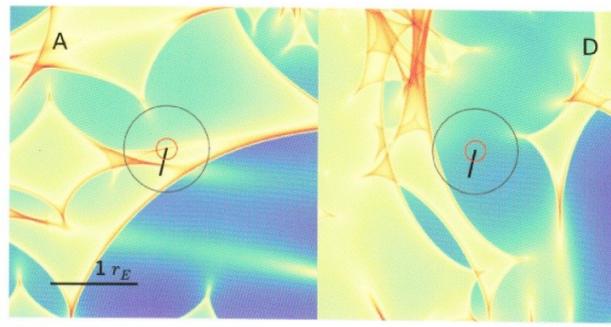
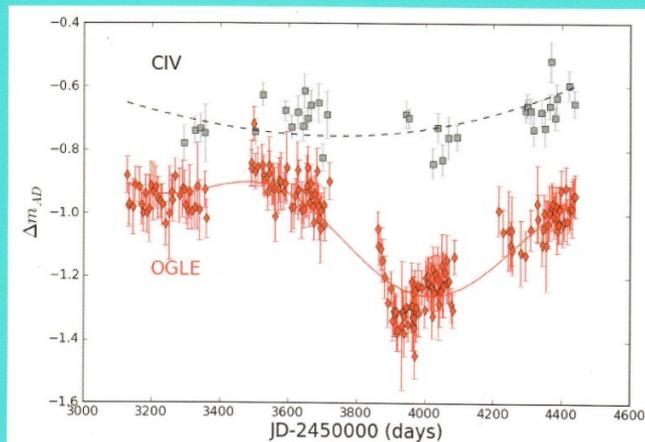


# Astronomy & Astrophysics



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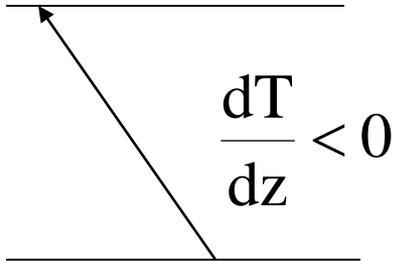
# MIXING IN STARS, OCEAN AND ATMOSPHERE

V.M. Canuto

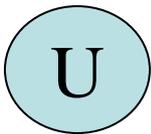
*NASA-Goddard Institute for Space Studies, New York*

*Dept. of Applied Phys. and Math., Columbia University, New York*

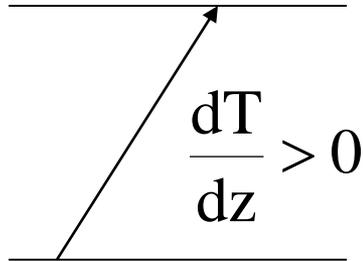
# Stars



Unstably  
Stratified



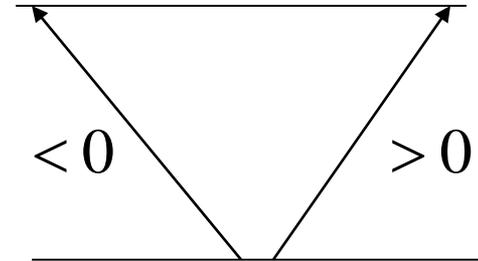
# Ocean



Stable



# Atmosphere



Global Codes (A-OGCMs, Stellar Codes) resolve the large scales  
Need: Reynolds stresses, heat fluxes, salt fluxes, etc

## OCEANS

Stably stratified (cold waters at the bottom)

Eddies are in general small

Richardson Number:  $Ri = N^2 \Sigma^{-2}$

## MIXED LAYER

- First ~ 100 meters
- Source of Mixing: Wind ~ 1TW
- Typical Values:  $D=200 \text{ cm}^2\text{s}^{-1}$ ,  $\nu=10^{-3} \text{ cm}^2\text{s}^{-1}$ ,  $Re=D/\nu=10^5$
- Due to Stable Stratification, Local models are OK:

$$\overline{uw} = -K_m \frac{\partial U}{\partial z}, \quad \overline{w\theta} = -K_h \frac{\partial T}{\partial z}, \quad \overline{w\sigma} = -K_s \frac{\partial S}{\partial z}$$

