The Ocean Component of Climate Models

Peter R. Gent

National Center for Atmospheric Research

Important differences between the ocean and atmosphere

- No change of state of seawater – makes it much easier. Just form ice when temperature <-1.8^{o}C.
- The density change from top to bottom is much smaller – 1.02 to 1.04 gm/cc. This makes the Rossby radius much smaller – 100s to 10s km.
- There is extremely small mixing across density surfaces once water masses are buried below the mixed layer base. This is why water masses can be named, and followed round the ocean.

What is needed from the ocean to get climate change correctly?

- Need to get heat and CO_2 uptake correct.
- Need a good representation of the circulation, including the meridional overturning (MOC).
- Need to parameterize the effects of mesoscale eddies; they’re not resolved in climate models.
- Need a good vertical mixing scheme to get correct mixed layer depths and deep water formation in small, local regions as observed.

North Atlantic Thermohaline Circulation

or the

meridional overturning circulation

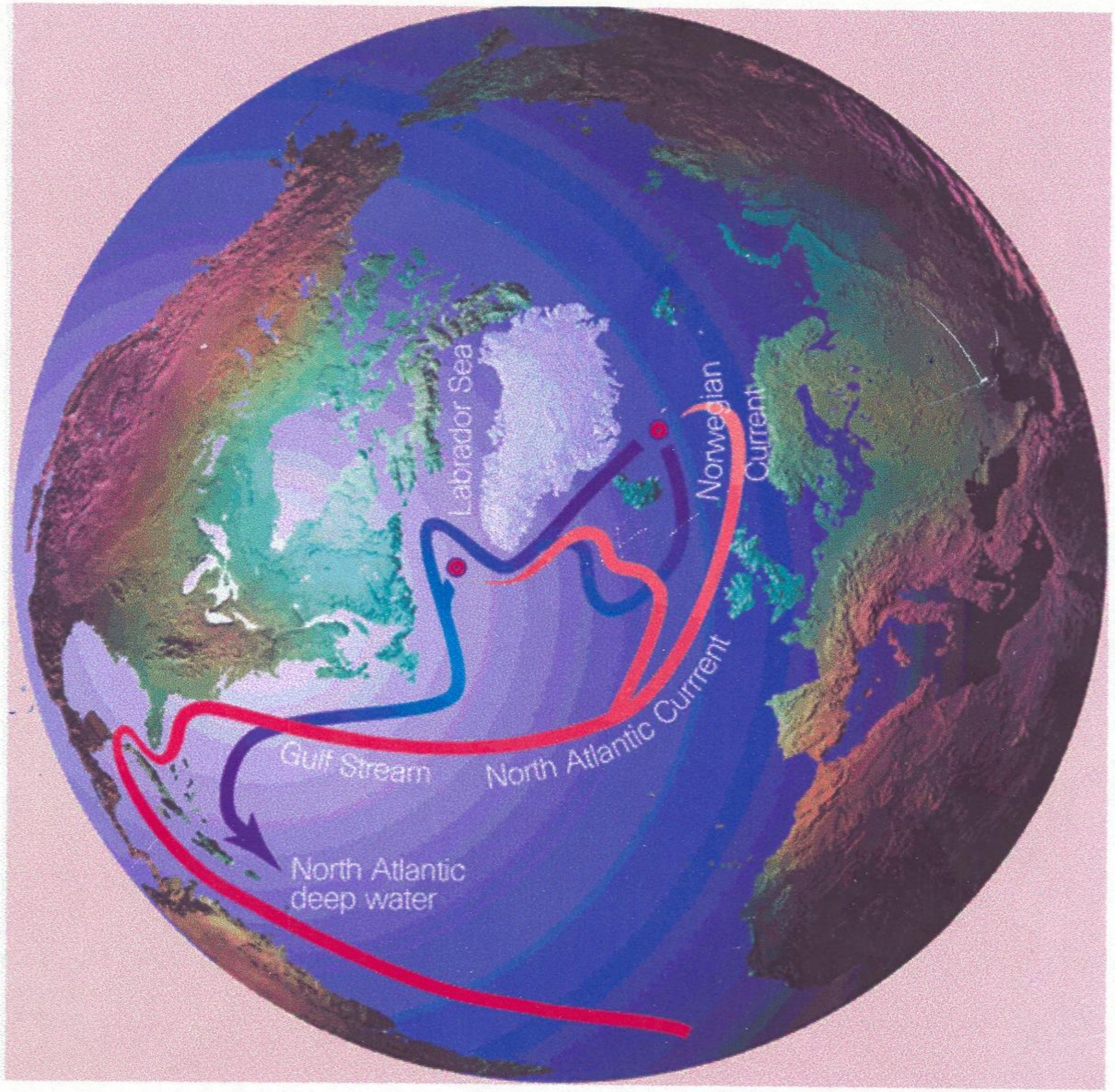


Figure 1 Simplified sketch of currents in the North Atlantic, showing the two main convection sites in the Greenland and Labrador Seas. Warm surface currents are shown in red; cold, deep currents in blue. Red–and–blue circles, convection sites.

