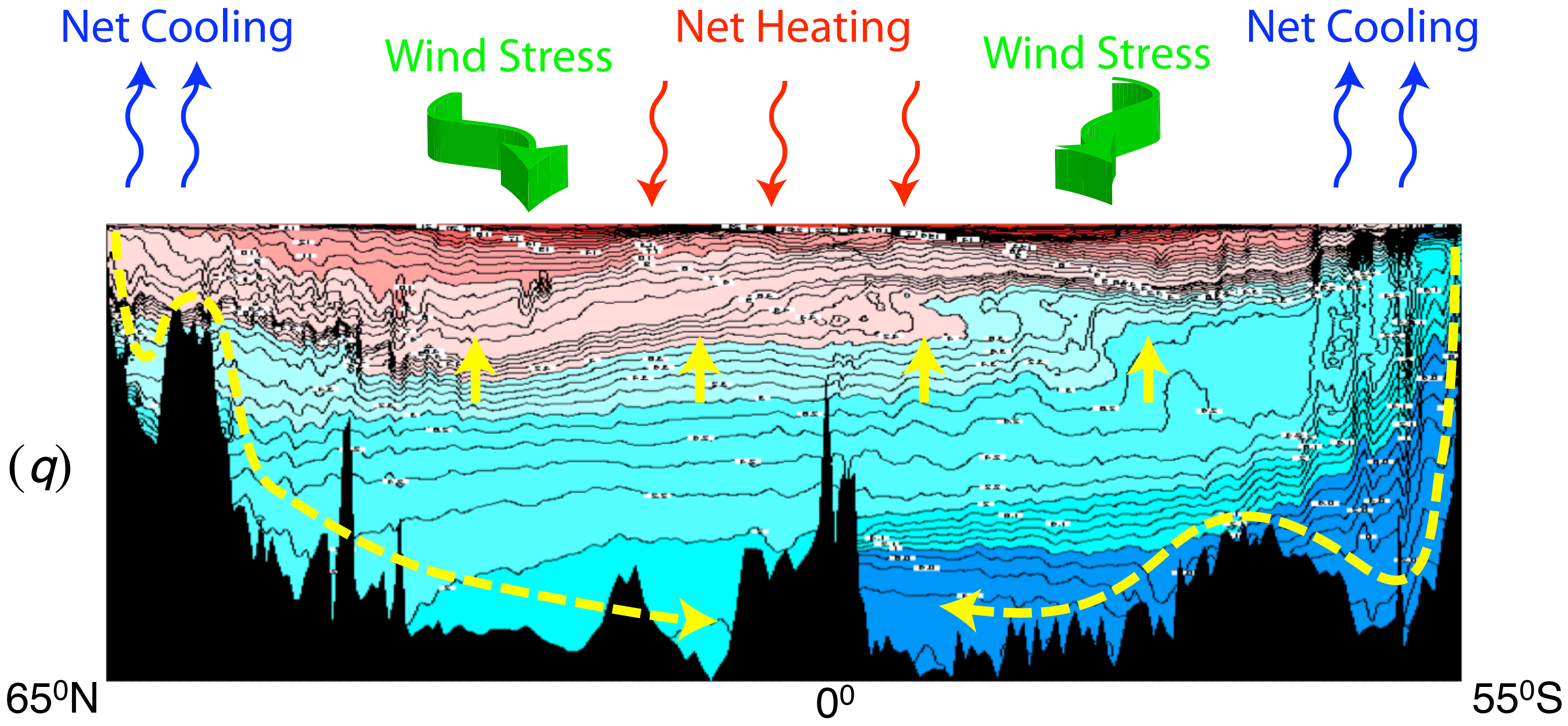
Ocean circulation and surface buoyancy fluxes: dynamics and energetics

Ross Griffiths

with credits: Graham Hughes, Andy Hogg,
Kial Stewart, Julia Mullarney, J.Tan

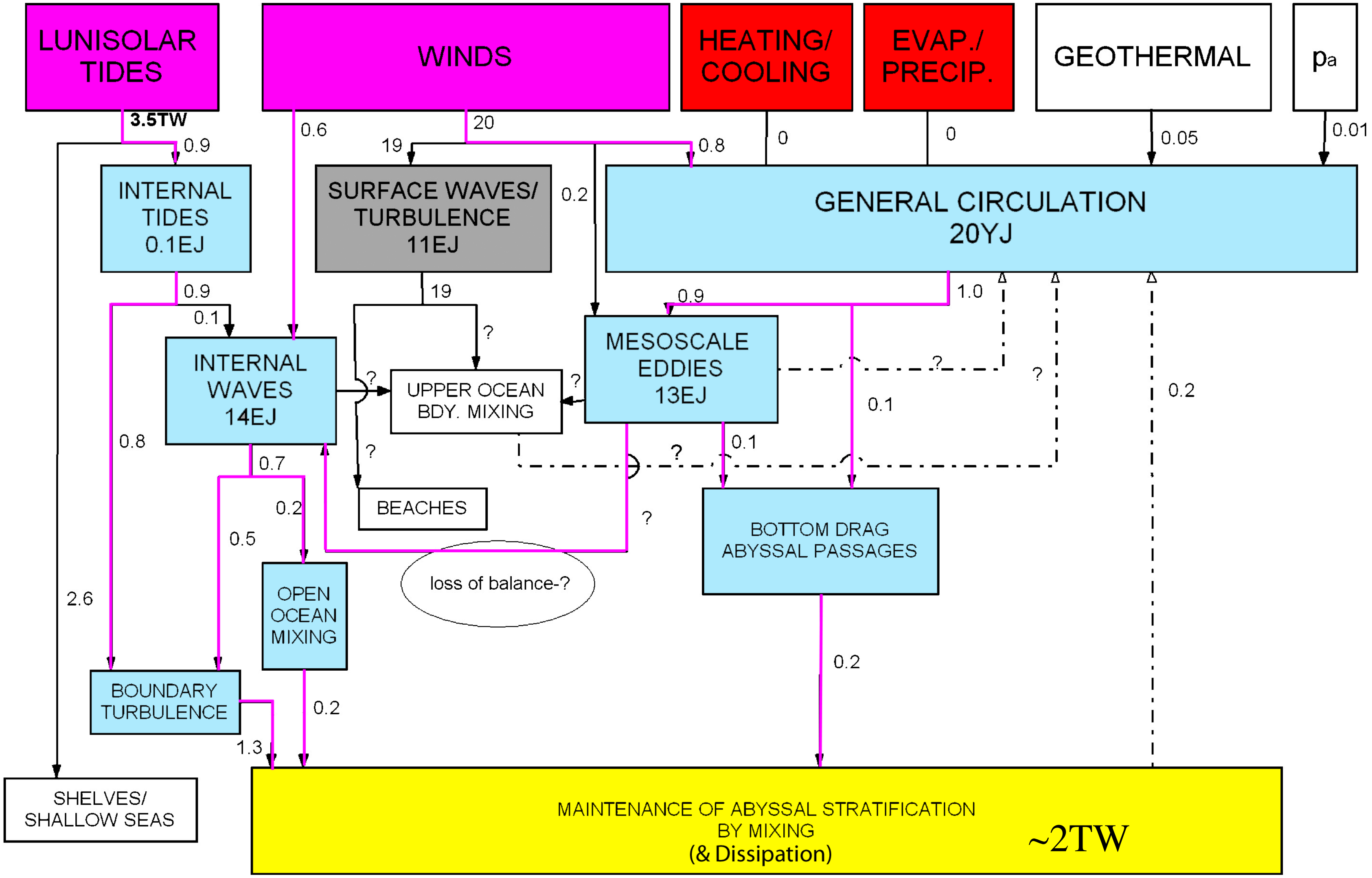
Research School of Earth Sciences
The Australian National University

Meridional Overturning Circulation (MOC)



- sinking of dense water; distributed upwelling
- vertical mixing maintains stratification
- energy inputs and rates of turbulent mixing?
- mean flow – roles of buoyancy, wind stress and mixing?

The ocean energy budget



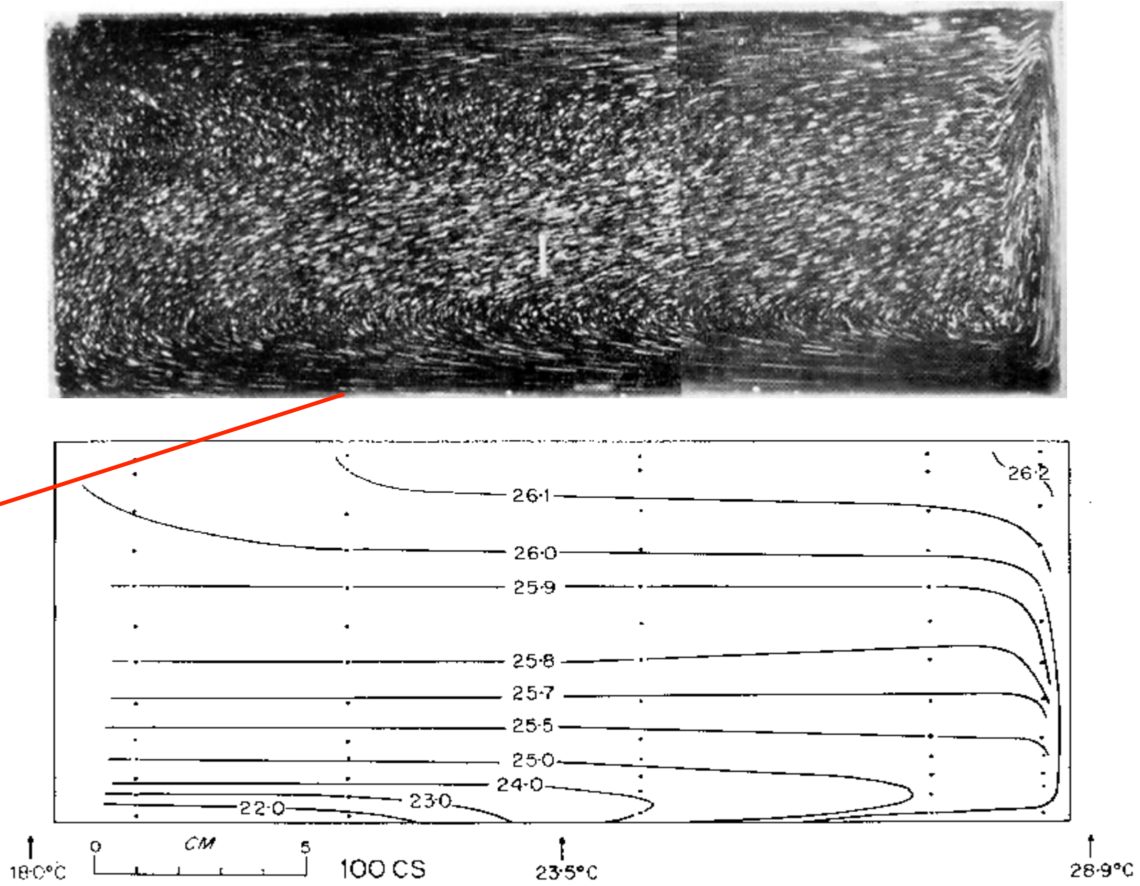
From Wunsch & Ferrari (2004)

- Role of buoyancy?

