OCEAN MODELING II

Parameterizations

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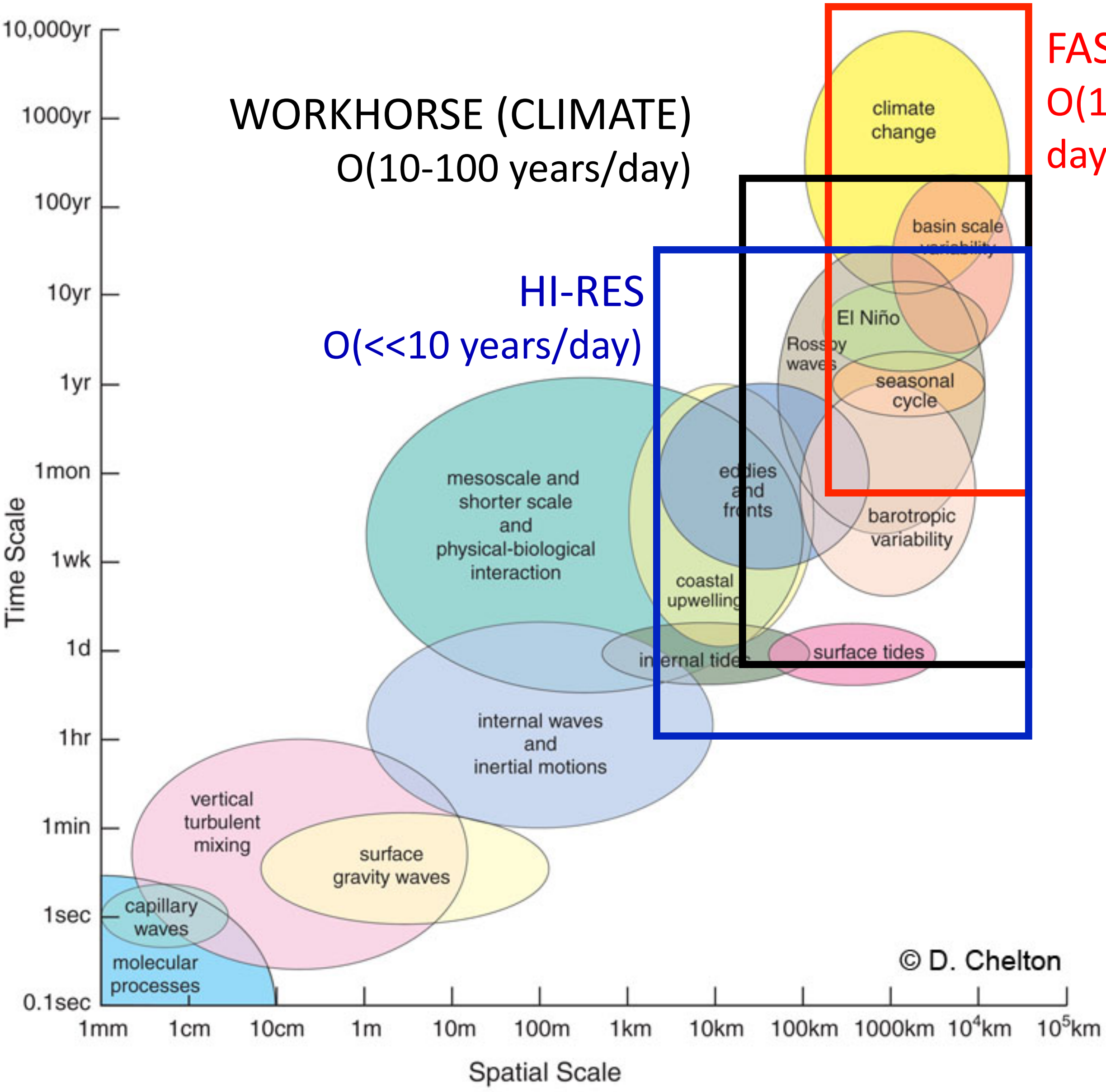
SPACE - TIME SCALES and OCEAN MODELS



WORKHORSE (CLIMATE)
O(10-100 years/day)

HI-RES
O(<<10 years/day)

FAST
O(100-1000 years/day)

PARAMETERIZATIONS:

- ACCOMPLISH PHYSICAL EFFECTS OF UNRESOLVED SUB-GRID-SCALE PROCESSES (ALL INVOLVING TURBULENCE),
- PHYSICALLY-BASED / JUSTIFIED,
- AS SIMPLE AS POSSIBLE,
- AS FEW PARAMETERS AS POSSIBLE.

- Development,
- Implementation,
- Verification,
- Impacts

PARAMETERIZATIONS IN CESM1 POP2

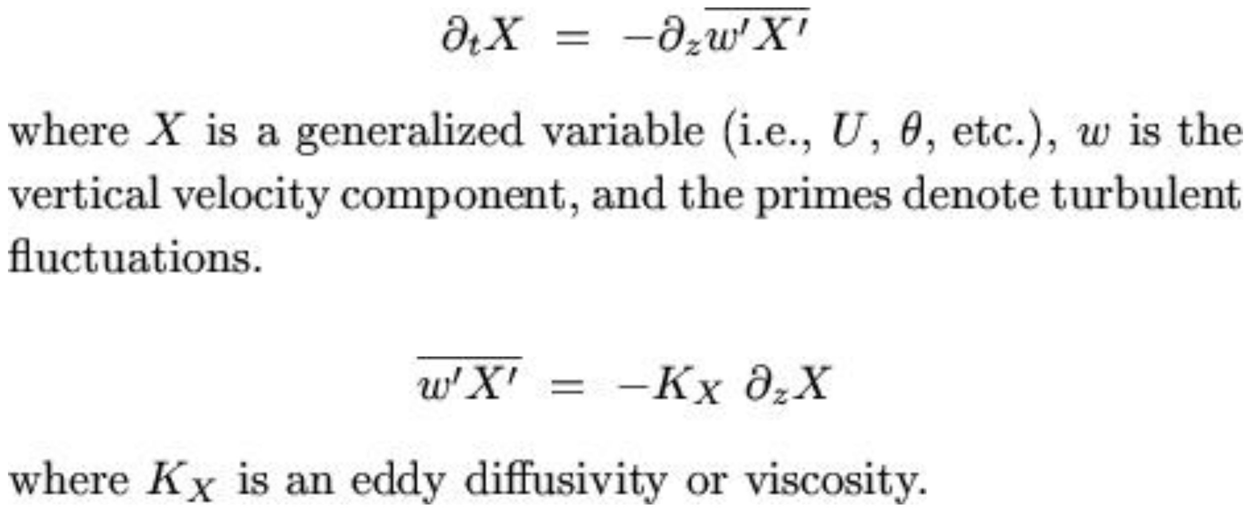
- Vertical mixing (momentum and tracers)
  - surface boundary layer,
  - interior
- Horizontal viscosity (momentum)
- Lateral mixing / mesoscale eddies (tracers)
- Overflows

- Submesoscale eddies (tracers)
- Diurnal cycle for short-wave heat flux
- Solar absorption

VERTICAL MIXING SCHEME:
K-PROFILE PARAMETERIZATION (KPP)

Large, McWilliams, and Doney (1994, Rev. Geophys.)

A first-order turbulent closure scheme



$$\partial_t X = -\partial_z \overline{w'X'}$$

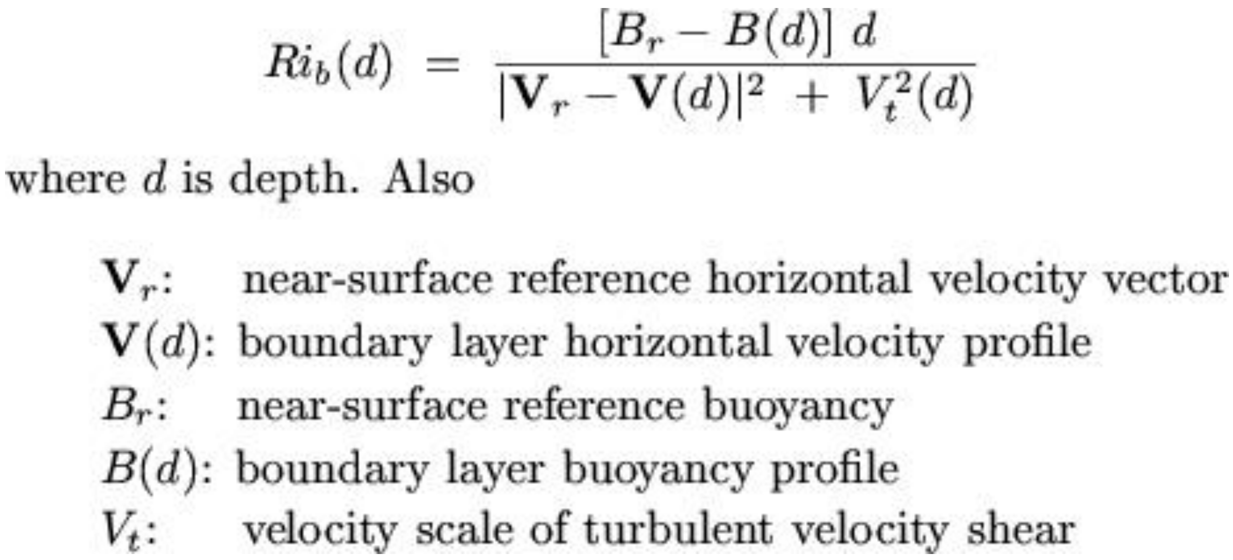
where X is a generalized variable (i.e., U, θ, etc.), w is the vertical velocity component, and the primes denote turbulent fluctuations.

$$\overline{w'X'} = -K_X\, \partial_z X$$

where K_X is an eddy diffusivity or viscosity.

KPP BOUNDARY LAYER DEPTH

The boundary layer depth, h, is determined based on a bulk Richardson number,



$$Ri_b(d) = \frac{[B_r - B(d)]\ d}{|\mathbf{V}_r - \mathbf{V}(d)|^2 + V_t^2(d)}$$

where d is depth. Also

$\mathbf{V}_r$: near-surface reference horizontal velocity vector
$\mathbf{V}(d)$: boundary layer horizontal velocity profile
B_r: near-surface reference buoyancy
$B(d)$: boundary layer buoyancy profile
V_t: velocity scale of turbulent velocity shear

h is equated to the smallest value of d at which the bulk Ri equals Ri_{cr}=0.3.

