Ocean Modeling II

Parameterized Physics

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NCAR

PARAMETERIZATIONS IN CESM2 POP2

- Vertical mixing (momentum and tracers)
  - surface boundary layer
  - interior
- Lateral mixing: mesoscale eddies (tracers)

- Horizontal viscosity (momentum)

- Overflows

- Submesoscale eddies (tracers)

- Estuary box model parameterization

- Solar absorption

VERTICAL MIXING SCHEME: K-PROFILE PARAMETERIZATION (KPP)

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

W. G. Large
J. C. McWilliams
S. C. Doney
National Center for Atmospheric Research
Boulder, Colorado

1994

• Unresolved turbulent vertical mixing due to small-scale overturning motions parameterized as a vertical diffusion.

• Guided by study and observations of atmospheric boundary layer

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

where K_x represents an "eddy diffusivity" or "eddy viscosity" and X = { 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: υ_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.

VERTICAL MIXING SCHEME:
K-PROFILE PARAMETERIZATION (KPP)

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

$$U_x(d) = U_x^s(d) + U_x^w(d) + U_x^d(d) + U_x^c(d) + U_x^t(d)$$

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

υ_x^s : (unresolved) shear instability

υ_x^w : internal wave breaking

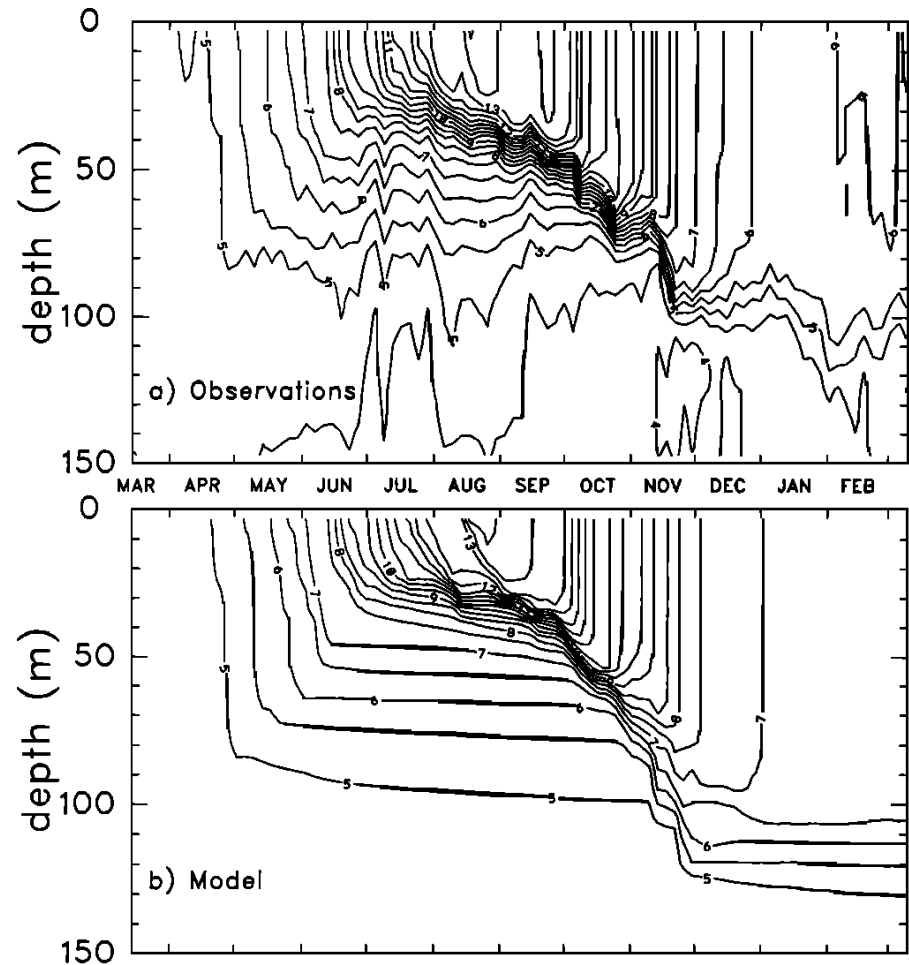υ_x^d : double diffusion

υ_x^c : local static instability (convection)

υ_x^t : tidal mixing

Superposition of processes sets interior vertical diffusivity, υ_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[†]

