Understanding the buoyancy-driven circulation

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Modelling climate change

Use general circulation models (GCMs)

e.g., double CO_2 and measure temperature change

But models parameterize processes, like:

- Sub-grid scale dissipation
- Tracer mixing
- Air-sea coupling
- Boundary conditions

Which approach is right? Why do different models give different results?

Idealized models

Take a simplified system, and examine its dependencies (e.g. boundary conditions) thoroughly

- Improve the GCMs
- Write simplified climate models
- Understand the physics

Idealized models

1) Meridional overturning circulation

2) Wind-driven oceanic variability

Global heat transport

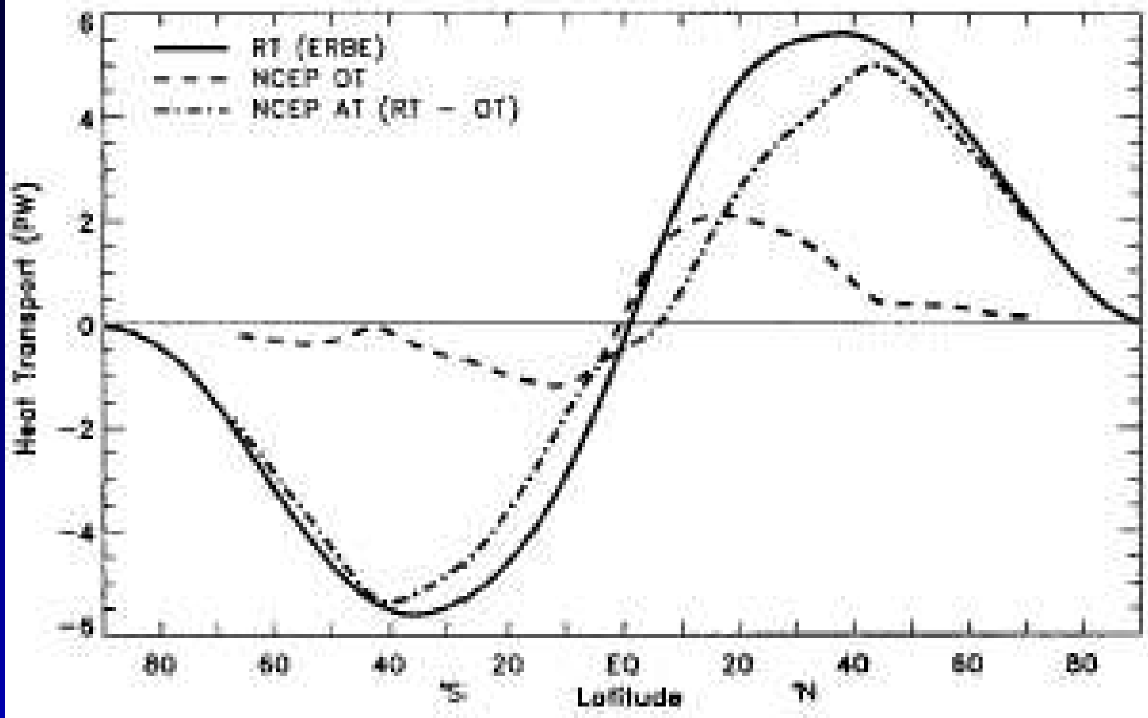


FIG. 7. The required total heat transport from the TOA radiation RT is compared with the derived estimate of the adjusted ocean heat transport OT (dashed) and implied atmospheric transport AT from NCEP reanalyses (PW).

Trenberth and Caron, 2001

Oceanic heat transport

2001 TRENBERTH AND CARON

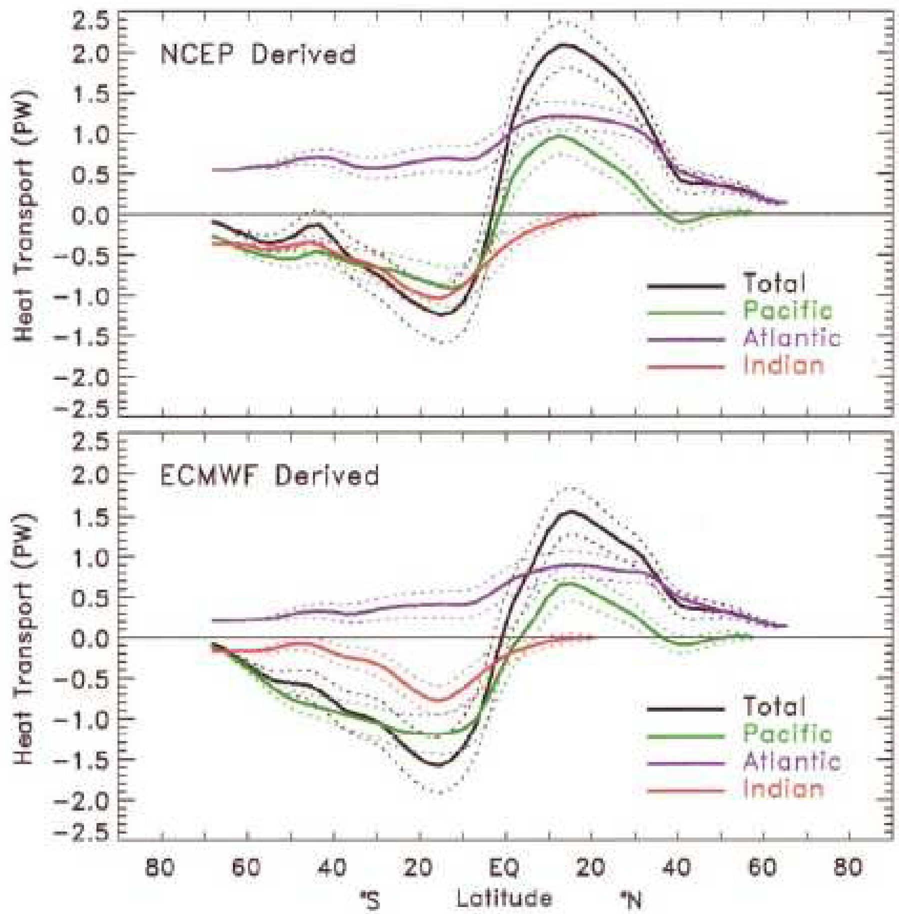


FIG. 5. Implied zonal annual mean ocean heat transports based upon the surface fluxes for Feb 1985–Apr 1989 for the total, Atlantic, Indian, and Pacific basins for NCEP and ECMWF atmospheric fields (PW). The 1 std err bars are indicated by the dashed curves.