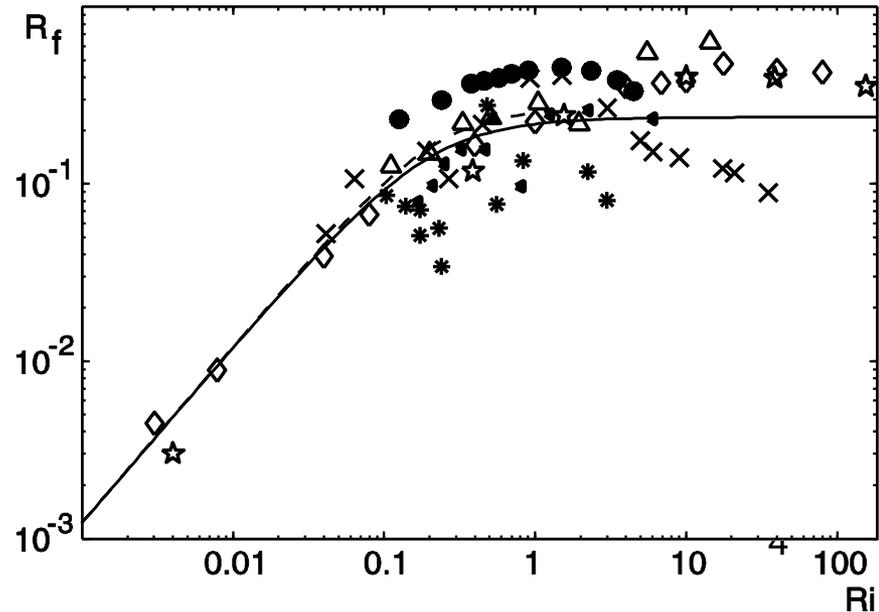
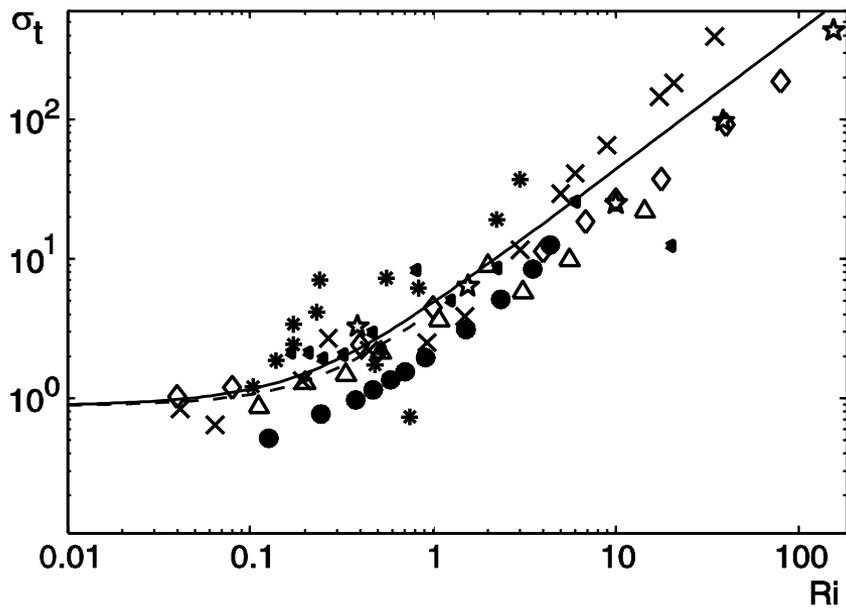
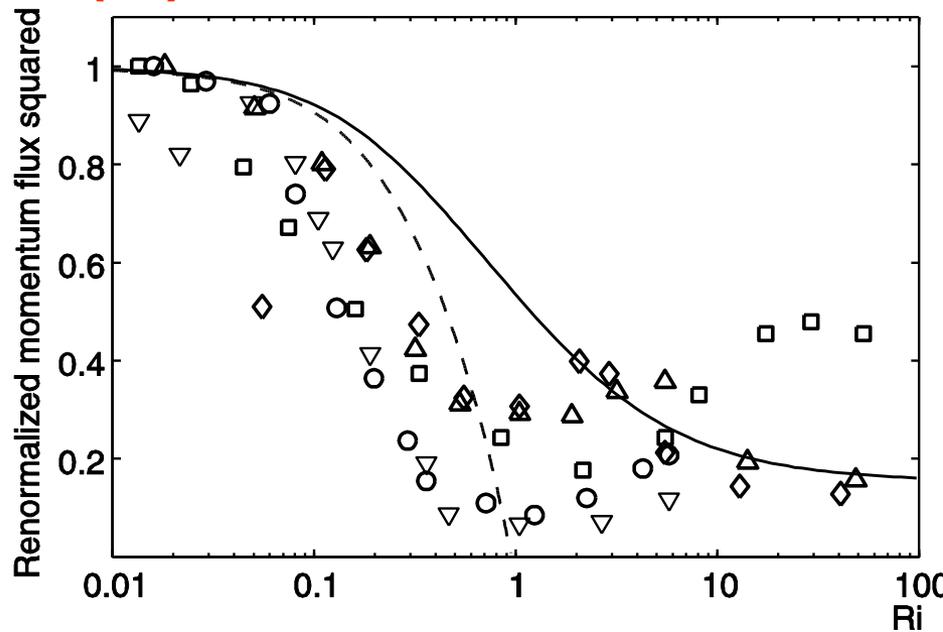
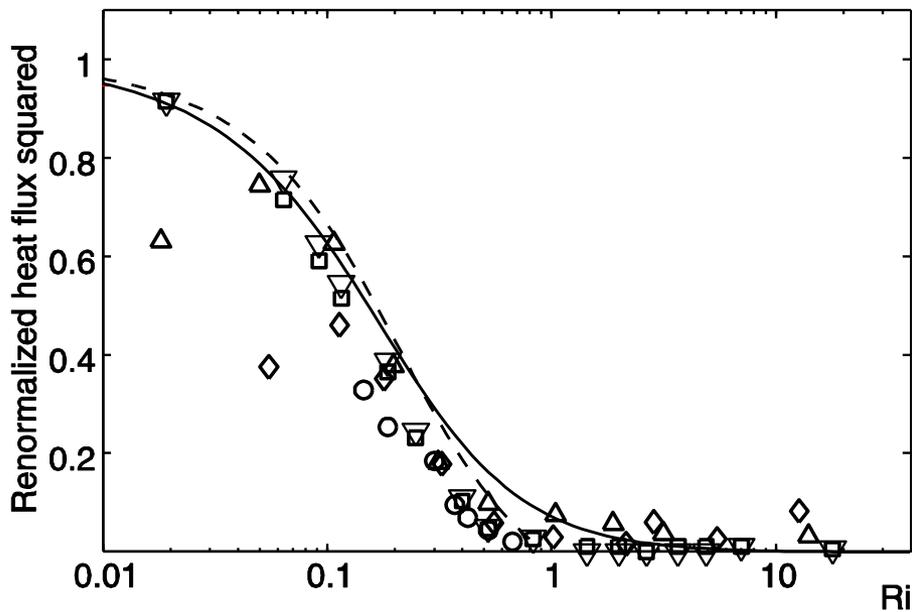
Critical issue:

