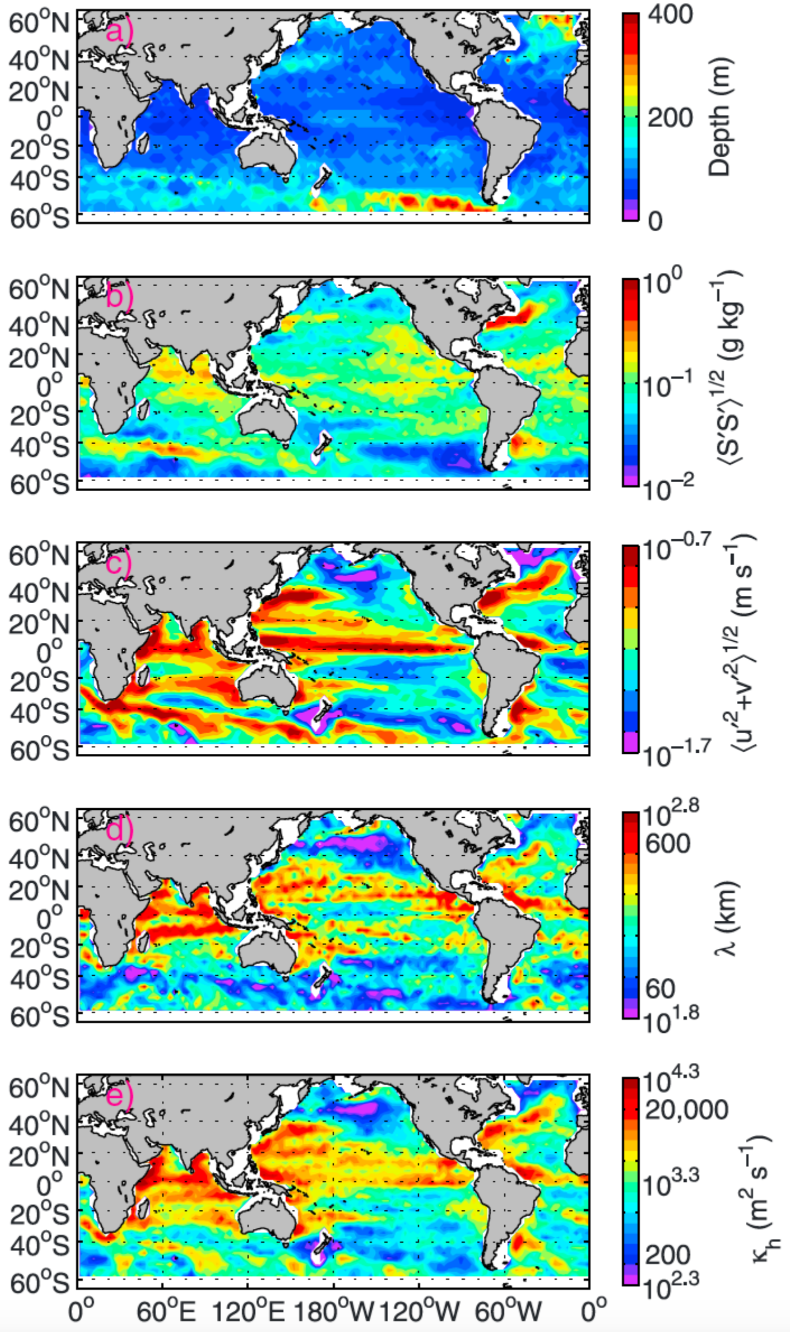


Figure 2. Statistics on the 27.0 kg m^{-3} density surface in 3° × 3° latitude bins of (a) mean salinity with depth contours in 200 m intervals and the 600 m surface in bold, (b) salinity standard deviation, (c) horizontal gradient of mean salinity, and (d) mixing length. Data gaps in Figure 2b correspond to grid boxes with less than 25 observations and in Figure 2d correspond to inferred mixing lengths greater than 600 km.

Cole et al. (2015)

Distributions at the Base of the Winter Mixed Layer



Cole et al. (2015)

Regularization of Tidal Diffusivities

$$k_v = k_{\text{bg}} + \frac{\Gamma \varepsilon}{N^2}$$

- Limit minimum value of N^2, e.g., 10^{-8} s^{-2}
- Limit k_v using $k_v = \min(k_v, k_{max})$, e.g., $k_{max} = 100$ cm^2 s^{-1}
- Limit both
- …

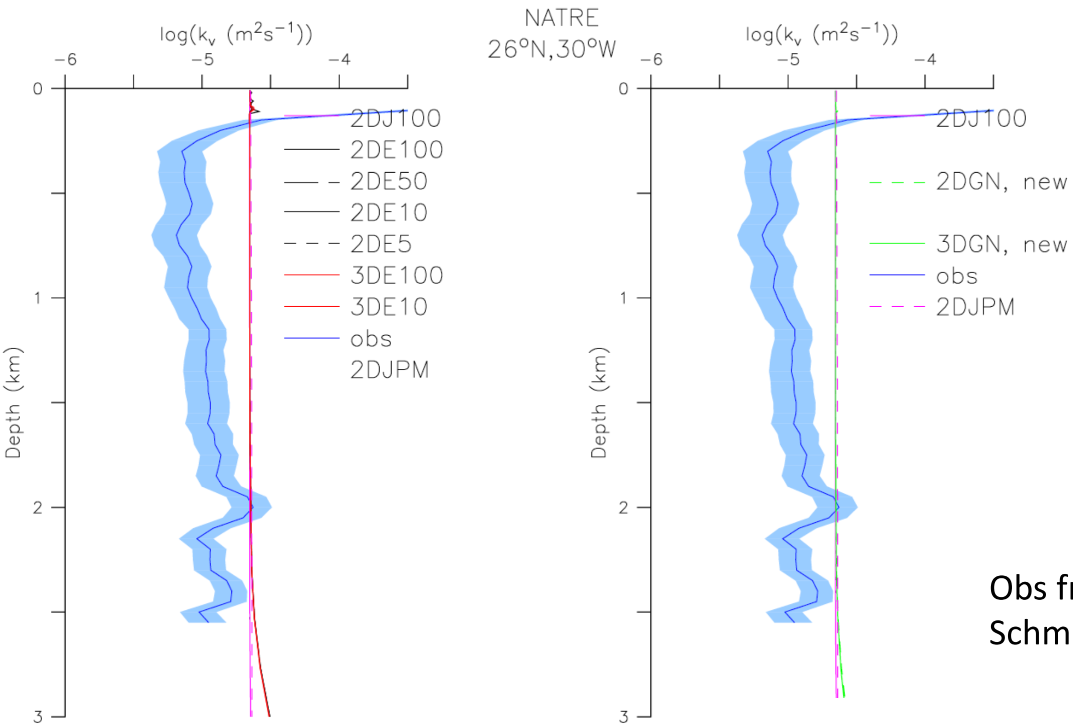
Value of k_{max} has substantial impacts on model solutions with the ER03 dissipation energy field only.