Outline

- Convection under differential surface heating/cooling
- Available Potential Energy (APE)
- Energy pathways in stratified / convecting flows
- A connection between turbulent mixing and buoyancy forcing
- Ocean models and the roles of surface buoyancy (and wind) forcing

Surface buoyancy forcing – Rossby’s experiment



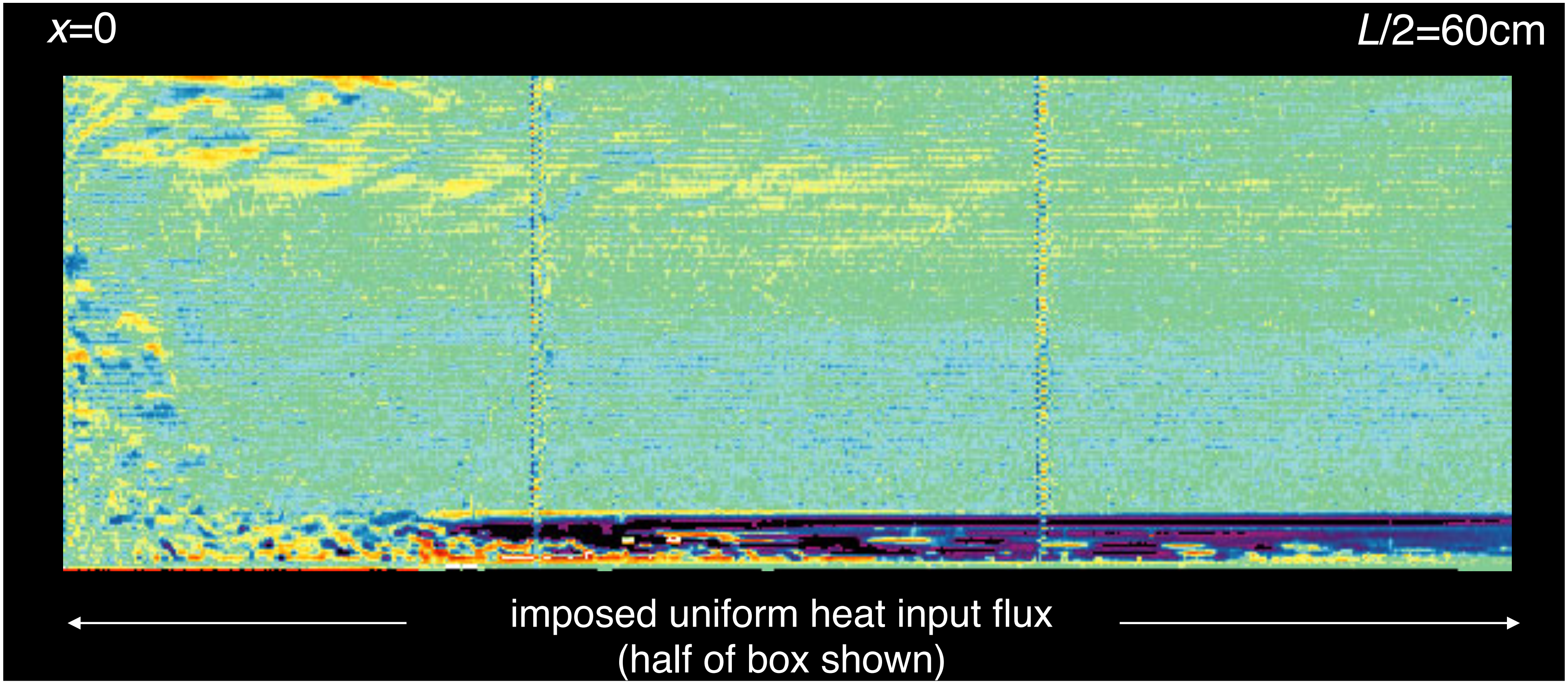
Ra~10^8

Temp gradient

Rossby (1965, 1998)

- Non-uniform heating/cooling at base; zero net heat input
- narrow end wall plume, broad downward return flow
- stratification relies on interior vertical diffusion

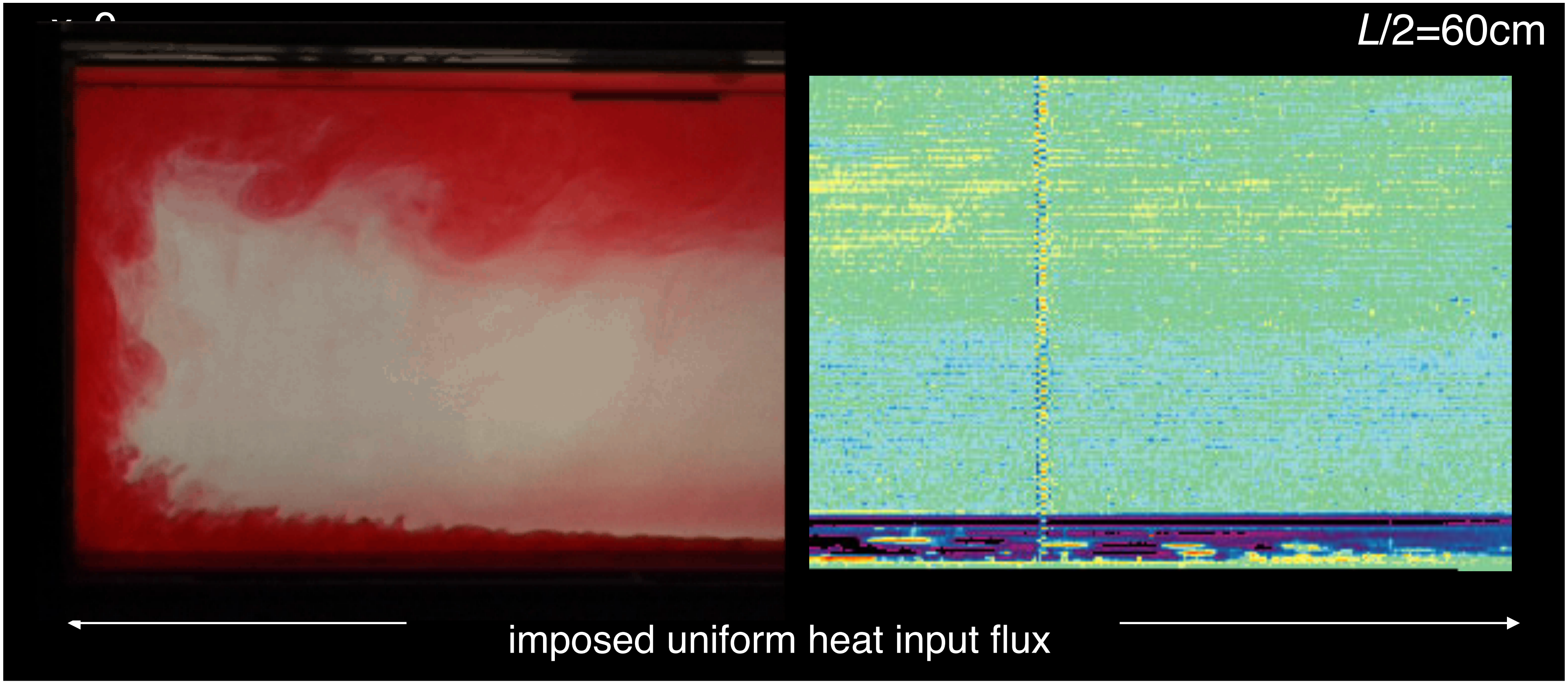
Horizontal convection at large *Ra*



Synthetic schlieren, Mullarney, et al. (2004)

- $Ra \sim 10^{12}$ or $Ra_F \sim 10^{14}$; flow insensitive to form of BCs
- transitions: small-scale convection within boundary layer, shear instability in plume, eddies in interior

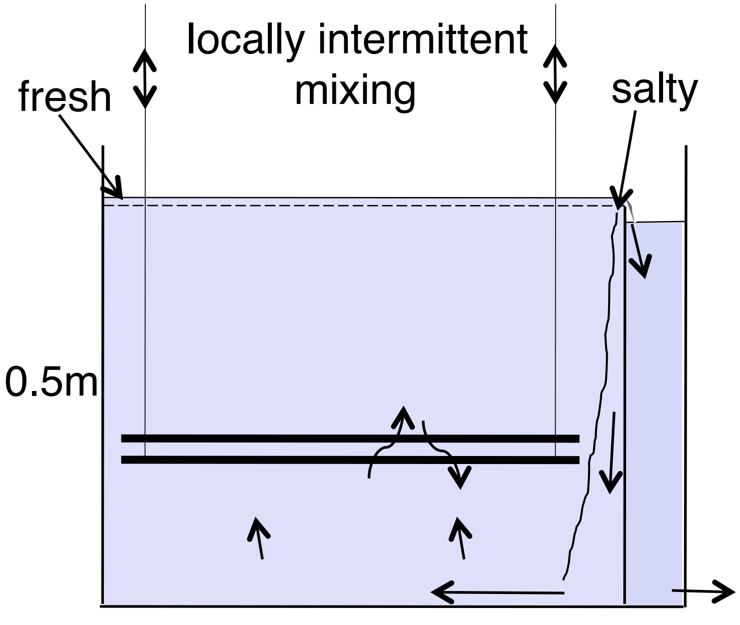
Horizontal convection at large *Ra*



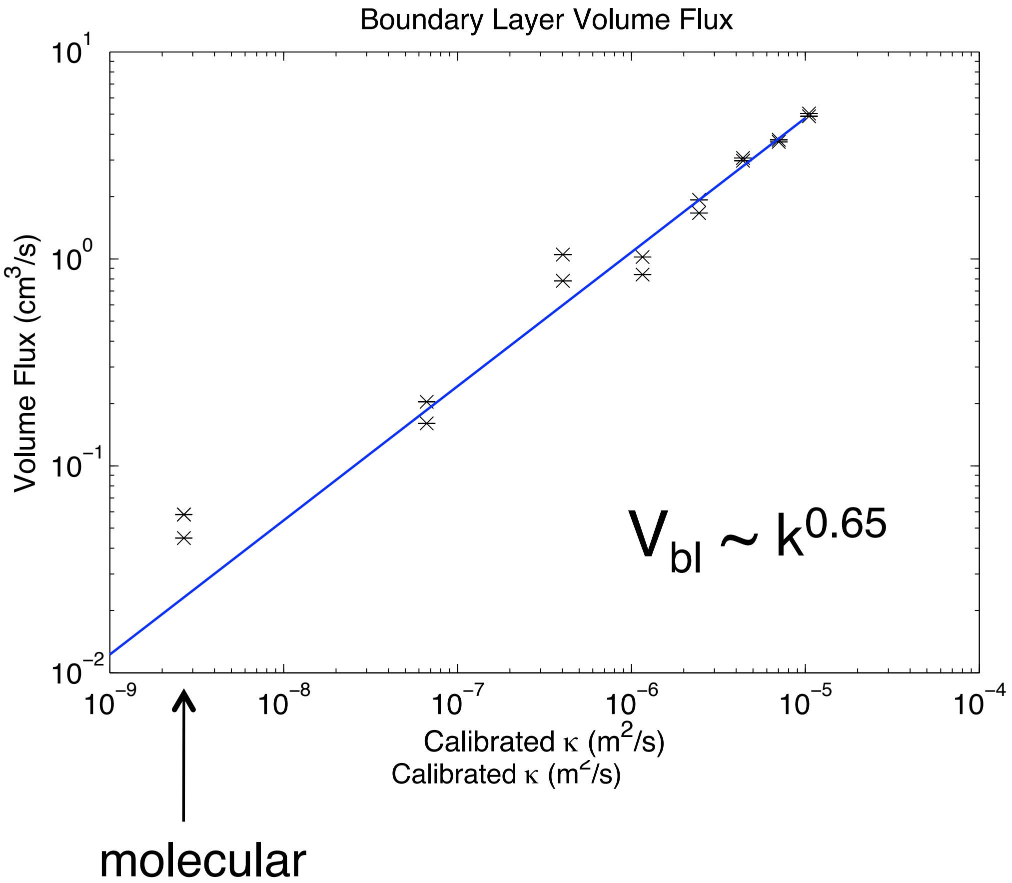
Passive tracer + synthetic schlieren, Mullarney, et al. (2004)

- $Ra \sim 10^{12}$ or $Ra_F \sim 10^{14}$; flow insensitive to BCs
- transitions: small-scale convection within boundary layer, shear instability in plume, eddies in interior

Adding turbulent mixing



large time equilibrium



Courtesy of K. Stewart

- vary vertical diffusivity by adding mechanical mixing
- mixing increases overturning convection

Adding turbulent mixing

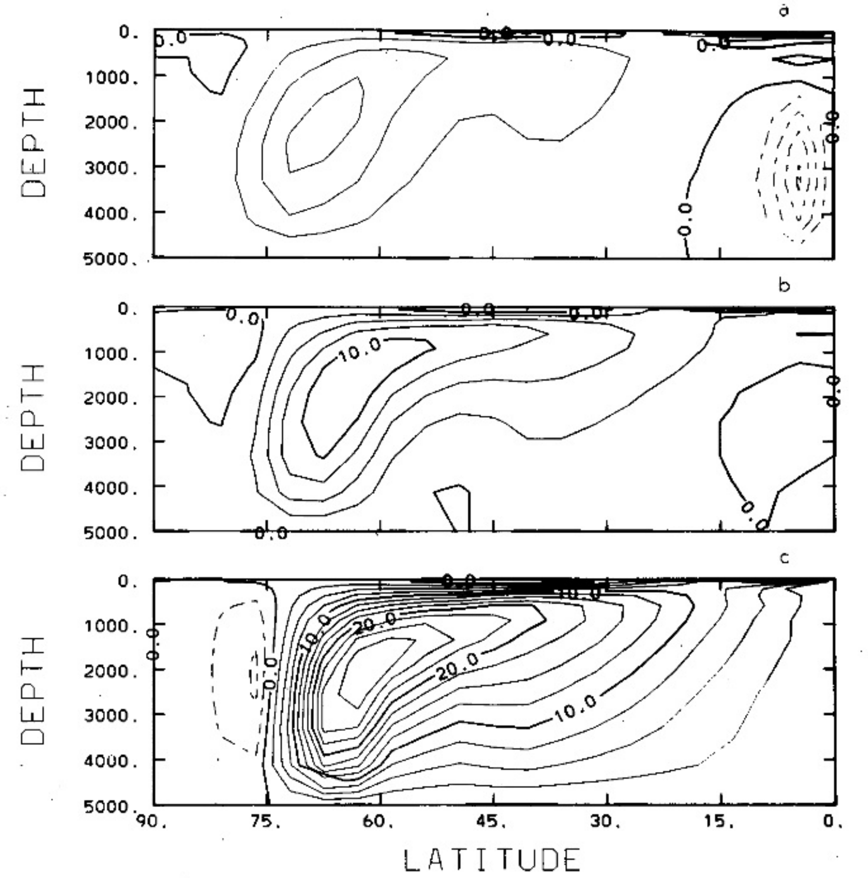


FIG. 7. Meridional overturning streamfunction for (a) $A_{HV} = 0.1$, (b) $A_{HV} = 0.5$, (c) $A_{HV} = 2.5$ (c.i. = $2.5 \times 10^6\ m^3\ s^{-1}$, solid contours indicate counterclockwise circulation).