INTERIOR MIXING

- Shear instability: $K_X{}^s$
- Internal wave breaking: $K_X{}^w$
- Double diffusion: $K_X{}^d$
- Local static instability (convection): $K_X{}^c$
- Tidal mixing: $K_X{}^t$

$$K_X(\text{interior}) = K_X{}^s + K_X{}^w + K_X{}^d + K_X{}^c + K_X{}^t$$

KPP BOUNDARY LAYER MIXING

$$K_X(l) = h \; w_X(l) \; G(l)$$

with

$l = d / h$,

$w_X(l)$: turbulent velocity scale,

$G(l)$: cubic shape function.

- K_X is non-local,
- Interior mixing at the base of the boundary layer influences the turbulence throughout the boundary layer,
- There is also a non-local counter-gradient term.

HORIZONTAL VISCOSITY

Spatially uniform, isotropic, Cartesian, Δ=250km grid for illustration

$$D(U) = A\ U_{xx} + A\ U_{yy}$$
$$D(V) = A\ V_{xx} + A\ V_{yy}$$

Grid Re (Diffuse Noise) → $A > 0.5\ V\,\Delta\ =\ 100{,}000\ \mathrm{m^2/s}$

Resolve WBC (Munk Layers) → $A > \beta\ \Delta^3\ =\ 80{,}000\ \mathrm{m^2/s}$

Diffusive CFL → $A < 0.5\ \Delta^2 / \Delta t\ =\ 8000{,}000\ \mathrm{m^2/s}$

Realism (EUC, WBC) → $A \sim \text{physical}\ =\ 1{,}000\ \mathrm{m^2/s}$

Smagorinsky → $A = C\,\Delta^2 \surd\ (\partial_x U)^2 + (\partial_y V)^2 + (\partial_x V + \partial_y U)^2$

ANISOTROPIC HORIZONTAL VISCOSITY

$$\partial_t u + \ldots = \partial_x (A \partial_x u) + \partial_y (B \partial_y u)$$

$$\partial_t v + \ldots = \partial_x (B \partial_x v) + \partial_y (A \partial_y v)$$

Grid Re (Diffuse Noise) → Live with the "noise"

Resolve WBC (Munk Layers) → $A = B = \beta \, \Delta^3$, only near WBC

elsewhere:
Realism (EUC, WBC) → $A = 300 \text{ m}^2/\text{s}$
$B = 300 \text{ m}^2/\text{s}$ in the tropics
$= 600 \text{ m}^2/\text{s}$ polewards of 30°

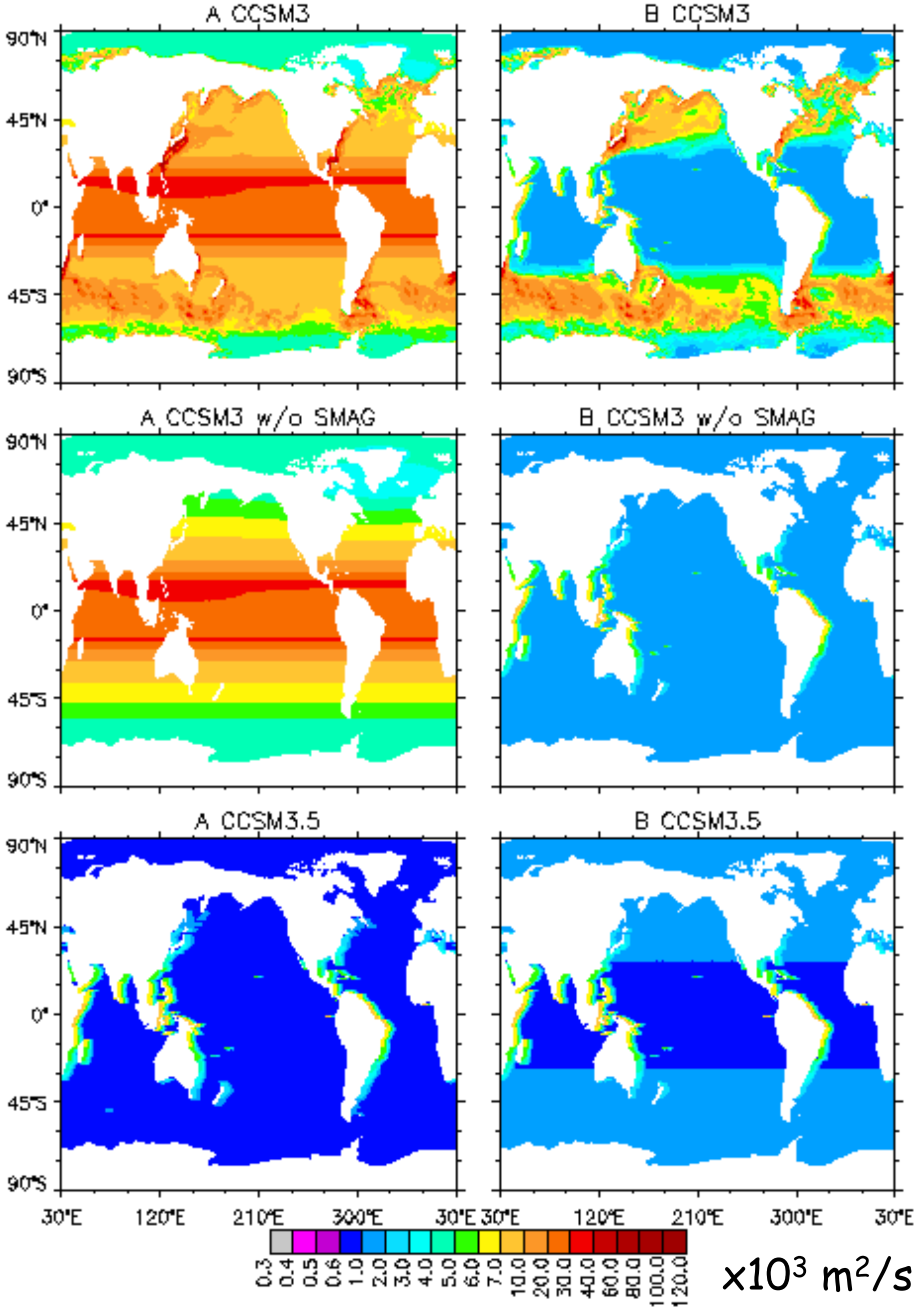
Subject to diffusive CFL, but NO Smagorinsky

ANISOTROPIC HORIZONTAL VISCOSITY at 100-m DEPTH

CCSM4 Ocean :

-Minimally Numerically Viscous

-Maximally Physically Viscous

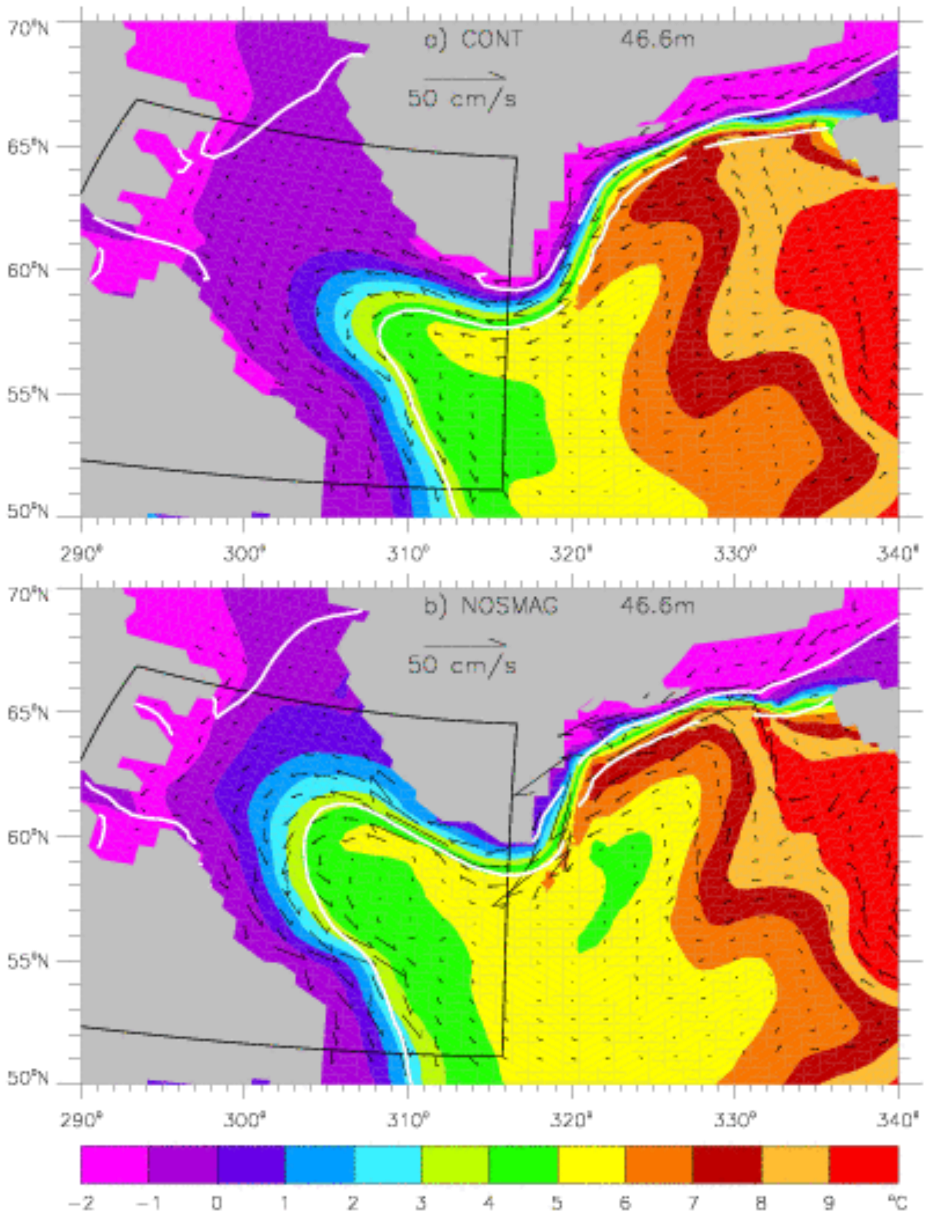


Large et al. (2001, JPO), Jochum et al. (2008, JGR)