Trenberth and Caron, 2001

Mean vs. eddies

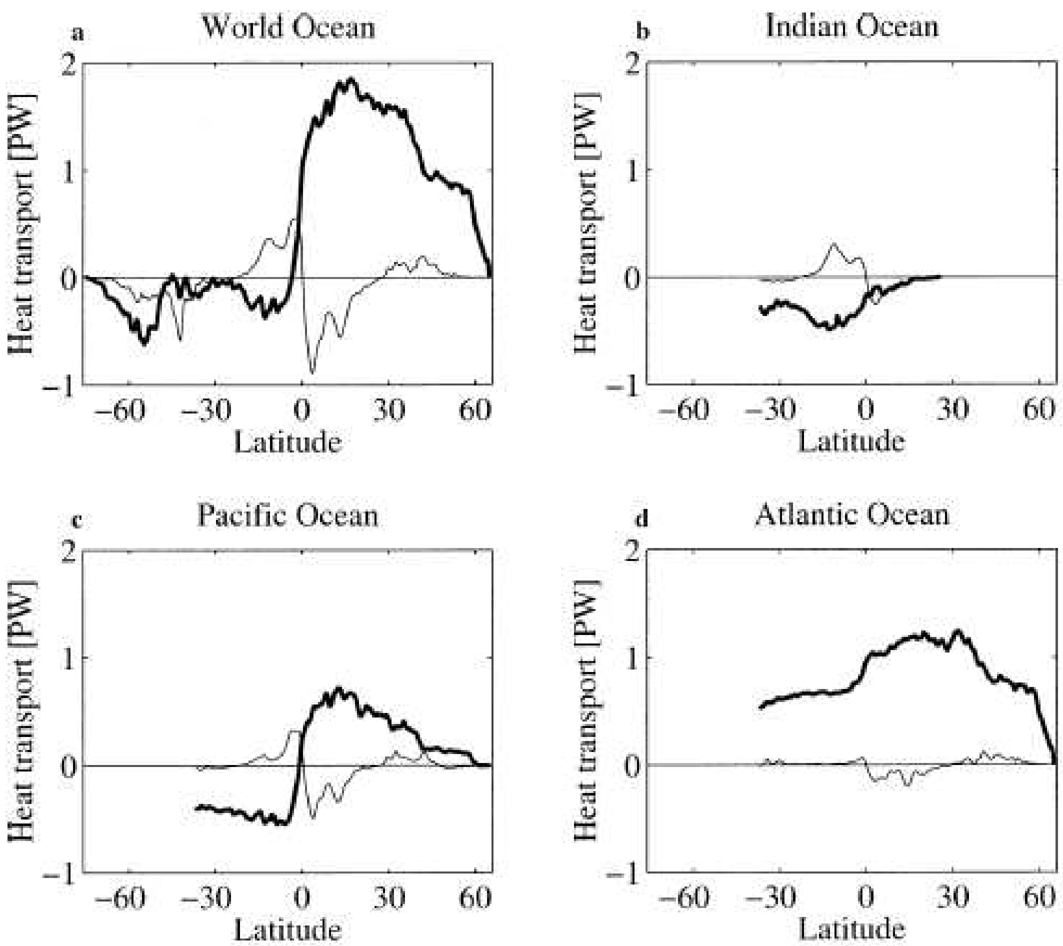
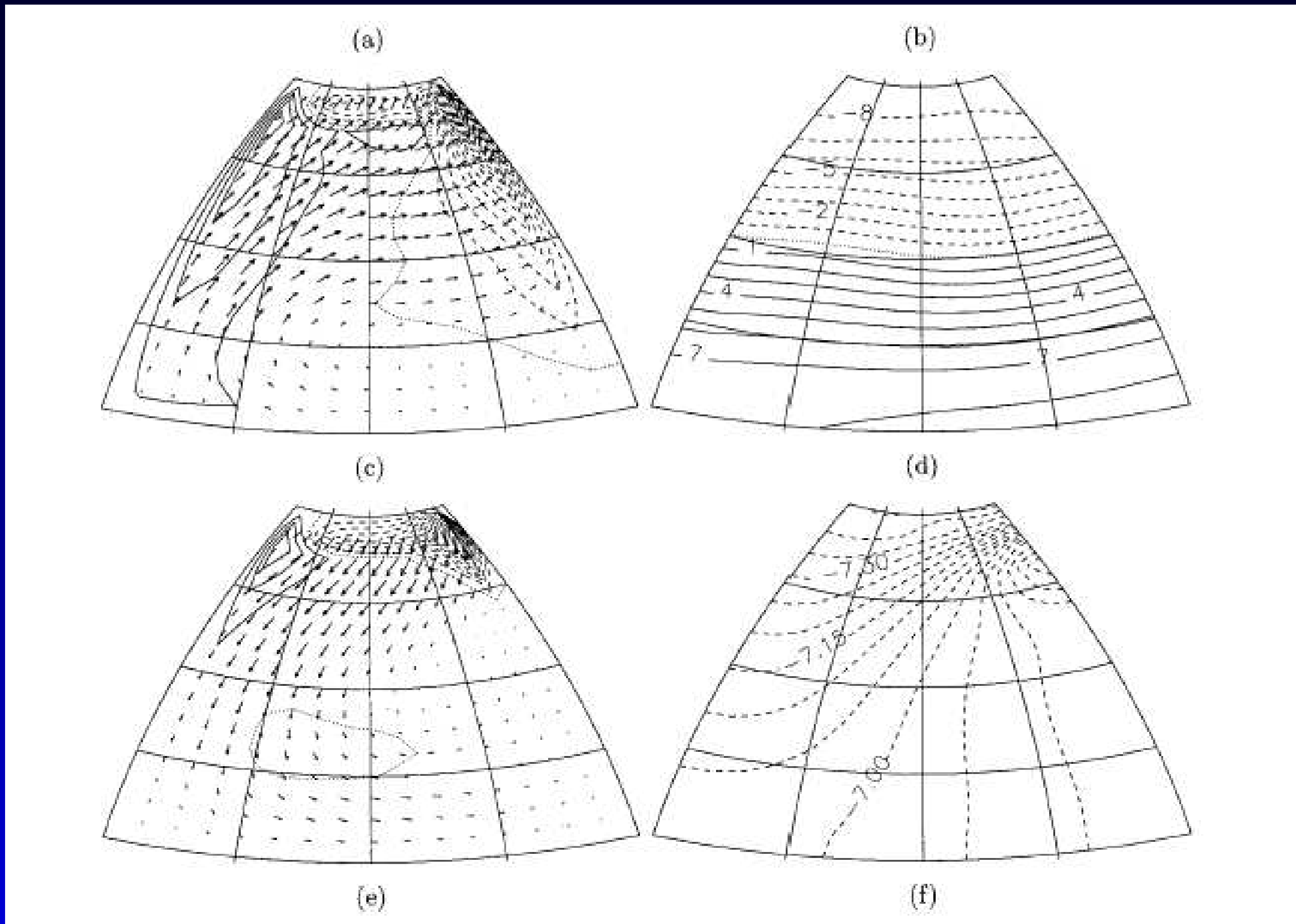


FIG. 1. Zonally integrated total time-mean northward heat transport (heavy line) and eddy portion of the total (thin line) for (a) the World Ocean, (b) the Indian Ocean, (c) the Pacific Ocean, and (d) the Atlantic Ocean.

Jayne and Marotzke, 2002

Model example



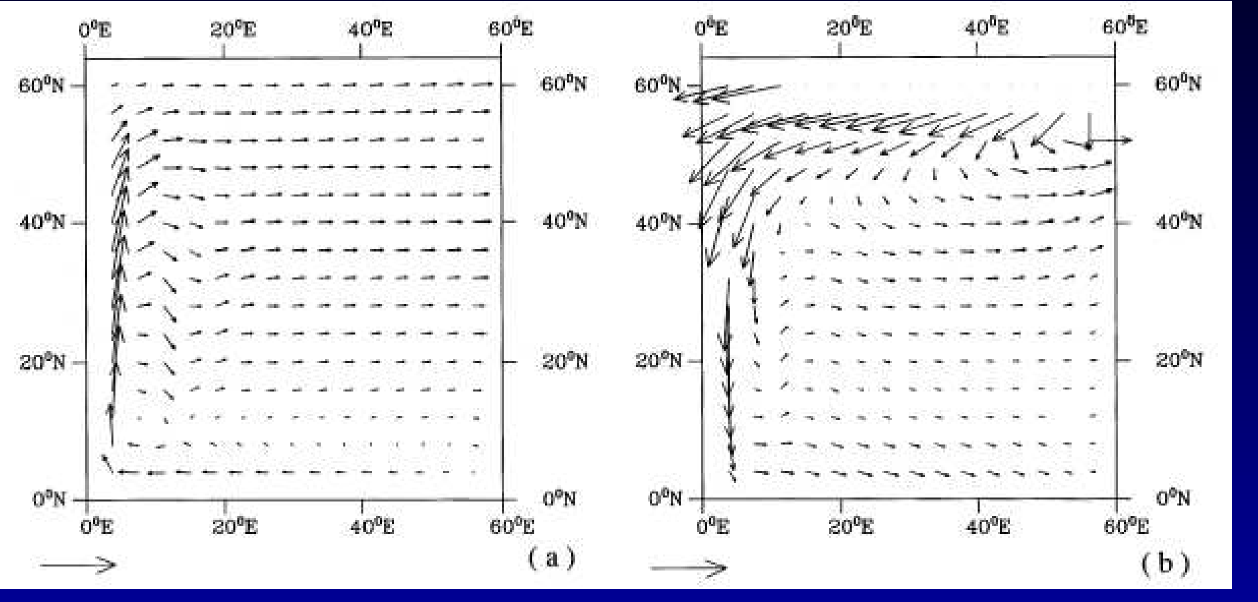
Te Raa and Dijkstra, 2002

Understanding the models

Questions:

- What drives the overturning (MOC)?
- How does MOC depend on mixing?
- On frictional parameterizations?
- On boundary conditions?