PETER R. GENT AND JAMES C. MCWILLIAMS

National Center for Atmospheric Research*, Boulder, Colorado

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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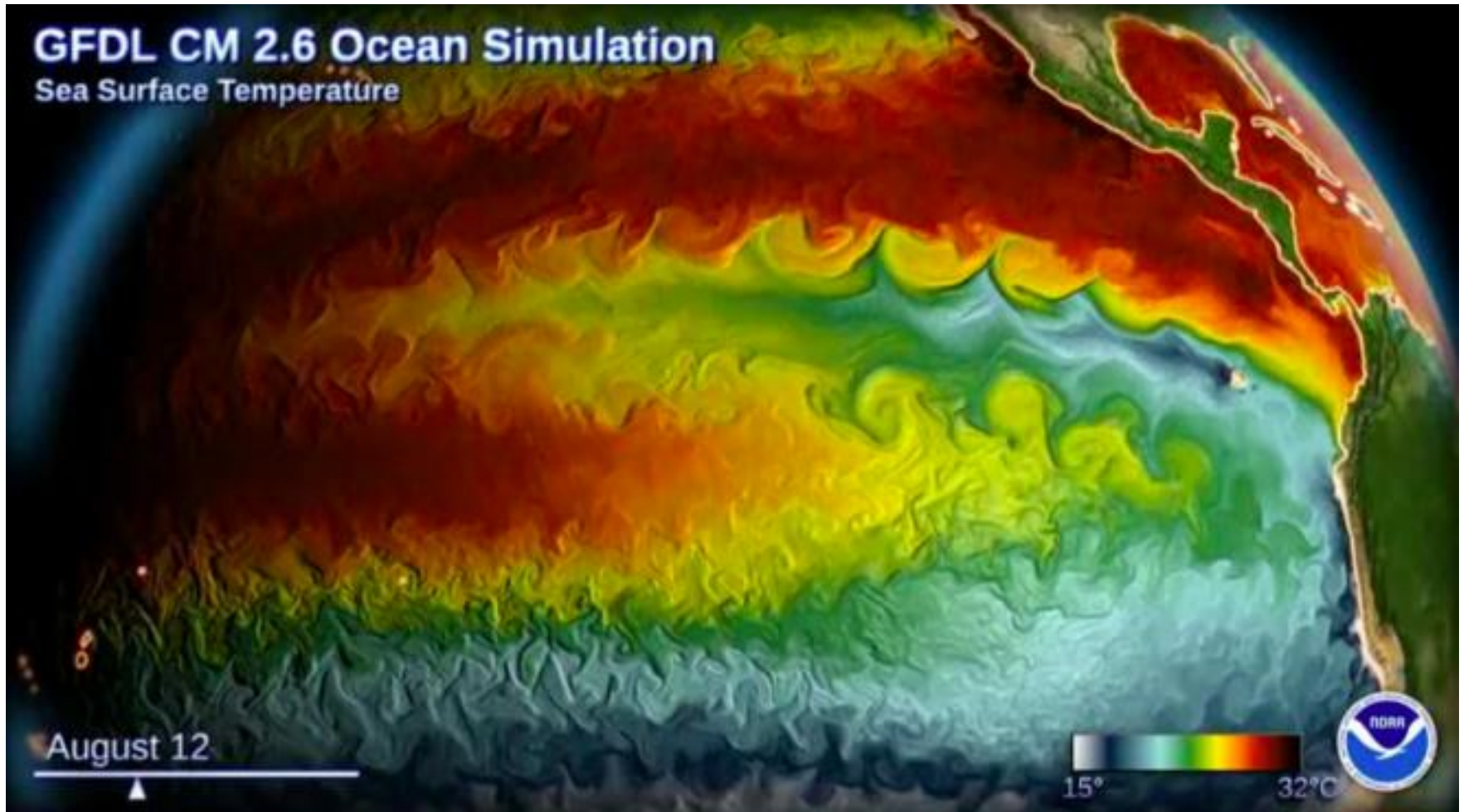
ELSEVIER