IMPACTS ON LABRADOR SEA CIRCULATION AND SEA-ICE

w/ SMAGORINSKY

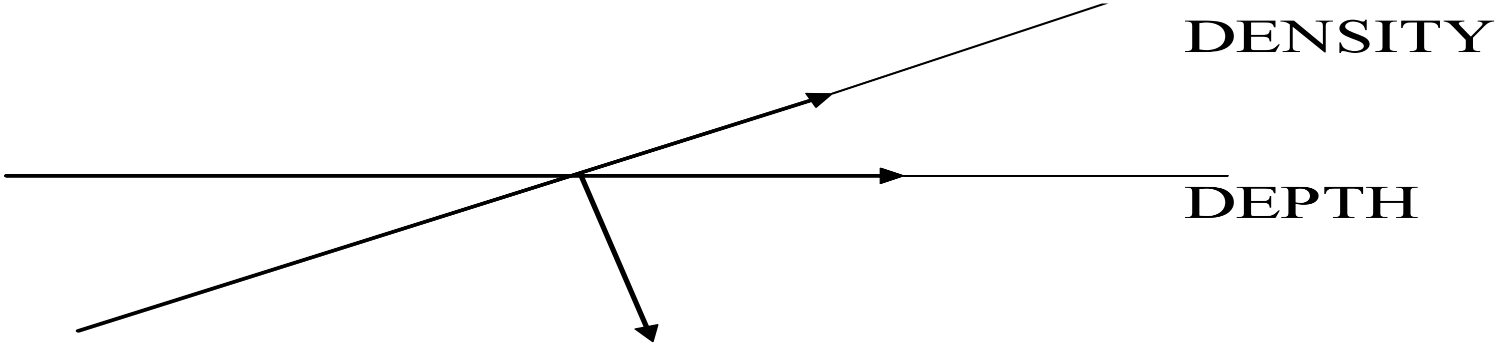
NO SMAGORINSKY



T (46.6m)

Jochum et al. (2008, JGR)

MESOSCALE EDDY PARAMETERIZATION FOR TRACERS



Ocean Observations suggest mixing along isopycnals is $\sim 10^7$ times larger than across isopycnals.
Horizontal mixing causes spurious diapycnal mixing.

An example: The Veronis (1975) effect

For steady WBC …

$$w\rho_z = \kappa\rho_{xx}$$

GENT & McWILLIAMS (1990) MESOSCALE EDDY PARAMETERIZATION

Mimics effects of unresolved mesoscale eddies as a sum of

- diffusive mixing of tracers along isopycnals (Redi),
- an additional advection of tracers by an eddy-induced velocity (u*, divergence-free),

Quasi-adiabatic and valid for the ocean interior,

Flattens isopycnals, thereby reducing PE,

Eliminates any need for horizontal diffusion, no Veronis effect.

Gent & McWilliams (1990, JPO)

GENT & McWILLIAMS (1990) MESOSCALE EDDY PARAMETERIZATION

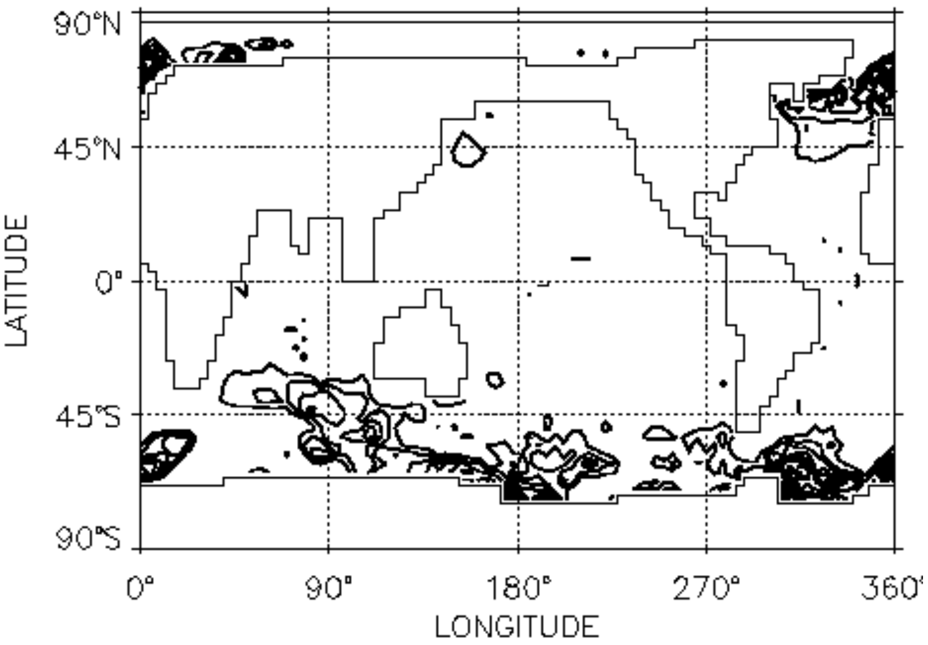
$$\frac{\partial T}{\partial t} + \nabla_{3D} \cdot (\mathbf{u} + \mathbf{u}^*) T = \nabla_{3D} \cdot \mathrm{K}^{\rho}\, \nabla_{3D} T + F^*$$

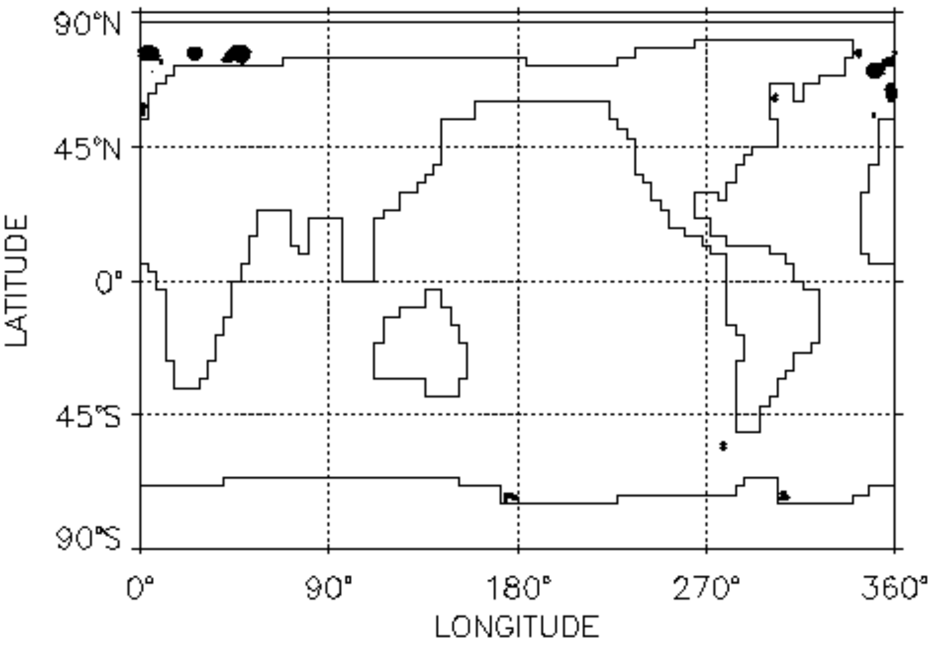
$$(u^*, v^*) = -\frac{\partial}{\partial z}\left(A_{ITD}\mathbf{s}\right) \qquad w^* = \nabla \cdot \left(A_{ITD}\mathbf{s}\right)$$

Here, *T* is a generic tracer, **s** is the 2D isopycnal slope vector, and K is the isopycnal diffusion tensor.

There are two diffusivities: A_I: isopycnal in K,
A_{ITD}: thickness

IMPACTS ON DEEP WATER FORMATION / CONVECTION


HORIZONTAL MIXING

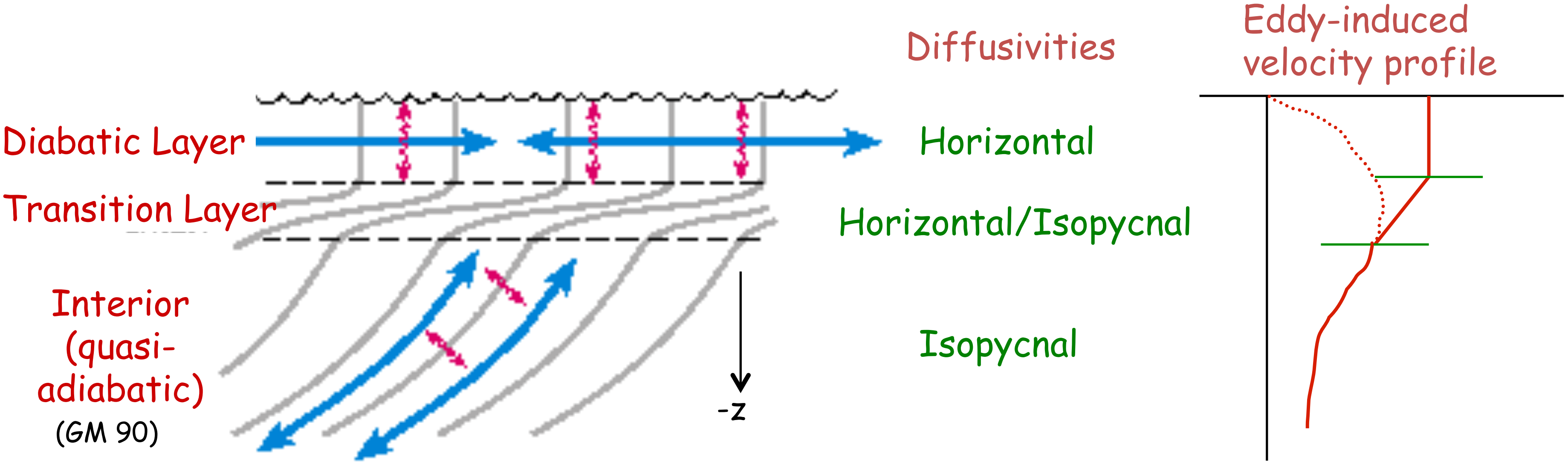

GM90 PARAMETERIZATION

4^ox3^ox20L ocean model

Danabasoglu et al. (1994, Science)