Examples of Experiment Designations

Case name	2D vs. 3D	Energy Field	limit on k_v ($cm^2\ s^{-1}$)
2DJ100	2D	JS01	100
2DE100	2D	ER03	100
3DE100	3D	ER03	100
3DE10	3D	ER03	10
3DGN	3D	GN13	100
...			
Polzin / Melet			
2DJPM	2D	JS01	100
2DGNPM	2D	GN13	100

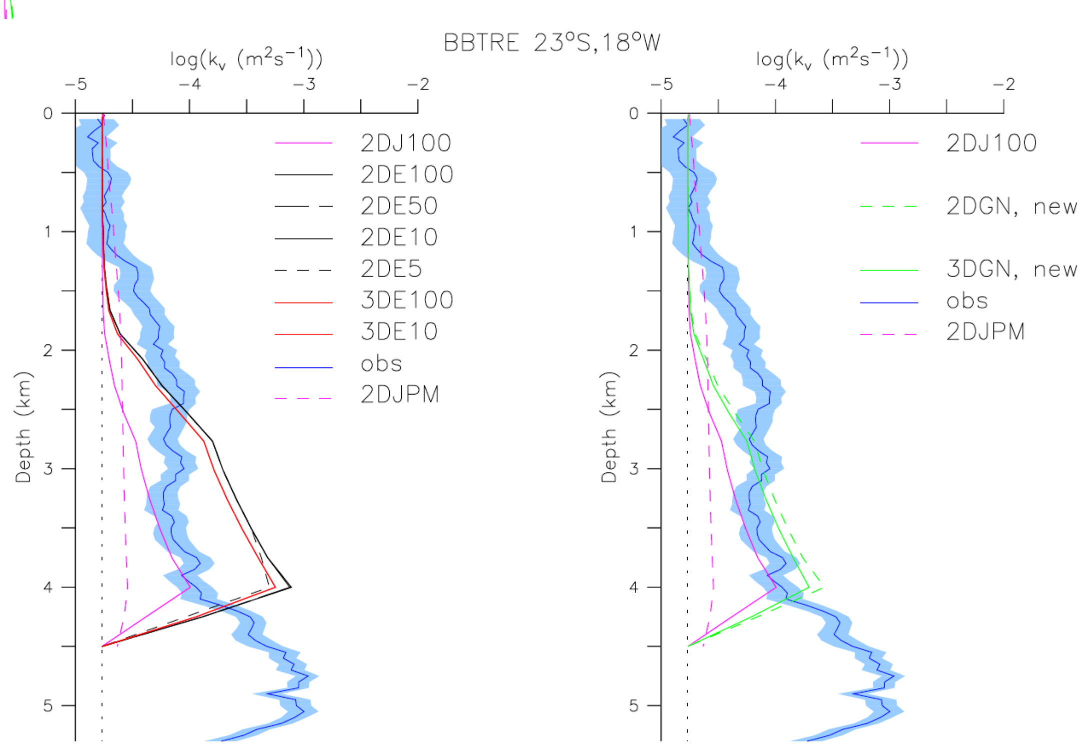
30+ experiments performed

North Atlantic Subtropical Gyre

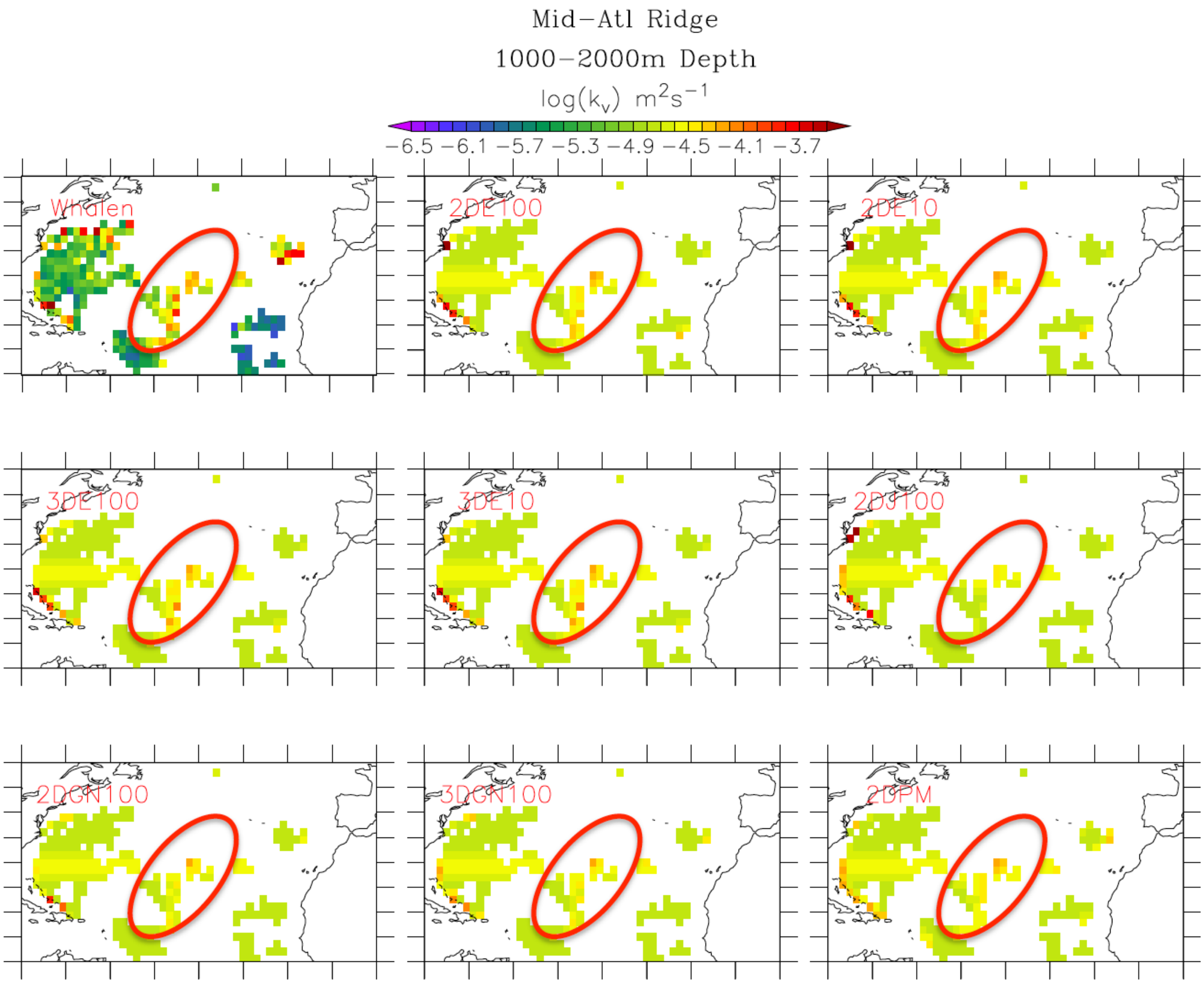


Obs from St. Laurent & Schmitt (1999)