**Ri(cr)**

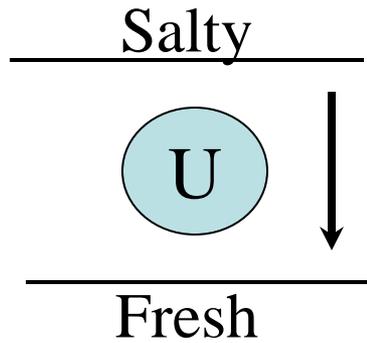
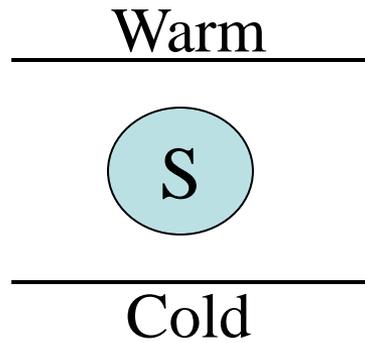
Mellor-Yamada  $Ri(cr)=0.2$ ; Empirical studies  $Ri(cr)=O(1)$

- RSM  $Ri(cr)=1$

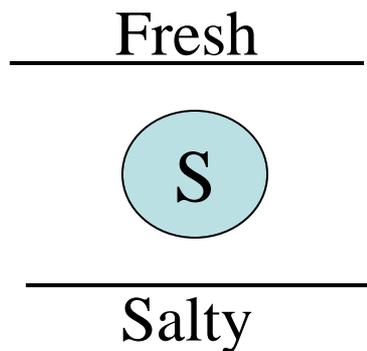
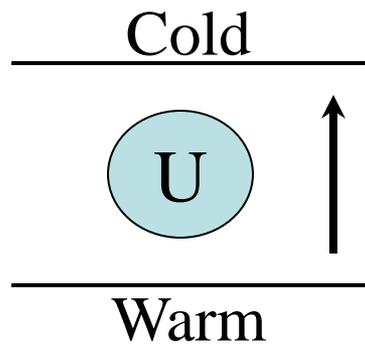
# No Ri(cr)