NEAR-SURFACE EDDY FLUX (NSEF) SCHEME

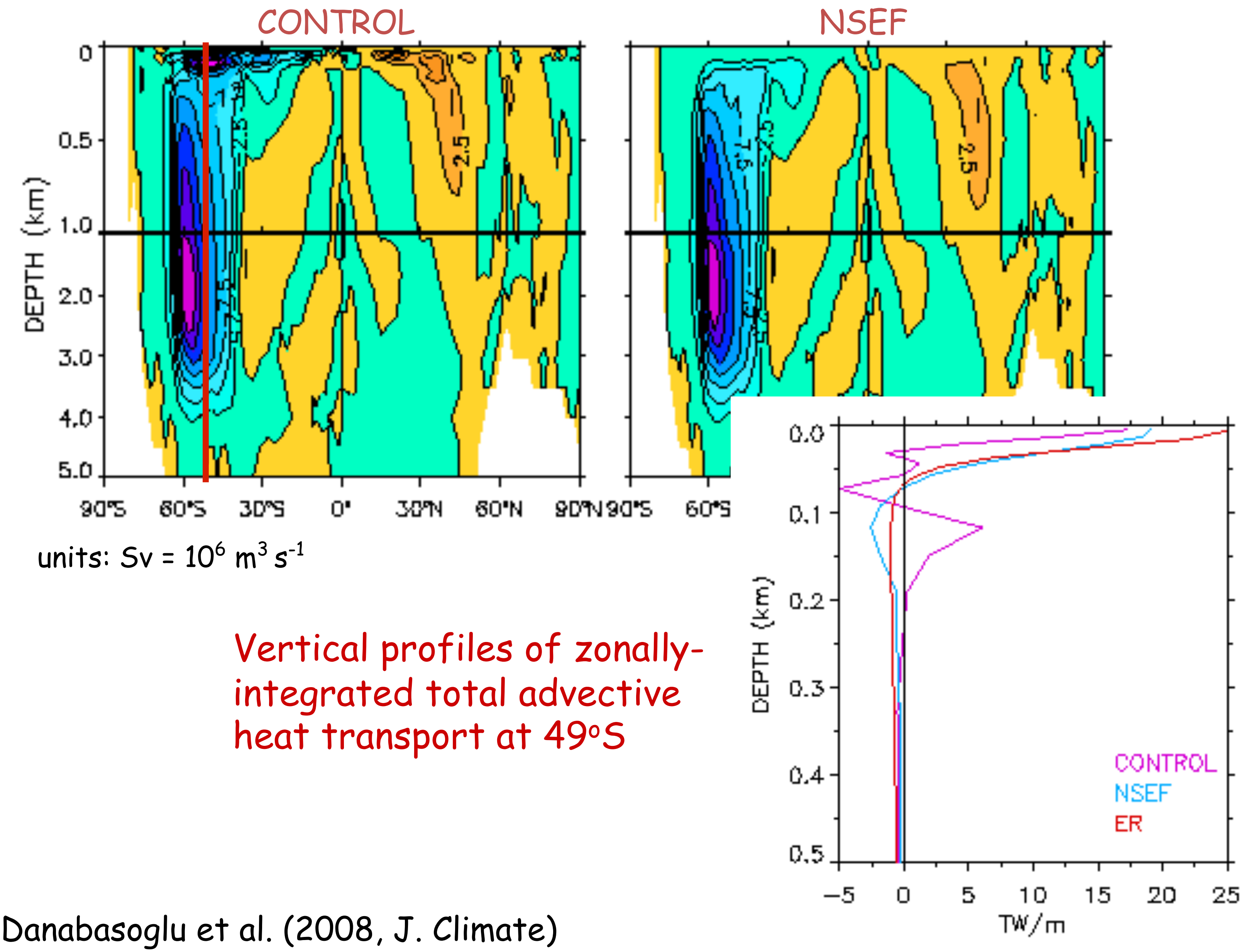
GM90 is valid only in the quasi-adiabatic ocean interior, therefore the usual practice has been to taper both A_I and A_{ITD} to zero as the surface is approached.



NSEF replaces the usual approach of applying near-surface taper functions for the diffusivities.

Ferrari et al. (2008, J. Climate), Danabasoglu et al. (2008, J. Climate)

EDDY-INDUCED MERIDIONAL OVERTURNING CIRCULATION



units: Sv = 10^6 m^3 s^{-1}

Vertical profiles of zonally-integrated total advective heat transport at 49°S

Danabasoglu et al. (2008, J. Climate)

SPATIAL VARIATIONS OF THE EDDY DIFFUSIVITIES

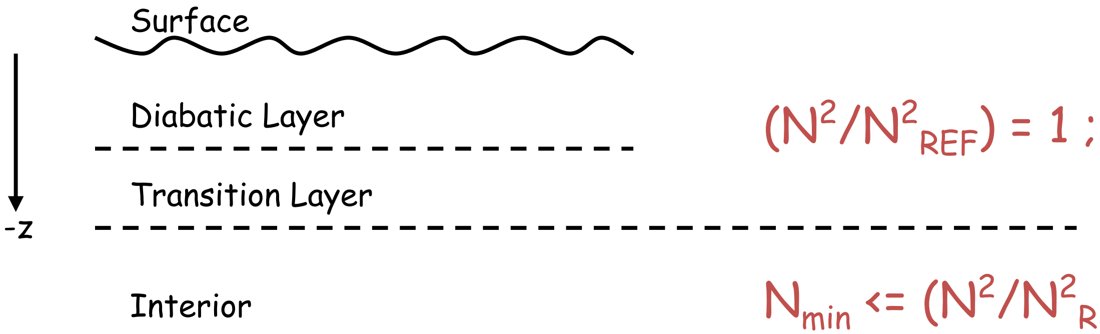
Following Ferreira et al. (2005), the diffusivities are specified as

$$A = A_{REF} \left(N^2 / N^2_{REF} \right)$$

N^2: Local buoyancy frequency,

N^2_{REF}: Reference buoyancy frequency just below the transition layer,

A_{REF}: Constant reference value of A within the surface diabatic region.



$(N^2/N^2_{REF}) = 1$; A_{REF}

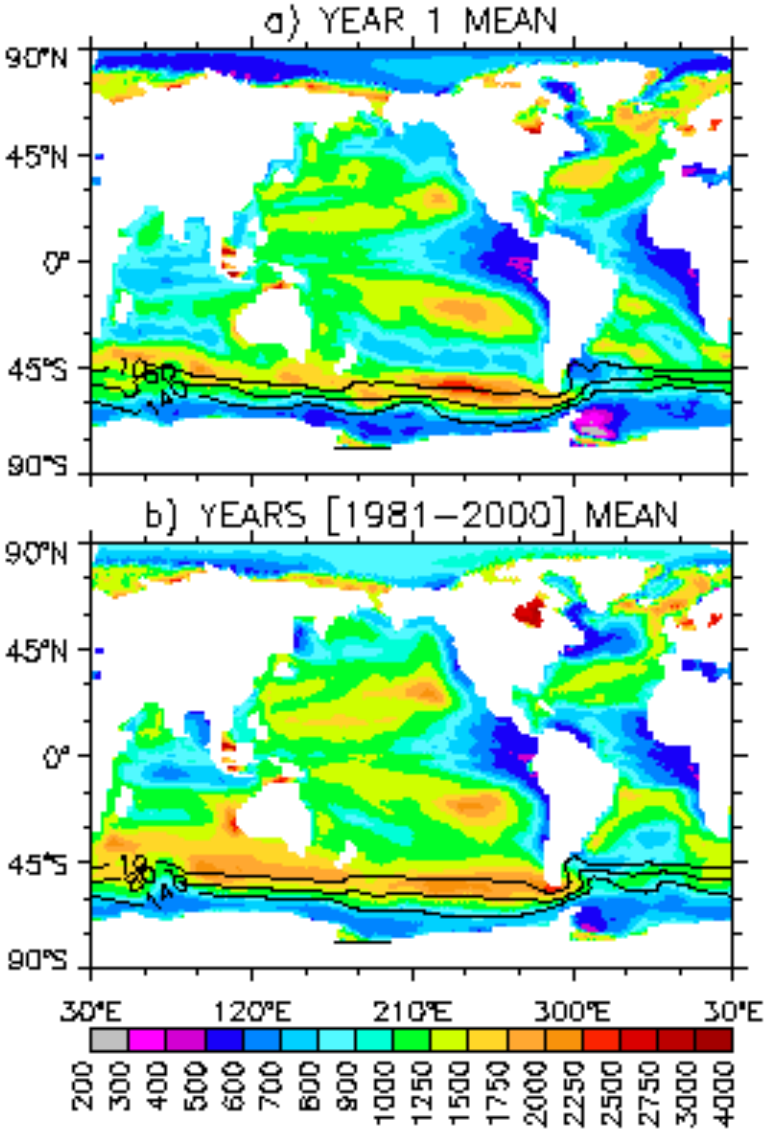
$N_{min} <= (N^2/N^2_{REF}) <= 1$

N_{min} is a lower limit, $N_{min} = 0.1$.

Ferreira et al. (2005, JPO)