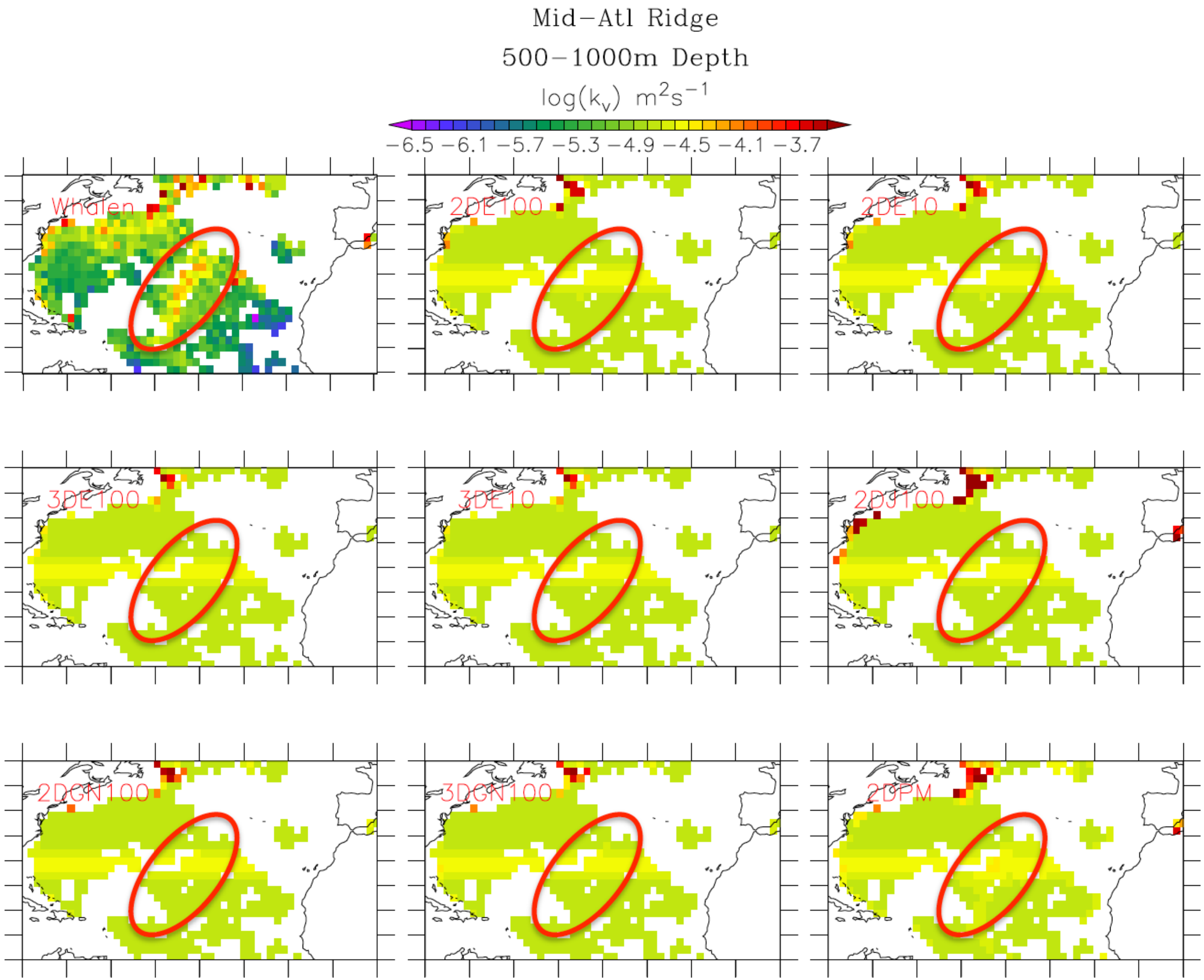
Brasil Basin



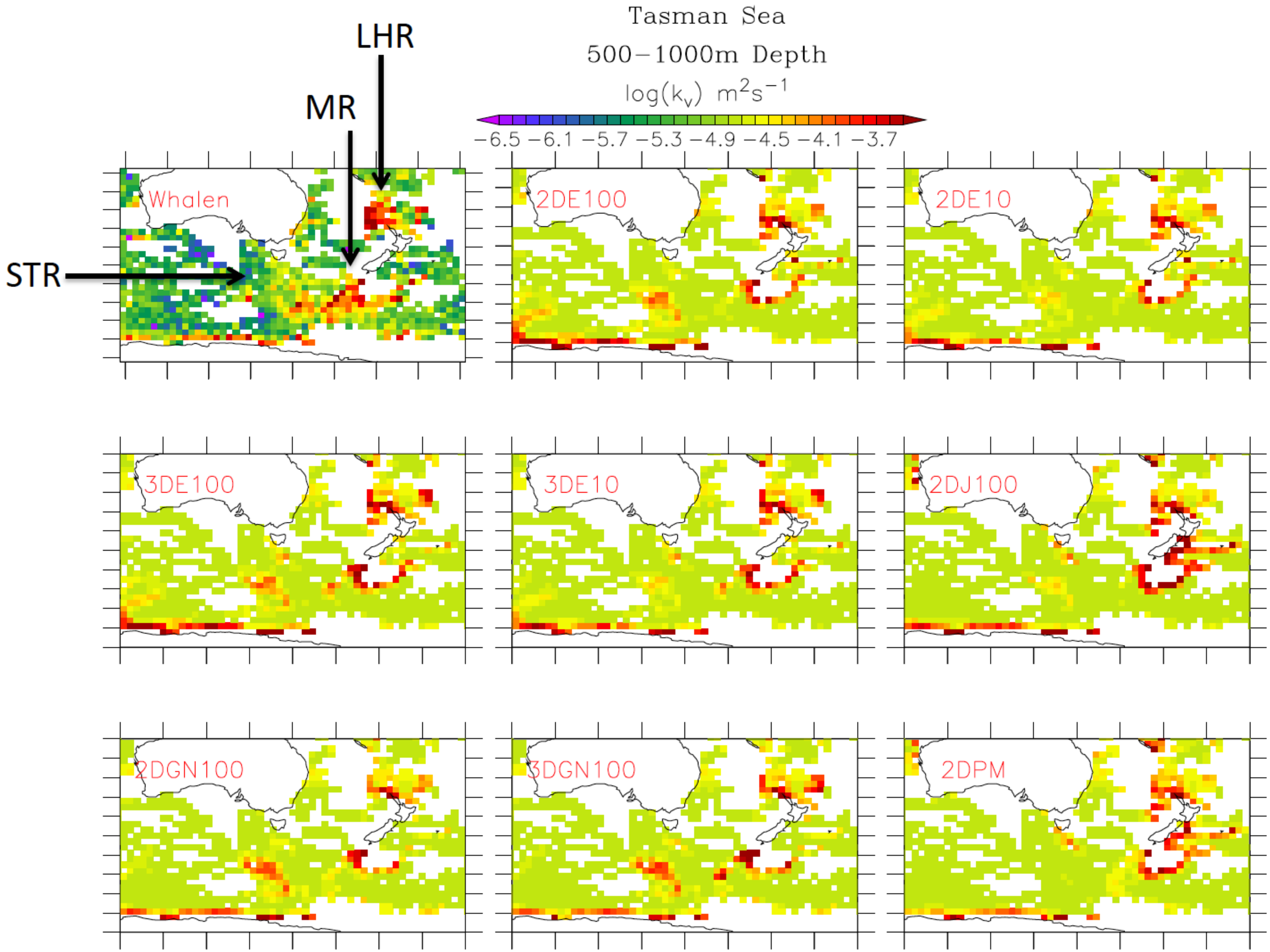
Obs from St. Laurent et al. (2001)