Models II

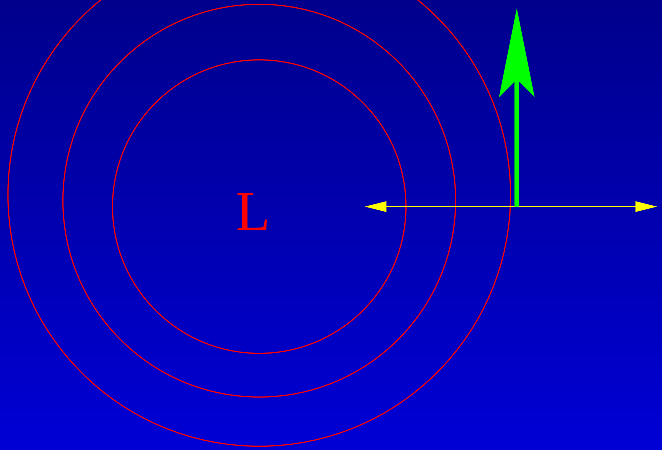


Marotzke, 1997

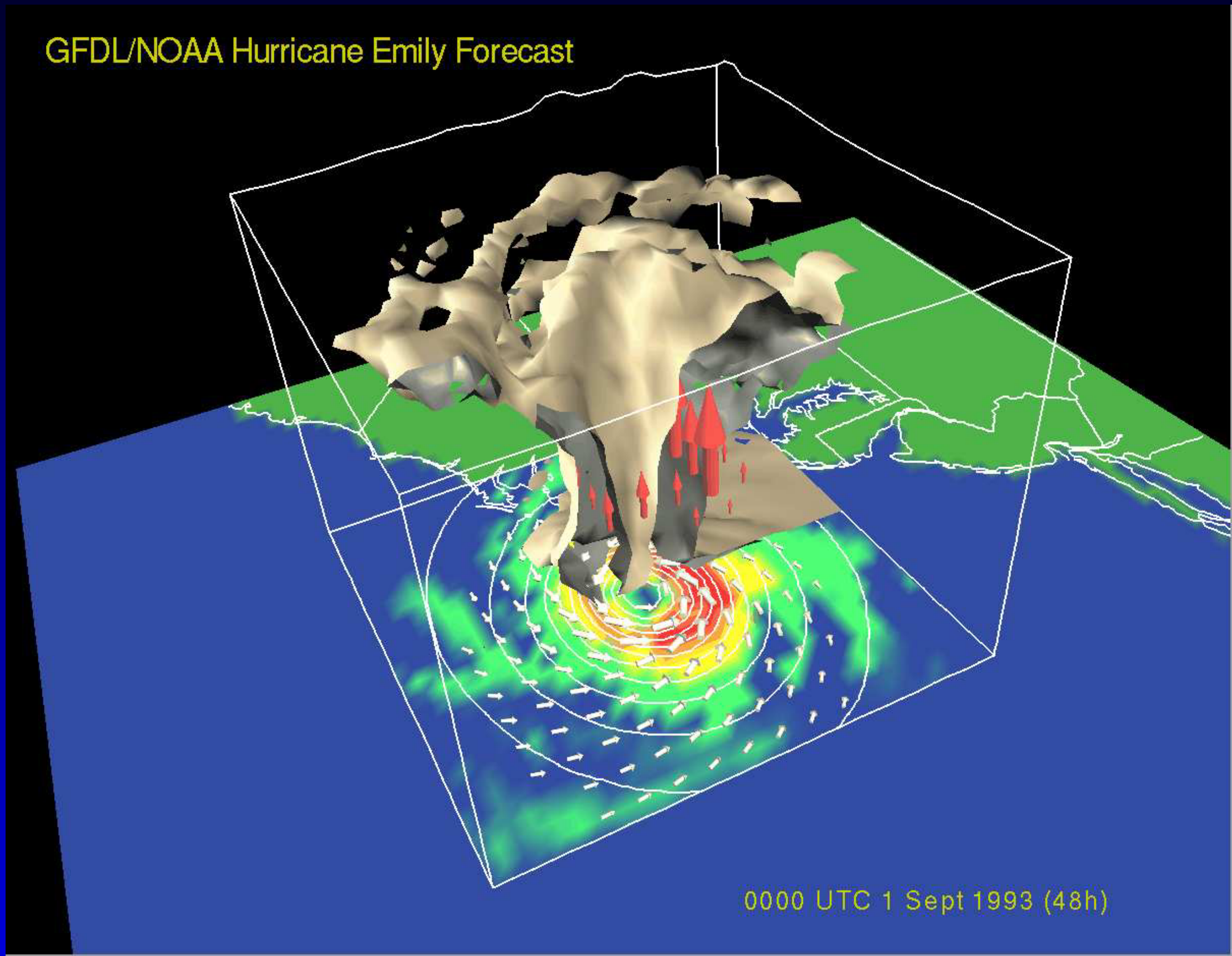
Geostrophy

Atmospheric and oceanic motion governed by the Navier-Stokes equations

But simplified dynamics possible at larger scales, where the Coriolis force approximately balances pressure gradients



Geostrophy



Scaling theory

e.g. Bryan and Cox, '67, Nilsson et al., 2003

Assume: 1) Geostrophic flow:

$$fu_0 = -\frac{1}{\rho}\frac{\partial}{\partial y}P, \quad fv_0 = \frac{1}{\rho}\frac{\partial}{\partial x}P$$

2) Hydrostatic balance

$$\frac{\partial}{\partial z}p = -\rho g$$

Scaling theory

3) Vertical advective-diffusive balance

$$w\frac{\partial}{\partial z}\rho = \kappa_v\frac{\partial^2}{\partial z^2}\rho$$

Yields:

$$h \propto \kappa_v^{1/3} \,\triangle\, \rho^{-1/3}$$

$$hUL \propto \kappa_v^{2/3} \,\triangle\, \rho^{1/3}$$

Scaling theory

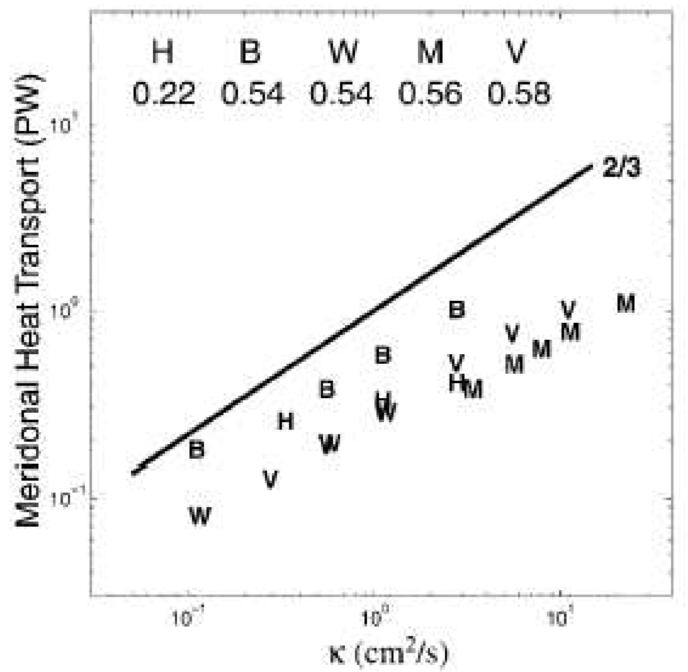
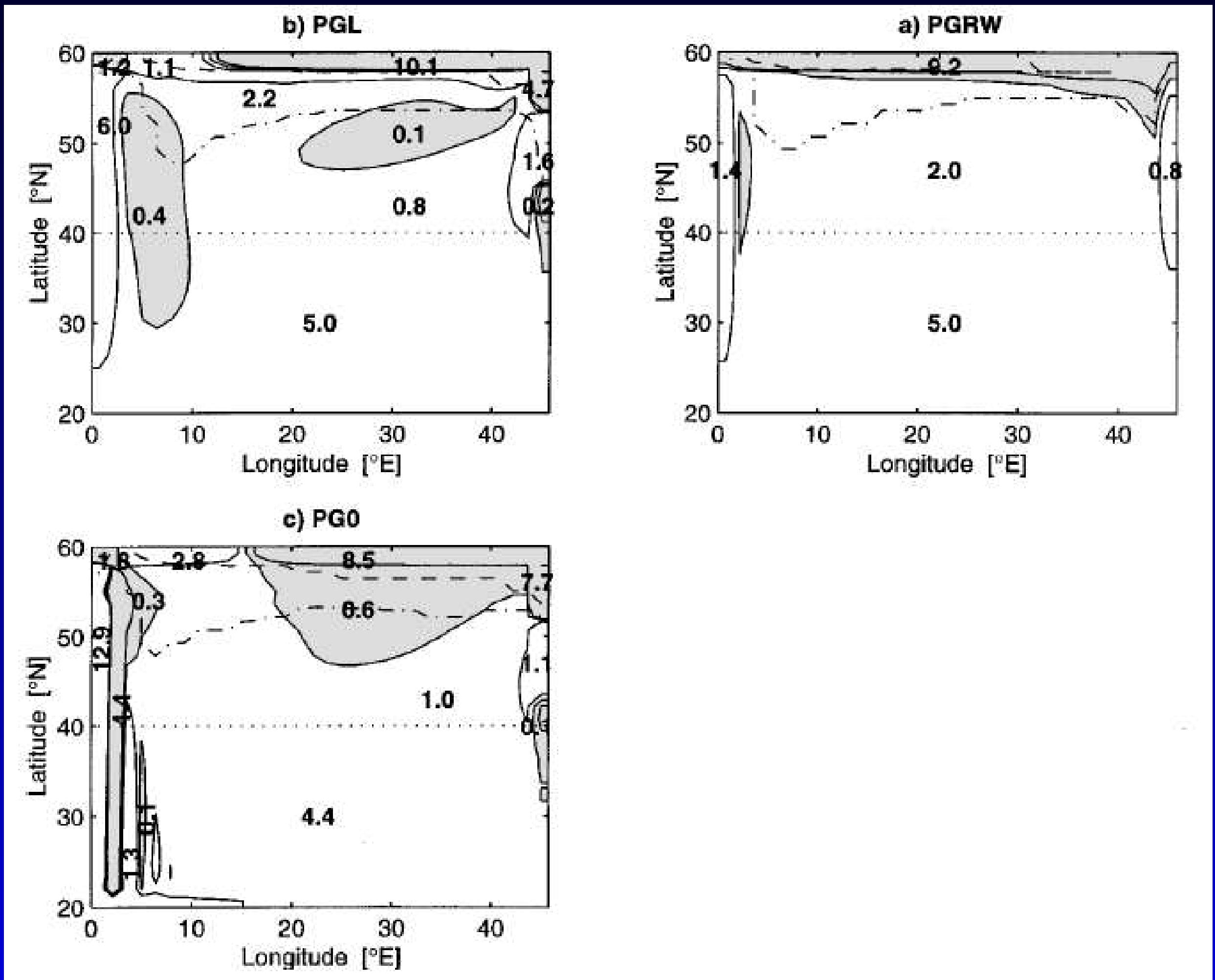


FIG. 1. Results from earlier studies. B is for Bryan (1987), V is for Colin de Verdière (1988), W is for Winton (1996), H is for Hu (1996), and M is for Marotzke (1997). Single hemispheric sector basins with flat-bottom geometry are used in all cases. B, W, and M are from depth coordinate models based on primitive equations, V is from a depth coordinate model based on planetary geostrophic equation, and H is from an isopycnal layer model. In M, κ is nonzero along eastern and western boundaries. In other cases κ is uniform throughout the domain. Surface wind stress is considered in B and H. Numbers represents the power dependence of the meridional heat transport on κ for each case.