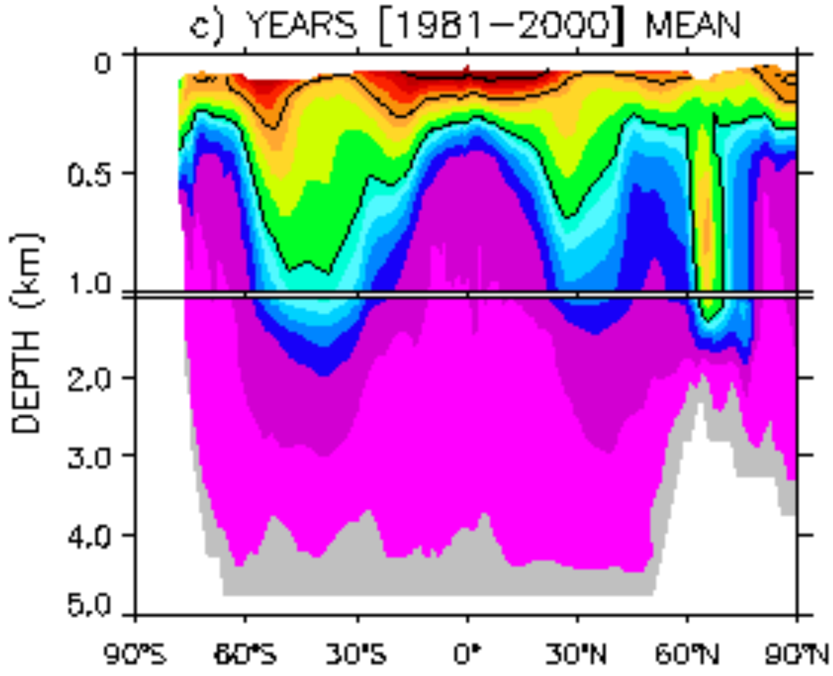
THICKNESS DIFFUSIVITY

UPPER-OCEAN [0-945 m] MEAN



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

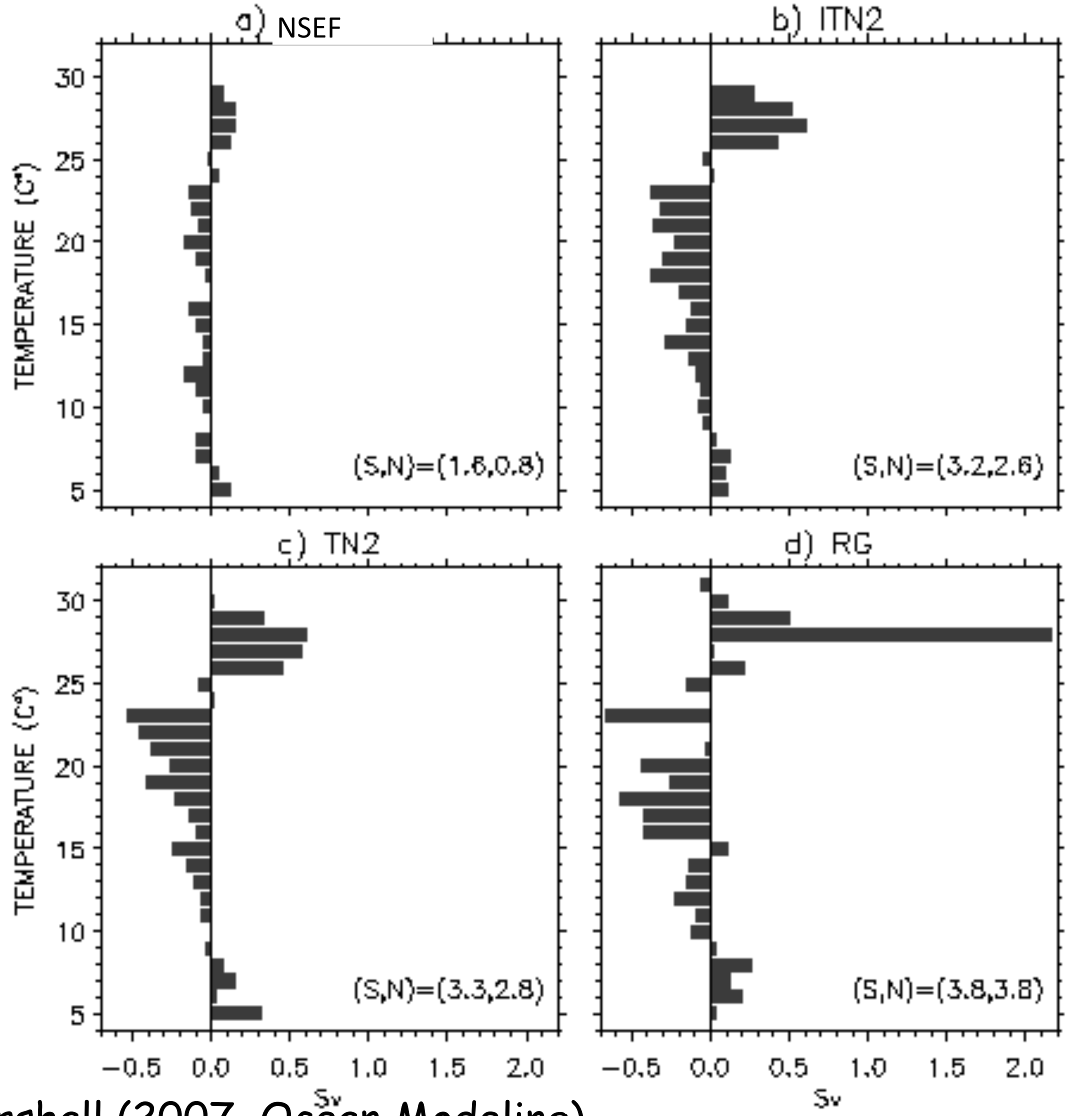
ZONAL-MEAN



Danabasoglu & Marshall (2007, Ocean Modelling)

Model Eddy-Induced Transport Comparisons with Roemmich and Gilson (2001) Observational Estimate

(Repeat hydrographic line in the North Pacific at an average latitude of 22°N)



Roemmich and Gilson (2001)

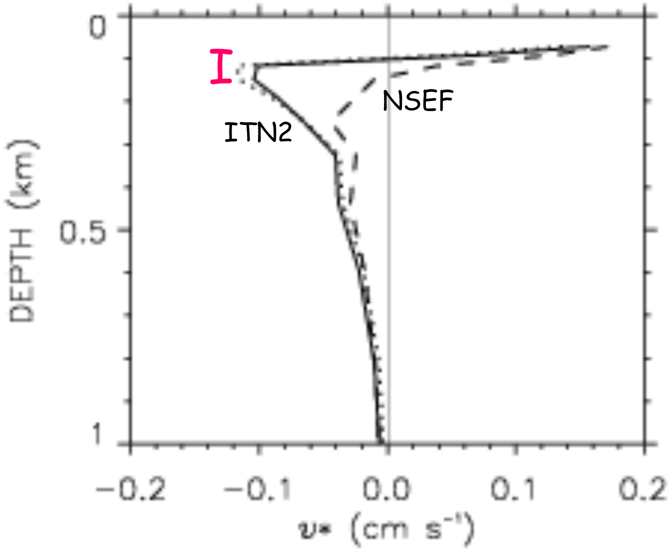
Danabasoglu & Marshall (2007, Ocean Modeling)

The eddy-induced meridional velocity is given by

$$v^* = -\frac{\partial\left(A_{ITD}S_y\right)}{\partial z} = -\left(\overset{\text{I}}{\frac{\partial A_{ITD}}{\partial z}}S_y + A_{ITD}\frac{\partial S_y}{\partial z}\right)$$

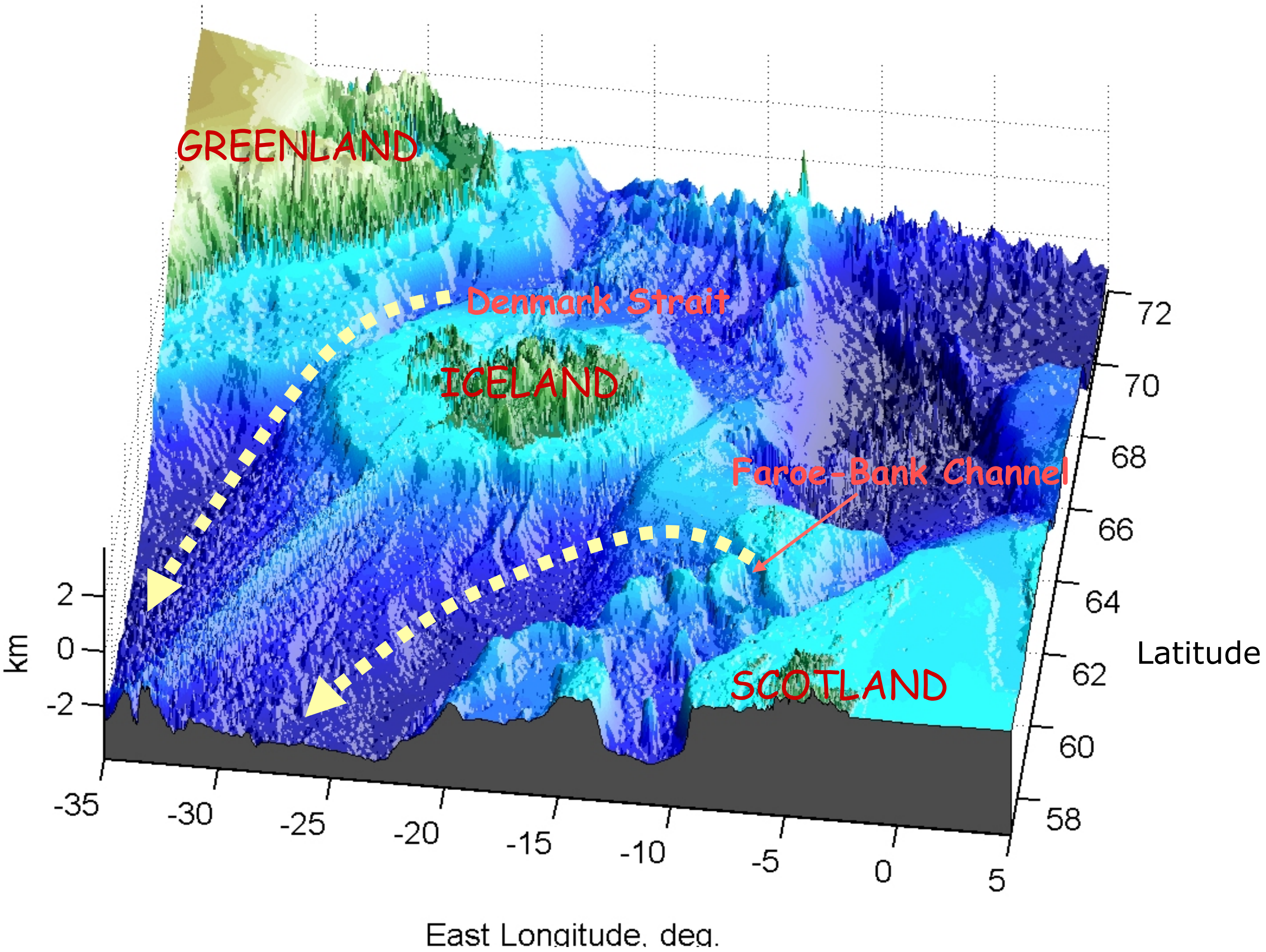
where S_y is the meridional slope of the isopycnal surfaces and z is the vertical coordinate (positive upwards).