Various Vertical Coordinates

- Depth: Traditional; most used. Advantageous near the surface, but requires extra work in deep ocean to calculate the density surfaces.
- Density: Advantageous in deep ocean, but problematic near the surface where density layers appear and disappear over the year.
- Sigma: Large pressure gradient errors because depths vary by a factor of 100. Still need to calculate the deep density surfaces. Mostly used for coastal ocean models, not global models.

PRIMITIVE EQUATIONS

$$\frac{D}{Dt}\mathbf{u} + f\mathbf{k} \times \mathbf{u} + \nabla p = \nu_H \; \nabla^2 \mathbf{u} + \nu_V \; \mathbf{u}_{zz}$$

where

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla + w \frac{\partial}{\partial z}$$

Hydrostatic $\quad p_z + g\rho/\rho_0 = 0$

Continuity $\quad \nabla \cdot \mathbf{u} + w_z = 0$

Temperature $\quad \frac{D}{Dt}\theta = \kappa_H \; \nabla^2 \theta + \kappa_V \; \theta_{zz}$

Salinity $\quad \frac{D}{Dt}S = \kappa_H \; \nabla^2 S + \kappa_V \; S_{zz}$

Eqn of State $\quad \rho = \rho(p, \theta, S)$

Comments on the equations

- Continuity: can't deform seawater, so what flows into a control volume must flow out.
- Eqn of state: density dominated by T in upper tropical ocean; by S at high latitudes and deep.
- Hydrostatic: when ocean becomes statically unstable ($\rho_z > 0$) => vertical overturning should occur, but cannot because vertical acceleration has been excluded. This mixing is accomplished by a very large coefficient of vertical diffusion.

Anisotropic Horizontal Viscosity

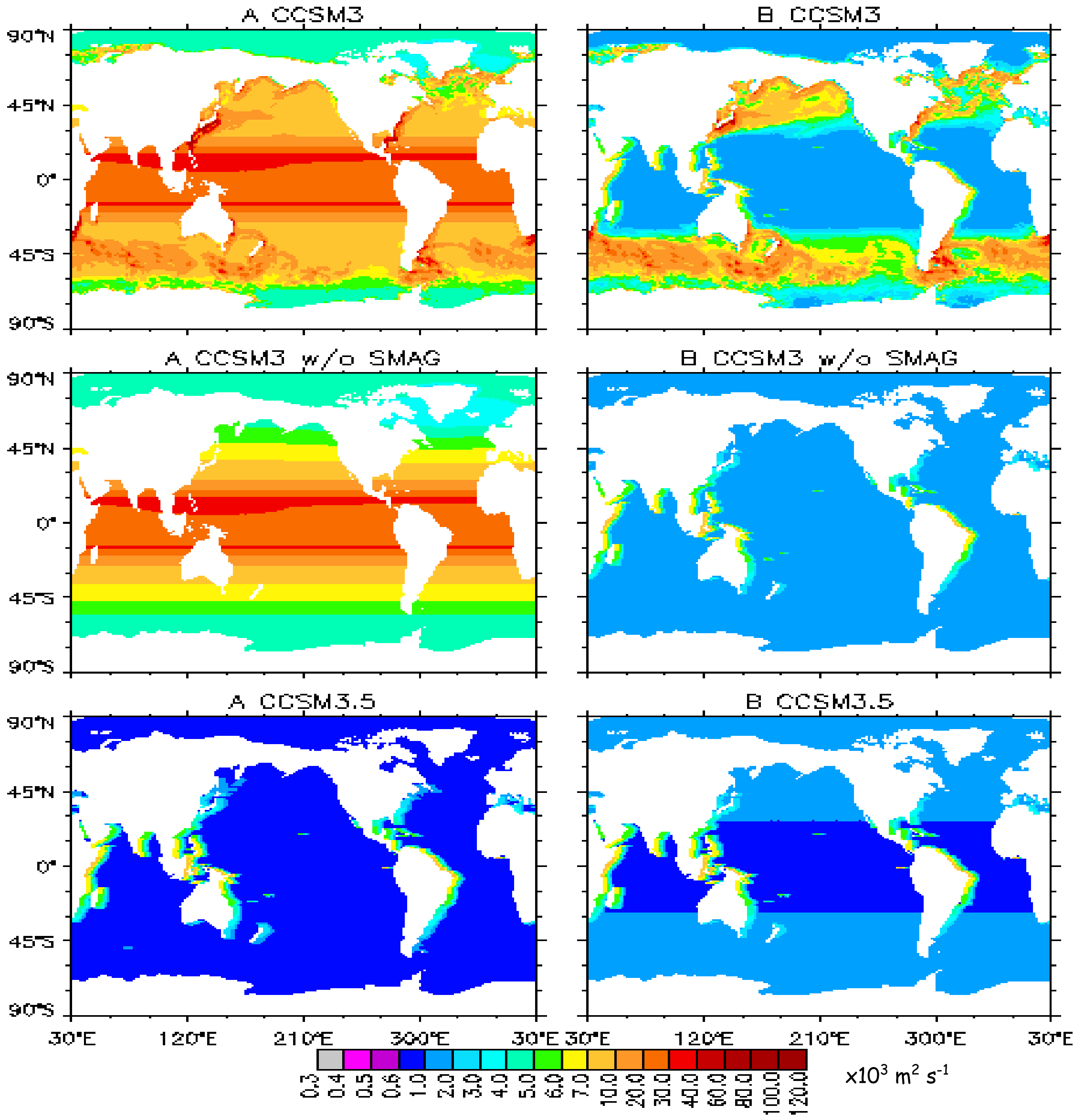
$$\partial_t u + \ldots = \partial_x (A \partial_x u) + \partial_y (B \partial_y u)$$