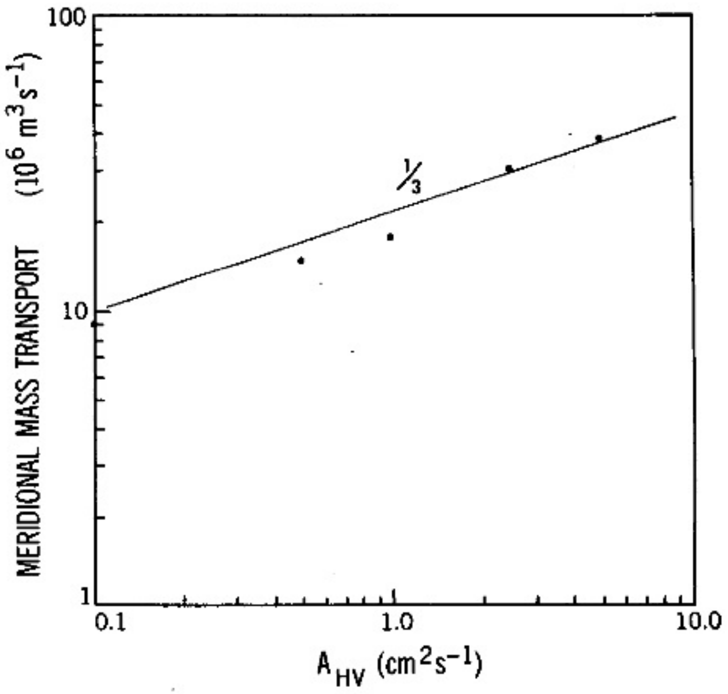
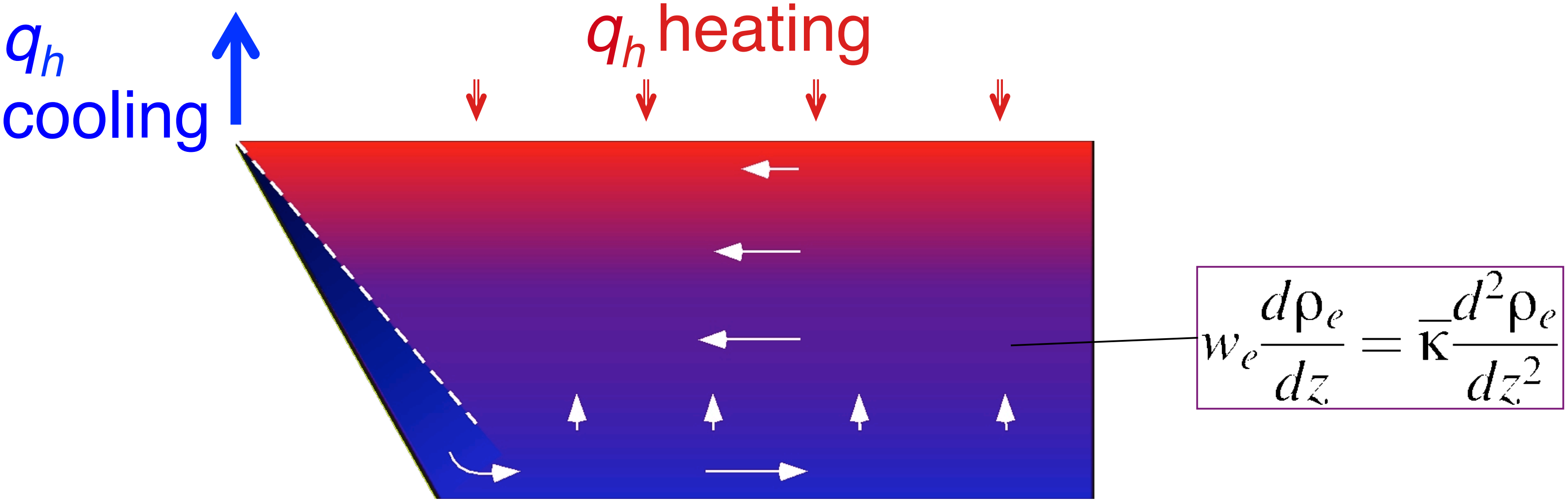


FIG. 8. Dependence of meridional overturning streamfunction on vertical diffusivity.

From Bryan 1987 (see also Winton 1995, Park & Bryan 2000)

- vary vertical diffusivity in numerical ocean models
- more ‘mixing’ increases overturning convection

A simple mechanical model



$$w_e \frac{d\rho_e}{dz} = \bar{\kappa} \frac{d^2\rho_e}{dz^2}$$

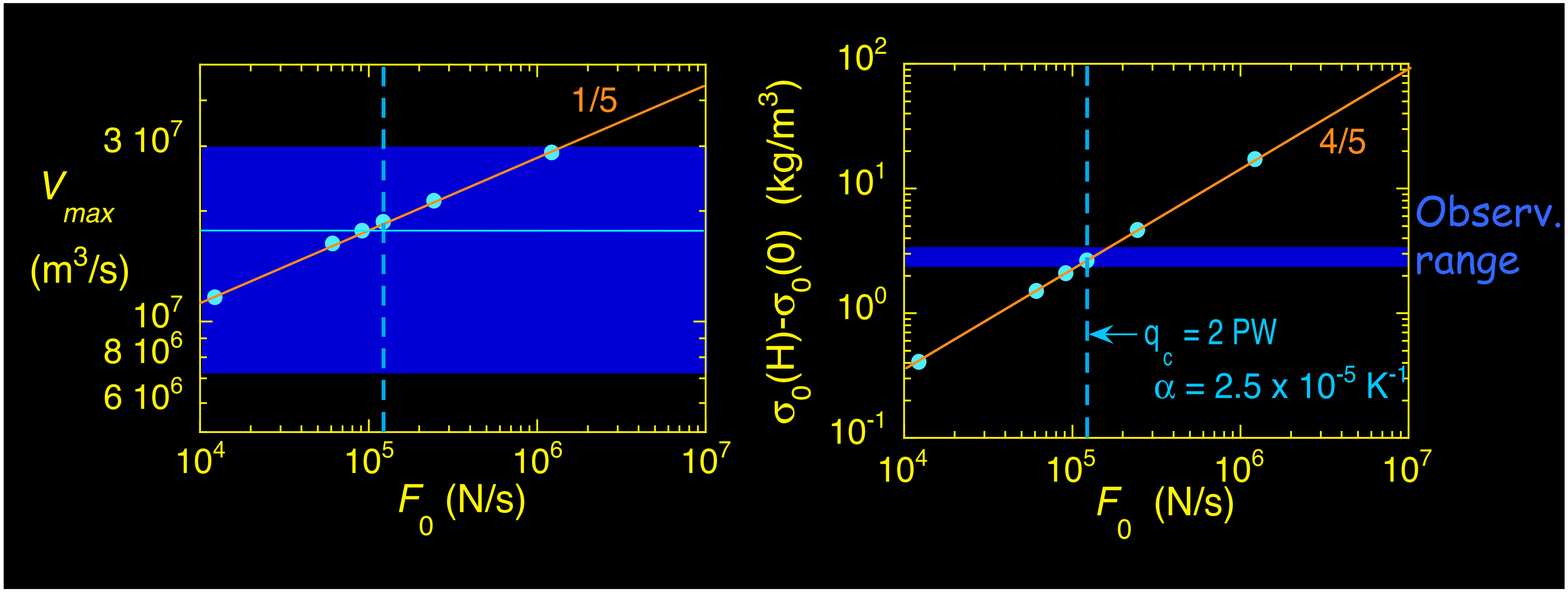
- zero net heating (steady state)
- single dominant plume sinking to bottom
- plume is a geostrophic slope current with entrainment
- interior return flow with vertical mixing
- surface buoyancy forcing and interior mixing are balanced

(plume buoyancy flux = buoyancy mixed down from surface)

Hughes & Griffiths, Ocean Modelling, 2006; JFM 2007

A simple mechanical model

For diffusivity $k = 10^{-5}$ m²/s, entrainment constant $E_z = 0.1$



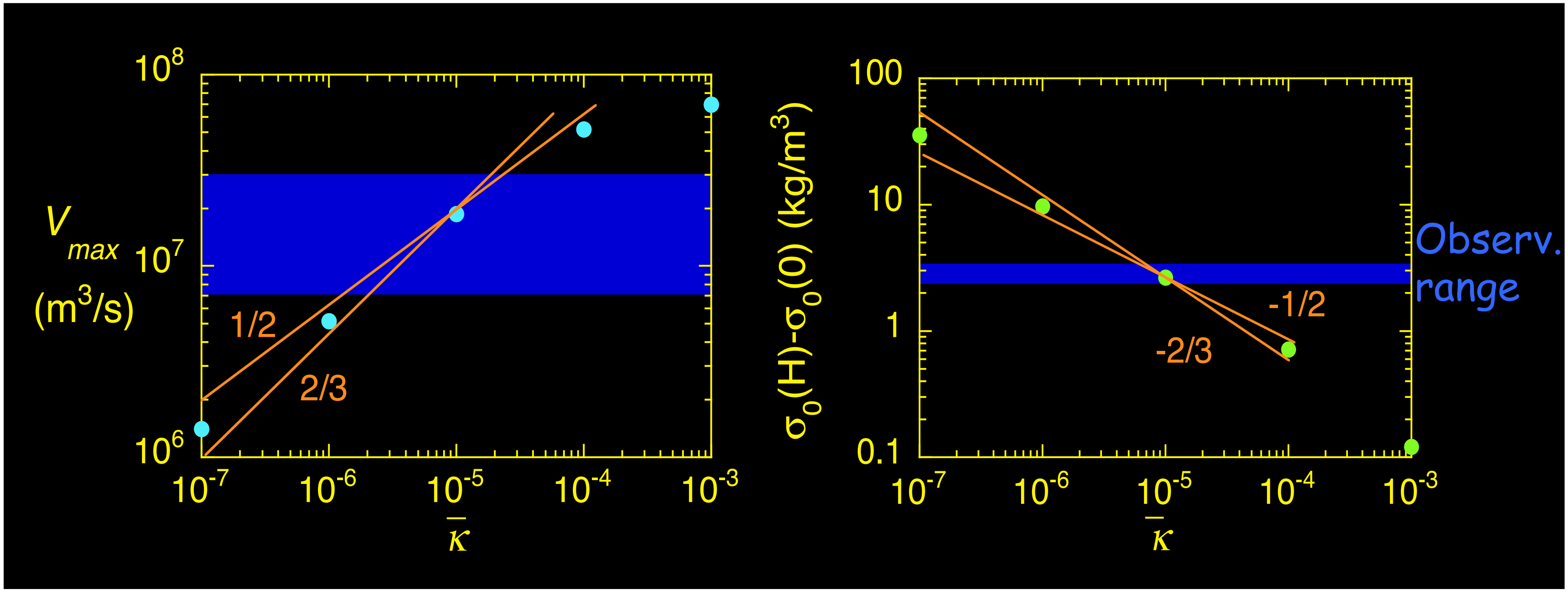
Overturning vol. flux $V_{max} \sim E_z^{0.45} k^{0.56} q_c^{1/5}$

