

Ocean Modeling II

Parameterized Physics

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NCAR

VERTICAL MIXING SCHEME: K-PROFILE PARAMETERIZATION (KPP)

OCEANIC VERTICAL MIXING: A REVIEW AND A MODEL WITH A NONLOCAL BOUNDARY LAYER PARAMETERIZATION

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- Unresolved turbulent vertical mixing due to small-scale overturning motions parameterized as a vertical diffusion.
- Guided by study and observations of atmospheric boundary layer

$$\partial_t X = -\partial_z \overline{w'X'} \quad \xrightarrow{\text{parameterize}} \quad \overline{w'X'} = -K_x \partial_z X$$

where K_x represents an “eddy diffusivity” or “eddy viscosity”
and $X = \{ \text{active/passive scalars or momentum} \}$

VERTICAL MIXING SCHEME: K-PROFILE PARAMETERIZATION (KPP)

- KPP is not just a vertical diffusion scheme because the scalars (Temp and Salinity) have non-local or “countergradient” terms γ_x

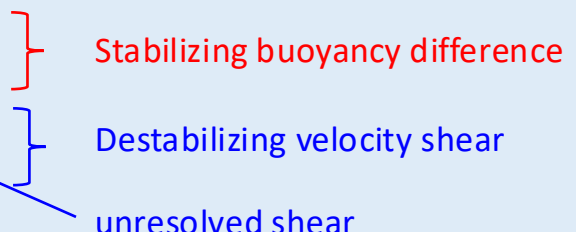
$$\overline{w'X'} = -K_x (\partial_z X - \gamma_x)$$

- KPP involves three high-level steps:
 1. Determination of the boundary layer (BL) depth: d
 2. Calculation of interior diffusivities: ν_x
 3. Evaluation of boundary layer (BL) diffusivities: K_x
- Diffusivity throughout the boundary layer depends on the surface forcing, the boundary layer depth, and the interior diffusivity.
- KPP produces quite large diffusivities below the boundary layer, which mixes temp and salinity quite deep in times of very strong surface wind stress, such as strong midlatitude atmosphere storms.

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1. BL depth d is minimum depth where the bulk Richardson # (Ri_b) referenced to the surface equals a critical Richardson # ($Ri_{cr}=0.3$).

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



Stabilizing buoyancy difference

Destabilizing velocity shear

unresolved shear

B_r : near-surface reference buoyancy

$\mathbf{V}_r$: near-surface reference horizontal velocity

$V_t(d)$: velocity scale of (unresolved) turbulent shear at depth d

Ri measures the stability of stratified shear flow. “Boundary layer eddies with mean velocity $\mathbf{V}_r$ and buoyancy B_r should be able to penetrate to the boundary layer depth, d , where they first become stable relative to the local buoyancy and velocity.”

VERTICAL MIXING SCHEME: K-PROFILE PARAMETERIZATION (KPP)

2. Calculation of interior diffusivities

$$\nu_x(d) = \nu_x^s(d) + \nu_x^w(d) + \nu_x^d(d) + \nu_x^c(d) + \nu_x^t(d)$$

ν_x : interior diffusivity at depth d (below the boundary layer)

ν_x^s : (unresolved) shear instability

ν_x^w : internal wave breaking

ν_x^d : double diffusion

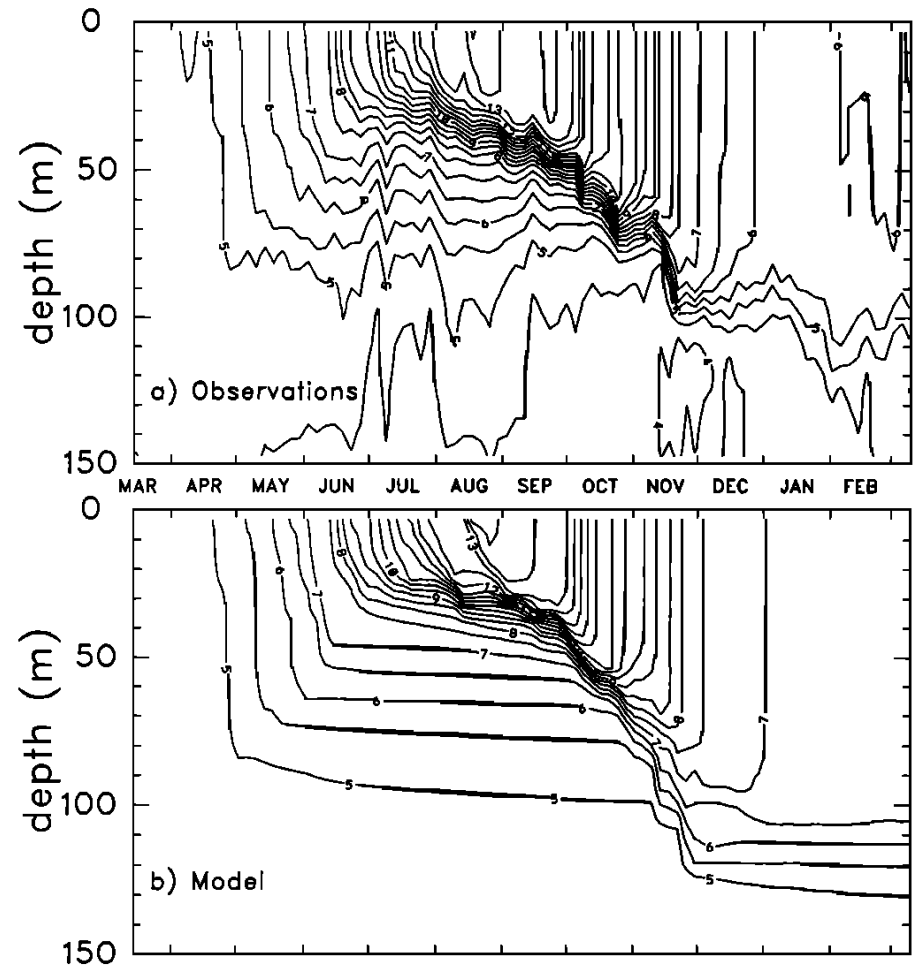
ν_x^c : local static instability (convection)

ν_x^t : tidal mixing

Superposition of processes sets interior vertical diffusivity, ν_x , below the surface boundary layer.