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

Need to have B very small near the equator where there are fast, thin zonal currents; e.g. the equatorial undercurrent. If B is too large, then this current becomes too wide and slow.

A,B viscosity coefficients at 100 m.

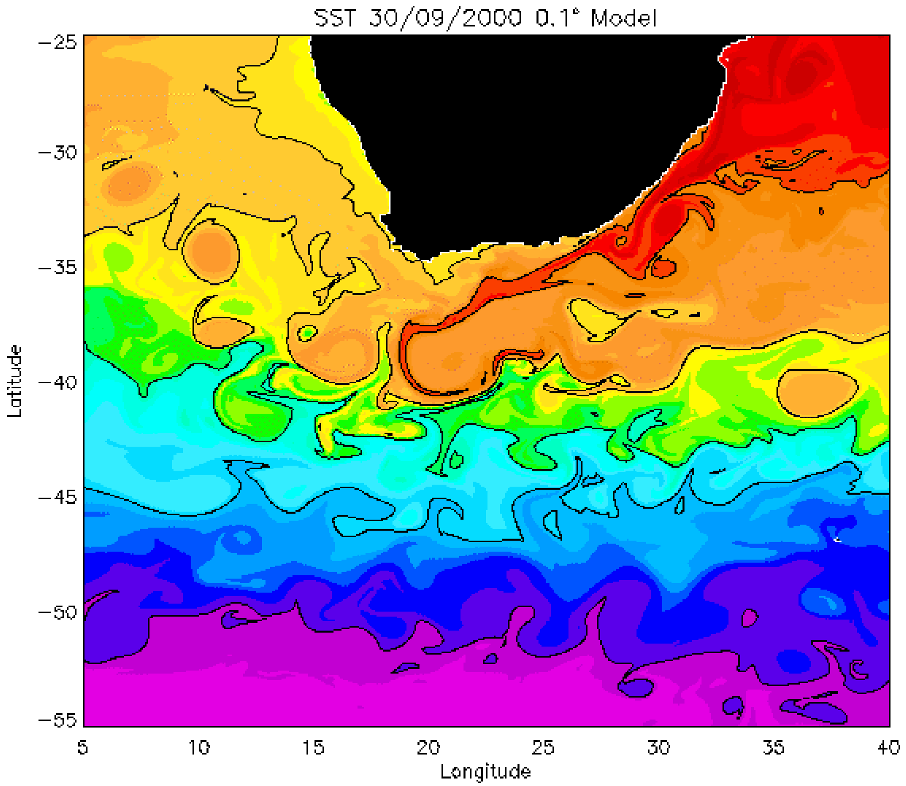
The values are much larger in the old CCSM3 than in the newer versions 3.5 and CCSM4.