OCEAN MODELLING

The Gent–McWilliams parameterization: 20/20 hindsight

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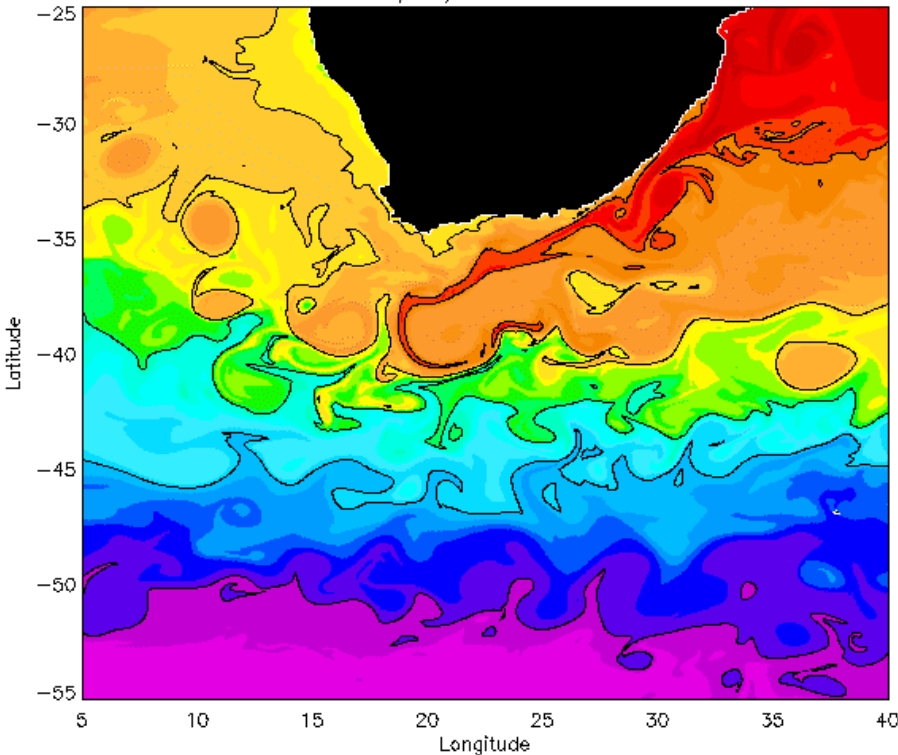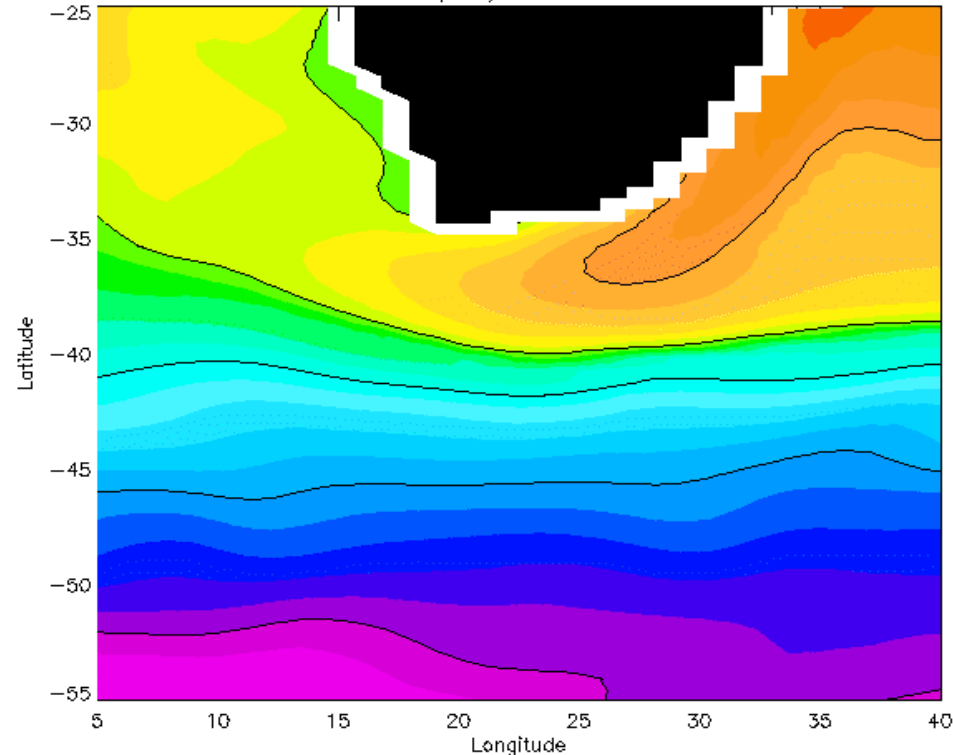
GFDL climate model with ocean resolution of 0.1°

Why is GM needed?

Agulhas Retroflection

SST 30/09/2000 0.1° Model
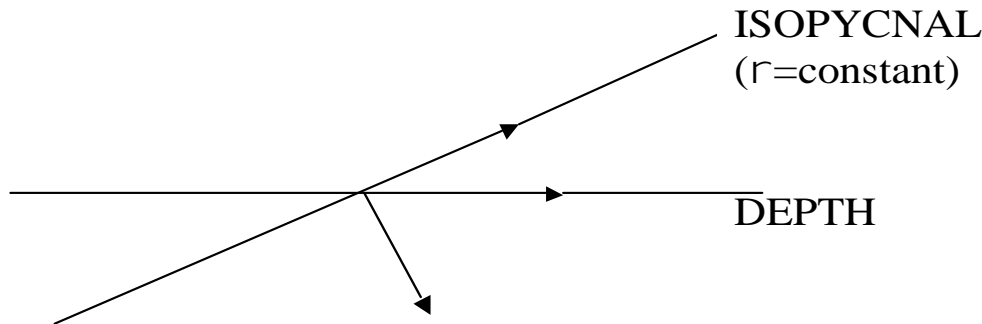
SST 30/09/2000 1° Model

O(1°) 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.

Why is GM needed?

ISOPYCNAL
(ρ=constant)

DEPTH

Isopycnal slopes are small O(10⁻³) at most

Ocean Observations suggest mixing along isopycnals is ~10⁷ times larger than across isopycnals.