VERTICAL MIXING SCHEME: K-PROFILE PARAMETERIZATION (KPP)

Verification example at
Ocean Weather Station
Papa (50°N, 145°W):



Large et al (1994)

Figure 9. Time-depth sections of 4-day averages of observed temperatures in degrees Celsius (a) from ocean weather station (OWS) Papa during the ocean year March 15, 1961, to March 15, 1962 and (b) from the standard KPP simulation of OWS Papa.

Mesoscale eddy mixing of tracers: Gent-McWilliams (GM) parameterization

150

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Isopycnal Mixing in Ocean Circulation Models[†]

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20 March 1989 and 14 August 1989

ABSTRACT

A subgrid-scale form for mesoscale eddy mixing on isopycnal surfaces is proposed for use in non-eddy-resolving ocean circulation models. The mixing is applied in isopycnal coordinates to isopycnal layer thickness, or inverse density gradient, as well as to passive scalars, temperature and salinity. The transformation of these mixing forms to physical coordinates is also presented.

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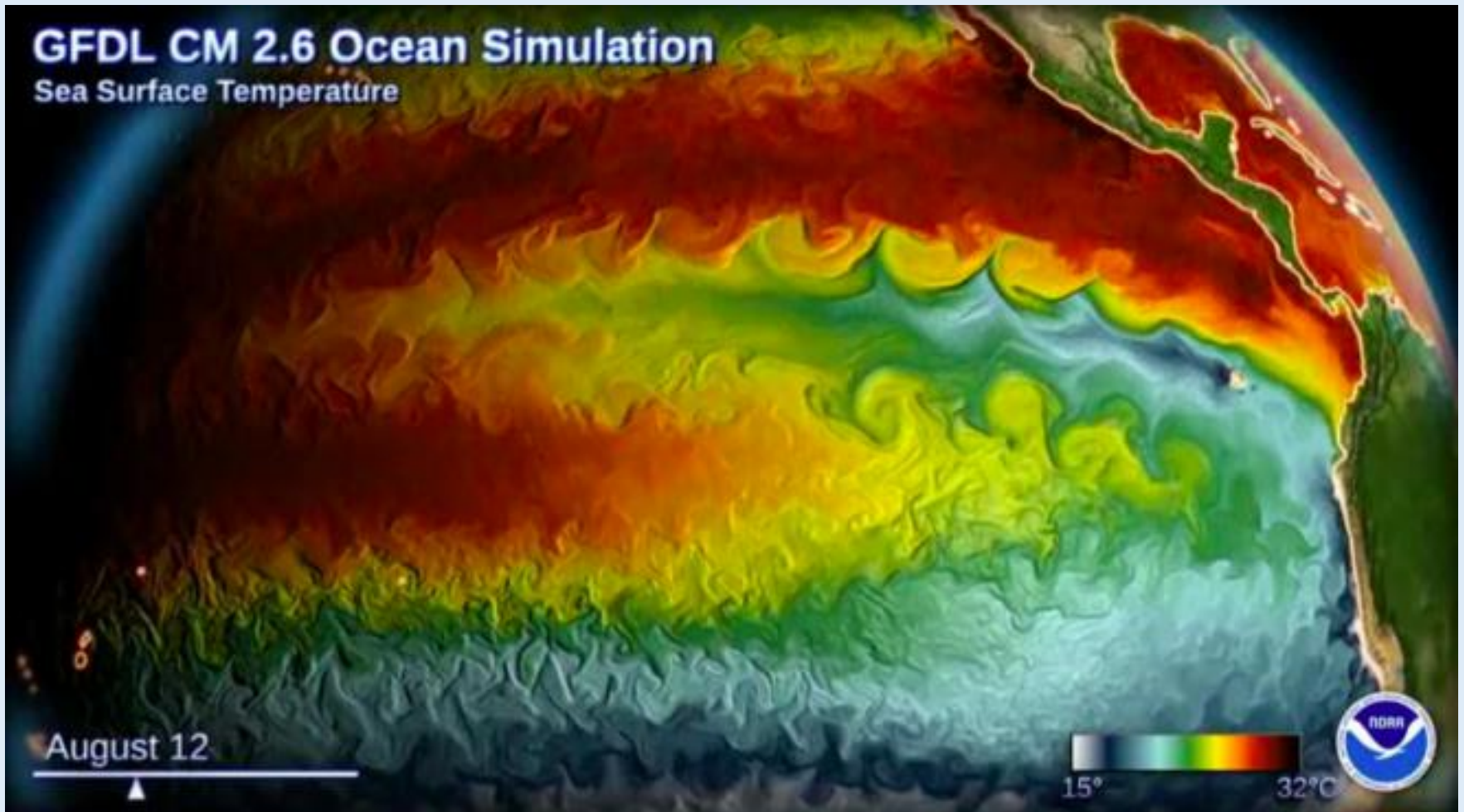