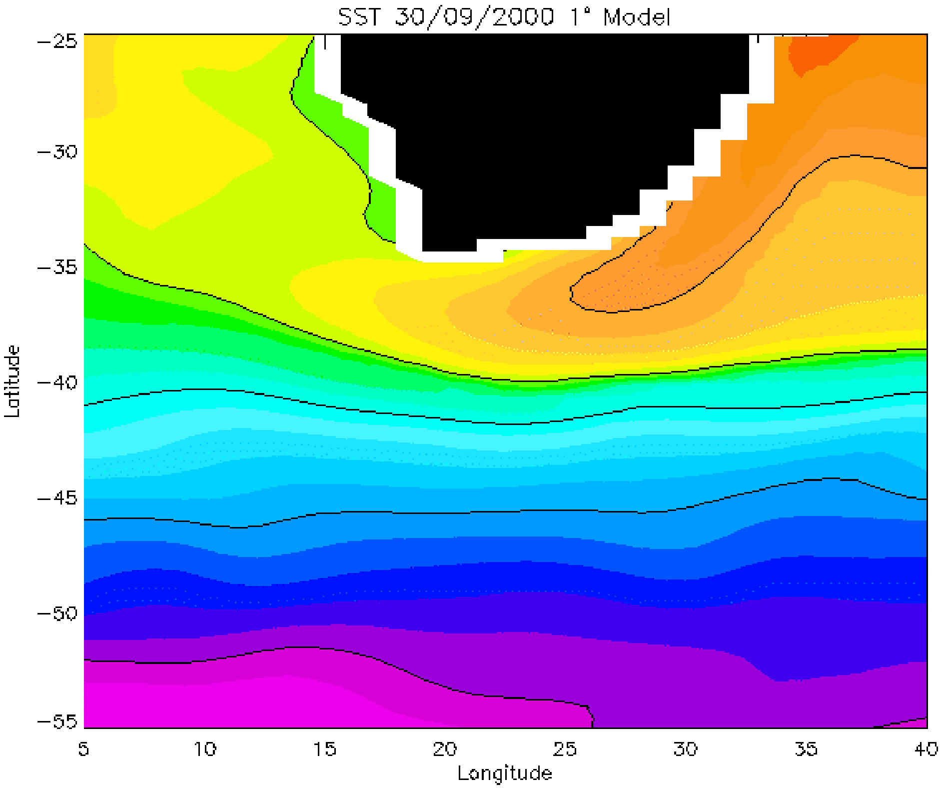


Vertical Mixing Scheme

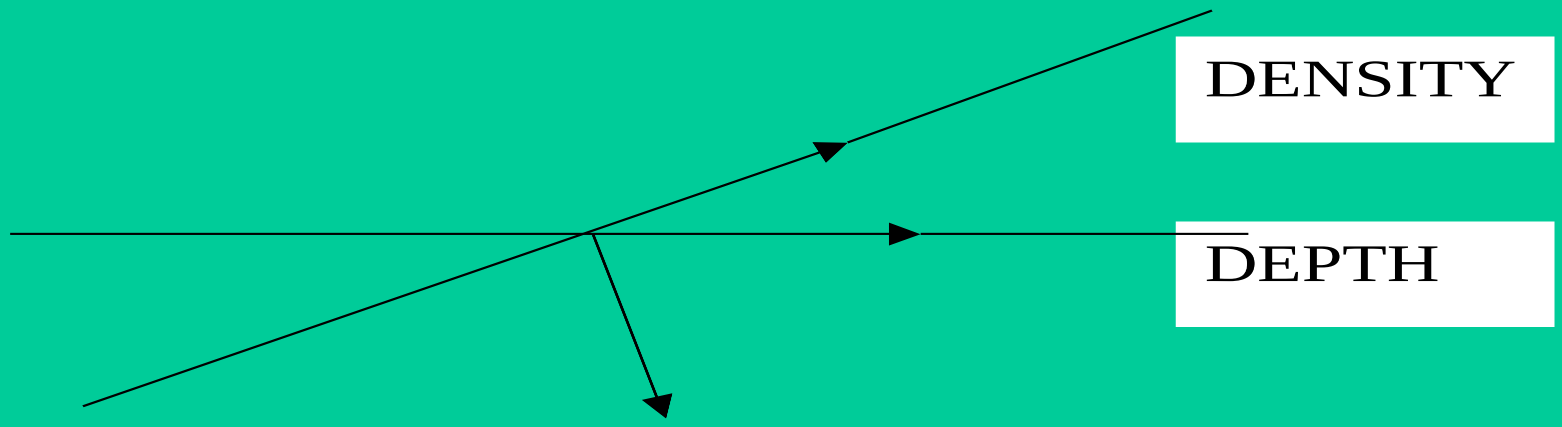
- CCSM and some other models use the K-Profile Parameterization scheme of Large et al (1994).
- It has large mixing in the upper ocean due to several processes, dominated by wind forcing, and very much weaker mixing in the deeper ocean due to processes such as inertial wave breaking and the ocean tides.
- It is a non-local scheme in the vertical.
- The momentum eqn vertical mixing coefficient is always taken to be 10x tracer mixing coefficient.