- overturning dependent on surface buoyancy forcing
- predictions consistent with observations

Hughes & Griffiths, Ocean Modelling, 2006

A simple mechanical model

For heat transport $q_c = 2$ PW, entrainment constant $E_z = 0.1$



Overturning vol. flux $V_{max} \sim E_z^{0.45} k^{0.56} q_c^{1/5}$

- entrainment reduces required interior k and energy input (a short-circuit pathway for buoyancy)
- balance between mixing and surface buoyancy forcing

Hughes & Griffiths, Ocean Modelling, 2006

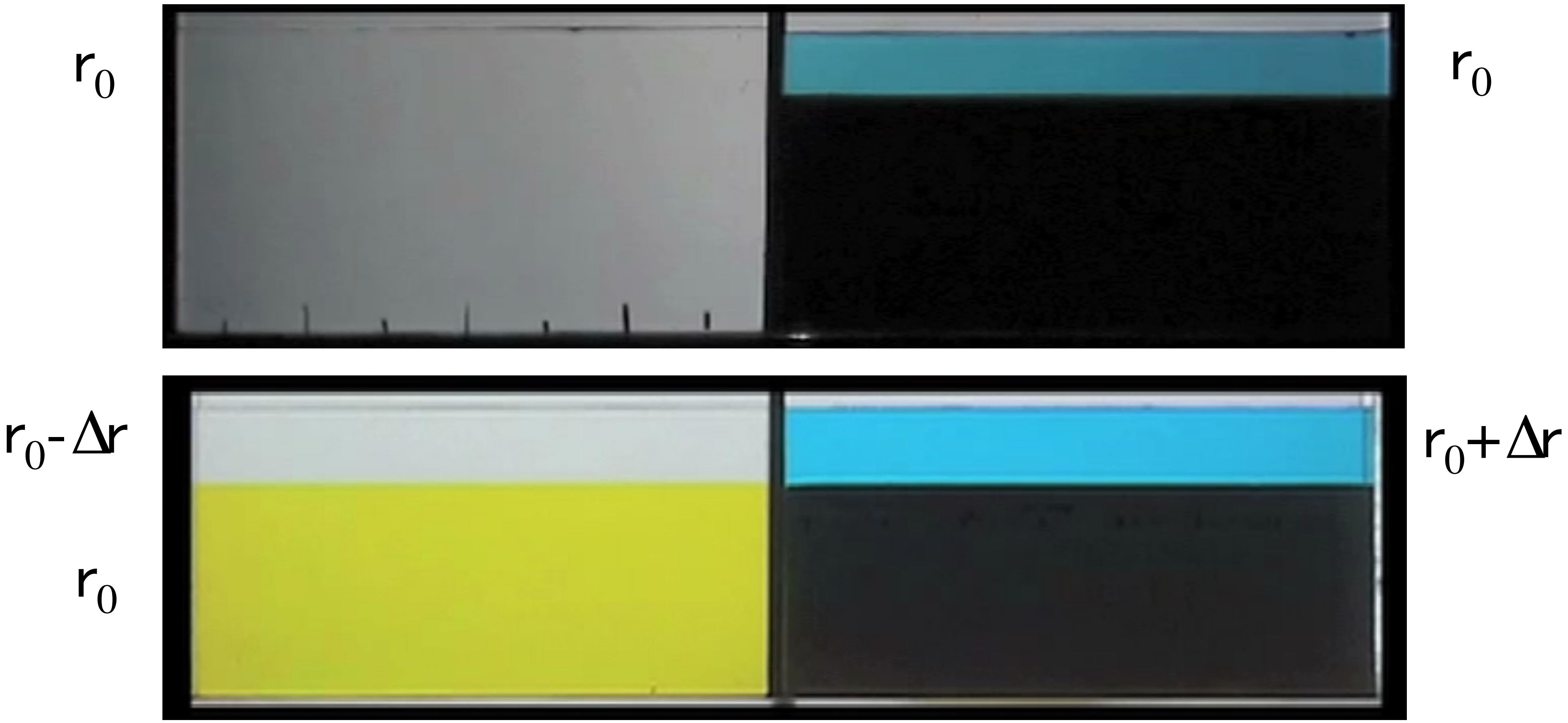
Roles of mixing and buoyancy?

- Hypothesis: the MOC is largely forced by surface buoyancy fluxes, with the rate of overturning governed also by the rate of vertical mixing.

- What are the energy pathways and global budget?

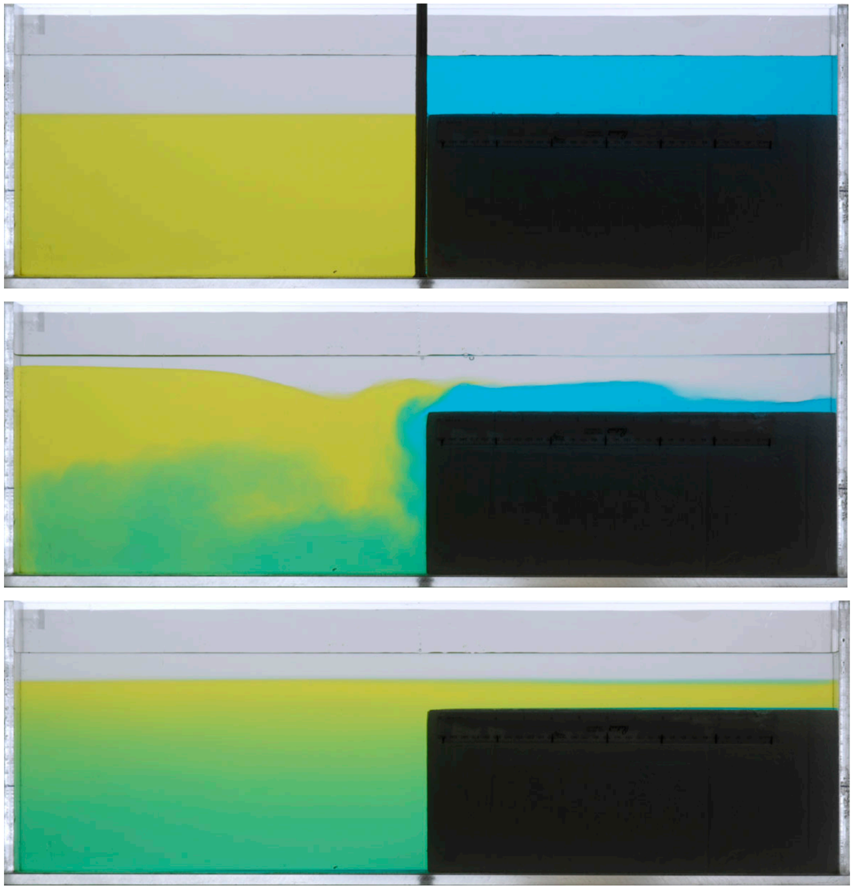
- Does wind stress play a dominant role?

Available potential energy



- Two cases: identical PE, different APE
- We cannot choose which to use
- Irreversible mixing increases background PE (‘mixing efficiency’)

Available potential energy



- surface buoyancy fluxes convert BPE to APE
- Mean flow buoyancy transport converts APE to KE
- Irreversible mixing converts APE to BPE (depends on mixing efficiency)

Available & background potential energy

Potential Energy:

$$\mathrm{PE} \equiv \int_V \rho g z dV$$

Background Potential Energy: The PE of an adiabatically re-sorted, statically stable state.

$$\mathrm{BPE} \equiv \int_V \rho g z_* dV$$

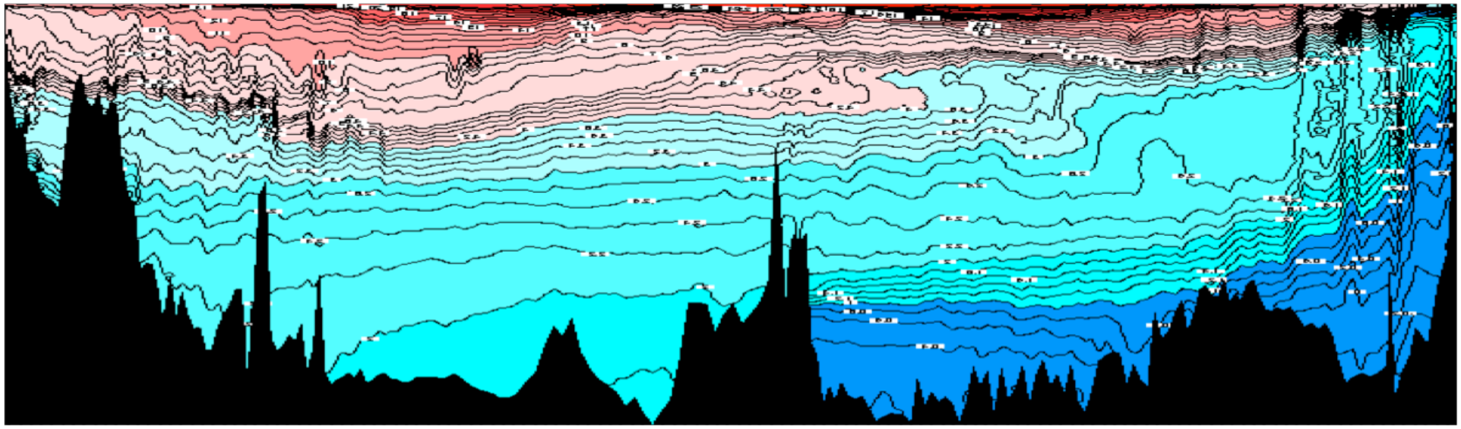
where

$$z_*(\mathbf{x},t) \equiv \frac{1}{A}\int_V H\left(\rho(\mathbf{x}',t) - \rho(\mathbf{x},t)\right) dV',$$

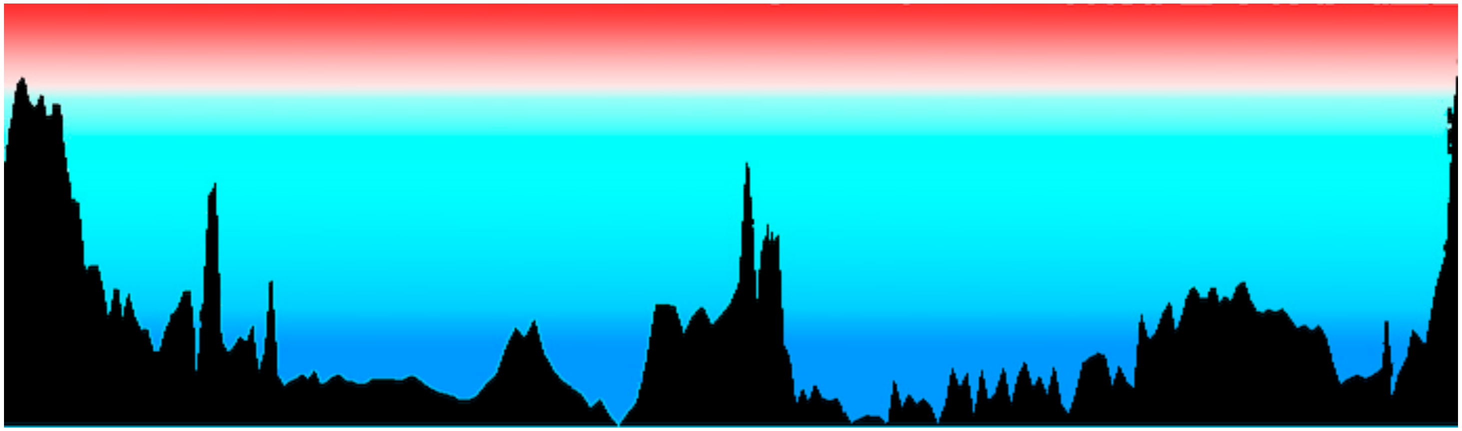
Available Potential Energy : The PE that could be released to generate motion.

$$\mathrm{APE} \equiv \mathrm{PE} - \mathrm{BPE} = \int_V \rho g (z - z_*) dV$$

Available potential energy



(WOCE section 25°W: 65°N–55°S)