2011

The Gent–McWilliams parameterization: 20/20 hindsight

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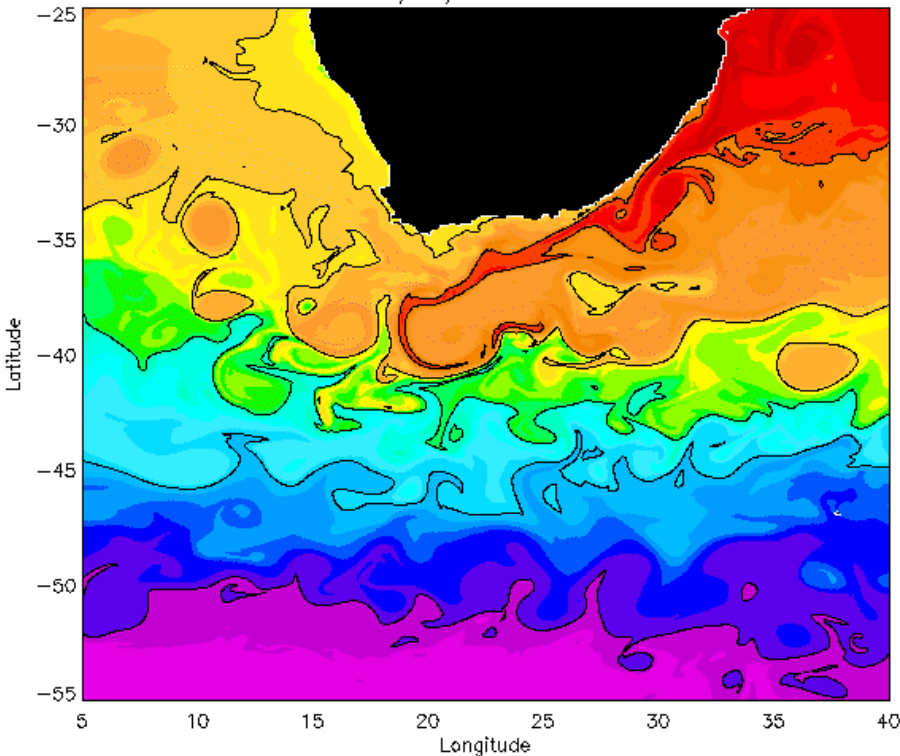


GFDL climate model with ocean resolution of 0.1°

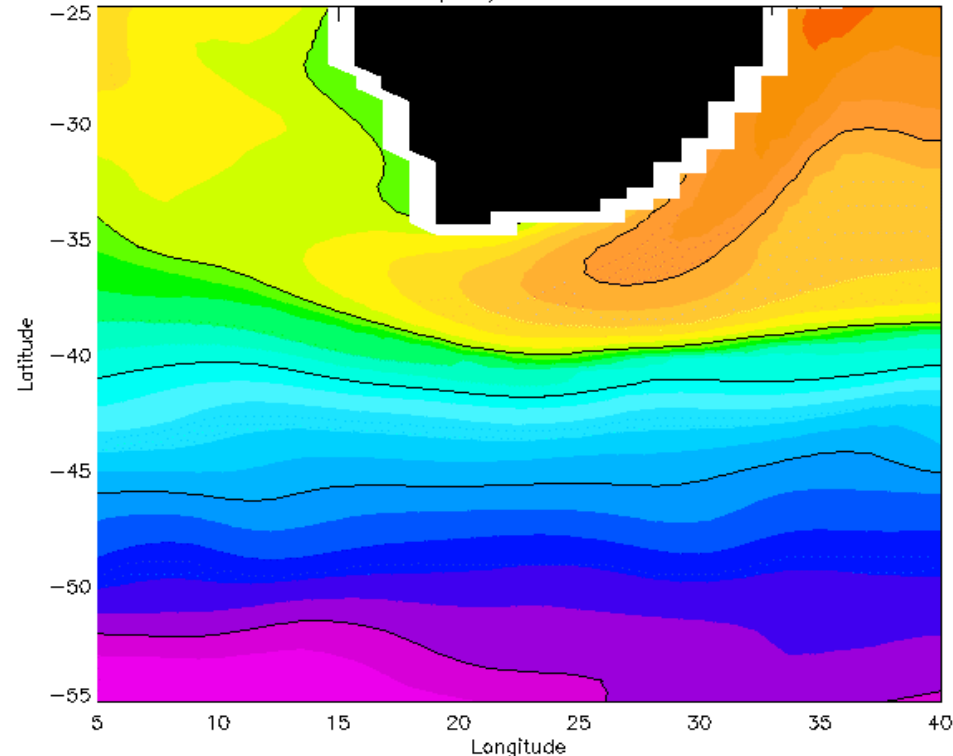
Effect of mesoscale eddies needs to be parameterized