Aghulas Retroflection





How are eddy effects to be parameterized in 1º model?



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

McDougall and Church, JPO (1986)

Diffusion along density surfaces

Cox (1987) implemented diffusion along density surfaces, using the small slope approximation:

$$\frac{\partial T}{\partial t} + \underline{u}.\underline{\nabla} T = \underline{\nabla}_{\rho}.(\kappa \underline{\nabla}_{\rho} T)$$

However, in long climate runs the model would fail, often near the ACC (Antarctic Circumpolar Current), and horizontal diffusion with a small coefficient was used to make the model stable.

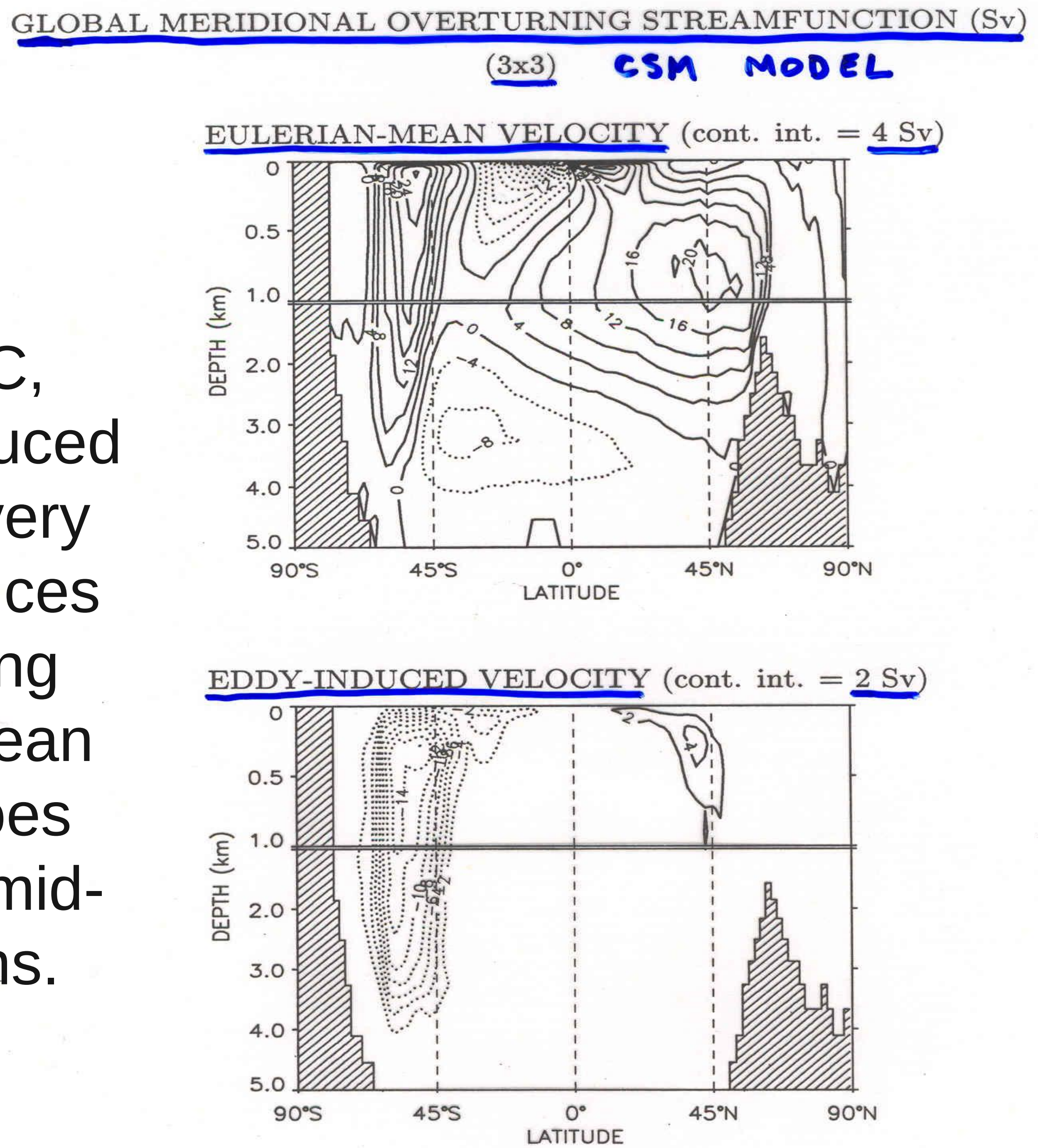
The Gent and McWilliams eddy parameterization