# Double Diffusion



**SF (Med.)**



**DC (water/ice)**

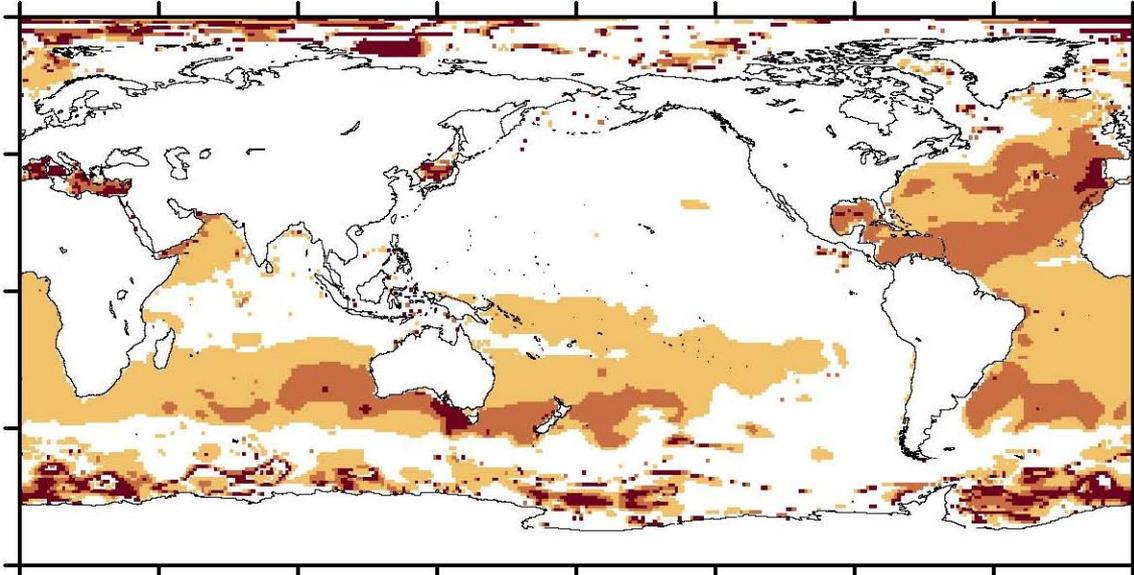
$$R_\rho = \frac{\alpha_s \partial S / \partial z}{\alpha_T \partial T / \partial z}, \quad \gamma = \frac{\overline{\alpha_T w \theta}}{\alpha_s \overline{w S}}$$