Agulhas Retroflection

SST 30/09/2000 0.1° Model

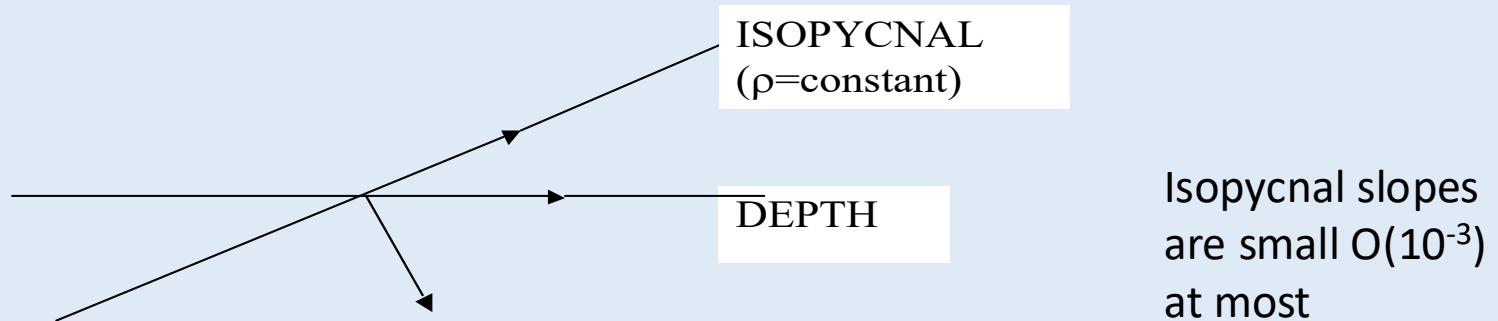


SST 30/09/2000 1° Model



$O(1^\circ)$ models do not resolve the 1st baroclinic deformation radius away from the equatorial regions, and hence lack the mesoscale turbulence which mixes temperature, salinity and passive tracers in the real ocean.

Diffusion needs to be along isopycnal surfaces



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

- Early ocean models parameterized the stirring effects of (unresolved) mesoscale eddies by Laplacian *horizontal* diffusion with $K_H = O(10^3 \text{ m}^2/\text{s})$, whereas the vertical mixing coefficient $K_V = O(10^{-4} \text{ m}^2/\text{s})$.
- Horizontal mixing results in excessive diapycnal mixing, which degrades the ocean solution: e.g. Veronis (1975) showed that it produces spurious upwelling in western boundary current regions which “short circuits” the N. Atlantic MOC.
- Thus, was a recognized need to orient tracer diffusion in z-coordinate models along isopycnal surfaces, to be consistent with observed ocean mixing rates.

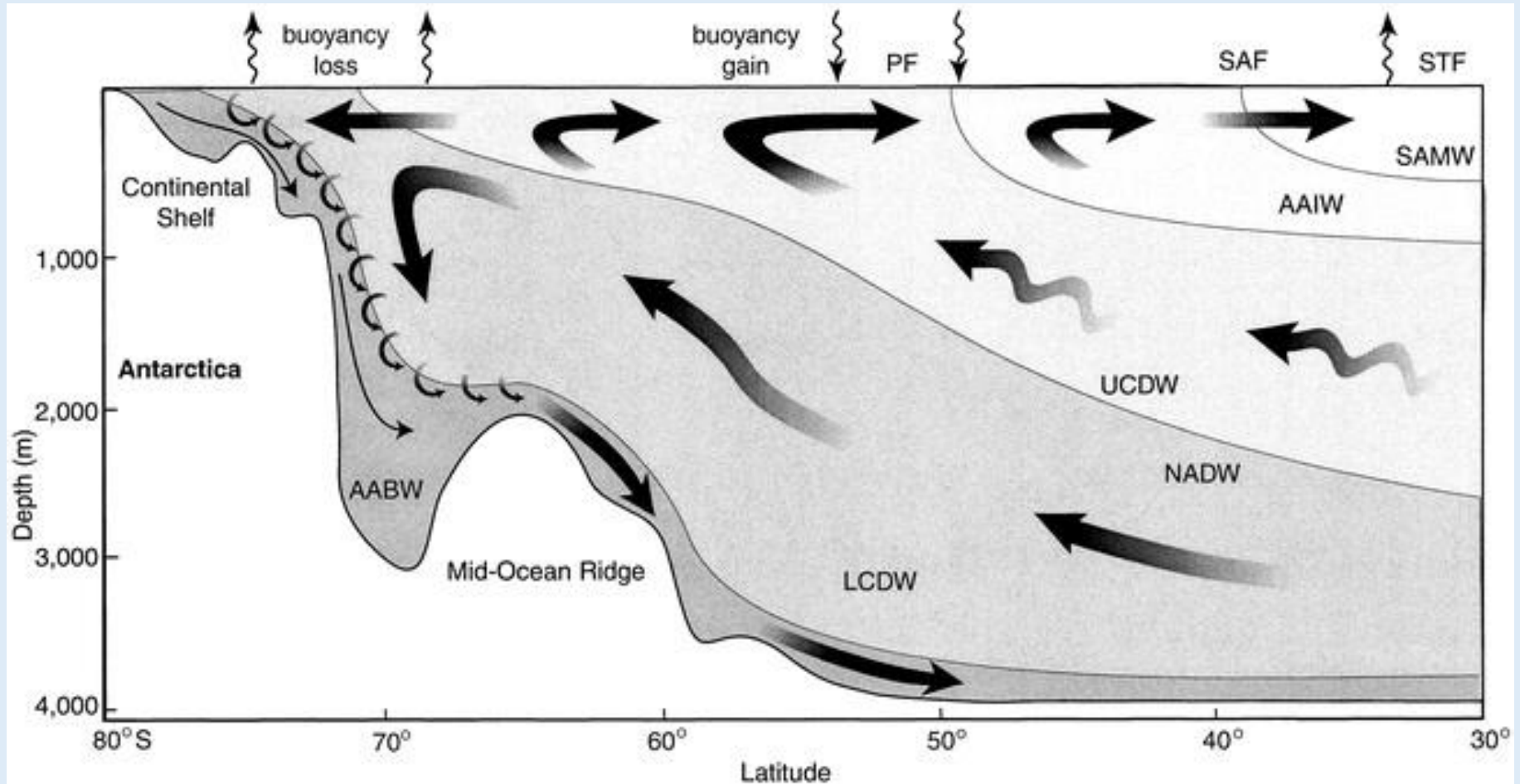
The GM Parameterization

$$\frac{\partial T}{\partial t} + (\underline{u} + \underline{u}^*) \cdot \underline{\nabla} T = \kappa \nabla_{\rho}^2 T$$

$$w^* = -\underline{\nabla} \cdot (\kappa \underline{\nabla} \rho / \rho_z), \underline{\nabla} \cdot \underline{u}^* = 0.$$