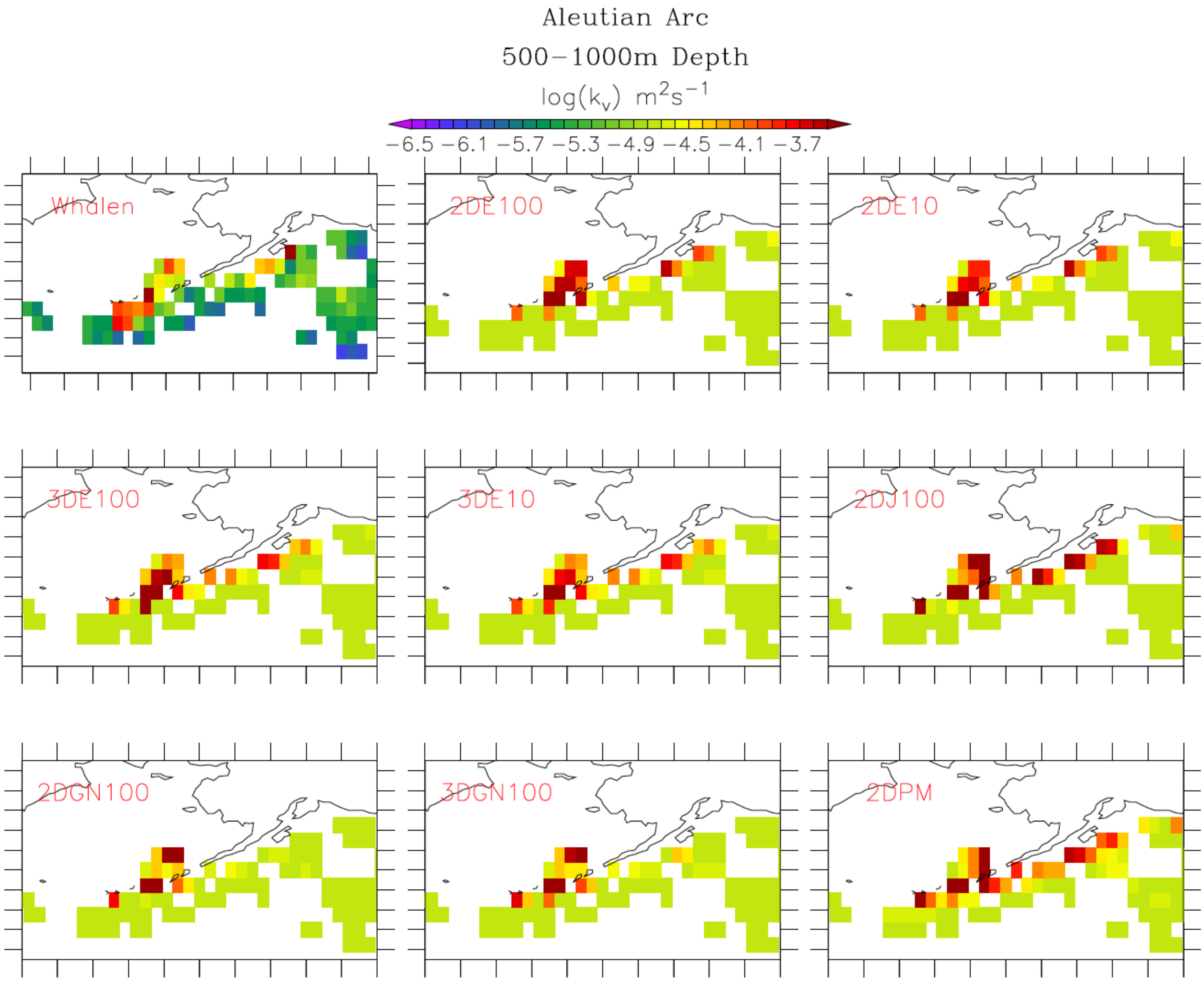
Updated from Whalen et al. (2012)



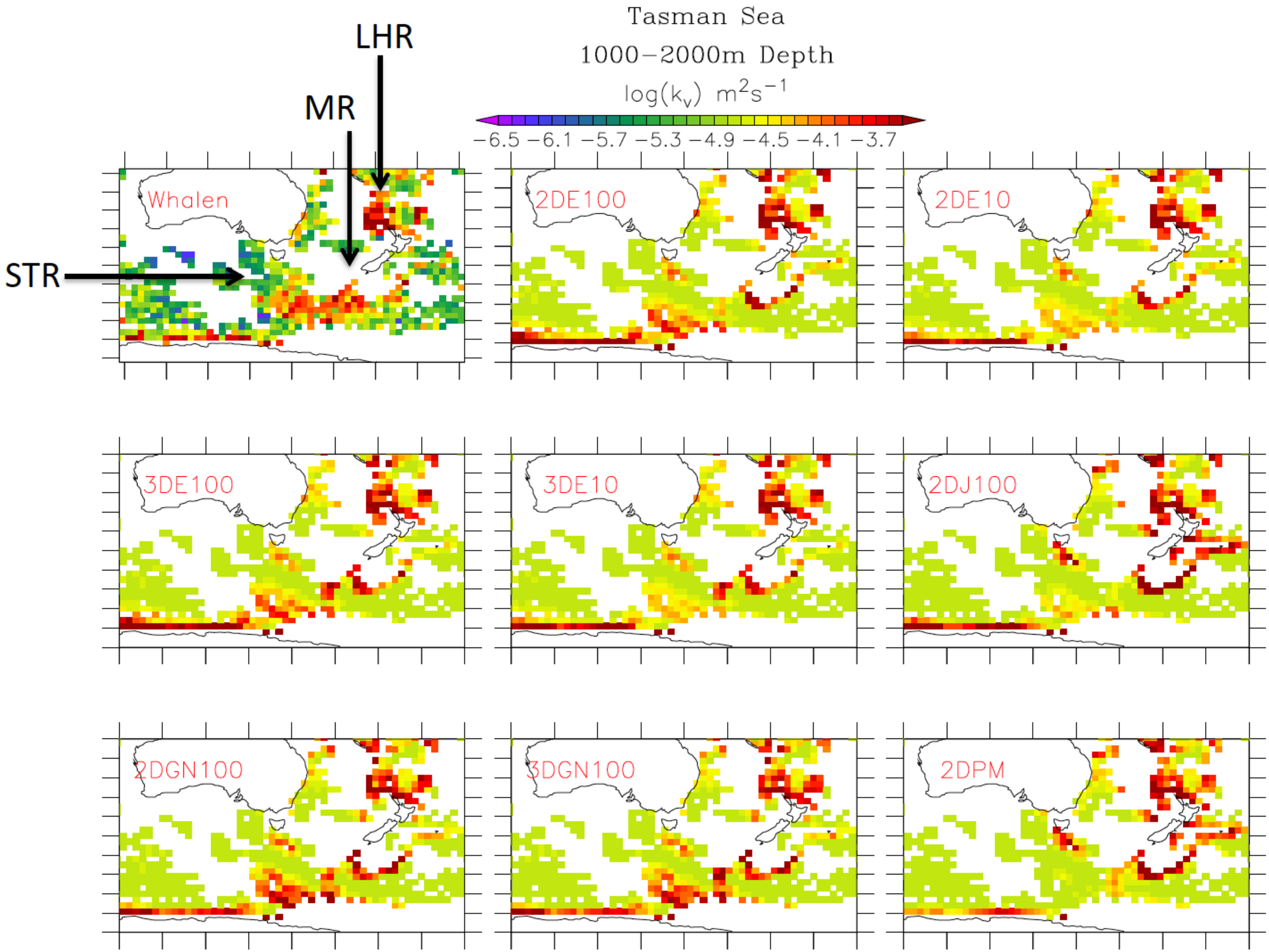
Updated from Whalen et al. (2012)