SF:  $R_\rho < 1; \quad \gamma < 1$

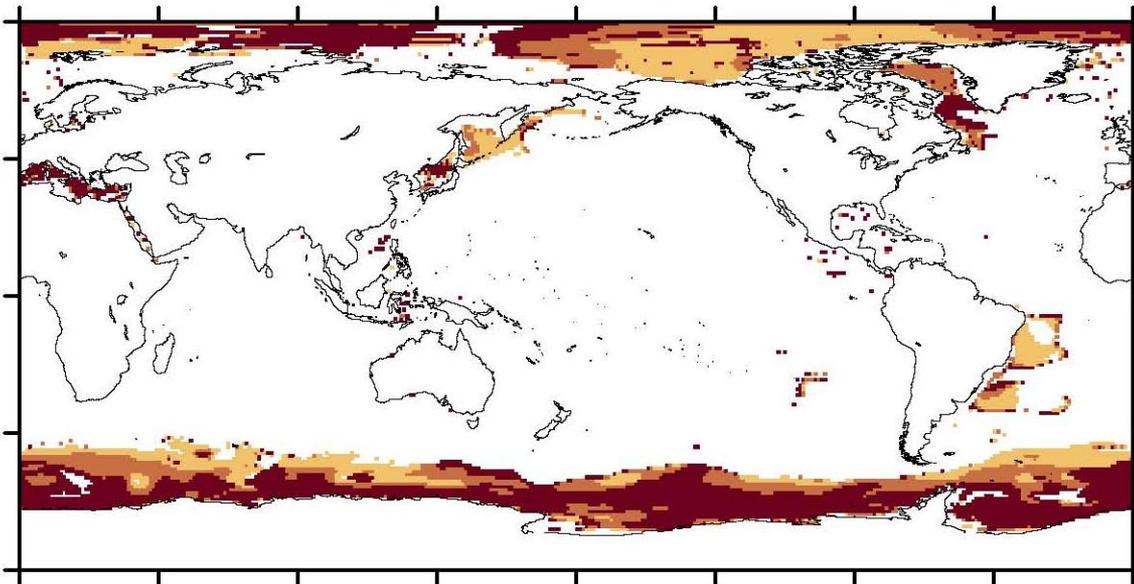
DC:  $R_\rho > 1; \quad \gamma > 1$

# Double Diffusion SF, DC

SF



DC



## DOUBLE DIFFUSION

- ✓ Weak turbulence:  $K(h) \neq K(s)$
- ✓ NATRE:  $K(s) = 1.38K(h)$

## SALT FINGERS

- ✓ Salty-warm / cold-fresh waters (Mediterranean Sea)
- ✓ **Star analogy: helium flask off center**
- ✓ **Higher  $\mu$ , hot/colder, low  $\mu$  gas**

## DIFFUSIVE CONVECTION

- ✓ Cold-fresh/warm-salty waters (Red Sea)
- ✓ **Star analogy: Semi-convection SN 1987A-Red vs. Blue**

$$Ri, \quad R_\rho = \frac{\beta \partial S / \partial z}{\alpha \partial T / \partial z}$$