- APE = PE released on relaxation to a state of no motion;
- APE is generated by stirring, wind stress, buoyancy fluxes

APE in the oceans

- Most of the mechanical energy in ocean circulation is APE

(eg. Gill, Green & Simmonds, 1979)

Basin average KE ~ 10^{-3} J/kg, APE ~ 10^{-1} J/kg

- Only rates of energy conversion are important

(order 10^{-9} W/kg for each term – surface buoyancy forcing, irreversible mixing, dissipation of TKE, reversible buoyancy fluxes, KE from surface stress)

A revised ocean energy budget

$$\frac{d\overline{\mathrm{KE}}}{dt} = \underbrace{\rho_0 \int_V \frac{\partial \overline{u_i}}{\partial x_j}\overline{u_i' u_j'}\,dV}_{\text{TKE Production}} - \underbrace{\int_V \overline{\rho}\,\overline{w} g\,dV}_{\text{Buoyancy Flux}} + \underbrace{\rho_0 \nu \oint \overline{u_i}\frac{\partial \overline{u_i}}{\partial x_j} n_j\,dS}_{\text{Wind stress}} - \underbrace{\rho_0 \nu \int_V \left(\frac{\partial \overline{u_i}}{\partial x_j}\right)^2 dV}_{\text{Mean Flow Dissipation}} ,$$

$$\frac{d\mathrm{KE}'}{dt} = \underbrace{-\rho_0 \int_V \frac{\partial \overline{u_i}}{\partial x_j}\overline{u_i' u_j'}\,dV}_{\text{TKE Production}} - \underbrace{\int_V \overline{\rho' w'}\, g\,dV}_{\text{Turb. Buoy. Flux}} + \underbrace{\rho_0 \nu \oint \overline{u_i' \frac{\partial u_i'}{\partial x_j}}\, n_j\,dS}_{\text{Wind stress}} - \underbrace{\rho_0 \nu \int_V \overline{\left(\frac{\partial u_i'}{\partial x_j}\right)^2}\, dV}_{\text{Dissipation}},$$

$$\frac{d\mathrm{PE}}{dt} = \underbrace{g \int_V \overline{w}\,\overline{\rho}\,dV}_{\text{Buoyancy Flux}} + \underbrace{g \int_V \overline{w' \rho'}\,dV}_{\text{Turb. Buoy. Flux}} + \underbrace{\kappa g \oint z \frac{\partial \overline{\rho}}{\partial x_i} n_i\,dS}_{\text{Surface Buoyancy Forcing}} - \underbrace{\kappa g A[\overline{\rho}_{top} - \overline{\rho}_{bottom}]}_{\text{Molecular Diffusion}} ,$$

see Winters et al. (1995)

A revised ocean energy budget

$$\frac{d\mathrm{PE}}{dt} = \underbrace{g\int_V \overline{w}\,\overline{\rho}\,dV}_{\text{Buoyancy Flux}} + \underbrace{g\int_V \overline{w'\rho'}\,dV}_{\text{Turb. Buoy. Flux}} + \underbrace{\kappa g \oint z\,\frac{\partial \overline{\rho}}{\partial x_i} n_i\,dS}_{\text{Surface Buoyancy Forcing}} - \underbrace{\kappa g A[\overline{\rho}_{top} - \overline{\rho}_{bottom}]}_{\text{Molecular Diffusion}}\,,$$

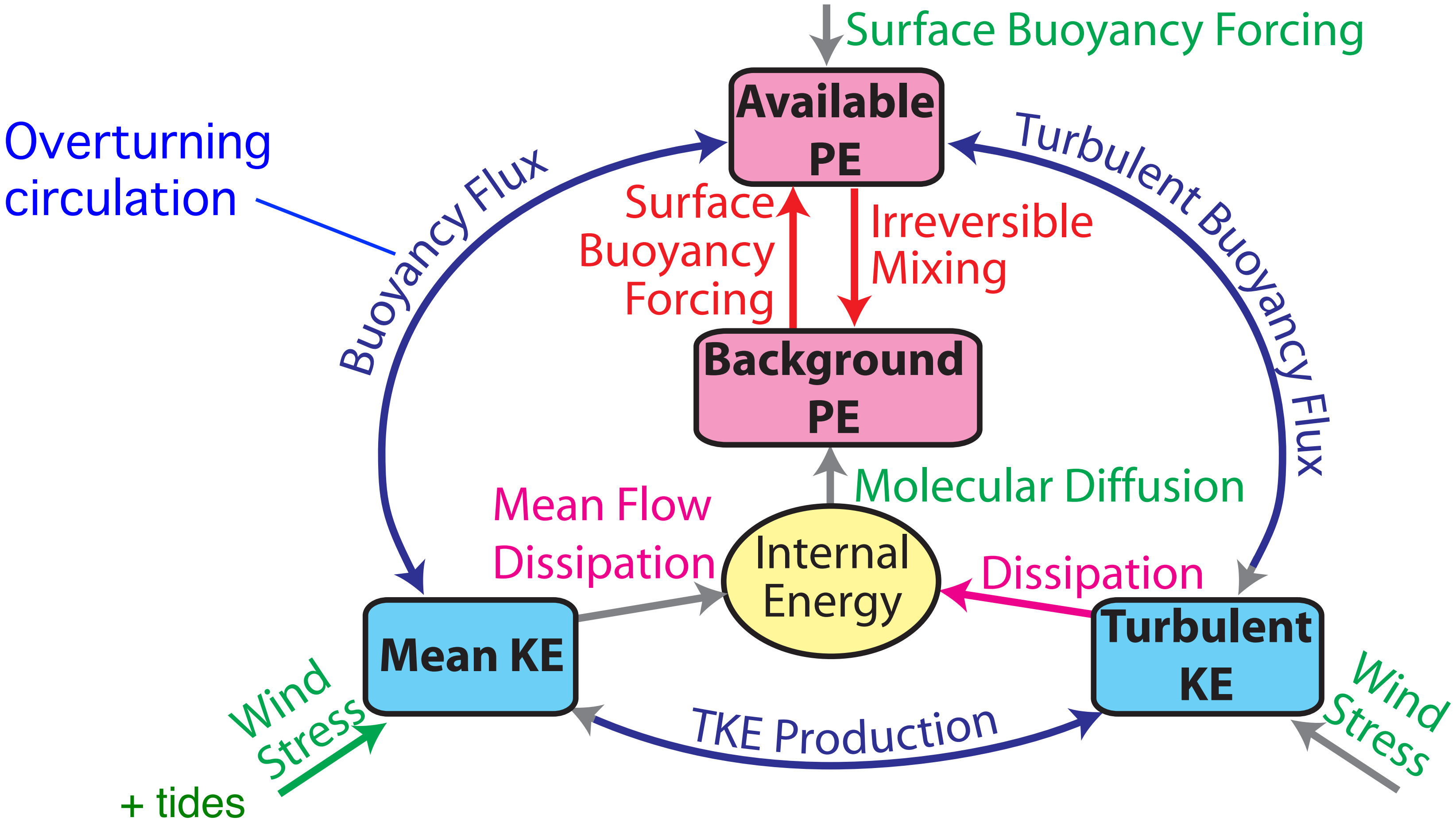
$$\frac{d\mathrm{BPE}}{dt} = \underbrace{\kappa g \oint z_*\,\frac{\partial \rho}{\partial x_i} n_i\,dS}_{\text{Surface Buoyancy Forcing}} - \underbrace{\kappa g \int_V \frac{dz_*}{d\rho}\left(\frac{\partial \rho}{\partial x_i}\right)^2 dV}_{\text{Irreversible Mixing}}\,.$$

$$\frac{d\mathrm{APE}}{dt} = \underbrace{g\int_V \overline{w}\,\overline{\rho}\,dV}_{\text{Buoyancy Flux}} + \underbrace{g\int_V \overline{w'\rho'}\,dV}_{\text{Turb. Buoy. Flux}} - \underbrace{\kappa g \oint z_*\,\frac{\partial \rho}{\partial x_i} n_i\,dS}_{\text{Surf. Buoyancy Forcing}}$$

$$+ \underbrace{\kappa g \int_V \frac{dz_*}{d\rho}\left(\frac{\partial \rho}{\partial x_i}\right)^2 dV}_{\text{Irreversible Mixing}} + \underbrace{\kappa g \oint z\,\frac{\partial \overline{\rho}}{\partial x_i} n_i\,dS}_{\text{Surf. Buoy. Forc.}} - \underbrace{\kappa g A[\overline{\rho}_{top} - \overline{\rho}_{bottom}]}_{\text{Mol. Diffusion}}.$$

Extension of Winters et al. (1995)

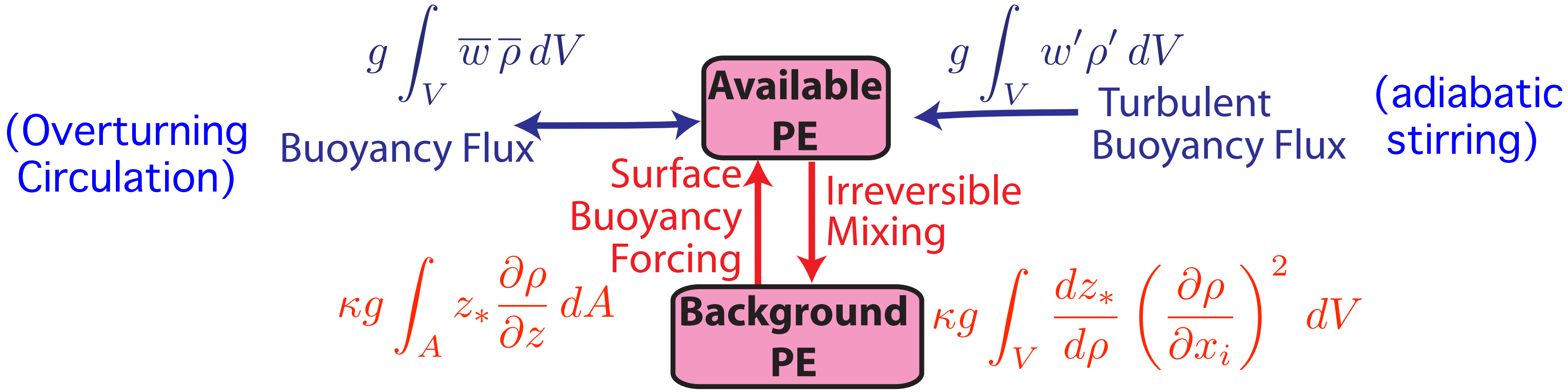
A revised ocean energy budget



- mechanical forcing is balanced by dissipation
- buoyancy transports due to overturning and adiabatic stirring are in balance

Hughes, Hogg & Griffiths (2009) *J. Phys. Oceanogr.* 39, 3130–3146.