Updated from Whalen et al. (2012)

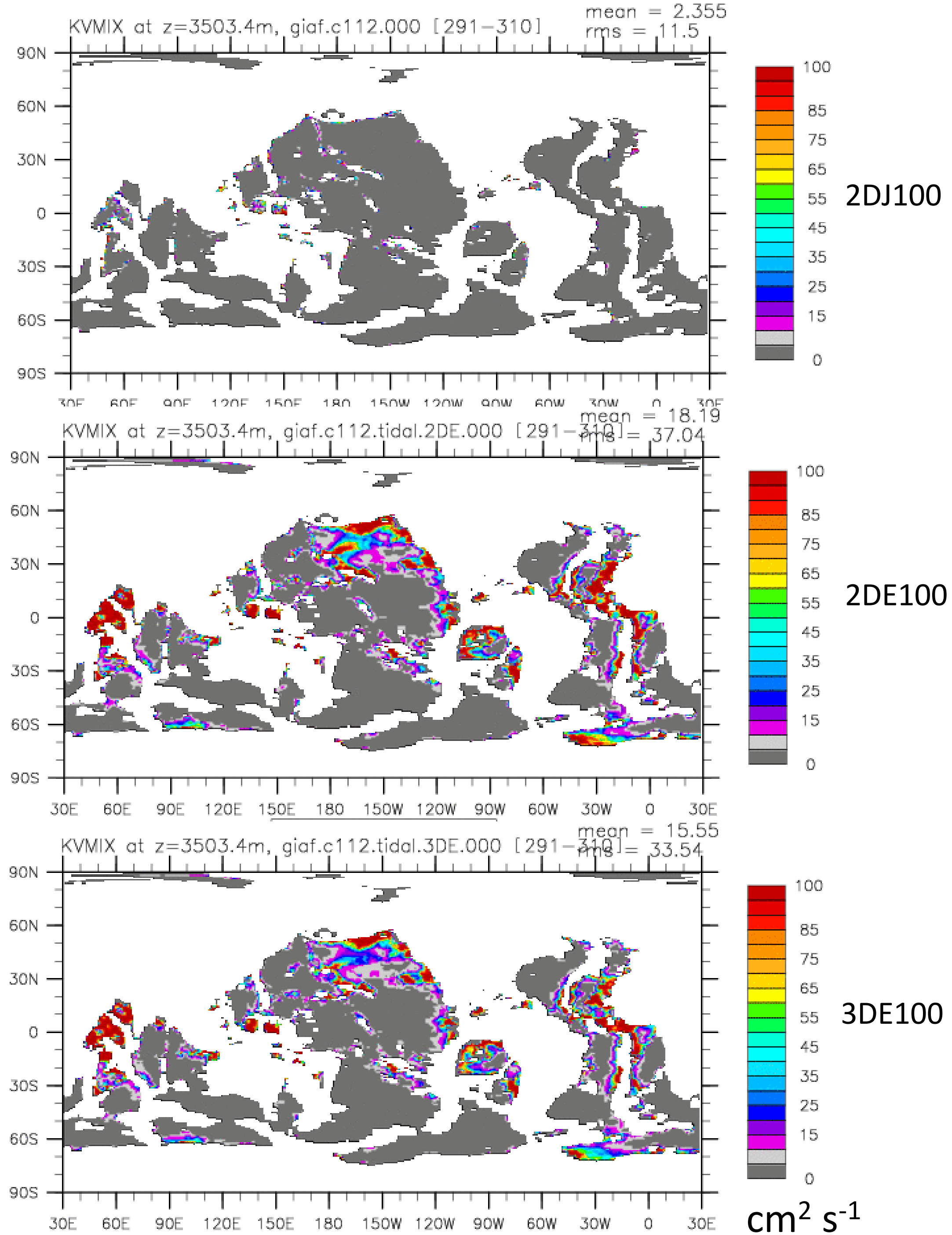


Updated from Whalen et al. (2012)