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

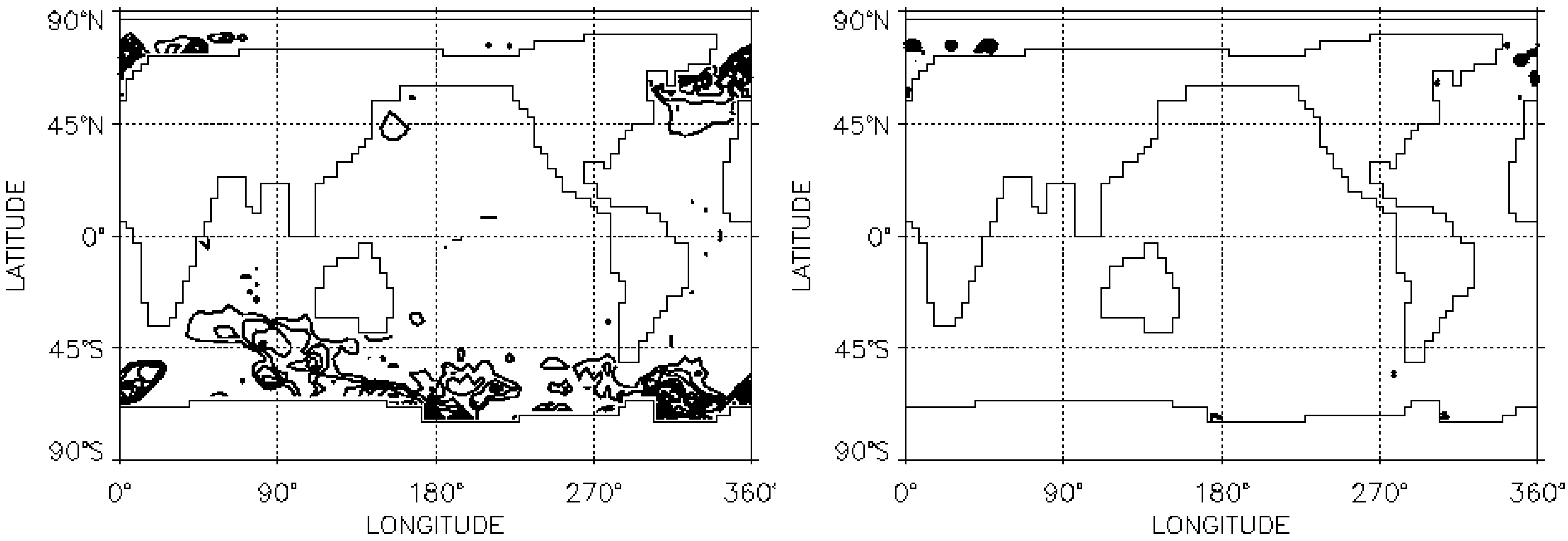
$$w^* = -\underline{\nabla}.(\kappa \underline{\nabla} \rho / \rho_z), \underline{\nabla}.\underline{u}^* = 0.$$

GM 90, Gent et al 95 proposed that eddies advect, as well as diffuse, tracers. The form of the eddy-induced velocity, u*, v*, w*, was chosen because it ensures a global sink of potential energy.

Near the ACC, the eddy-induced overturning very closely balances the overturning due to the mean flow. This does not occur in mid-latitude basins.