The APE loop



$g \int_V \overline{w}\, \overline{\rho}\, dV$

(Overturning Circulation)

Buoyancy Flux

Available PE

$g \int_V w' \rho' \, dV$

Turbulent Buoyancy Flux

(adiabatic stirring)

Surface Buoyancy Forcing

$\kappa g \int_A z_* \frac{\partial \rho}{\partial z} \, dA$

Irreversible Mixing

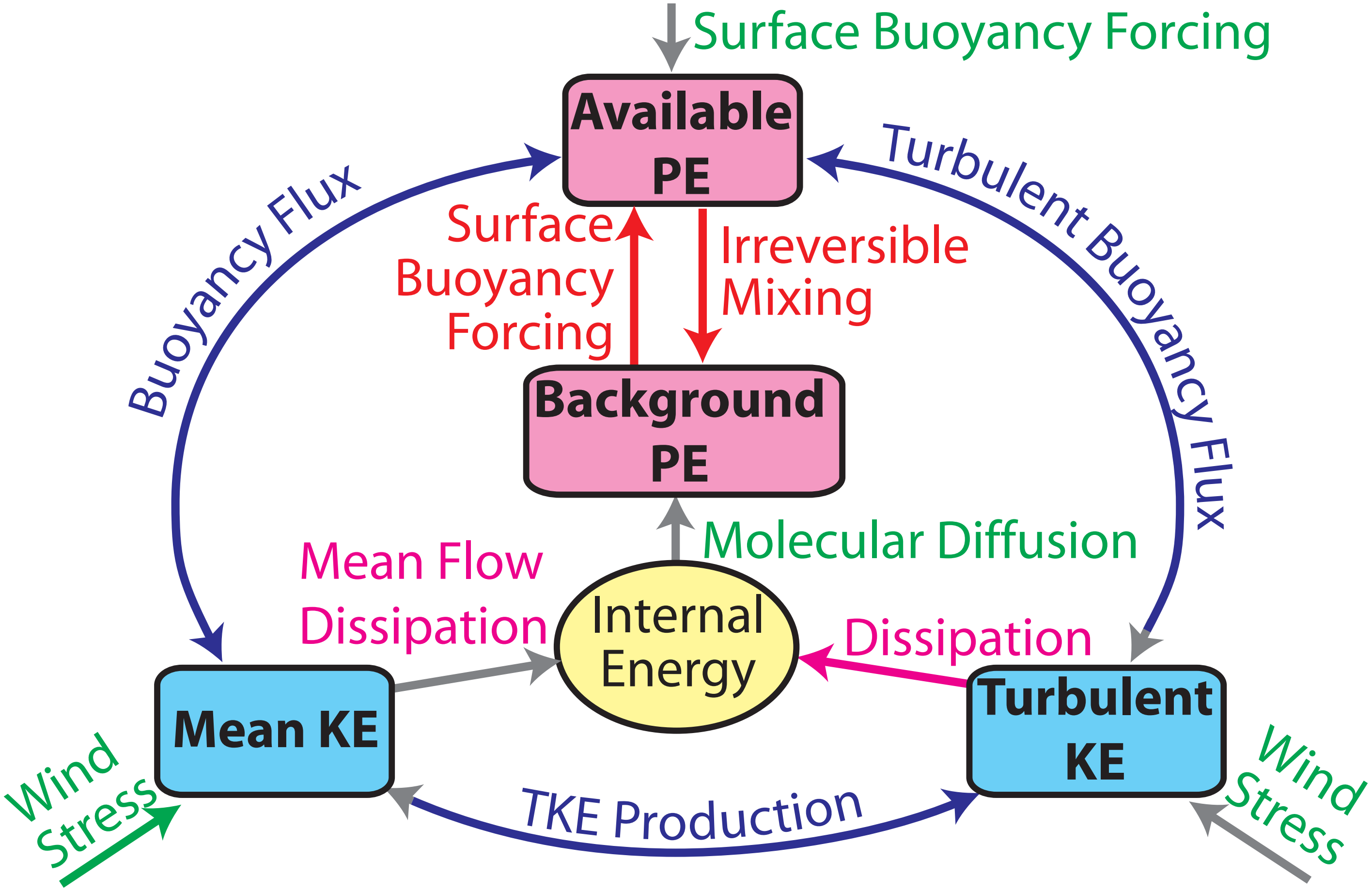
Background PE

$\kappa g \int_V \frac{dz_*}{d\rho} \left(\frac{\partial \rho}{\partial x_i} \right)^2 dV$

diabatic processes: “APE loop”

- APE is generated by surface buoyancy fluxes and mechanical forcing
- In steady state, surface buoyancy forcing is exactly balanced by irreversible mixing
- Same conclusion as from mechanical model.

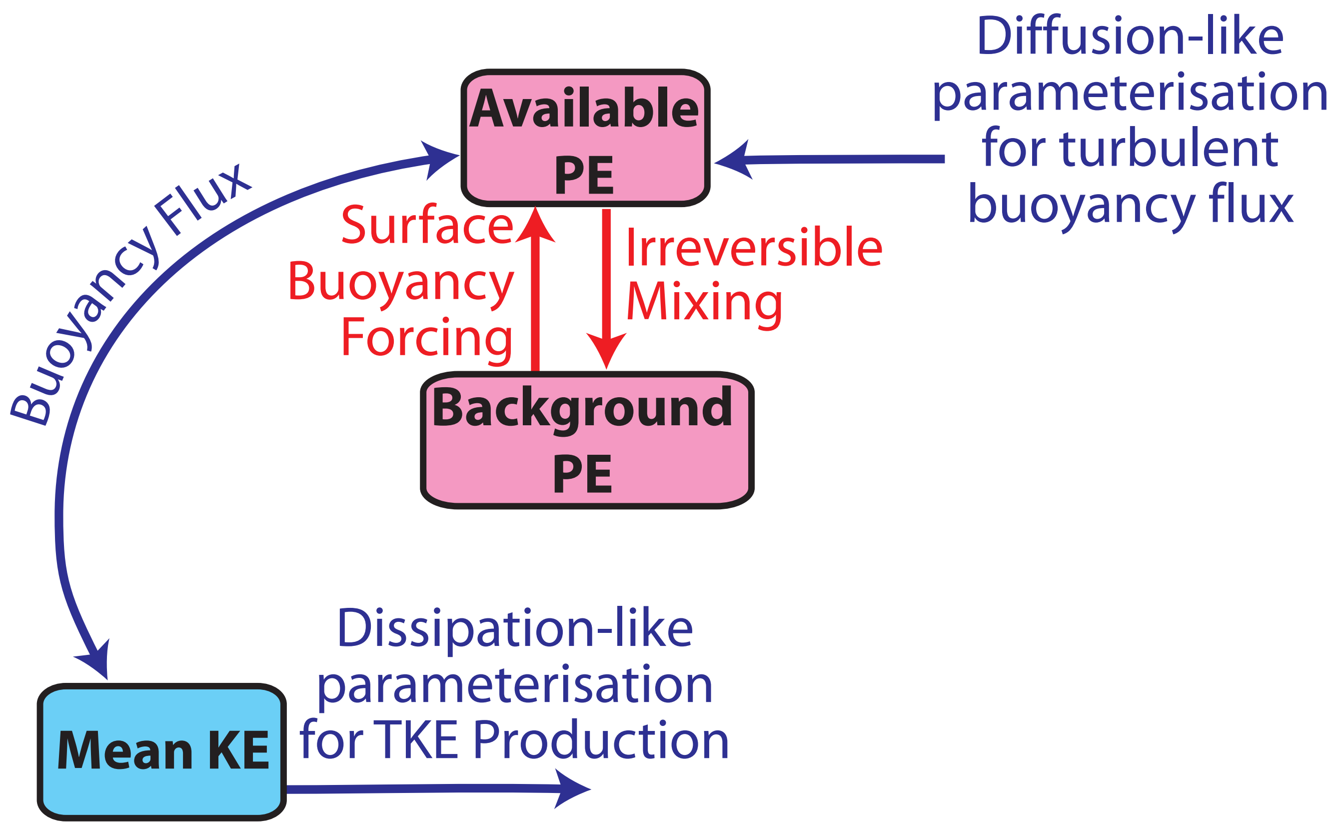
Numerical ocean models



- how well are energy conversions modelled?

Hughes, Hogg & Griffiths (2009) *J. Phys. Oceanogr.* 39, 3130–3146.