• Early ocean models parameterized the stirring effects of (unresolved) mesoscale eddies by Laplacian *horizontal* diffusion with K_H = O(10³ m²/s), whereas the vertical mixing coefficient K_v = O(10⁻⁴ m²/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

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

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

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

GM impacts

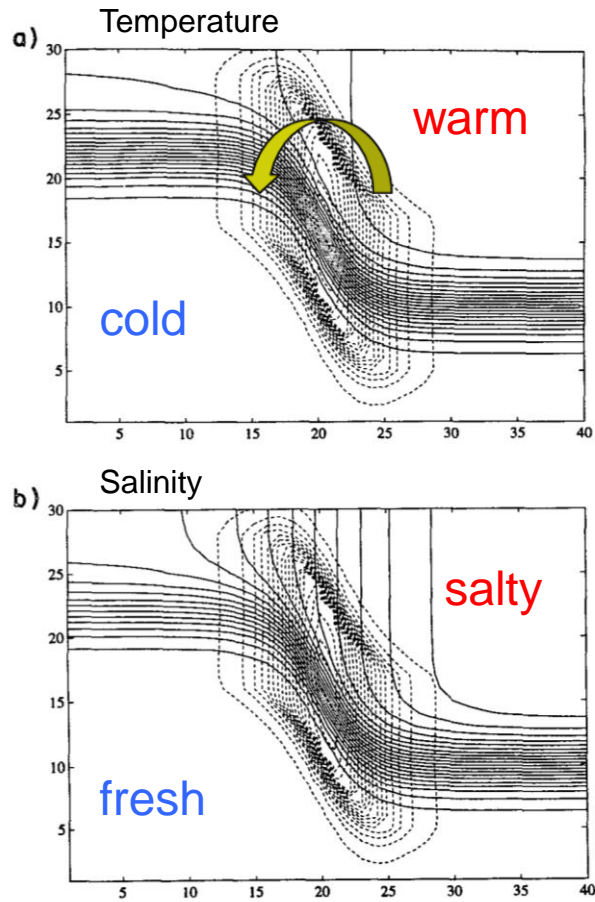Gent et al. (JPO, 1995): Eddy-induced velocity (v*,w*) acts to flatten isopycnals and minimize potential energy.