Deep Water Formation $3° \times 3°$

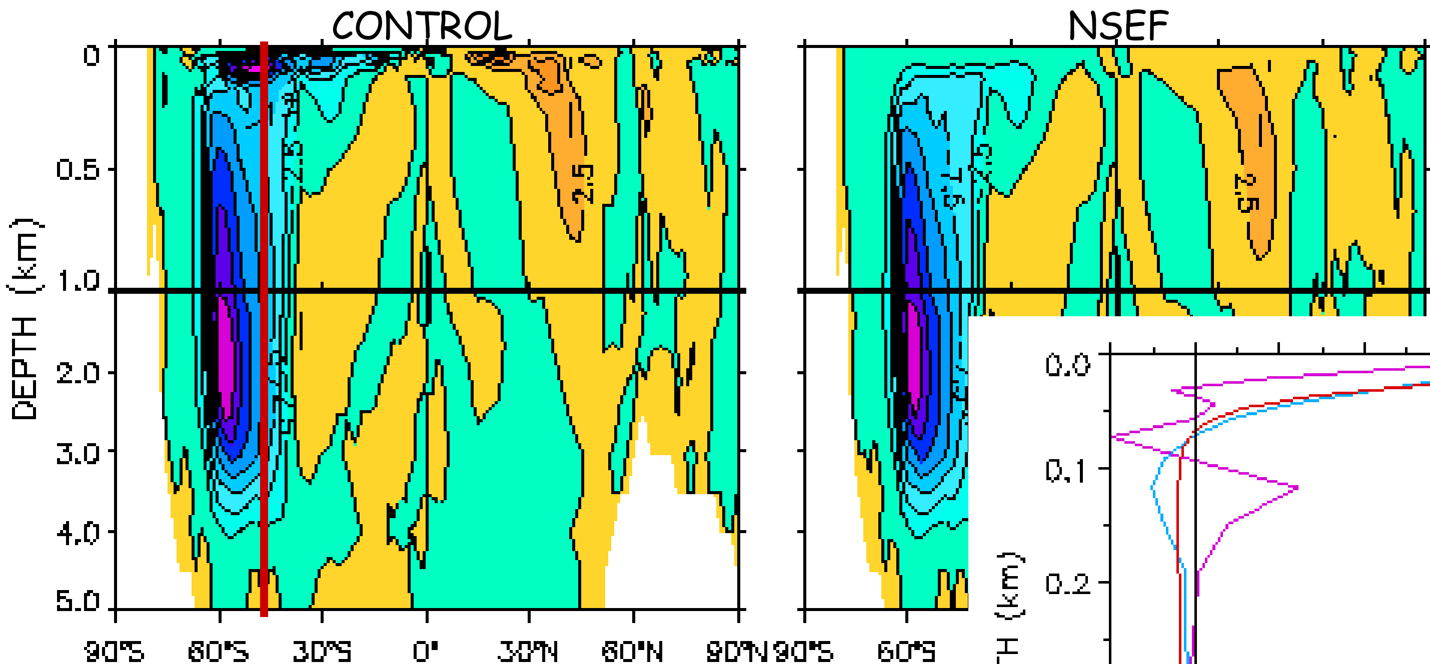


Horizontal Mixing GM 1990

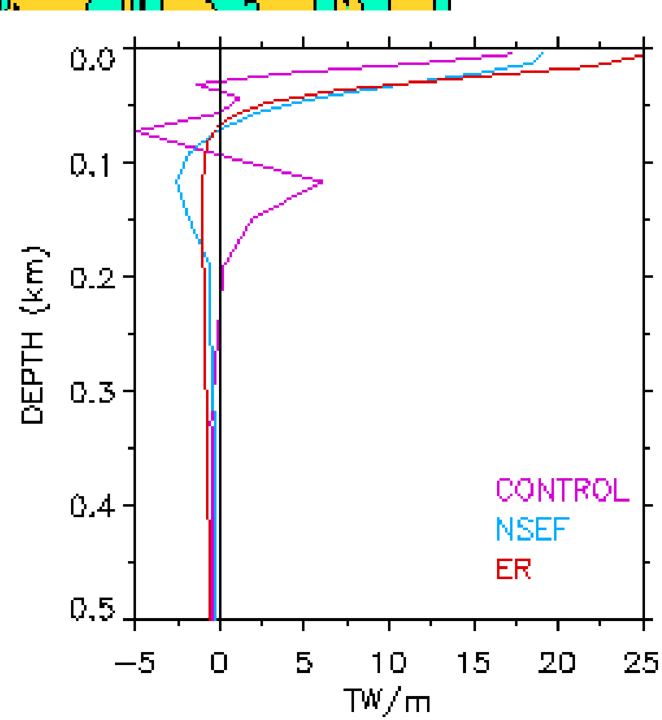
Danabasoglu et al. 1993

Near-surface eddy flux (NSEF) scheme (Ferrari & McWilliams, 2007)