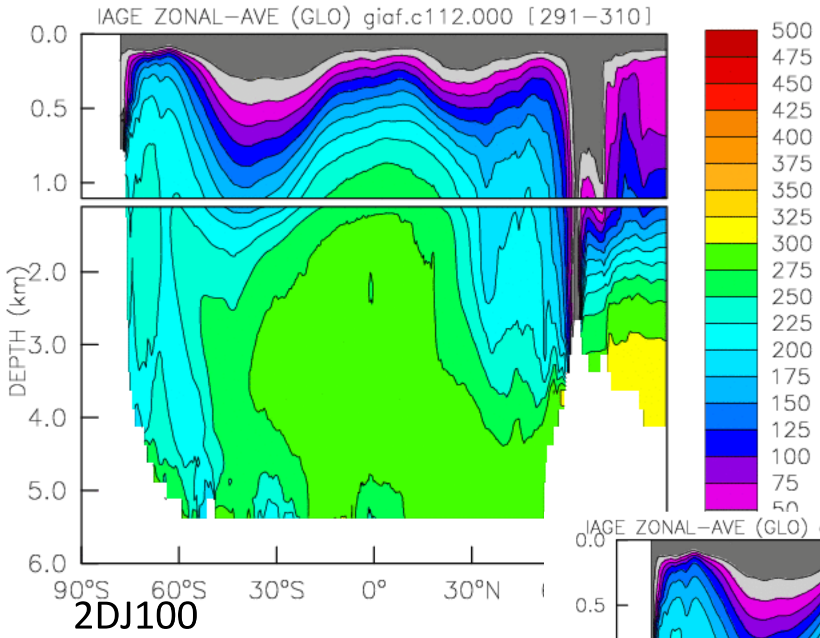


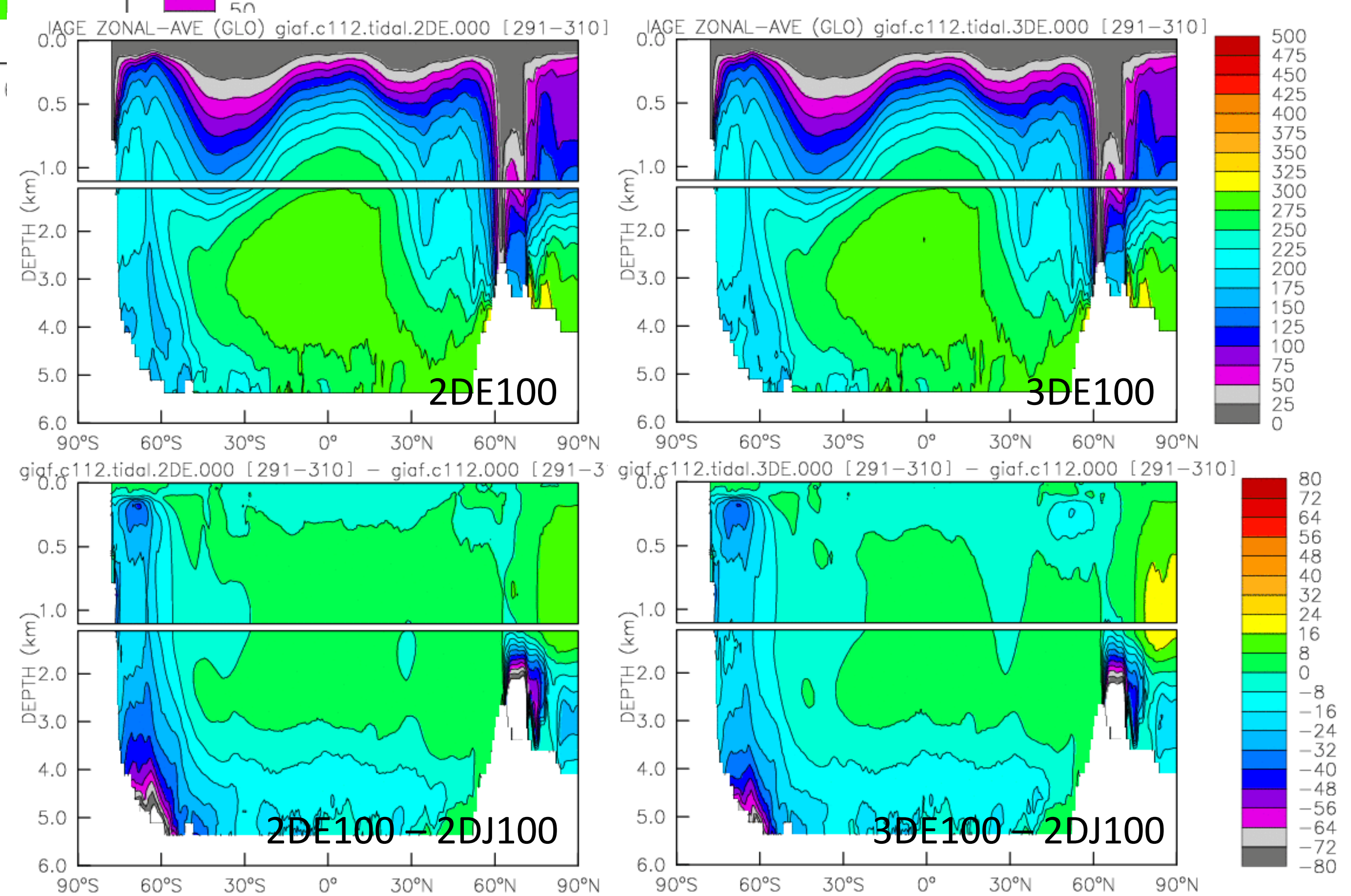
Updated from Whalen et al. (2012)