FIG. 3. Initial states of (a) temperature and (b) salt [contour interval one-quarter that of (a)]. Both panels also show the streamfunction $\kappa\rho_x/\rho_z$ for the parameterized eddy-induced transport velocity.
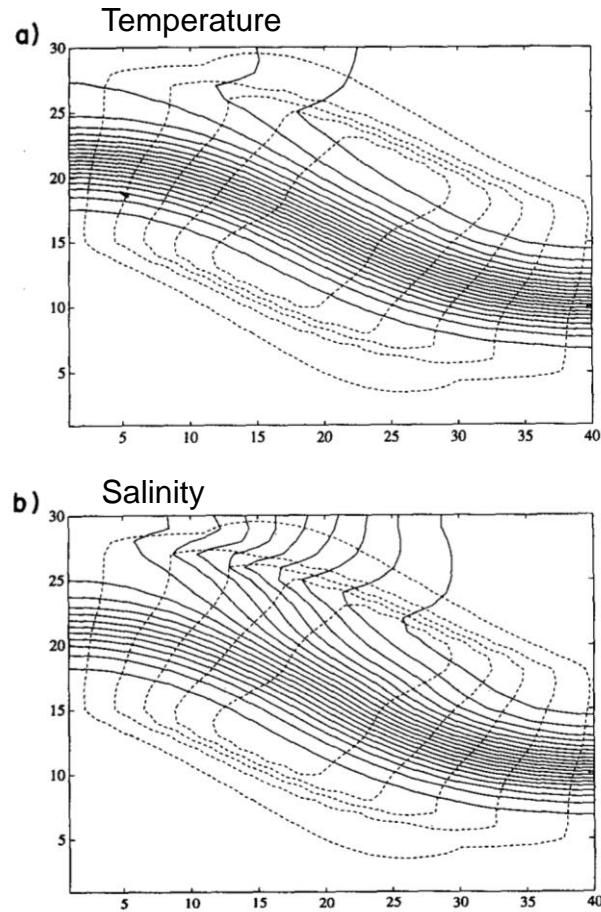
FIG. 4. Distributions of (a) temperature and (b) salt after an integration time of $20\Delta s^2/\kappa$. Both panels also show the streamfunction $\kappa\rho_x/\rho_z$ for the parameterized eddy-induced transport velocity. Contour intervals are the same as in Fig. 3.
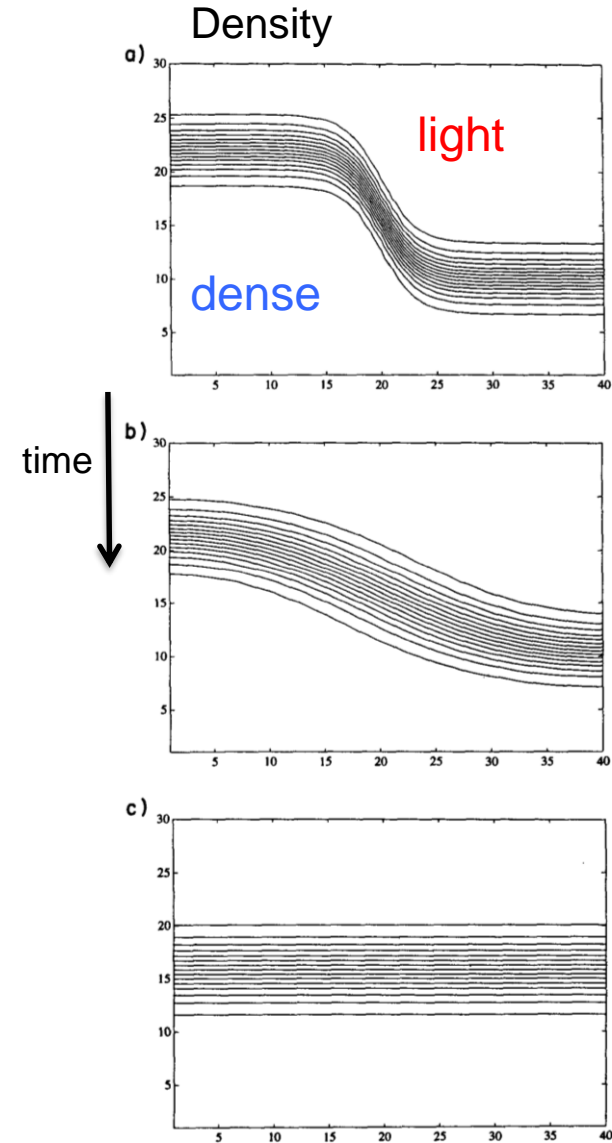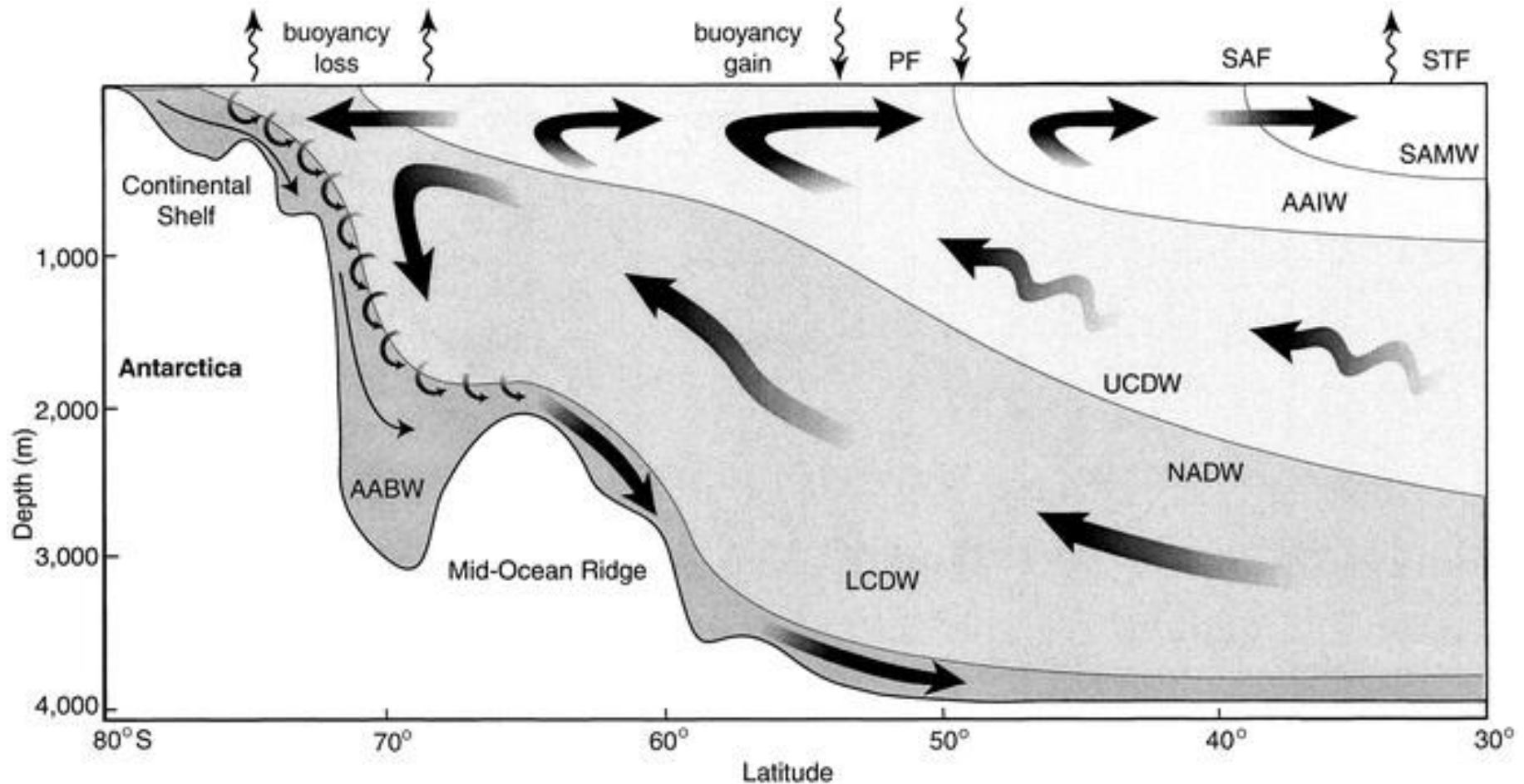
FIG. 5. Density distribution at various times of the integration. (a) Initial, (b) $20\Delta s^2/\kappa$, and (c) $1000\Delta s^2/\kappa$.
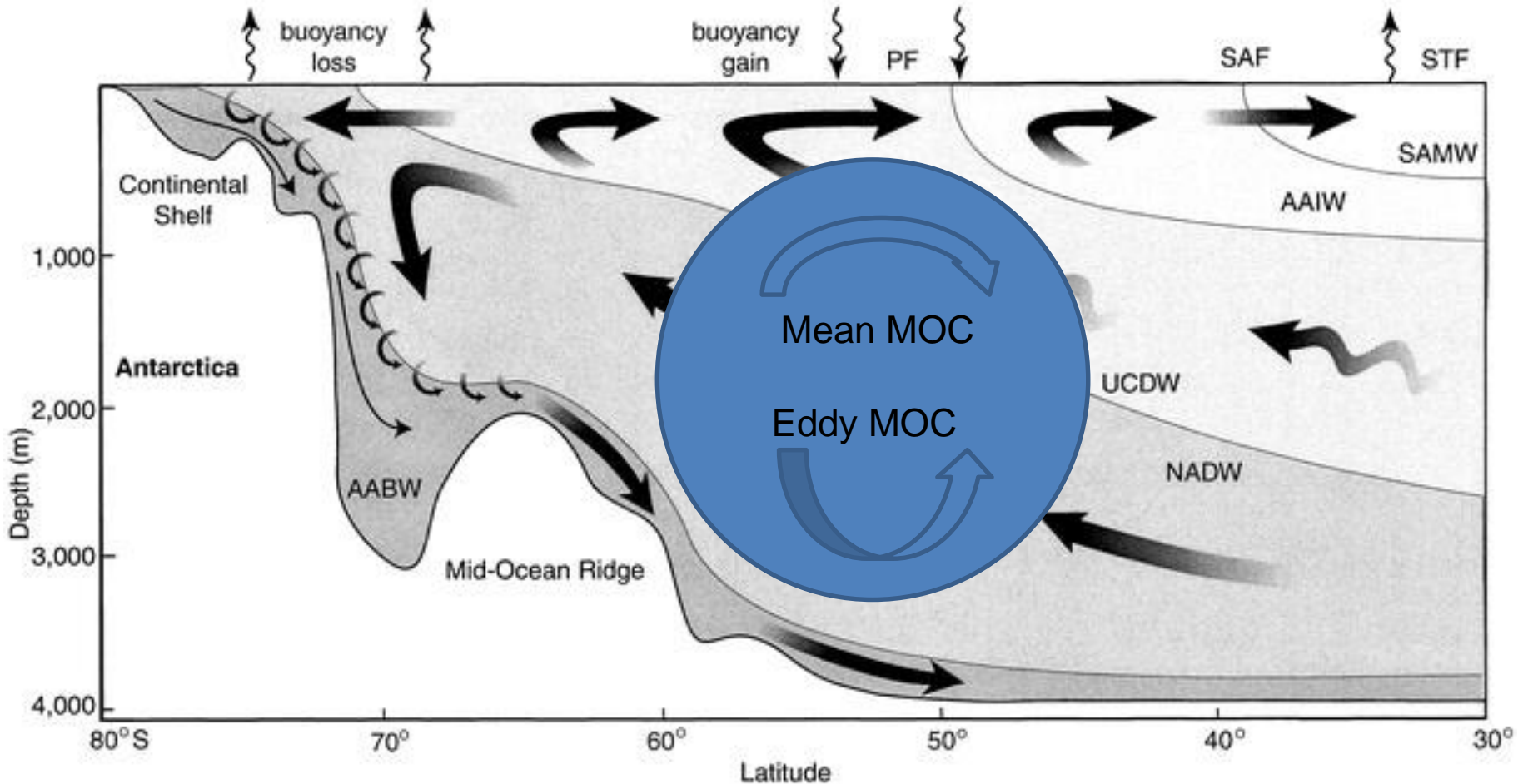
Southern Hemisphere zonal wind jet