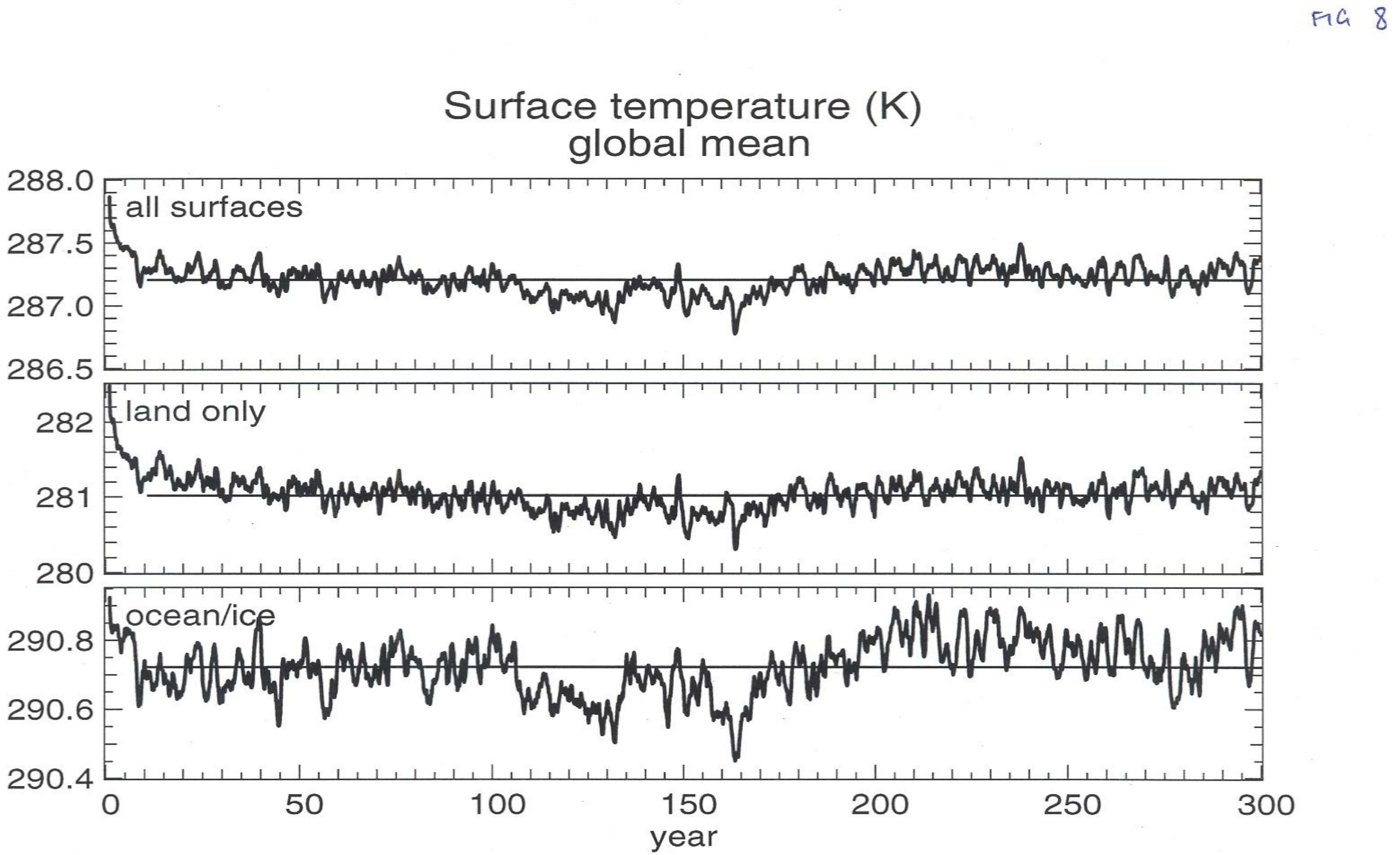
EDDY-INDUCED MERIDIONAL OVERTURNING (GLOBAL)



Vertical profile of zonally-integrated total advective heat flux at 49°S



CSM 1 was the first climate model to produce a non-d r i f t i n g c o n t r o l r u n w



Comments

- In 1996, the CSM 1 was the first climate model to run without flux correction, and maintain a reasonable present day climate.
- Other climate models with GM ran without, or with much smaller, flux corrections.
- A paper documenting the no flux correction result of CSM 1 was rejected by *Science*.
- By now, the large majority of climate models run without flux corrections.

THE END