Horizontal-mean v* profiles computed between 20°N and 40°N in the North Pacific



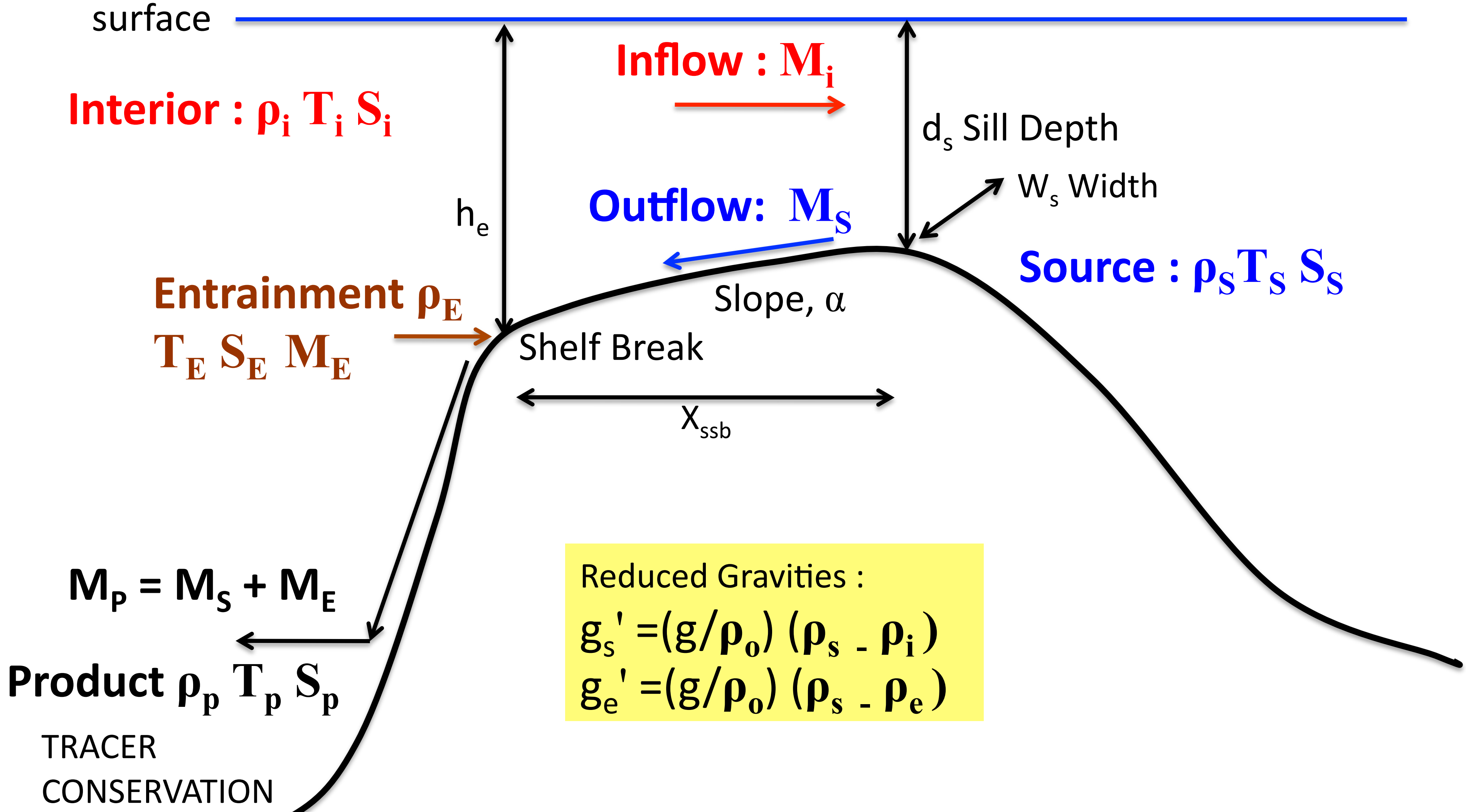
Danabasoglu & Marshall (2007, Ocean Modelling)

GRAVITY CURRENT OVERFLOWS



from J.Price

GRAVITY CURRENT OVERFLOW PARAMETERIZATION



surface

Interior : ρ_i T_i S_i

Inflow : M_i

d_s Sill Depth

W_s Width

h_e

Outflow: M_S

Source : $\rho_S T_S$ S_S

Entrainment ρ_E

T_E S_E M_E

Slope, α

Shelf Break

X_{ssb}

$M_P = M_S + M_E$

Product ρ_p T_p S_p

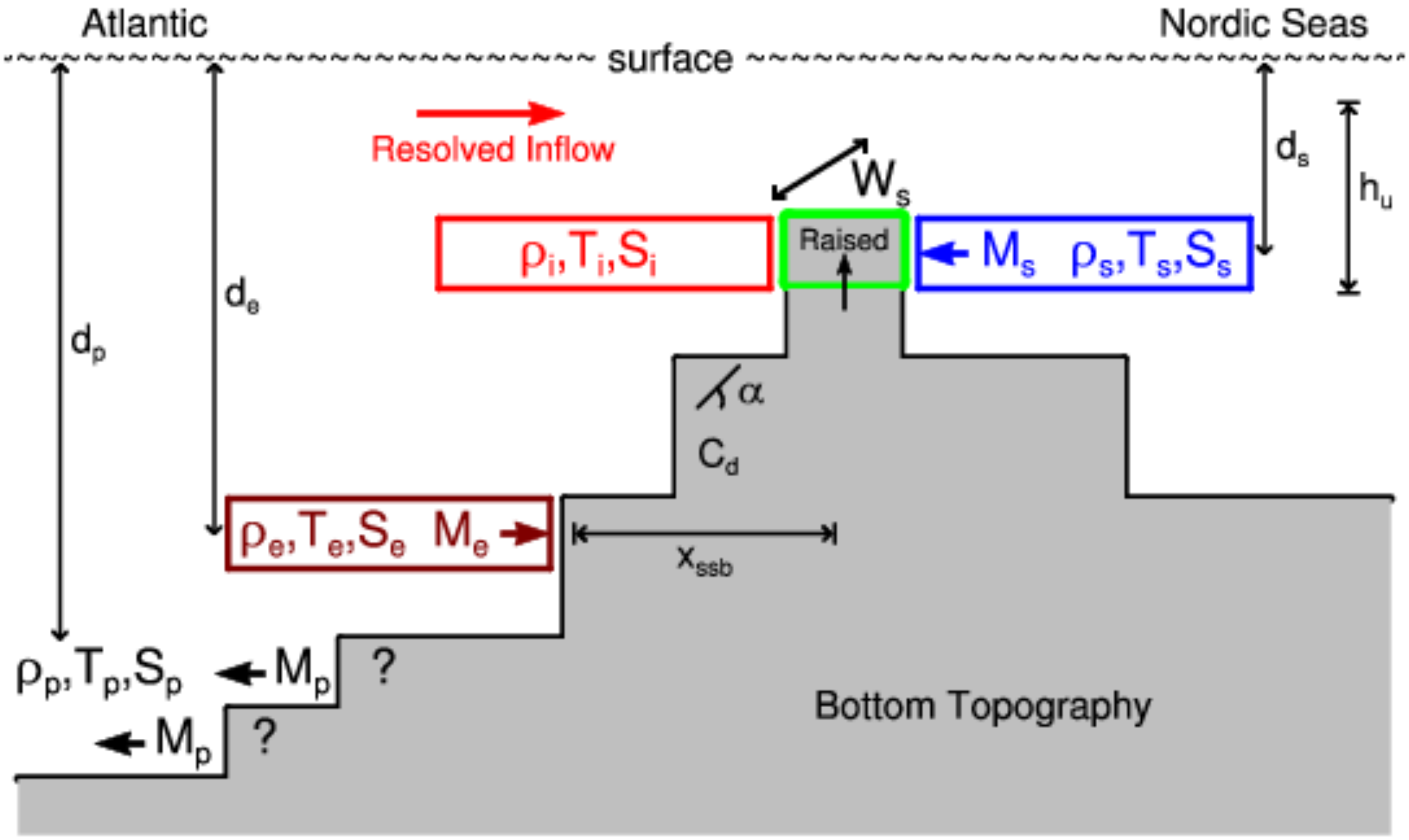
TRACER
CONSERVATION

Reduced Gravities :

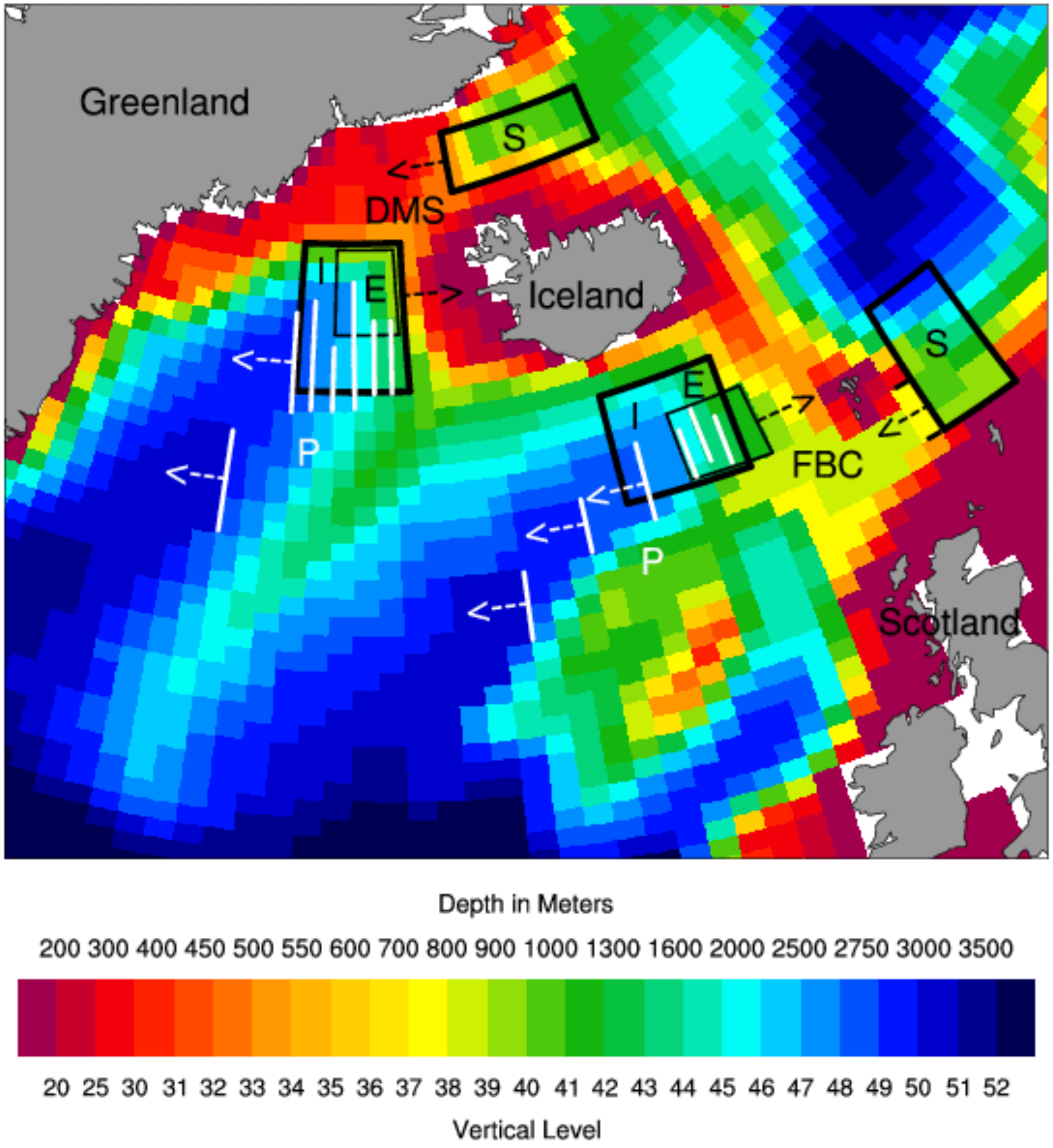
$$g_s' = (g/\rho_o)\ (\rho_s - \rho_i)$$
$$g_e' = (g/\rho_o)\ (\rho_s - \rho_e)$$