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.
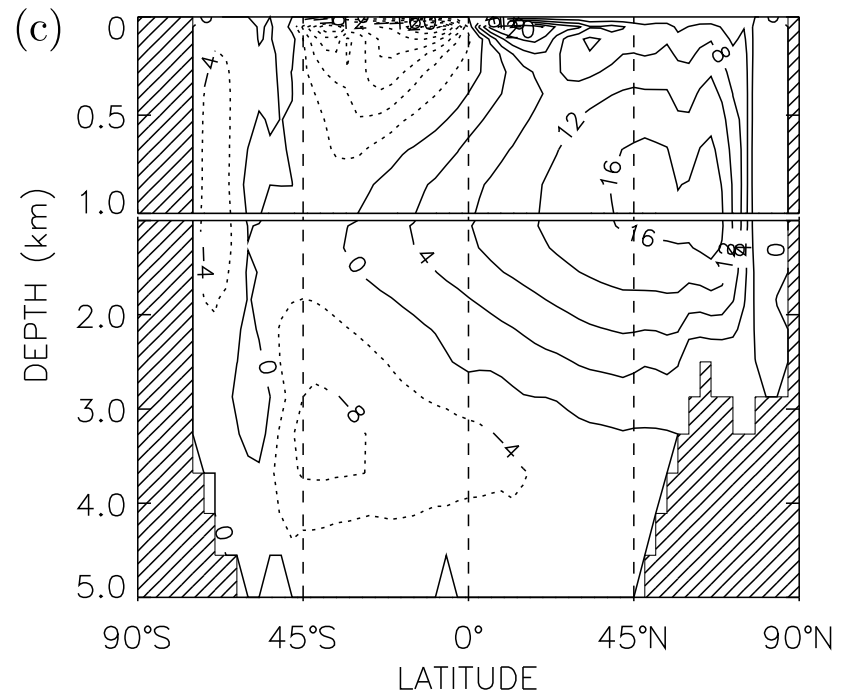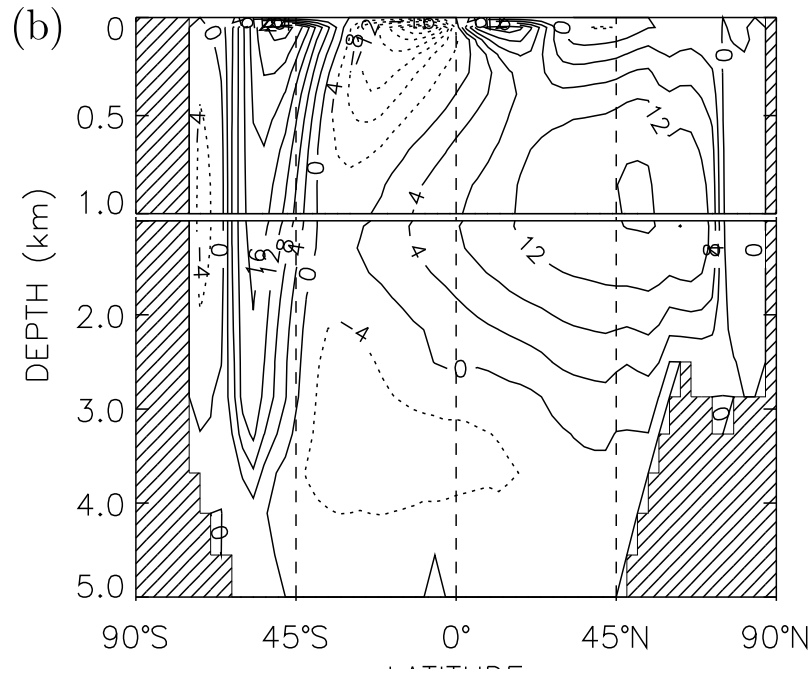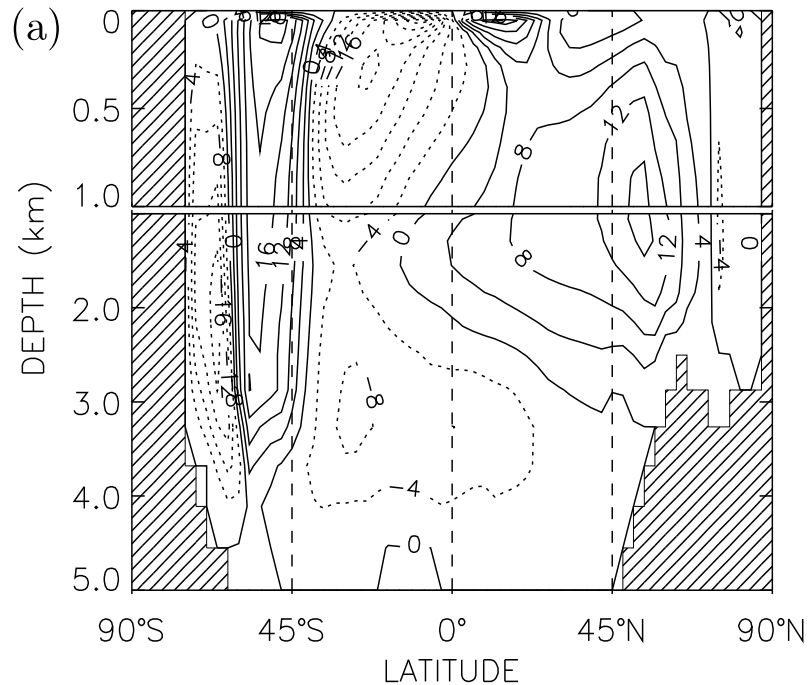
Impacts of GM