Numerical ocean models

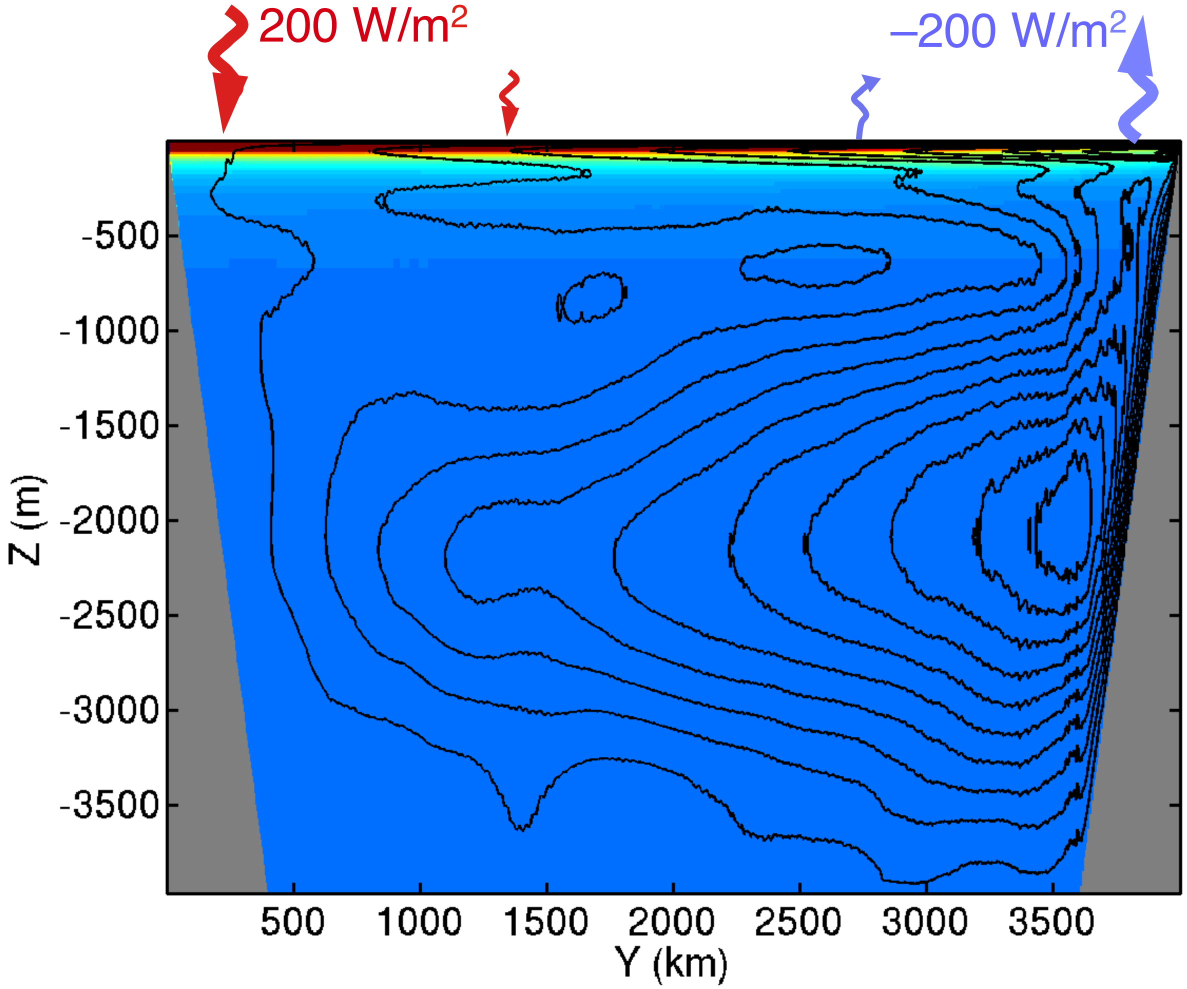


Diffusion-like parameterisation for turbulent buoyancy flux

Dissipation-like parameterisation for TKE Production

- simple turbulent viscosity and diffusion parameterisation

Numerical ocean models

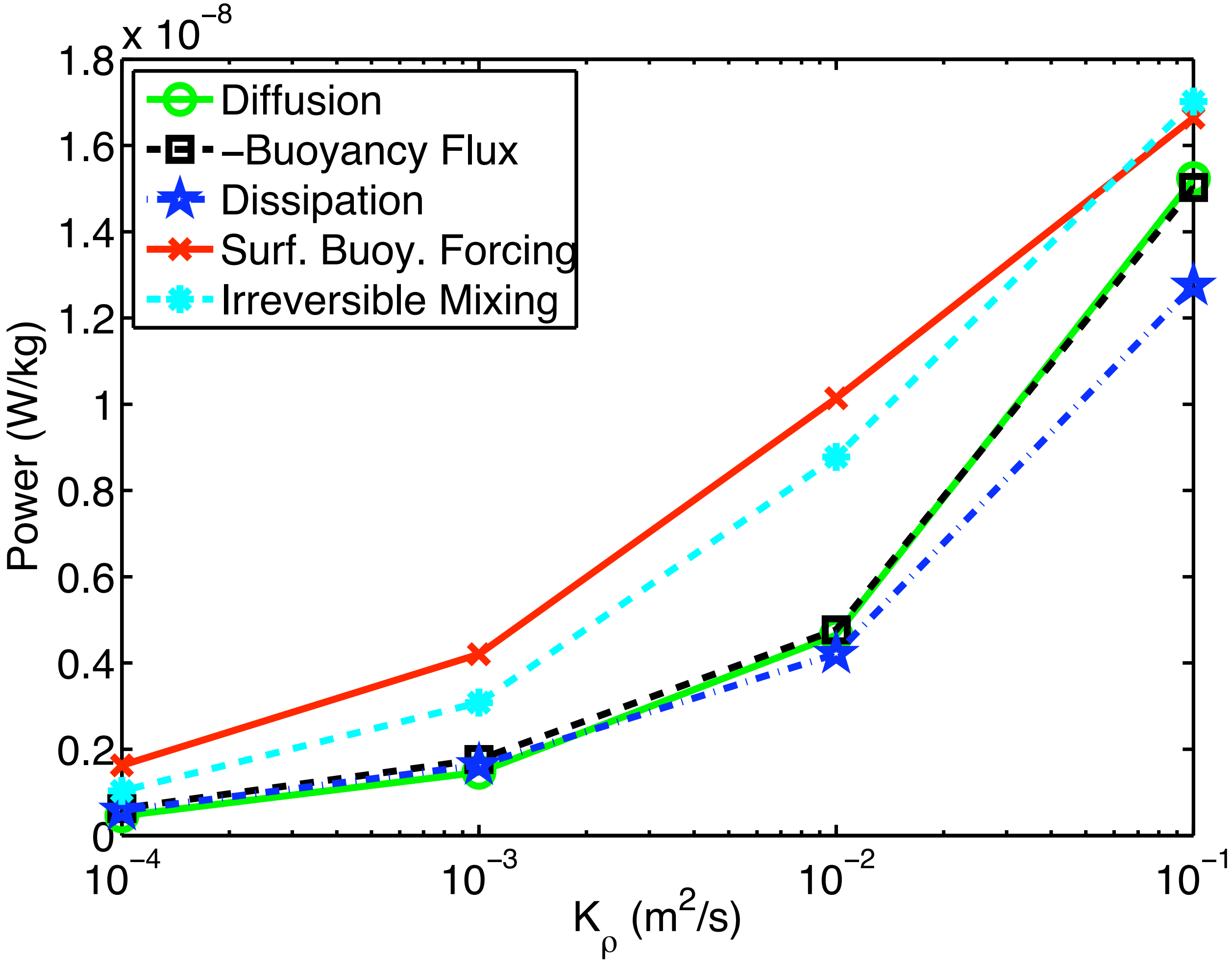


- surface buoyancy forcing only (cos y)
- MITgcm, high res (10-75m x 0.7-7km, 2 x 1600 x 64 points)
- 2-D, non-rotating, nonhydrostatic
- resolved convection
- $K_z = 10^{-4}$ m²/s (external energy input)

- Resolving convection makes circulation deeper and stronger

Hughes, Hogg & Griffiths (2009) *J. Phys. Oceanogr.* 39, 3130–3146.

Numerical ocean models

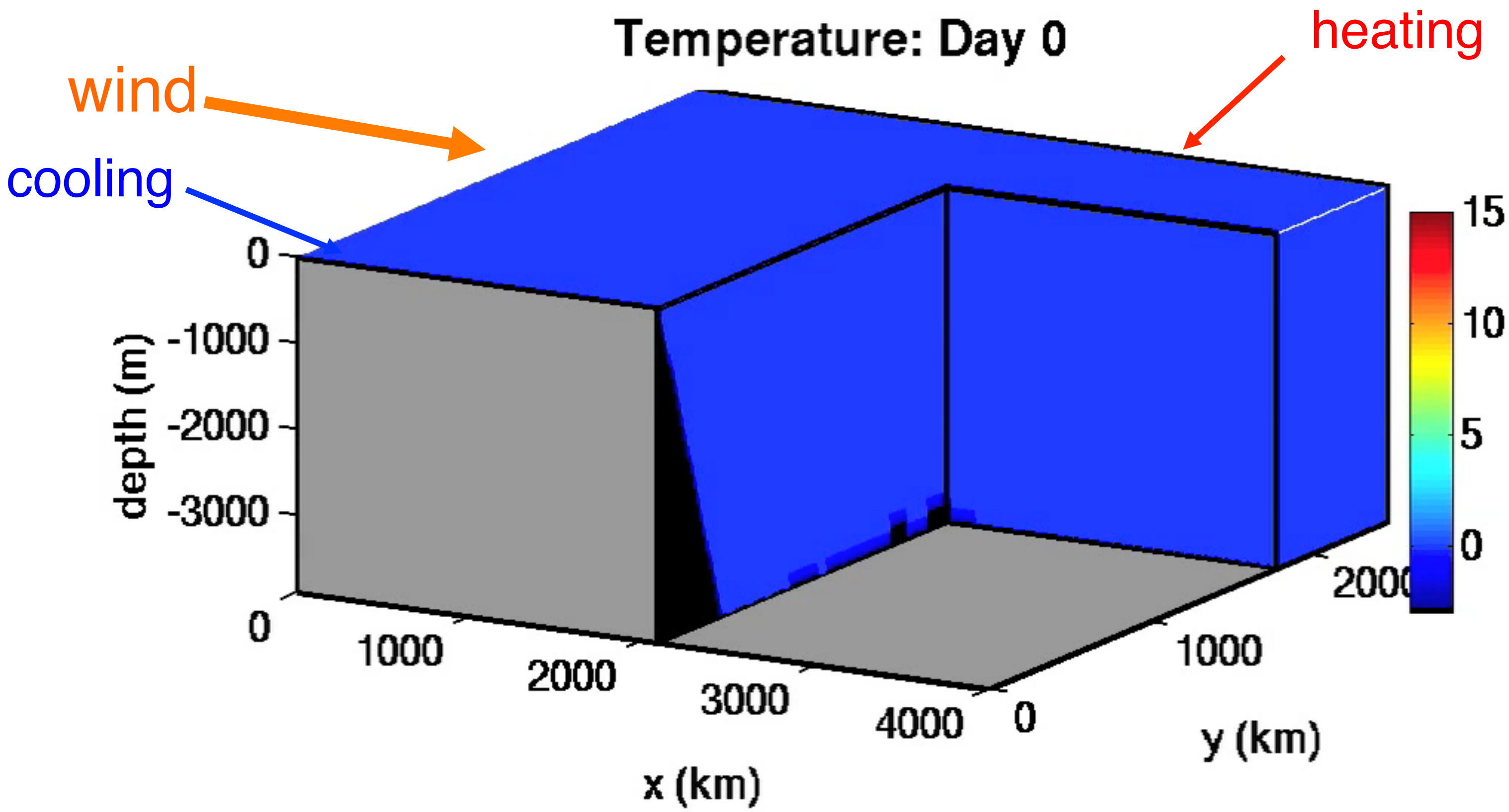


- Irreversible mixing rate balances surface buoyancy forcing
- APE loop also sets transient response time

Hughes, Hogg & Griffiths (2009) *J. Phys. Oceanogr.* 39, 3130–3146.

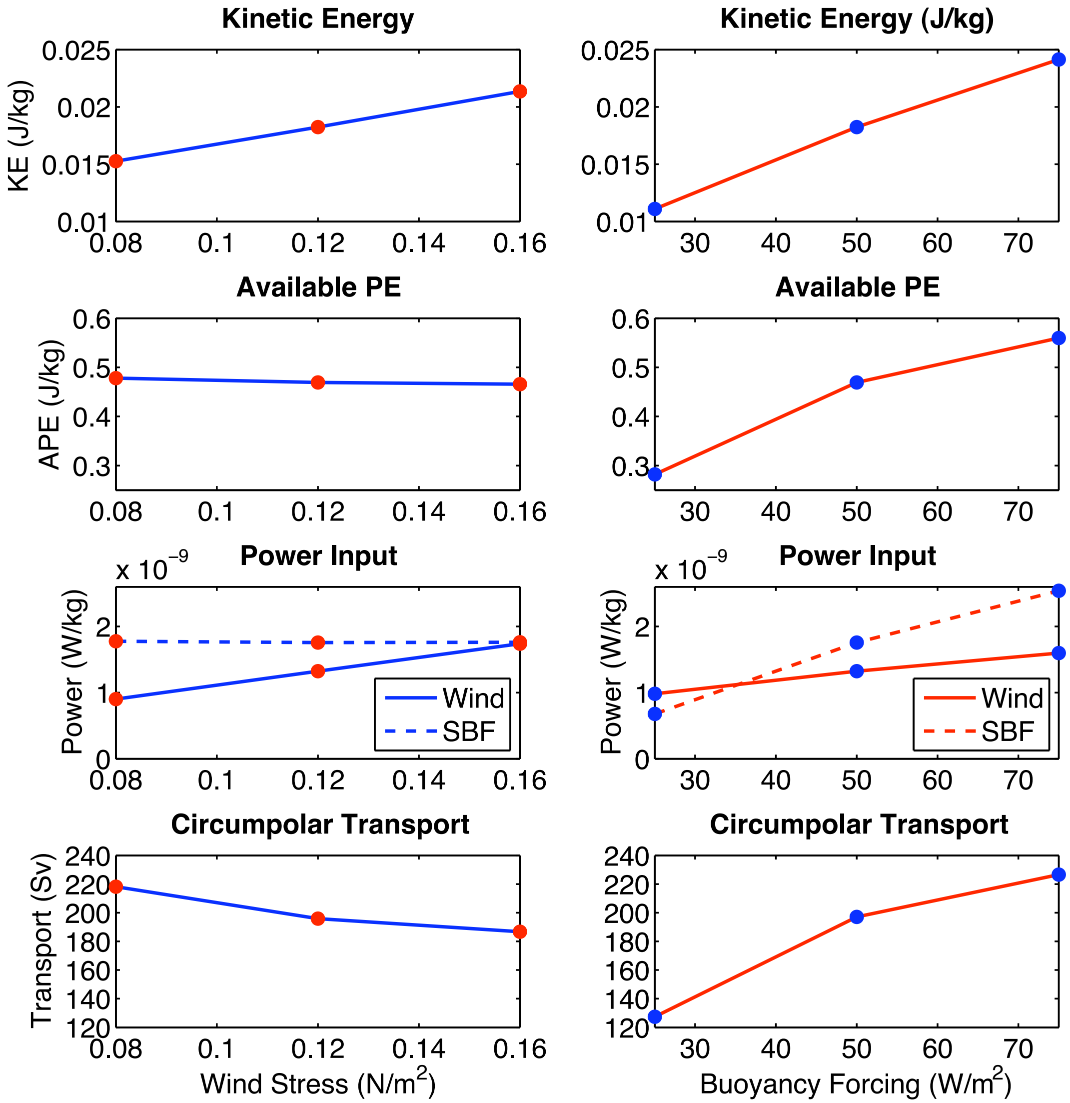
Ocean models – buoyancy & wind

- Antarctic Circumpolar Current – wind driven??
- rotating b-plane, wind stress, buoyancy forcing, topography
- Hydrostatic



Antarctic Circumpolar Current model, courtesy of A.McC. Hogg

Ocean models – buoyancy & wind

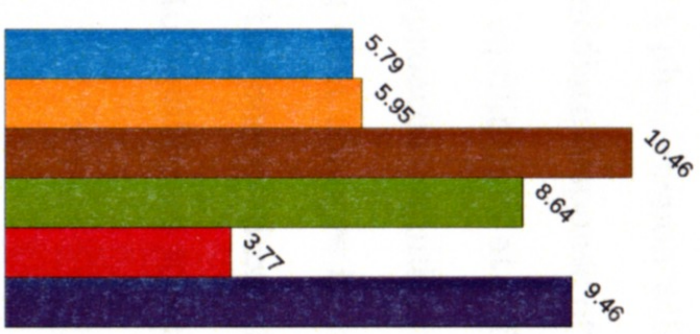


Antarctic Circumpolar Current model, courtesy of A.McC. Hogg

Ocean models – buoyancy & wind

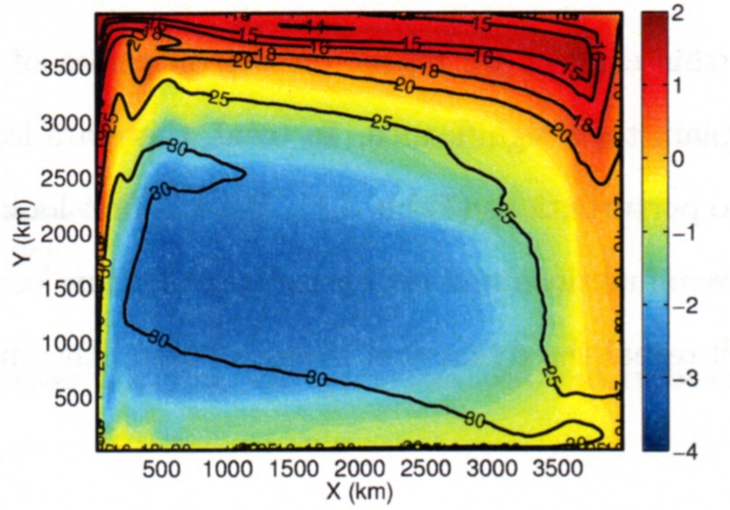
- Mid-latitude double gyre + meridional overturning
- rotating b-plane, sinusoidal zonal wind stress (+/-0.08 N/m^2), surface buoyancy fluxes (+/-100 W/m^2)
- MITgcm, hydrostatic mode w convective adjustment
- k = 10^{-4} m^2/s   (horiz. diffusivity 50 m^2/s)

mean buoy
turb buoy
surf buoy
mixing
surf stress
dissipation



Energy transformation rate (10^{-10} W/kg)

Y, T - top 50m



Courtesy of J. Tan & A.McC. Hogg

Conclusion

- APE conversions are crucial in ocean circulation

- Mixing and surface buoyancy fluxes are closely coupled (the flow governs how much mixing is achieved by external energy input?)