Based on Price & Yang (1998); described in Briegleb et al. (2010, NCAR Tech. Note) and Danabasoglu et al. (2010, JGR)

OVERFLOW PARAMERERIZATION MODEL SCHEMATIC



BOTTOM TOPOGRAPHY OF THE x1 RESOLUTION OCEAN MODEL



VERIFICATION AND IMPACTS OF THE OVERFLOW PARAMETERIZATION

	UNCOUPLED	COUPLED
Control (no overflows)	OCN	CCSM
With overflows	OCN*	CCSM*

Each experiment is run for 170 years.

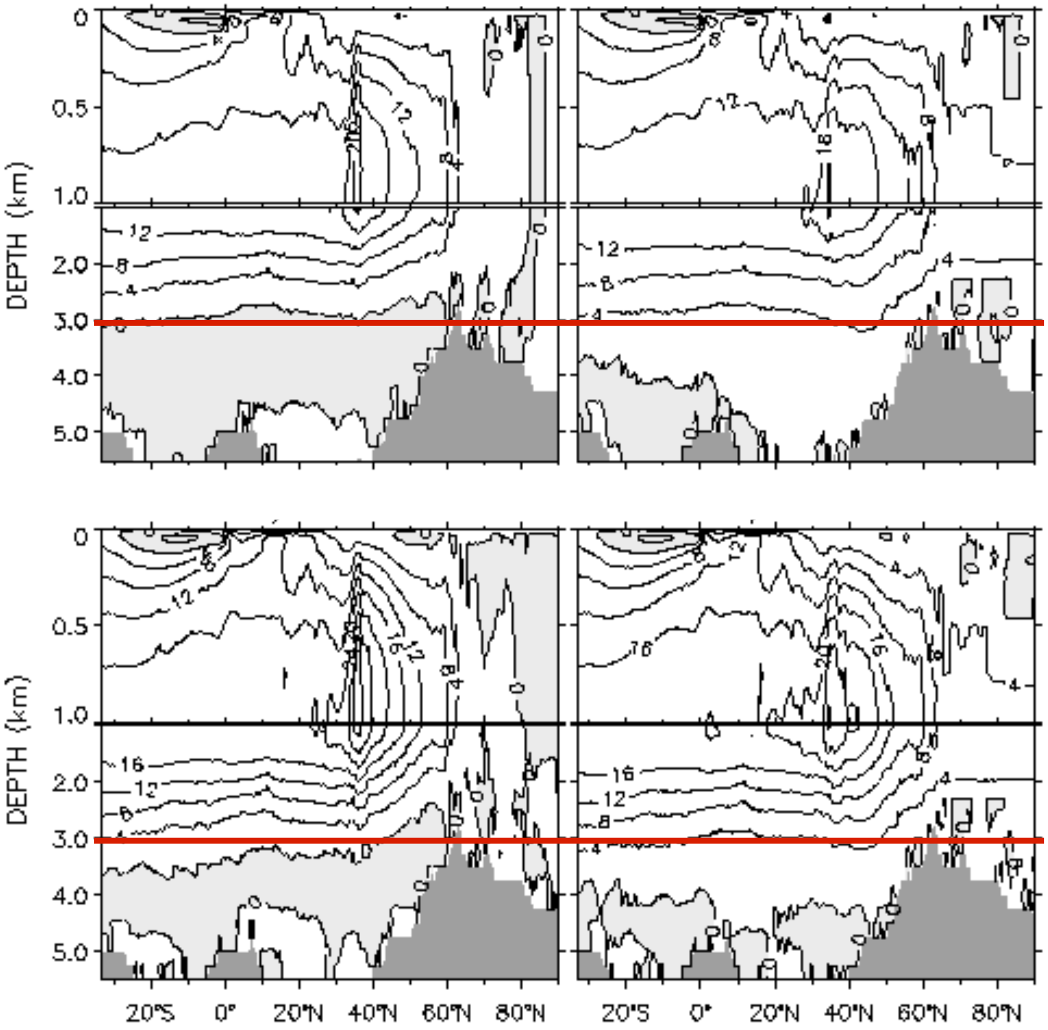
NORDIC SEA OVERFLOW TRANSPORTS

Verification Steps

All in Sv

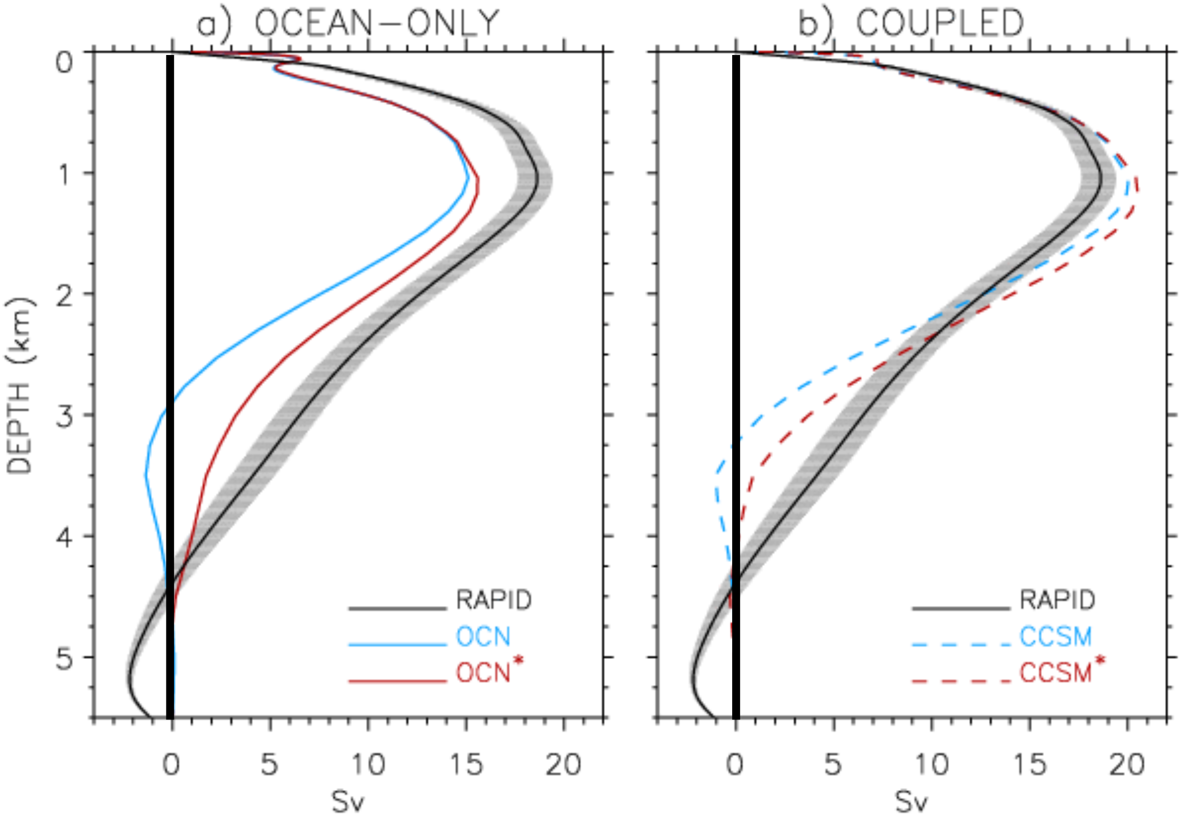
		1	2	3
	Observed	Diagnostic model (offline)	OCN*	CCSM*
M_I				
M_S	4.1 - 7.5	5.2	4.7	4.4
M_E	1.5 – 3.7	1.2	0.9	1.1
M_P	6.4 – 9.4	6.4	5.6	5.5

ATLANTIC MERIDIONAL OVERTURNING CIRCULATION (AMOC)