# Lab. Data

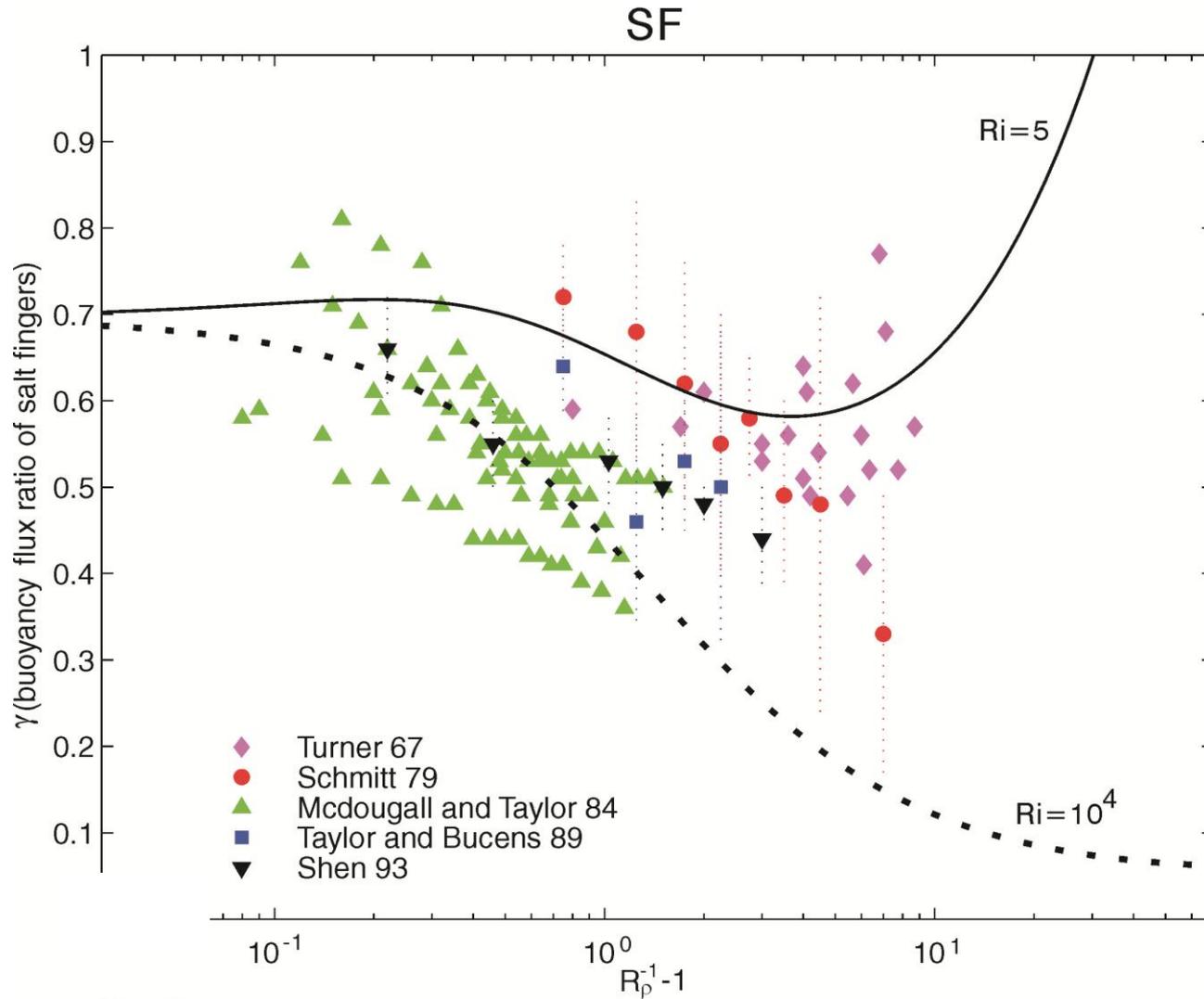
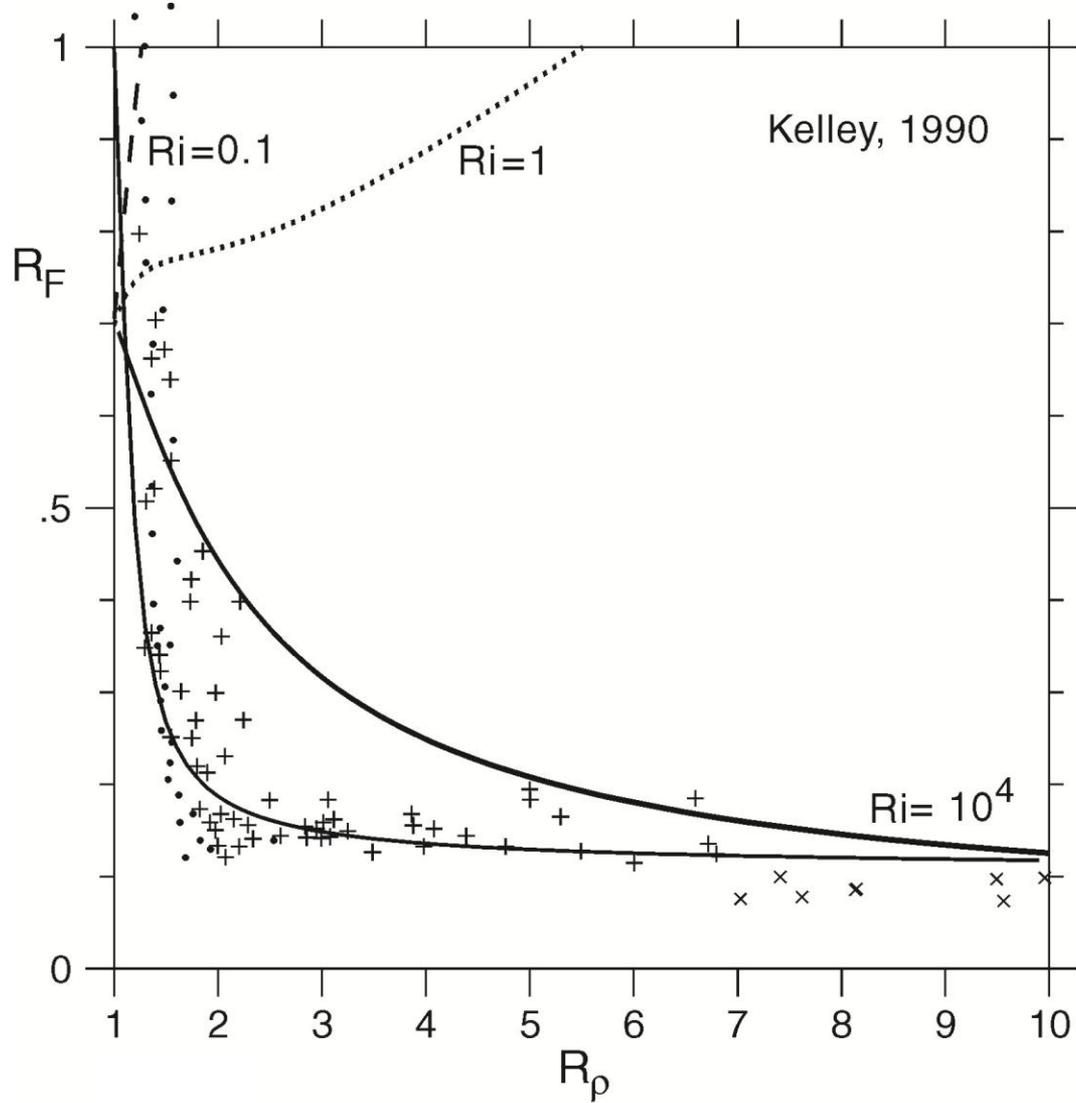