- The MOC requires external energy for mixing, but we predict a mixing rate matching surface buoyancy forcing

- Links between APE and TKE loops? (can we assume 20% mixing efficiency?)

- Surface buoyancy fluxes might also be important where wind stress appears dominant.

Surface buoyancy forcing – with rotation

Baroclinic instability in a cylindrical annulus

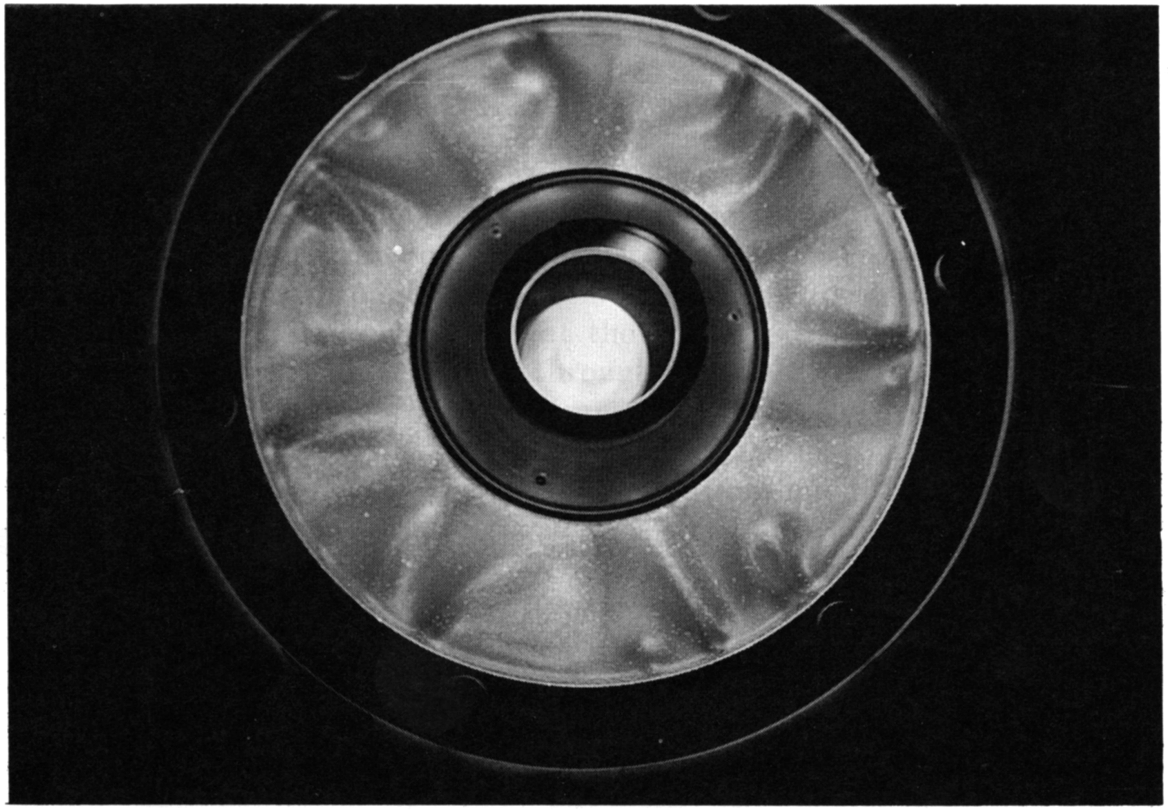
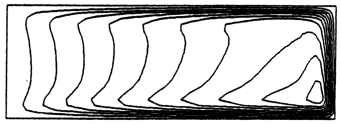


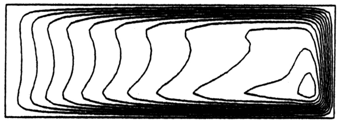
FIGURE 6. Photo of the quasi-equilibrated flow pattern for the case with $\Omega = 120°/\mathrm{s}$ and $\Delta T = 6.9\,°\mathrm{C}$ ($Ro = 0.0040$, $Ta = 2.32 \times 10^6$).

ds

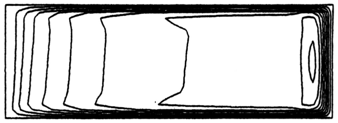
(*c*)



Contour interval = 0.01
Max = 0.106



Contour interval = 0.005
Max = 0.0578

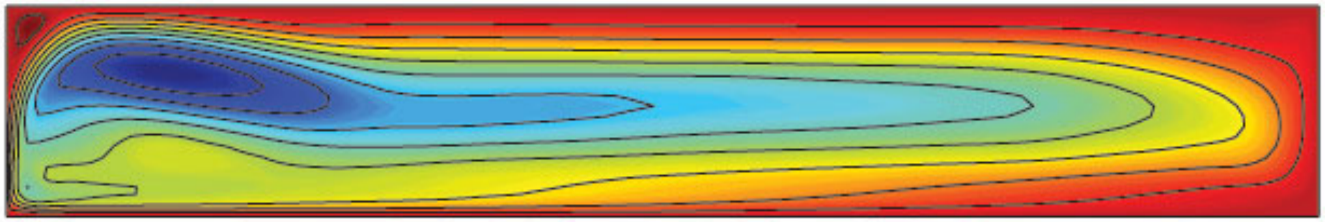


Contour interval = 5.0×10^{-4}
Max = 4.65×10^{-3}

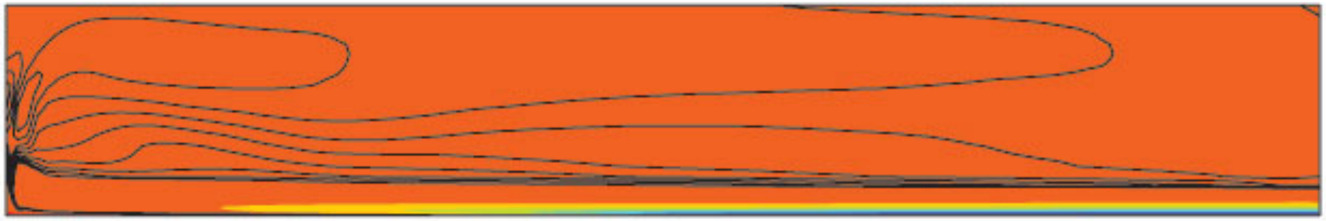
- Non-uniform heating/cooling at base; zero net heat input
- narrow plume, broad downward return flow
- stratification relies on interior vertical diffusion

Horizontal convection at large *Ra*

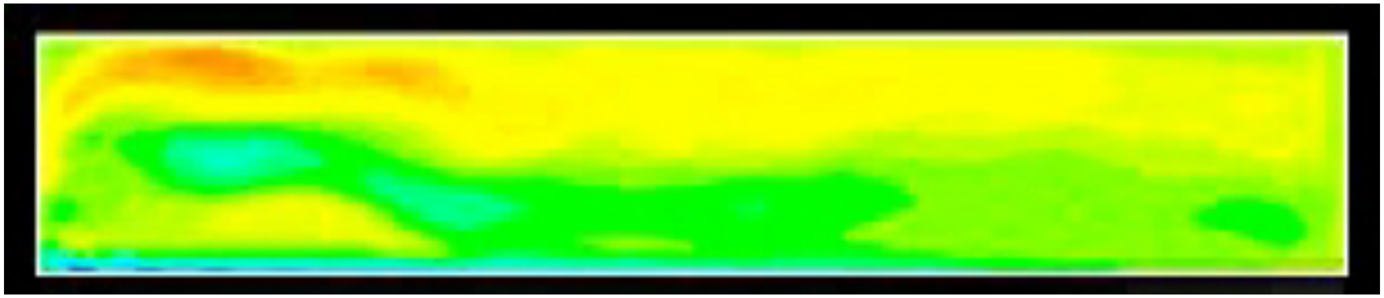
Av y



Av T

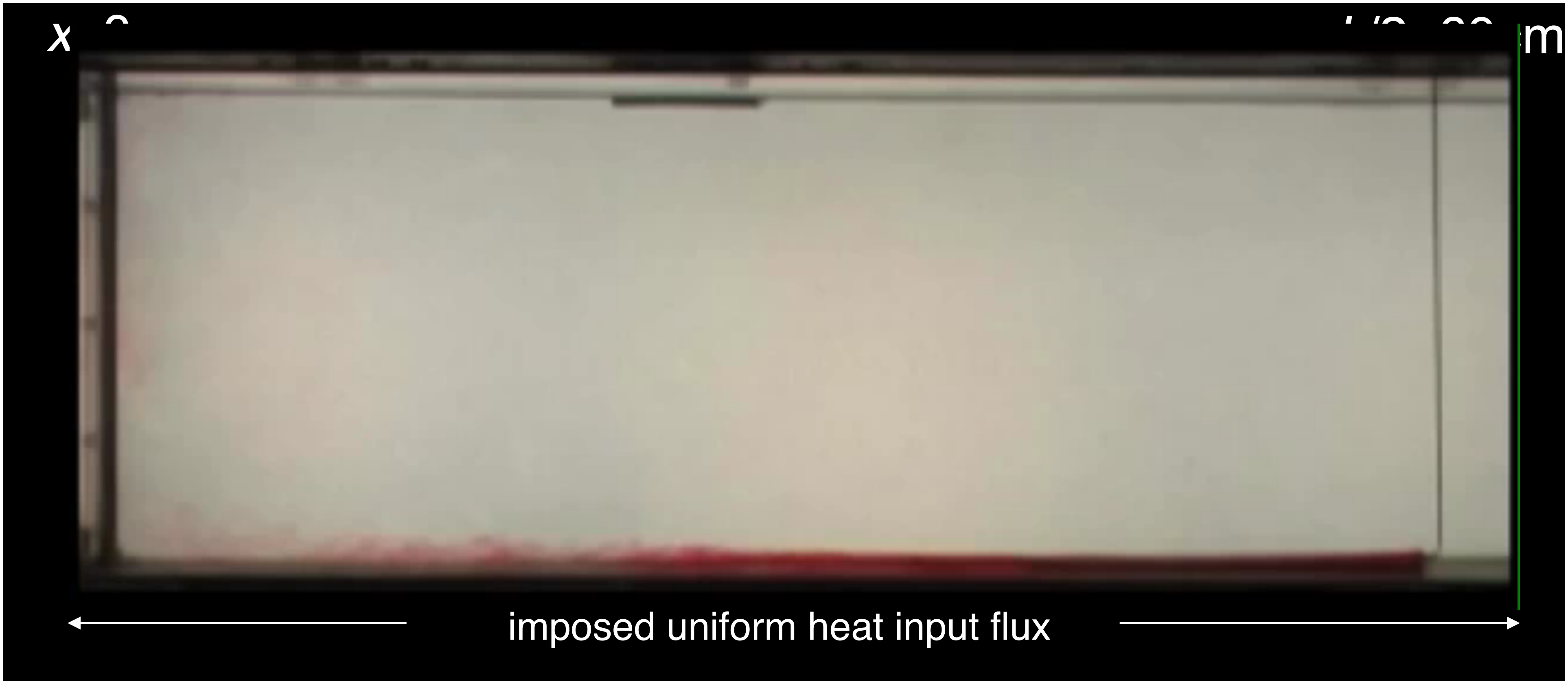


horiz
vel



Mullarney et al. (2004)

Horizontal convection at large *Ra*



Mullarney, et al. (2004)

- $Ra \sim 10^{12}$ or $Ra_F \sim 10^{14}$; flow insensitive to BCs
- transitions: small-scale convection within boundary layer, shear turbulence in plume, eddies in interior