Park and Bryan, 2000

Viscosity dependence



Huck et al., 1999

Scaling

Scaling theory approximately correct when constant mixing over the whole basin

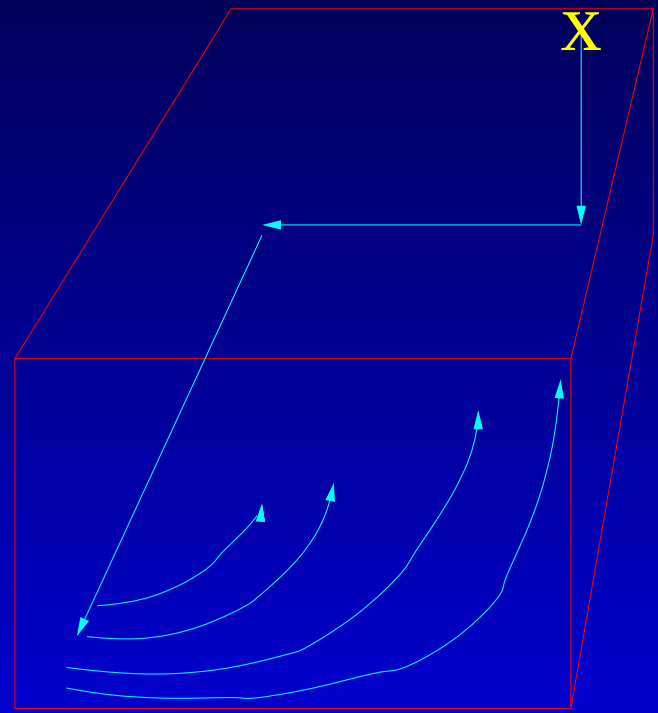
Numerical simulations suggest mixing is *intensified near the boundaries* and viscosity-dependent

Observations (Polzin, Ledwell) also suggest boundary-intensified mixing

$\rightarrow$ Scaling theory probably inadequate

Abyssal circulation

Stommel and Arons, 1960; Kawase, 1987



Equations

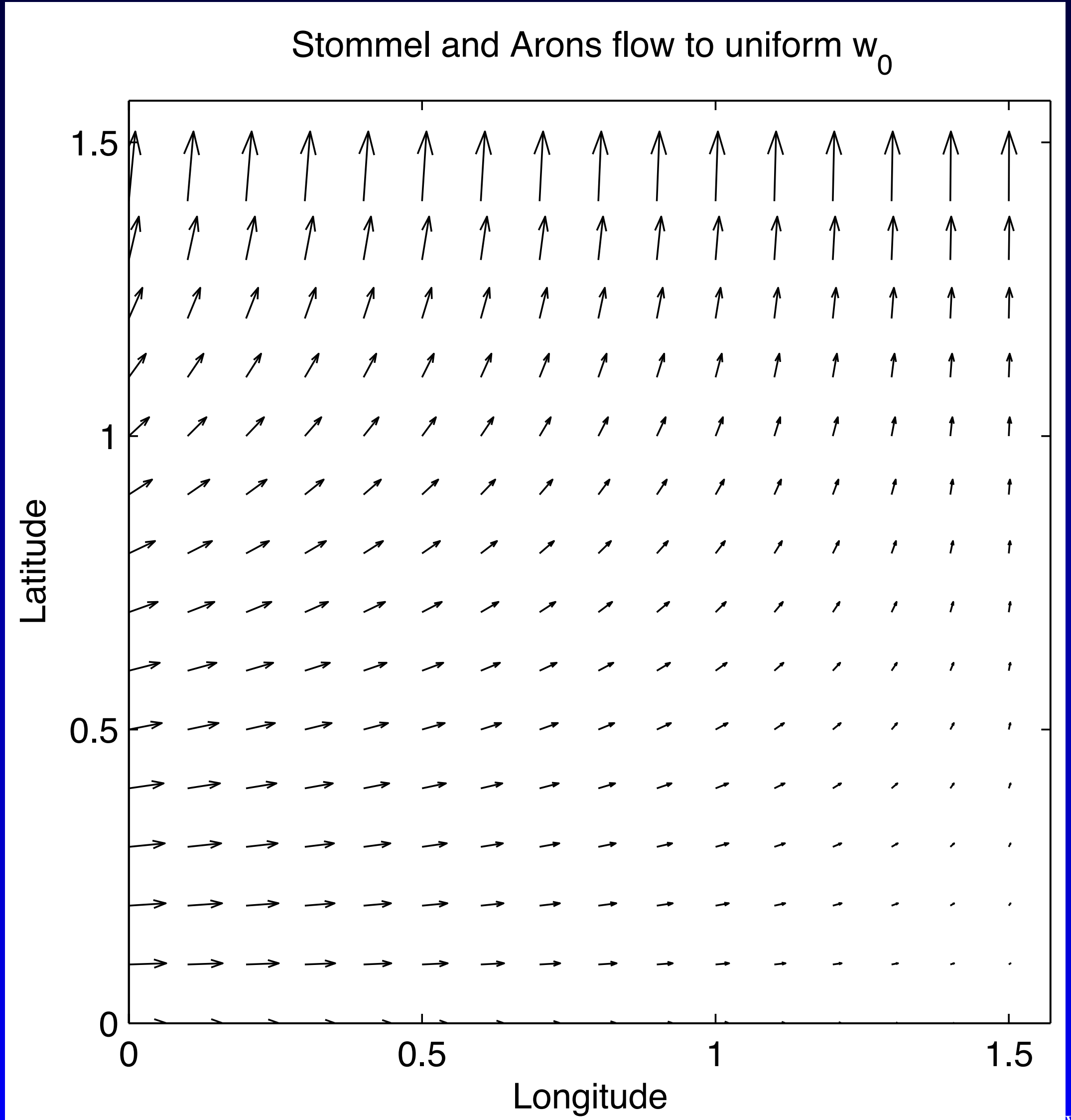
$$v sin\theta = \frac{1}{cos\theta}\frac{\partial p}{\partial \phi}$$

$$u sin\theta = -\frac{\partial p}{\partial \theta}$$

$$\frac{\partial (hu)}{\partial \phi} + \frac{\partial (hv cos\theta)}{\partial \theta} = -cos\theta\, w_0(\theta, \phi)$$

Abyssal flow

Stommel and Arons, 1960



Abyssal solutions

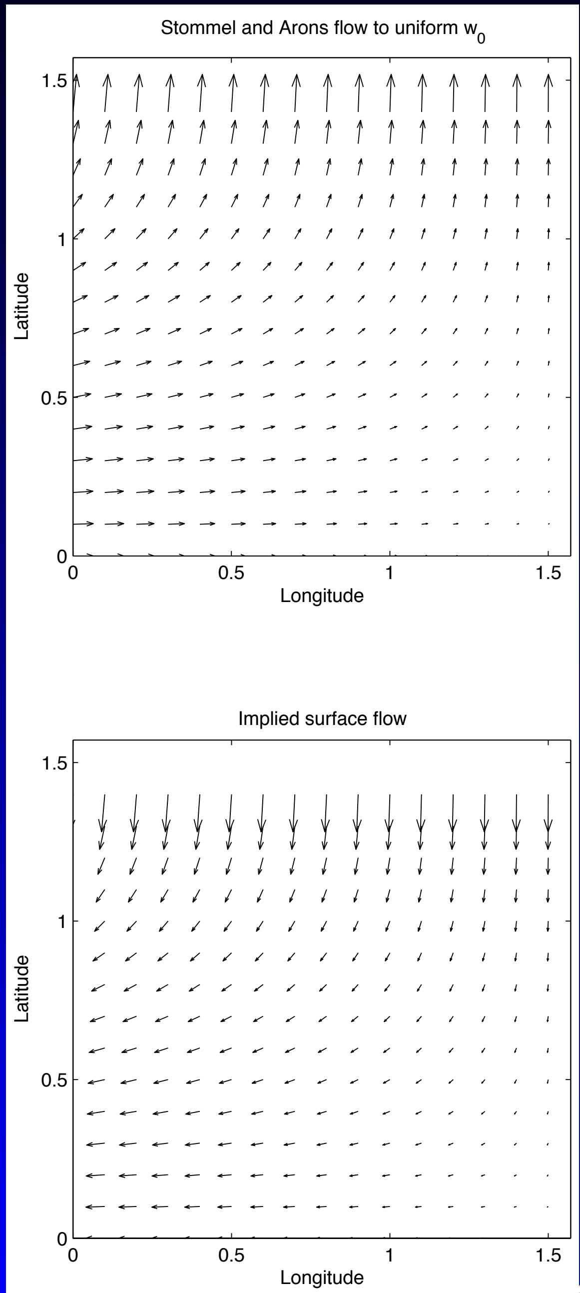
Good:

- Dynamically plausible
- Predicted Deep Western Boundary current
- Viscosity dependence in boundary layer

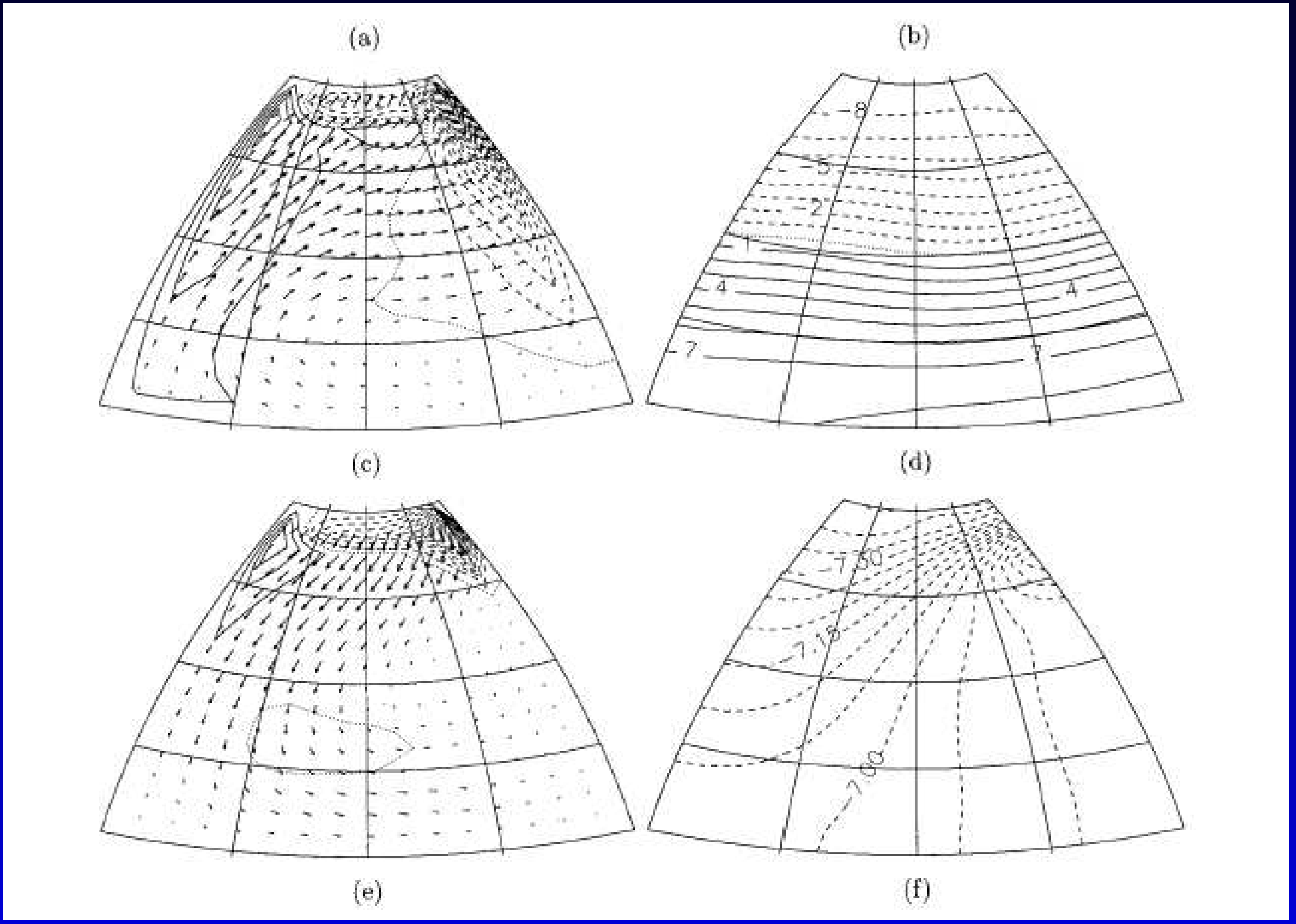
Less good:

- Must specify upwelling
- Buoyancy driving produces purely *baroclinic* flow

Implied flow



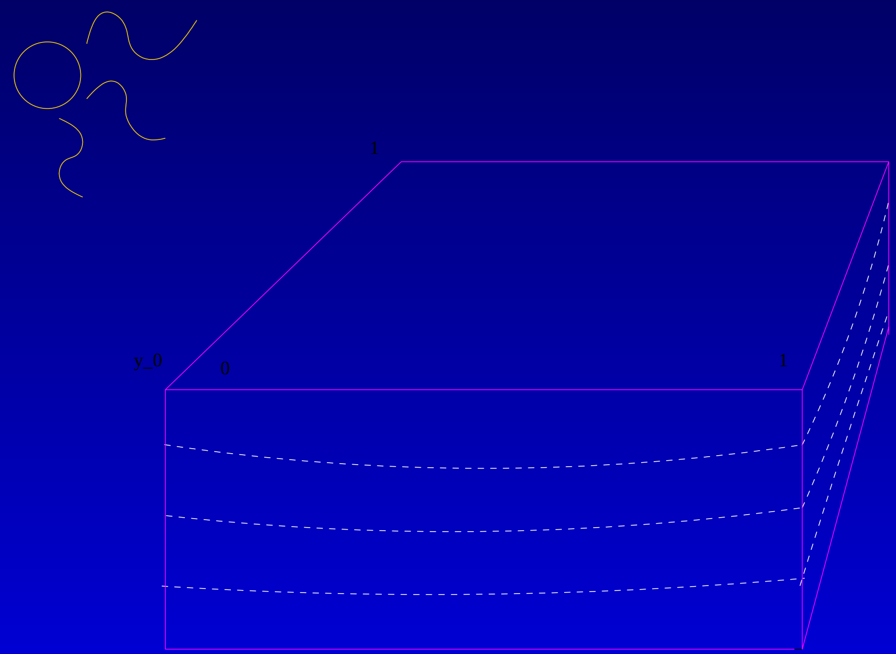
Model example



Te Raa and Dijkstra, 2002

Linear model

Pedlosky, 1968,1969; Salmon, 1986



Planetary Geostrophy

$$-fv = -\frac{\partial}{\partial x}\phi + \mathcal{D}_x$$

$$fu \;=\; -\frac{\partial}{\partial y}\phi + \mathcal{D}_y$$

$$0 = -\frac{\partial}{\partial z}\phi + T$$

$$\frac{\partial}{\partial x}u + \frac{\partial}{\partial y}v + \frac{\partial}{\partial z}w = 0$$

$$u\frac{\partial}{\partial x}T + v\frac{\partial}{\partial y}T + w\frac{\partial}{\partial z}T \;=\; \kappa_H\nabla^2 T + \kappa_V\frac{\partial^2}{\partial z^2}T$$

Linear PG

$$T(x, y, z) = \mathcal{T}_0(z) + \theta(x, y, z)$$

$$\rightarrow \quad |T_0| \gg |\theta|$$

Temperature equation becomes:

$$Sw \; = \; \kappa_H \nabla^2 \theta + \kappa_V \frac{\partial^2}{\partial z^2} \theta$$