Fig. 2

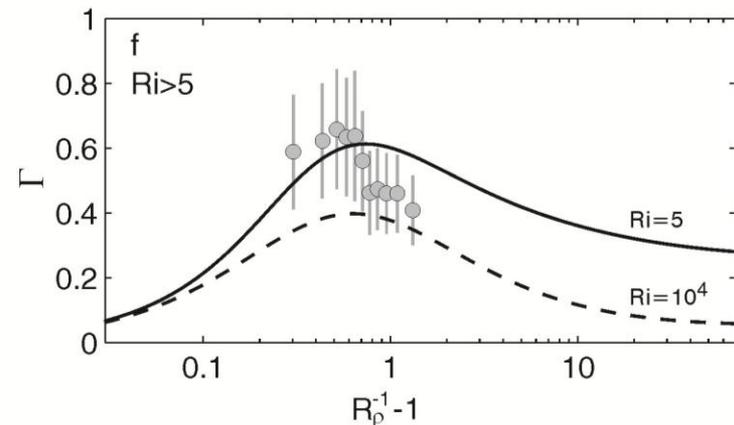
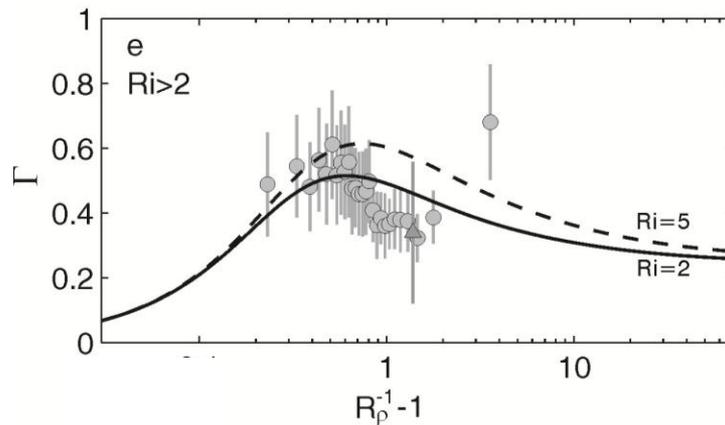
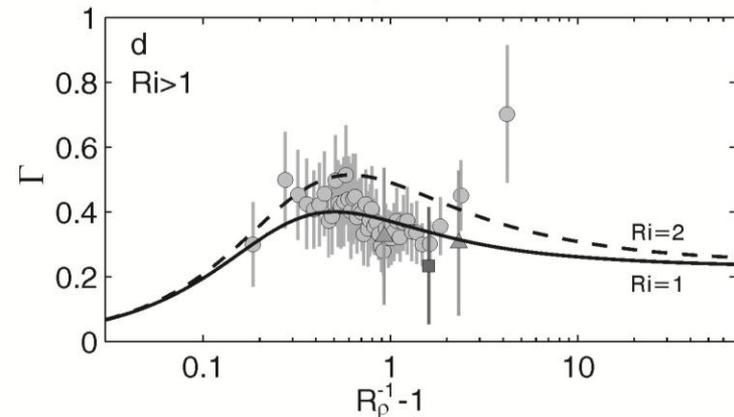
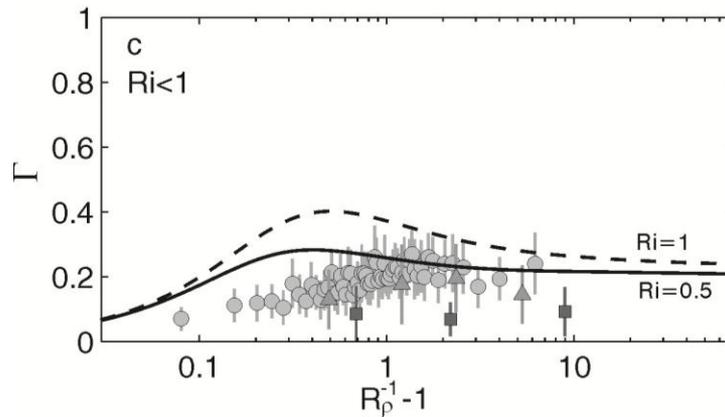
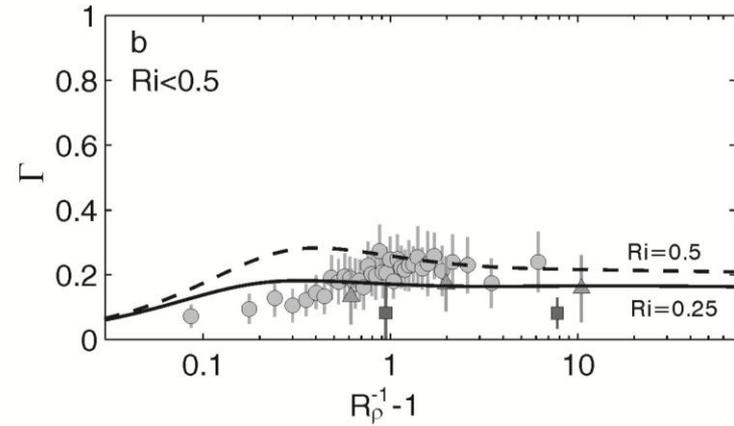
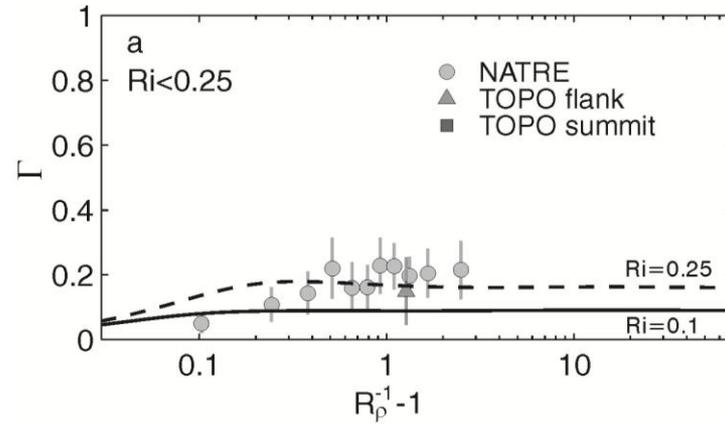
# Lab. Data