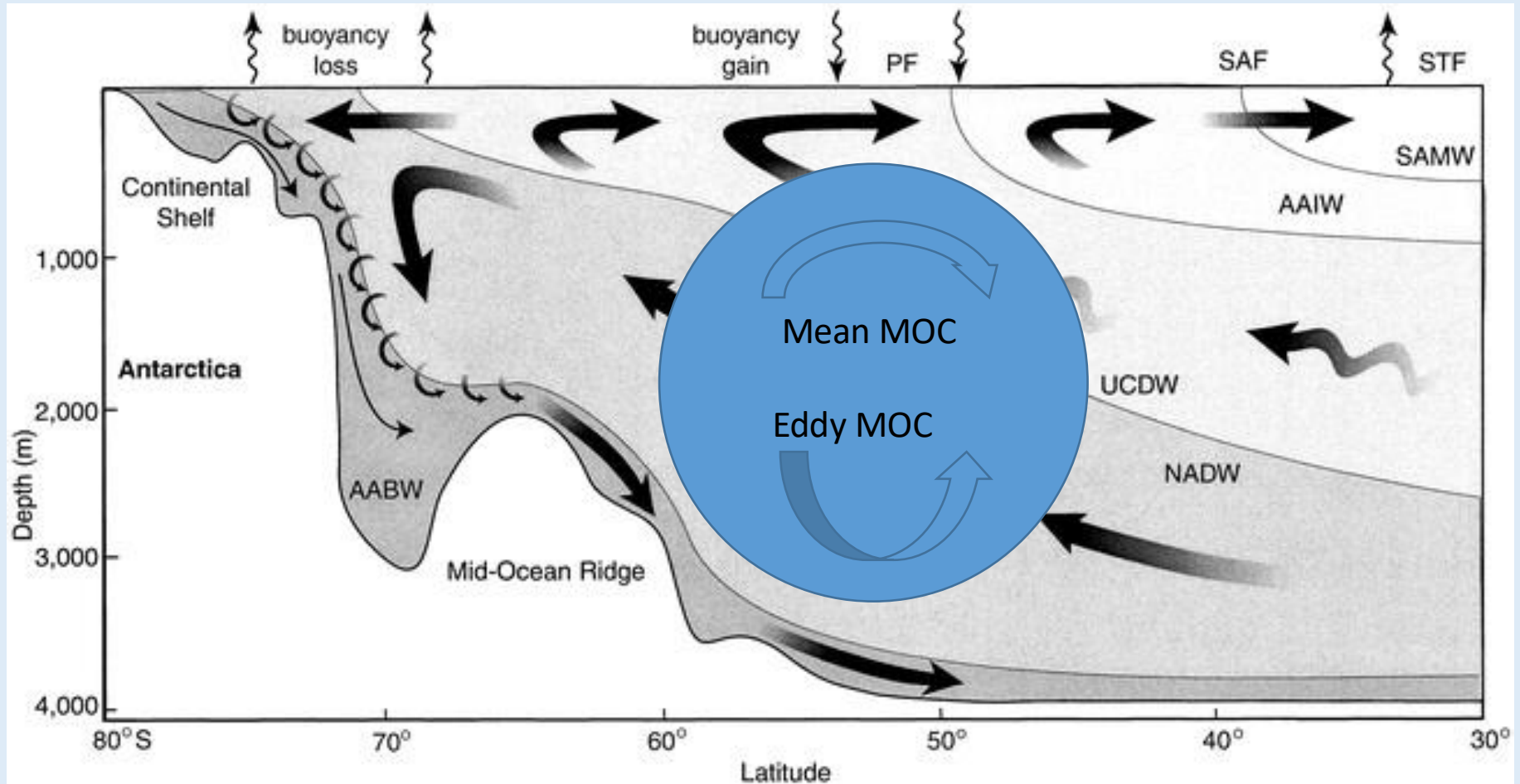
GM (1990) proposed an eddy-induced velocity $\underline{u}^*$ in addition to diffusion along isopycnal surfaces.

Southern Hemisphere zonal wind jet



Baroclinic instability produces ACC eddies that try to flatten the isopycnals and produce a MOC that opposes the mean flow MOC.

Southern Hemisphere zonal wind jet



Baroclinic instability produces ACC eddies that try to flatten the isopycnals and produce a MOC that opposes the mean flow MOC.