where $S \propto \frac{\partial}{\partial z} T_0$

Characteristics

1) Flow driven by vertical mixing

2) Flow confined to surface boundary layer

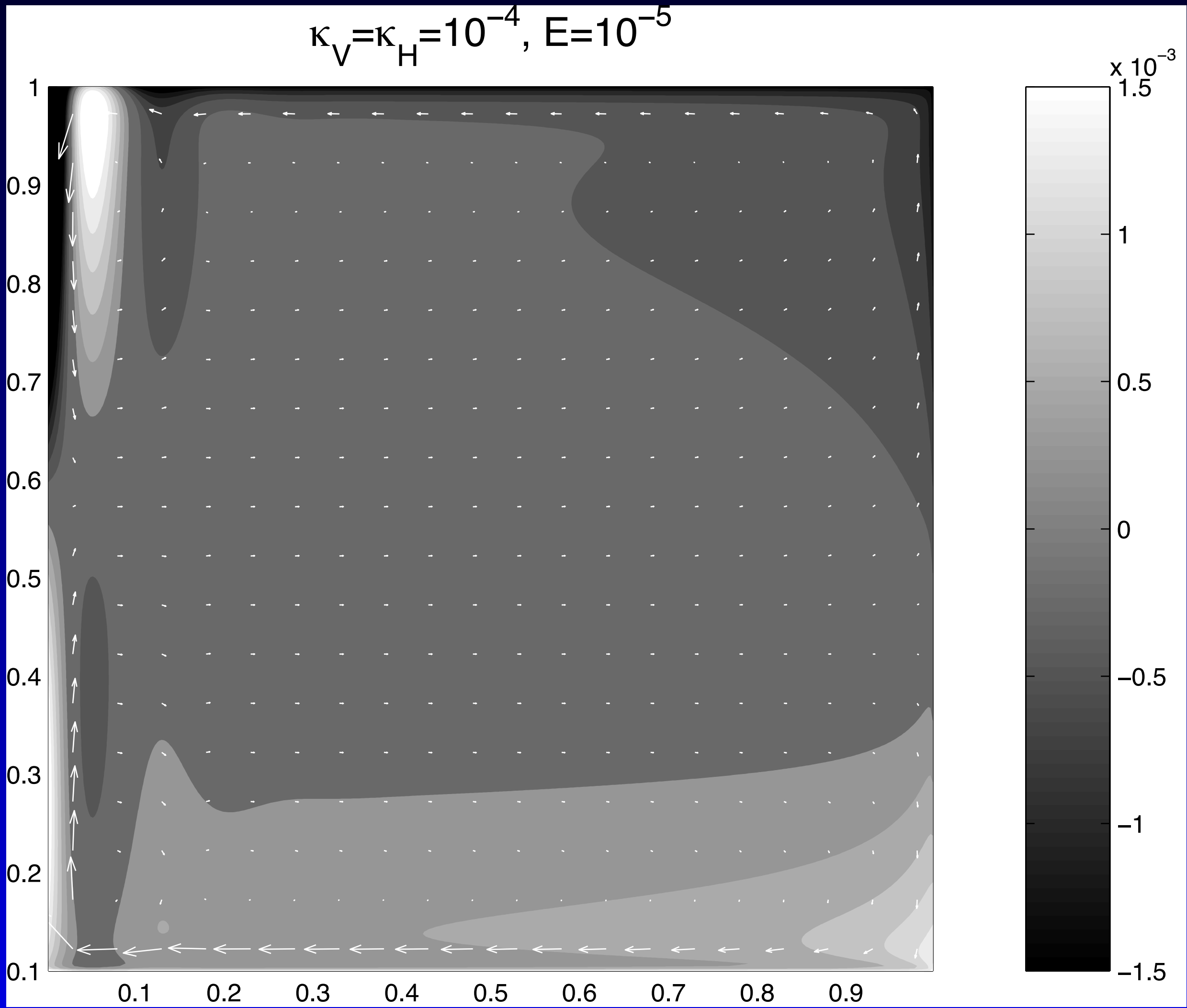
about 500 m thick

3) Baroclinic velocities

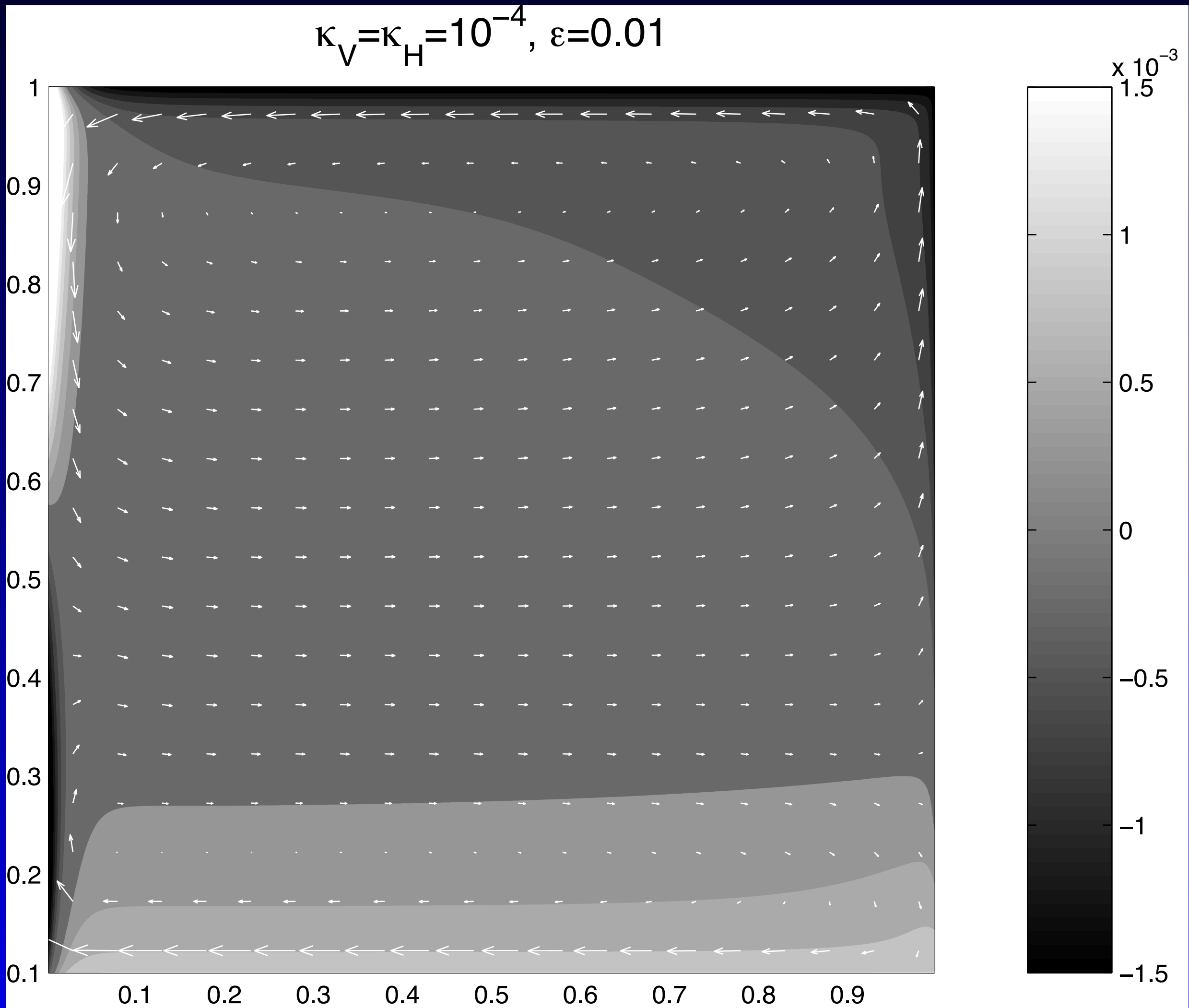
4) Viscosity, lateral diffusion important only at west, North, South walls