(a) Horizontal Diffusion, MOC (**u**)

(b) GM, MOC (**u**)

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

4° x 3° x 20L ocean model

Danabasoglu et al. (1994, Science)
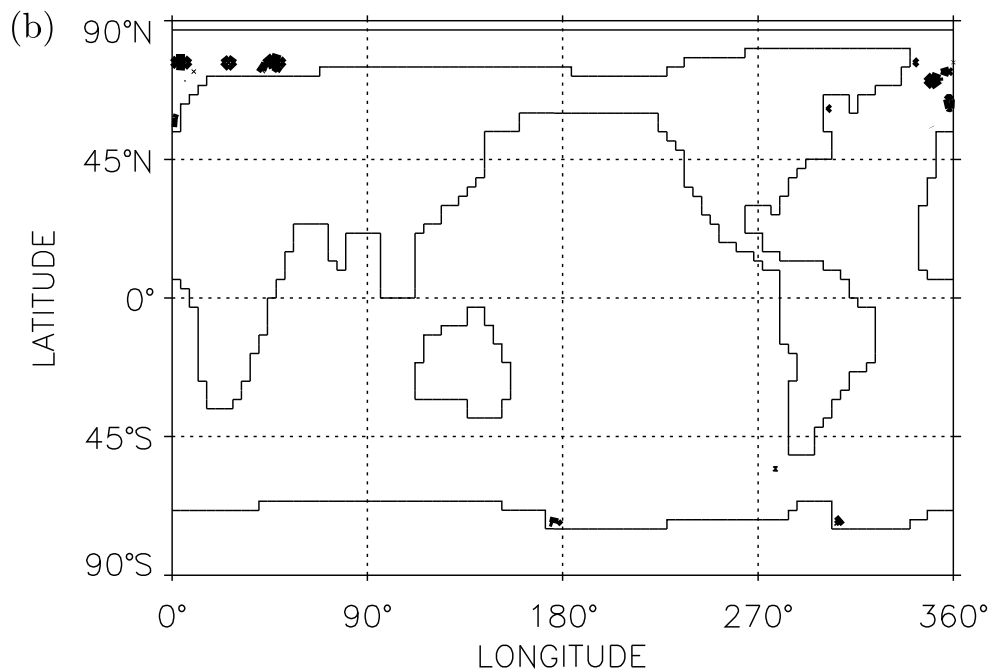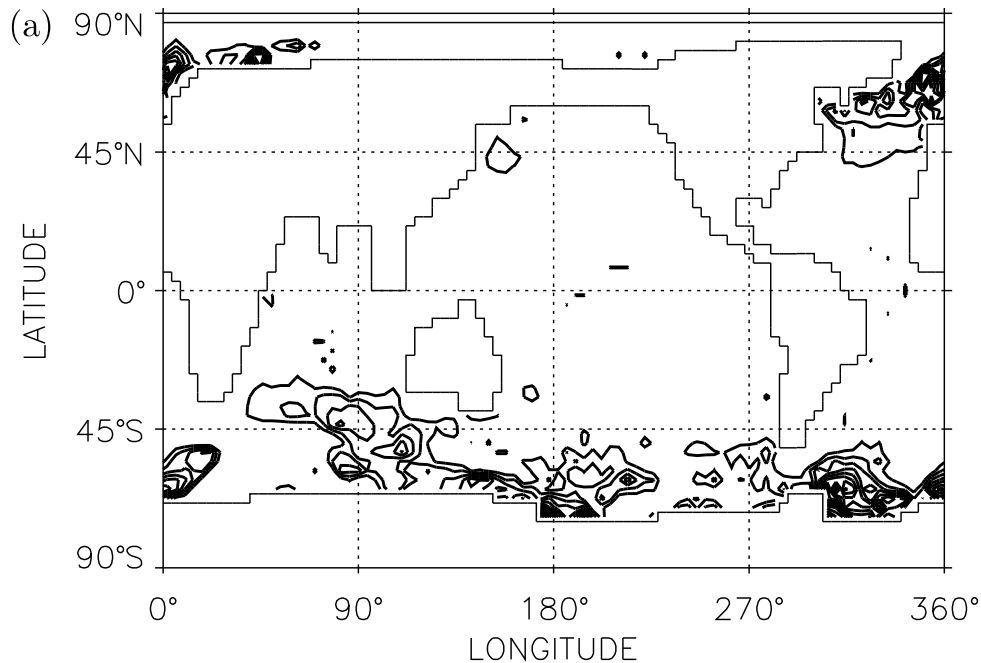
Impacts of GM

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.

$4° \times 3° \times 20L$ ocean model

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 $\underline{u}*$

Scheme is adiabatic and therefore valid for the ocean interior.

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 ocean component was a major factor enabling
     stable coupled climate model simulations without "flux adjustments".

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.