k_v at 3500 m depth

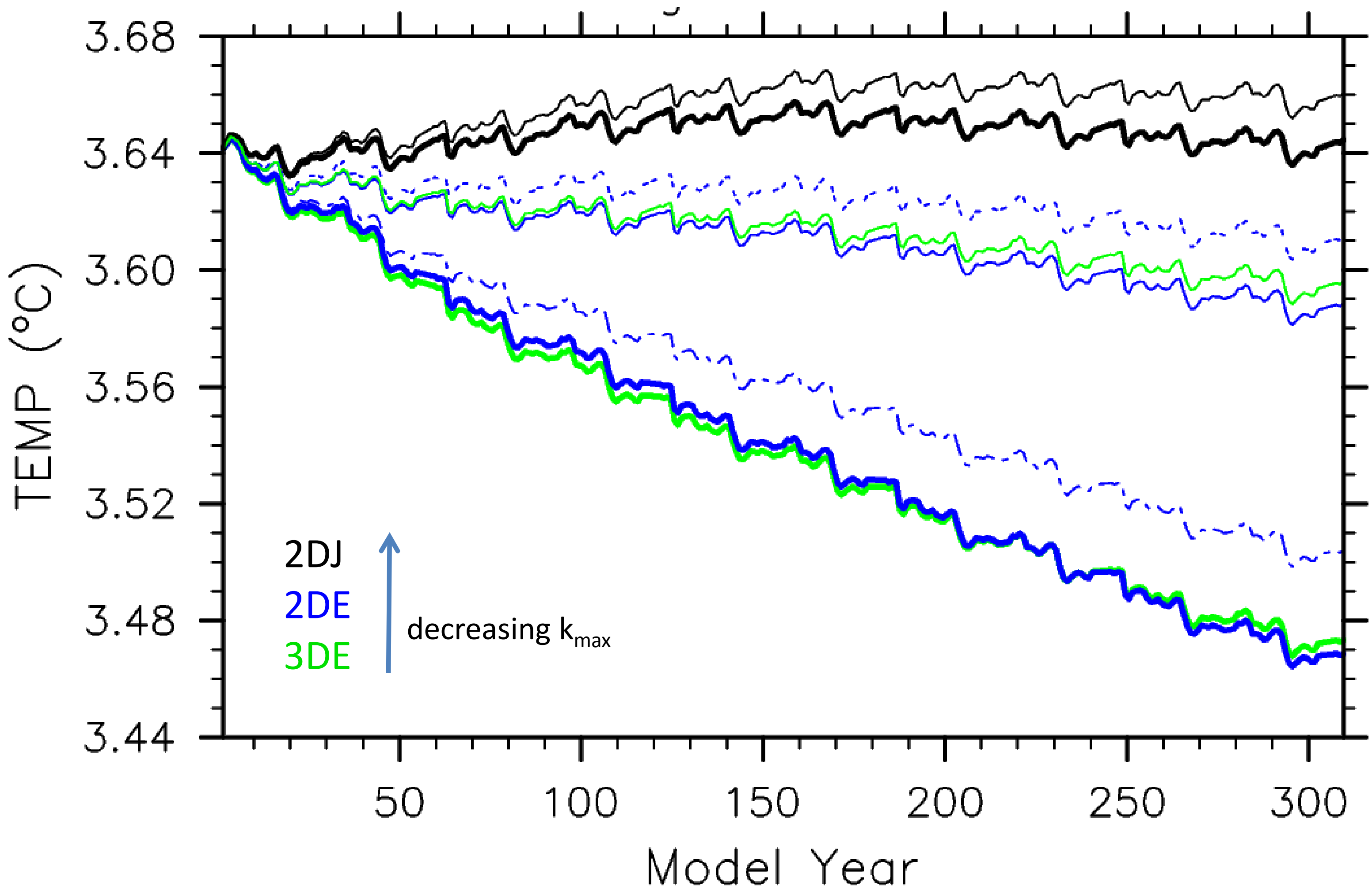


Zonal-Mean Ideal Age (yr)

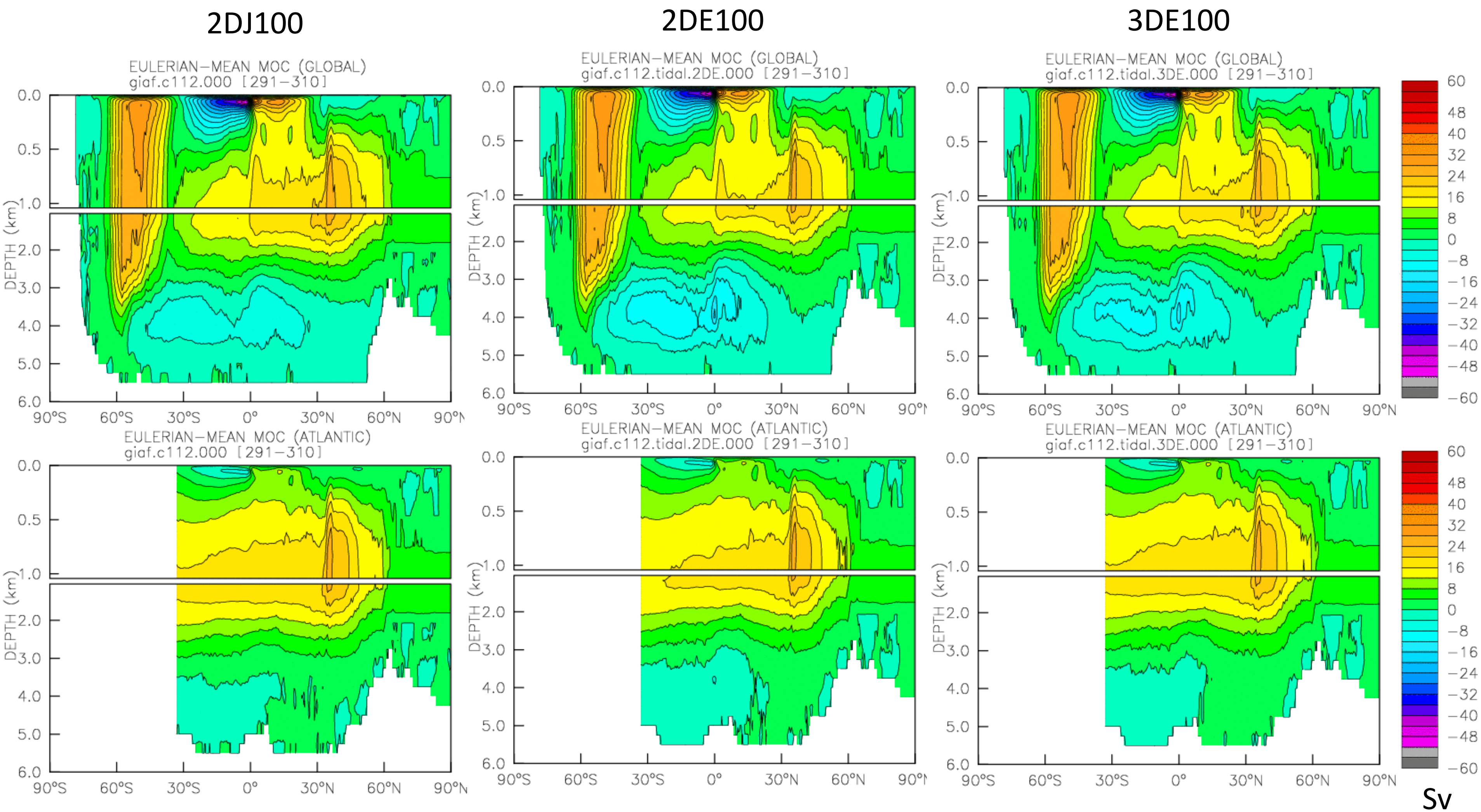




Global-mean Potential Temperature



Global and Atlantic Meridional Overturning Streamfunction



Global and Atlantic Meridional Overturning Streamfunction