5) Upwelling/downwelling occurs mostly near lateral boundaries

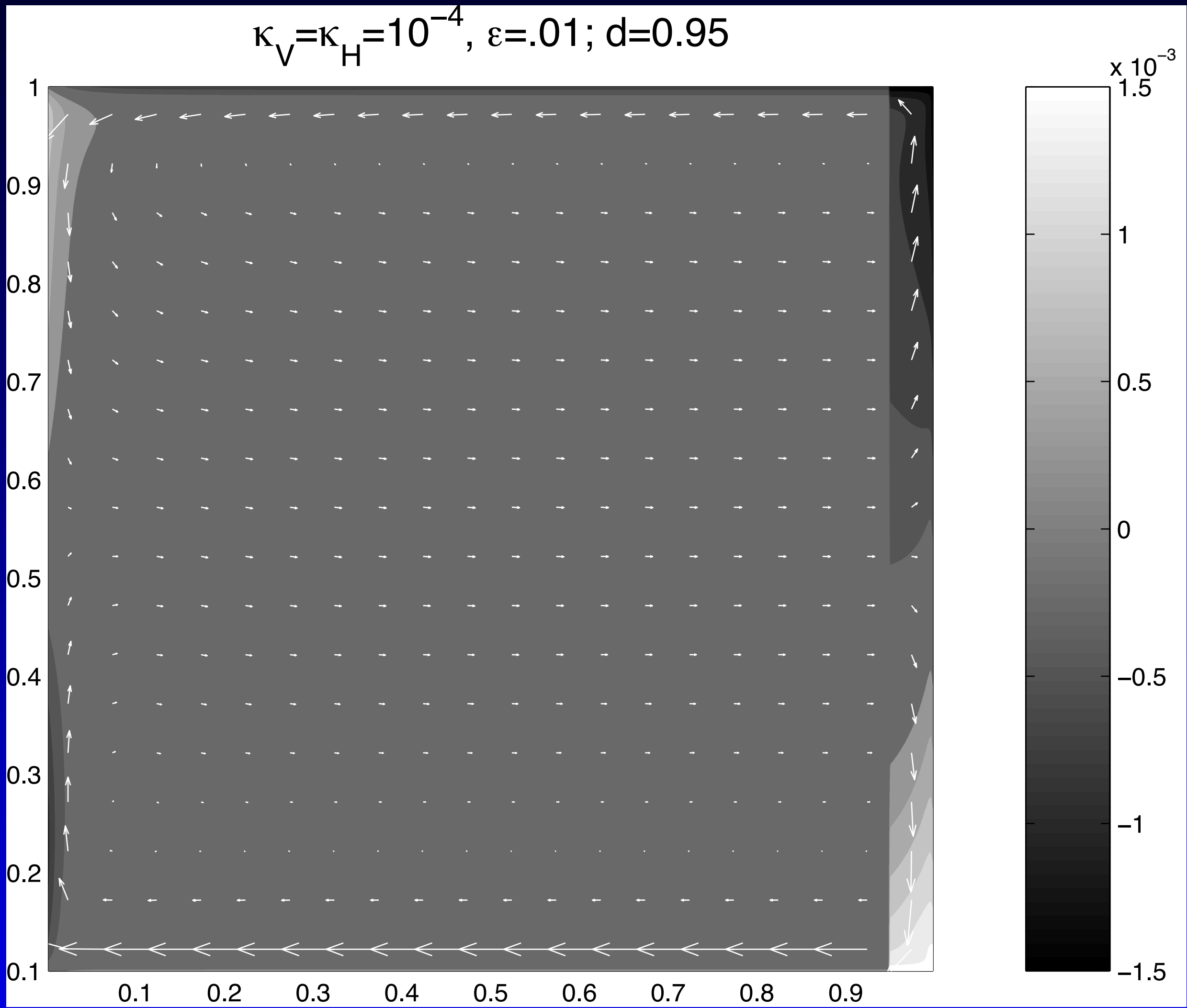
Diffusive viscosity



Rayleigh viscosity



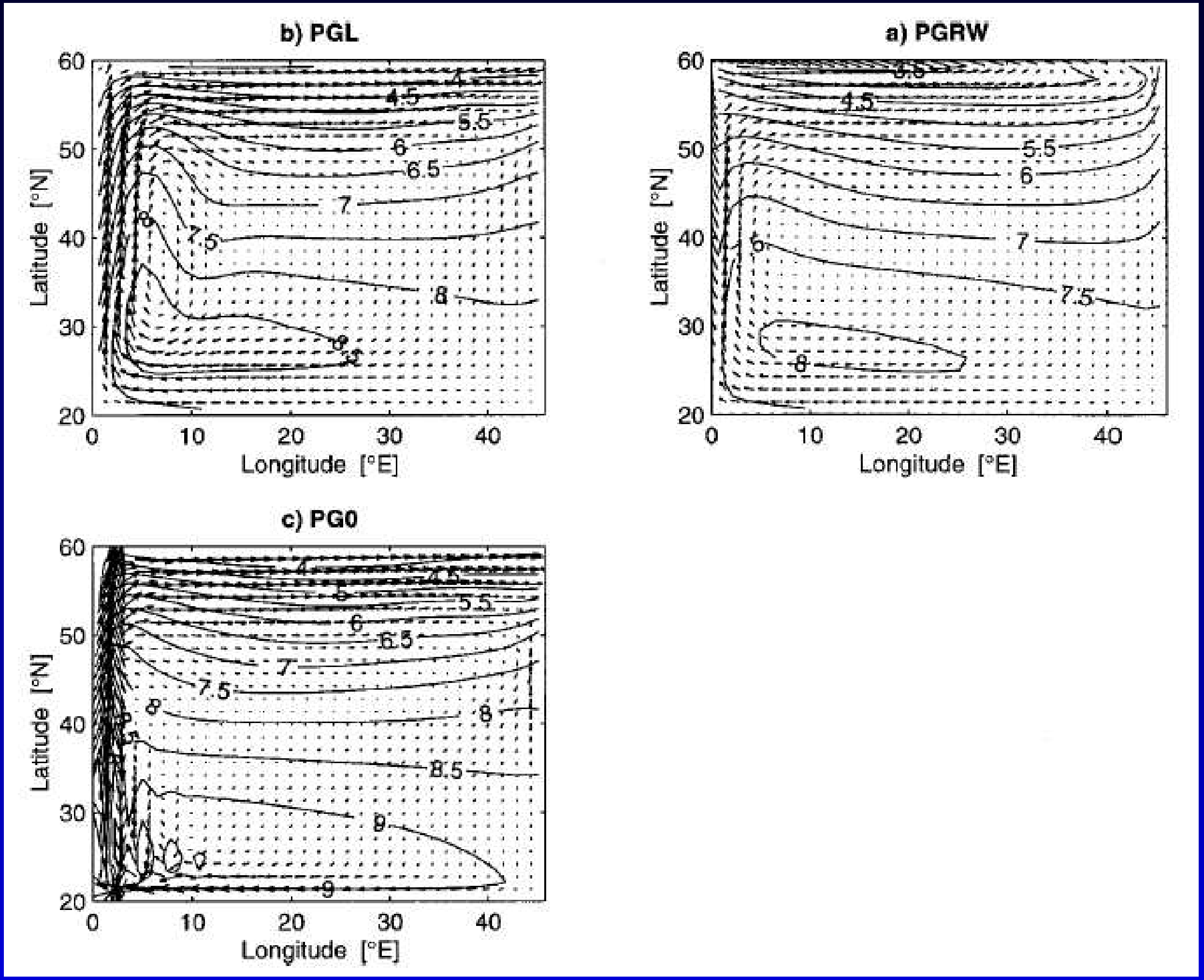
Boundary mixing



Comparison to models

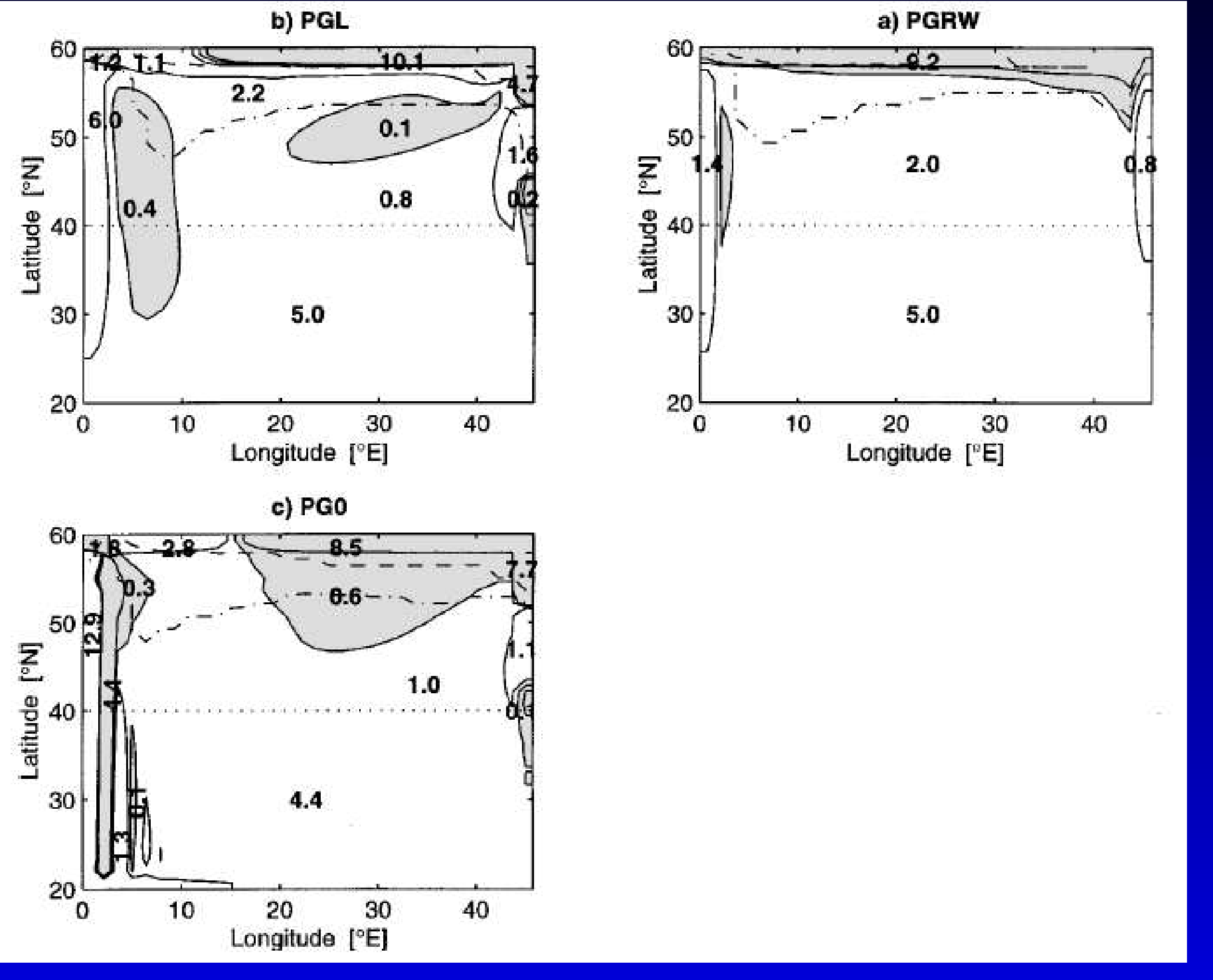
- Similarities
  - Boundary-intensified vertical velocities
  - Western boundary current with large w
  - w sensitive to viscosity and BC
  - Zonal thermocline flow with BT κ_V
- Differences
  - Sense of surface flow
  - Magnitudes of vertical velocities