Impacts of GM

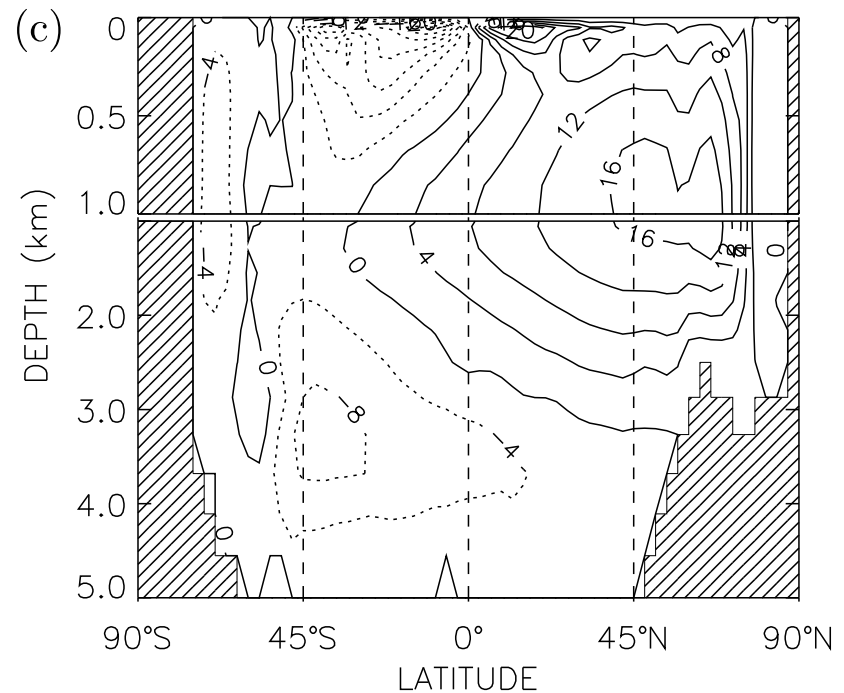
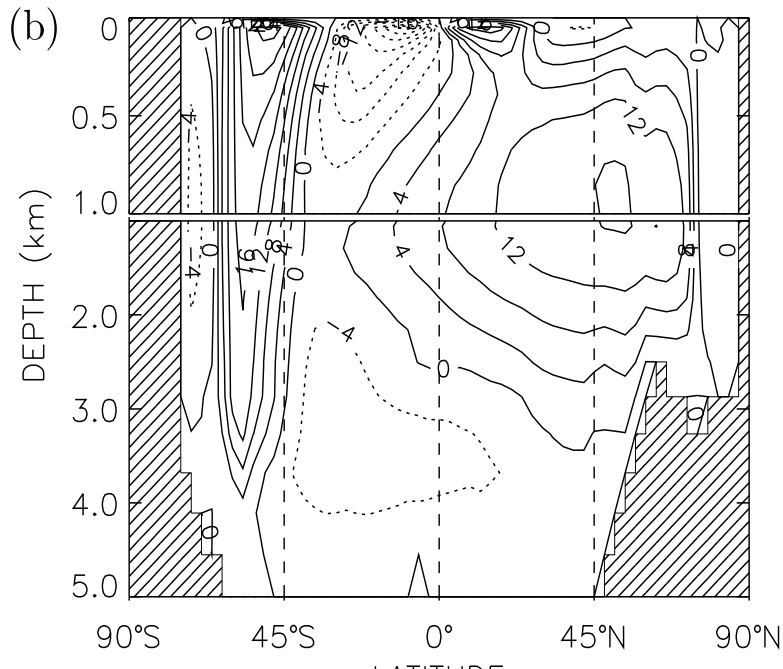
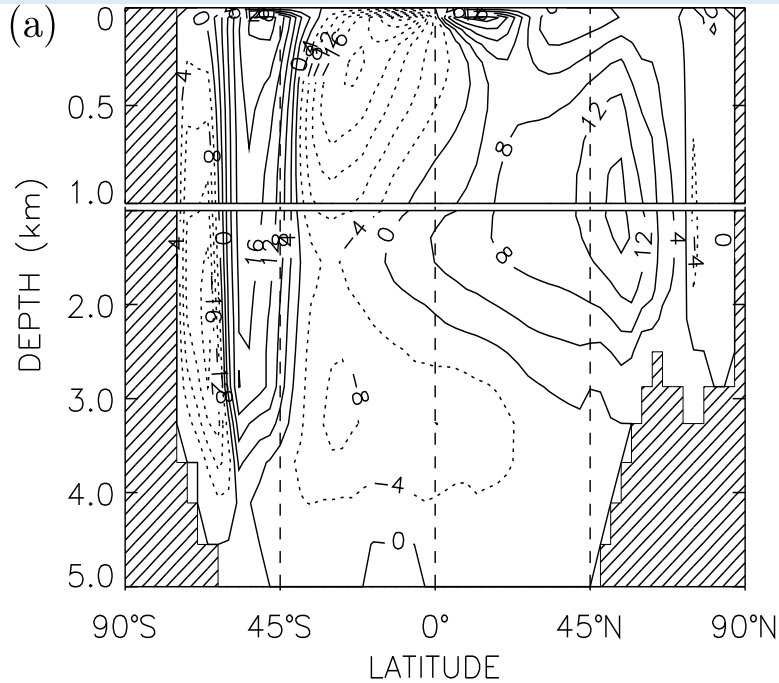
(a) Horizontal Diffusion, MOC (u)

(b) GM, MOC (u)

(c) GM, MOC ($u+u^*$)

4° x 3° x 20L NCAR CSM ocean model NCOM

Danabasoglu et al. (1994, Science)