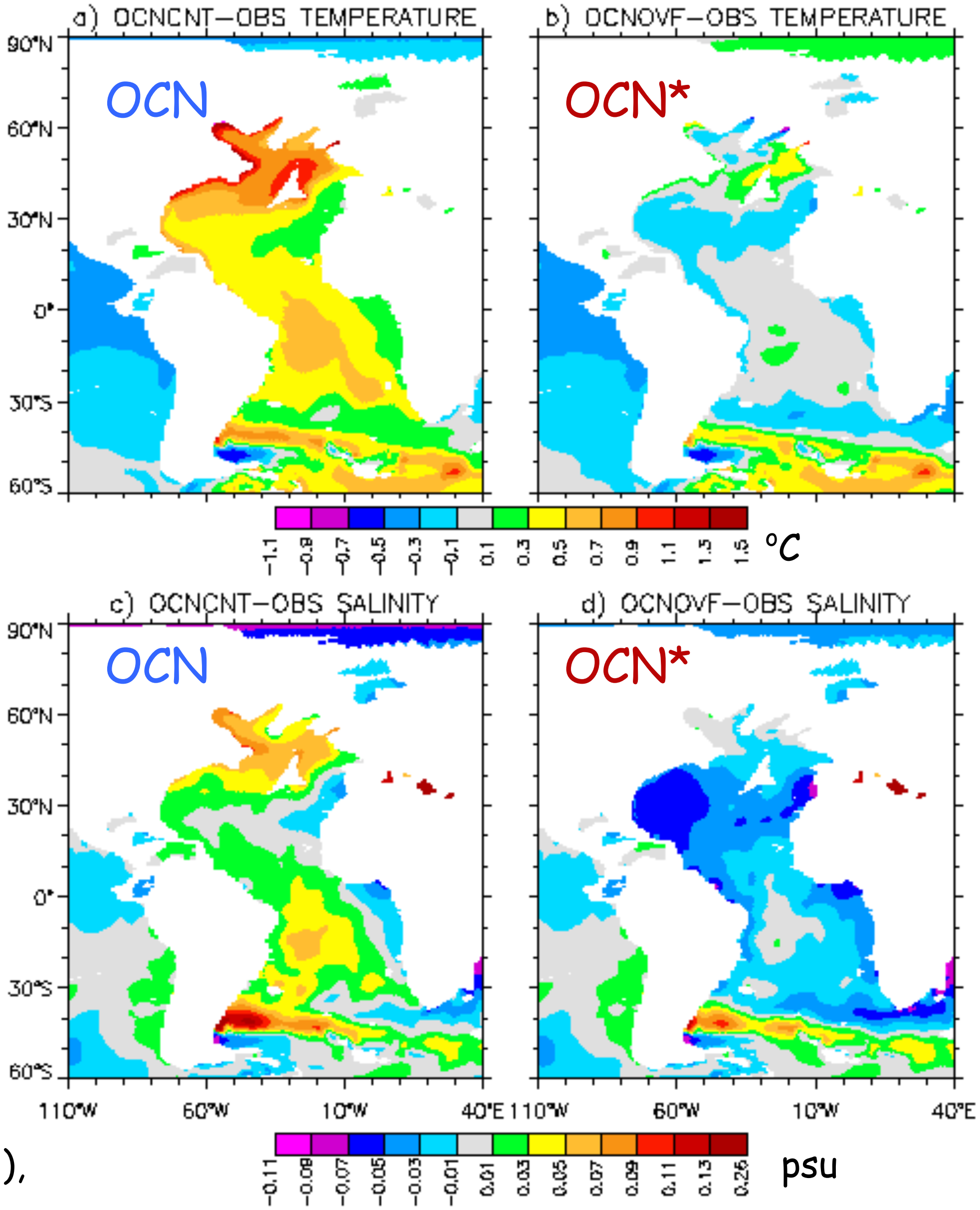
in Sv

AMOC TRANSPORT AT 26.5°N



RAPID is observational data

TEMPERATURE AND SALINITY DIFFERENCES FROM OBSERVATIONS AT 2649-m DEPTH



mean= 0.45°C

rms= 0.50°C

mean= -0.04°C

rms= 0.13°C

mean= 0.02 psu

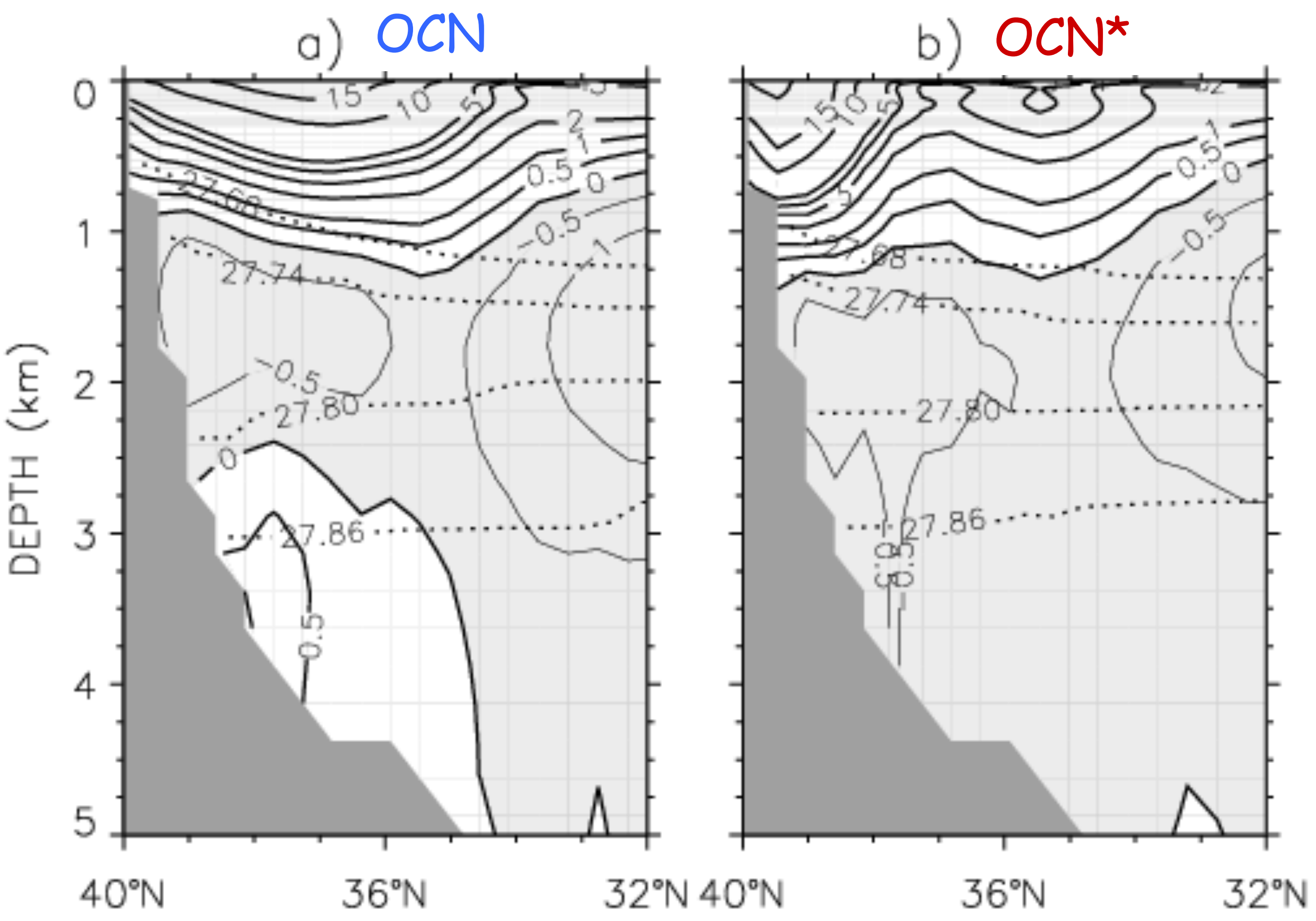
rms= 0.03 psu

mean= -0.03 psu

rms= 0.03 psu

Obs: Levitus et al. (1998),
Steele et al. (2001)

ZONAL VELOCITY ACROSS 69°W IN THE NORTH ATLANTIC



velocity: cm/s, density:kg/m^3

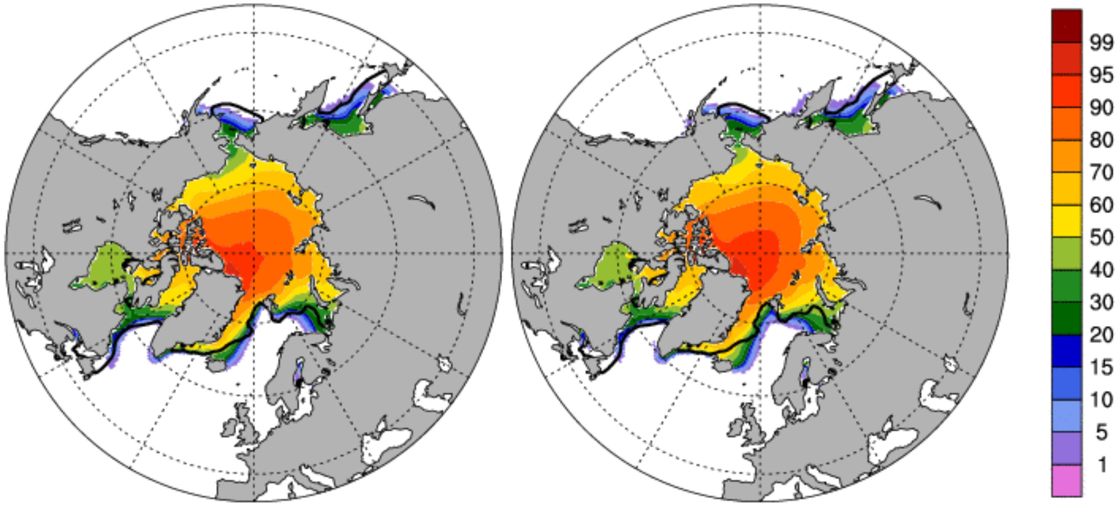
EQUATORWARD VOLUME TRANSPORTS

$\sigma_o \geq$	44°W 27.80	49.3°W 27.80	49.3°W 27.74	69°W 27.80
OCN	5.3	3.5	17.3	0.2
OCN*	10.7	9.3	26.7	2.0
OBS	13.3 Dickson and Brown(1994)	14.7 Fischer et al. (2004)	26 ± 5 Fischer et al. (2004)	12.5 Joyce et al. (2005)

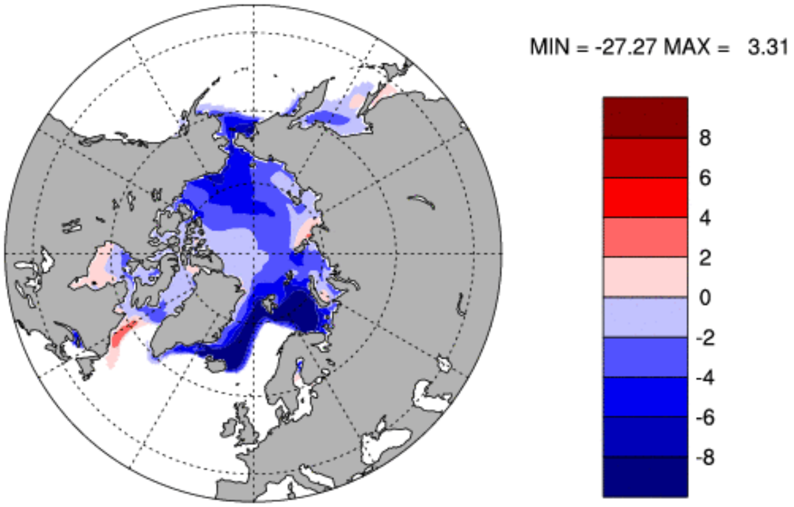
All in Sv

IMPACTS ON SEA-ICE CONCENTRATION

CCSM* CCSM



CCSM* - CCSM



% of grid area

THANK YOU