Models



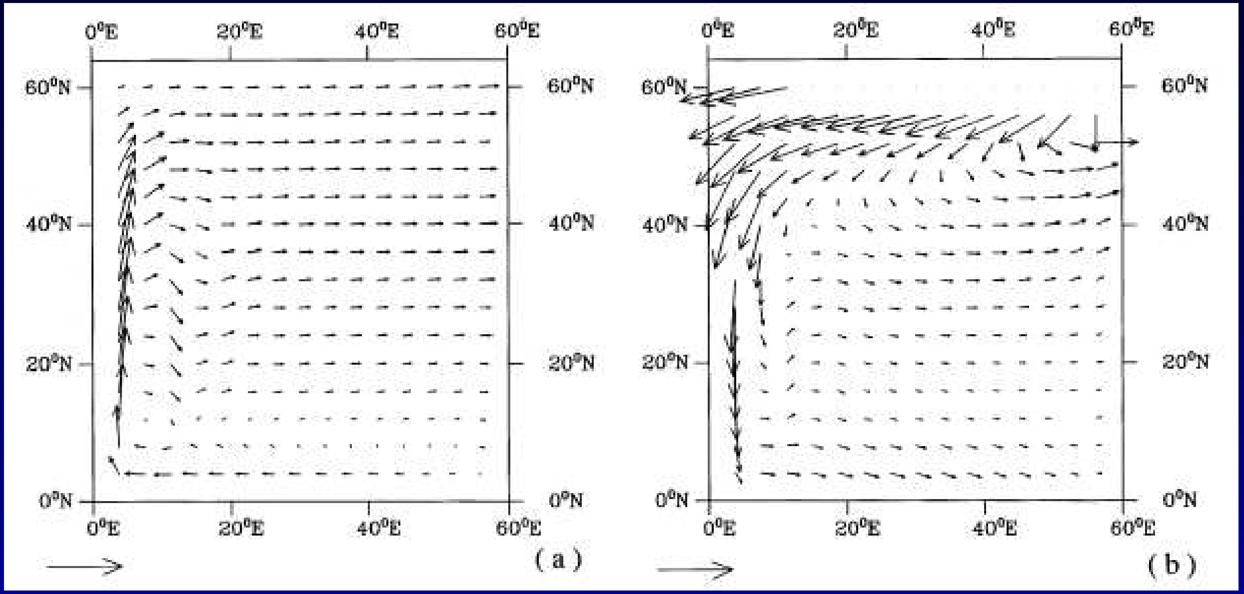
Huck et al., 1999

Models



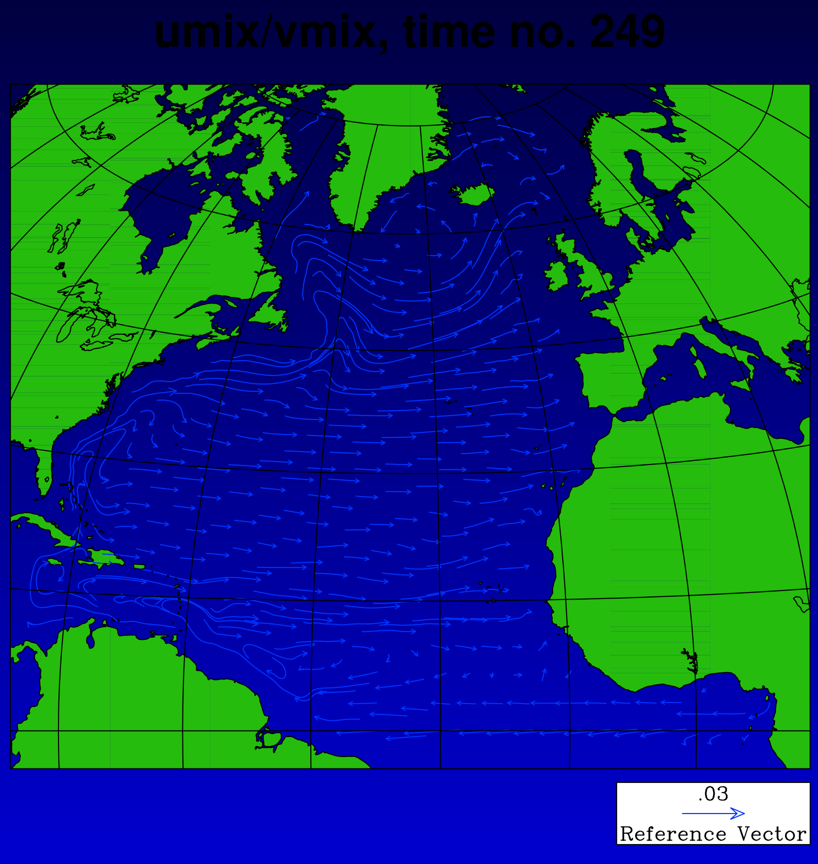
Huck et al., 1999

Models

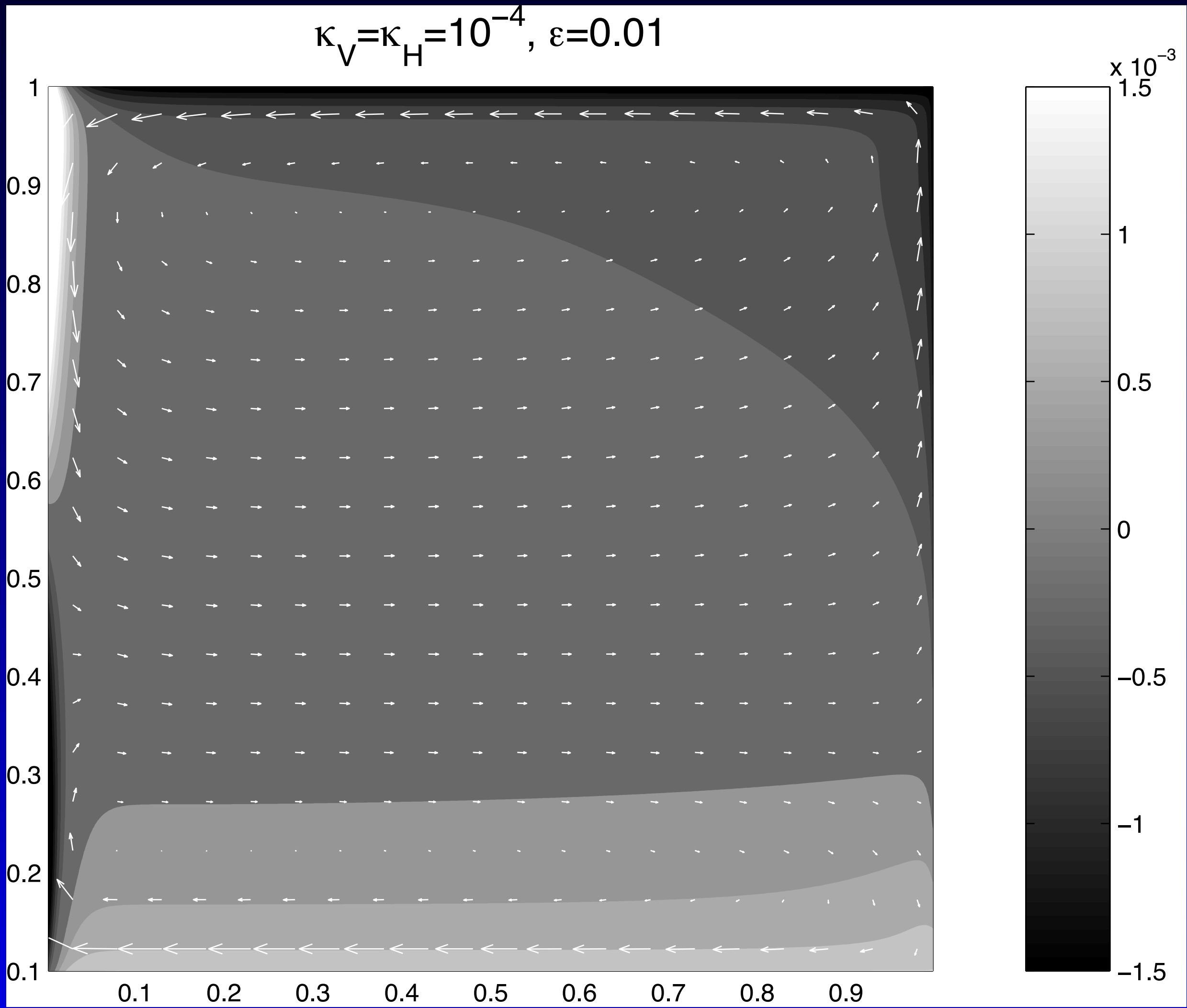


Marotzke, 1997

Models



Comparison to observations



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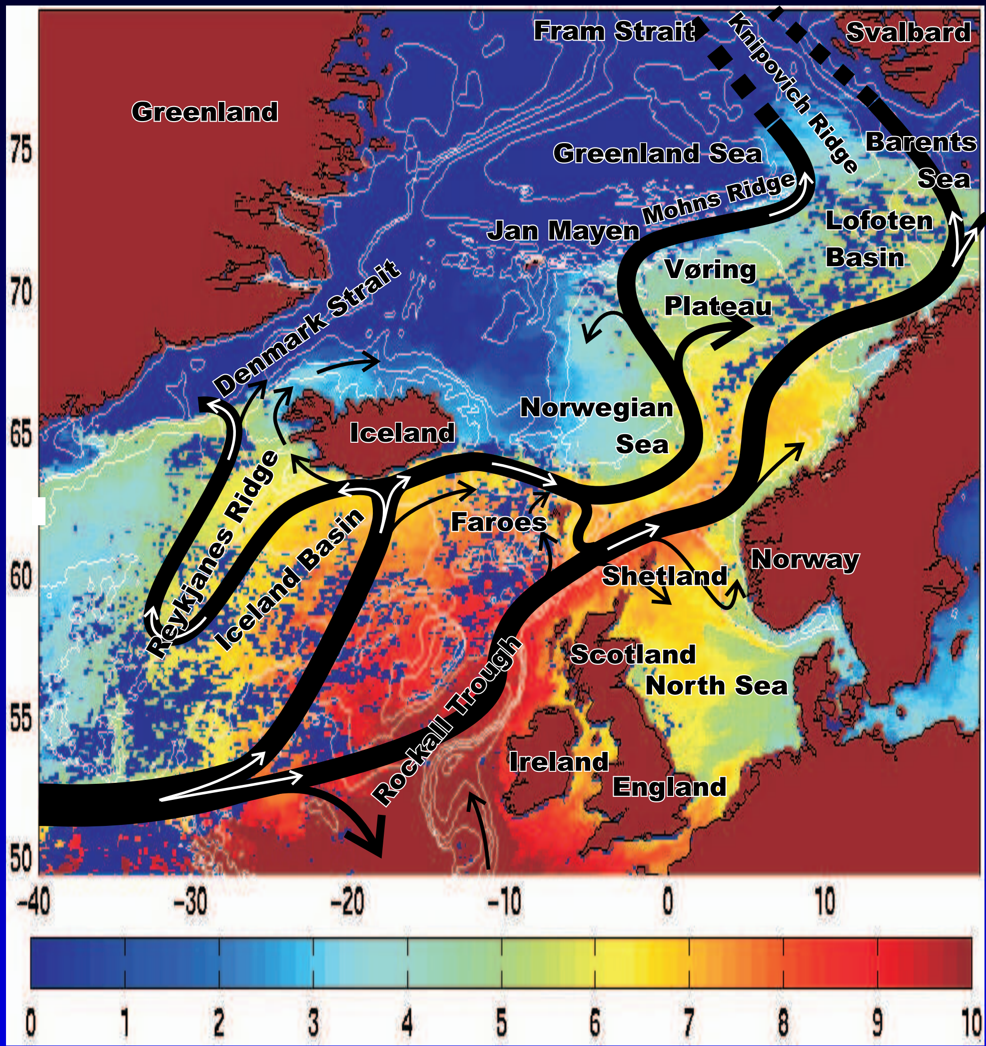
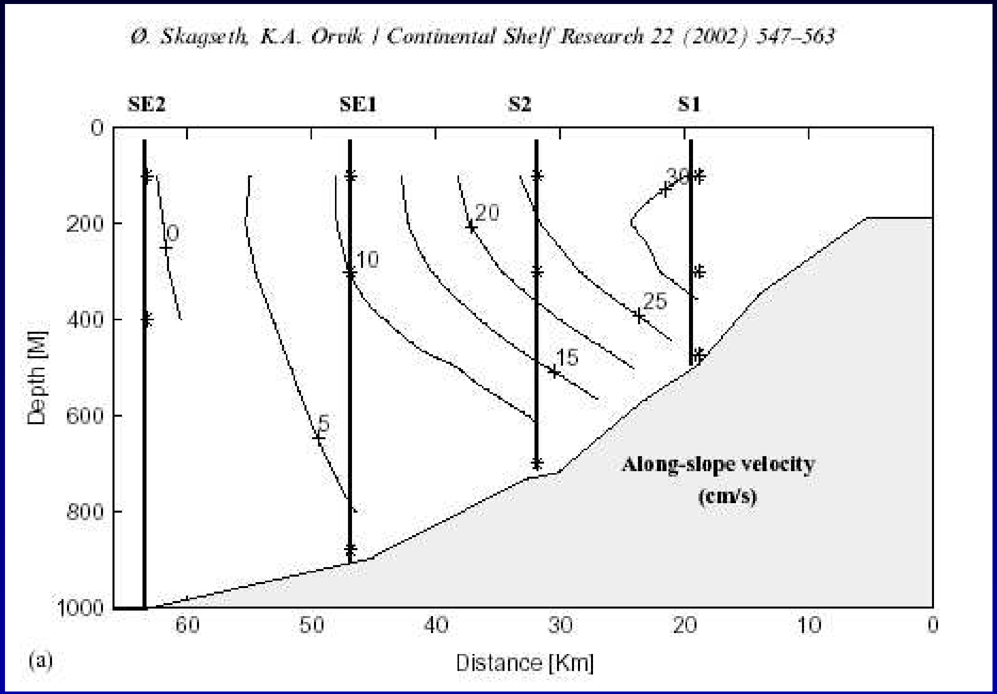


Orvik and Niiler, 2002

Comparison to observations



Skagseth and Orvik, 2002

Summary

- Idealized thermocline models capture some elements of observed circulation (Deep Western Boundary Current, Norwegian Atlantic Current)
- But none (so far) capture the flow exhibited by most numerical models
- Need for an improved analytical representation