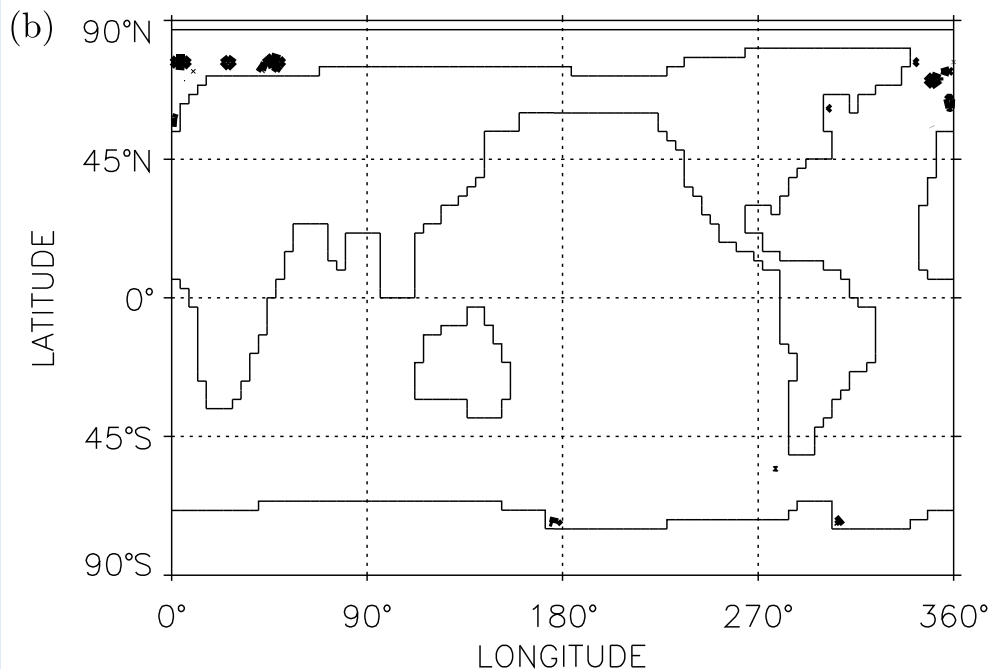
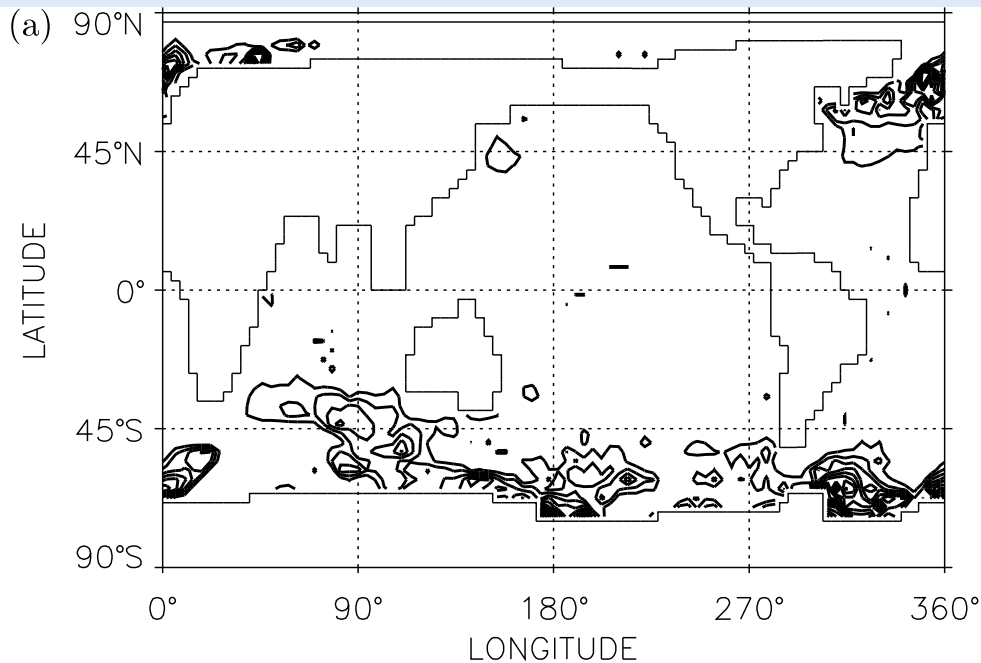


Impacts of GM

Deep Water Formation

(a) Horizontal Diffusion

(b) GM



In (b), deep water is formed only in the Greenland/Iceland/Norwegian Sea, the Labrador Sea, the Weddell Sea and the Ross Sea.

4° x 3° x 20L NCAR CSM ocean model NCOM

Danabasoglu et al. (1994, Science)

GM summary

Mimics effects of unresolved mesoscale eddies as the sum of

- diffusive mixing of tracers along isopycnals (Redi 1982),
- an additional advection of tracers by the eddy-induced velocity $\underline{u}^*$

GM scheme is adiabatic and therefore valid for the ocean interior.

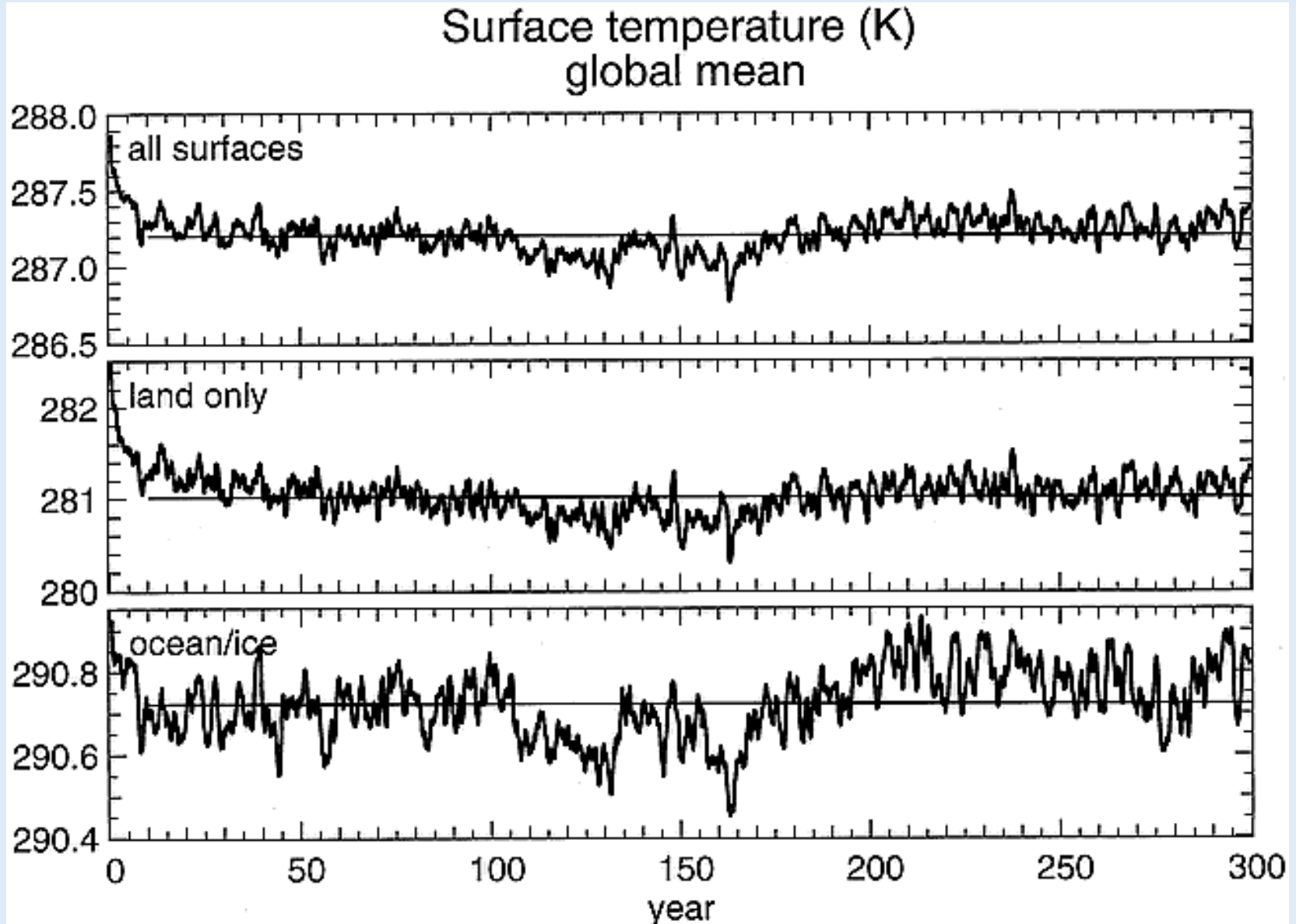
GM acts to flatten isopycnals, thereby reducing potential energy.

Eliminates any need for horizontal diffusion in z-coordinate OGCMs

➔ eliminates Veronis effect.

Implementation of GM in the ocean model NCOM was a major factor enabling stable coupled climate model simulations without “flux adjustments”.

CSM1 was the first climate model to produce a non-drifting control run without flux adjustments

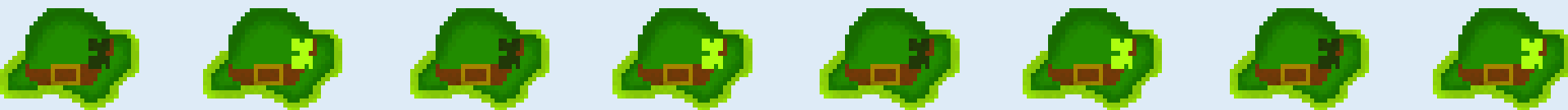




Limerick 2000



*There once was an ocean model called MOM,
Which occasionally used to bomb,
But eddy advection, and much less convection,
Turned it into a stable NCOM.*

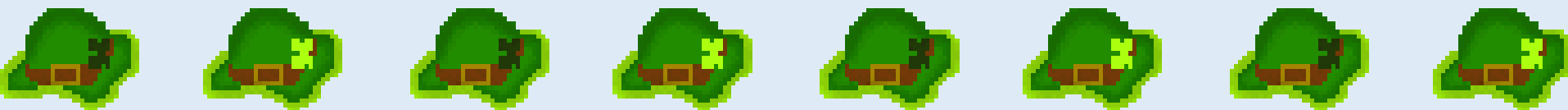




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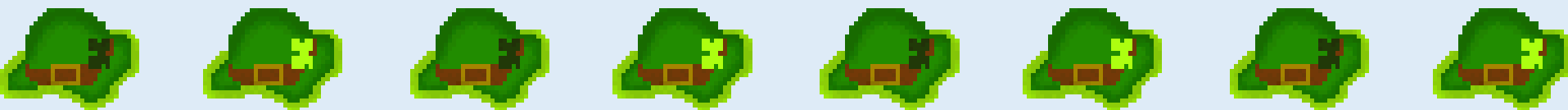




Limerick 2004



There once was an ocean model called POP,





Limerick 2004



*There once was an ocean model called POP,
Which occasionally used to flop,
But eddy advection, and much less convection,
Turned it into the cream of the crop.*