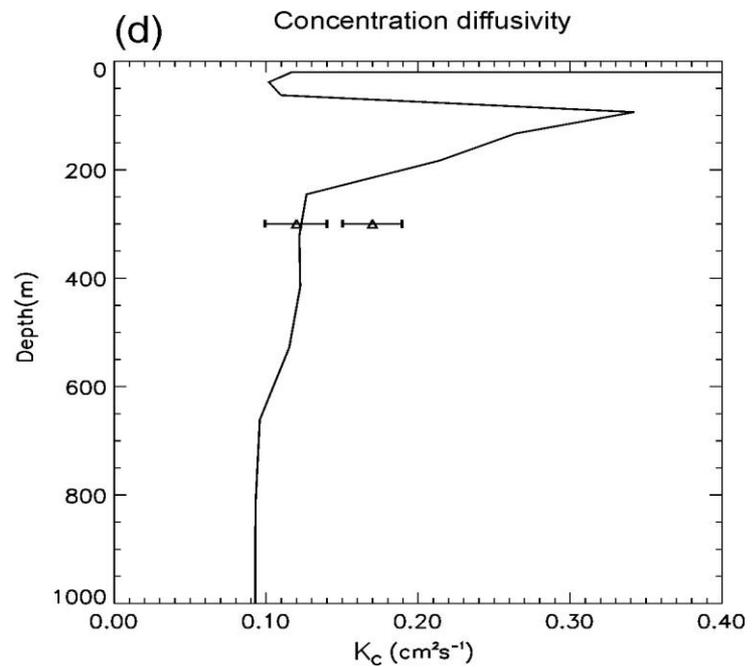
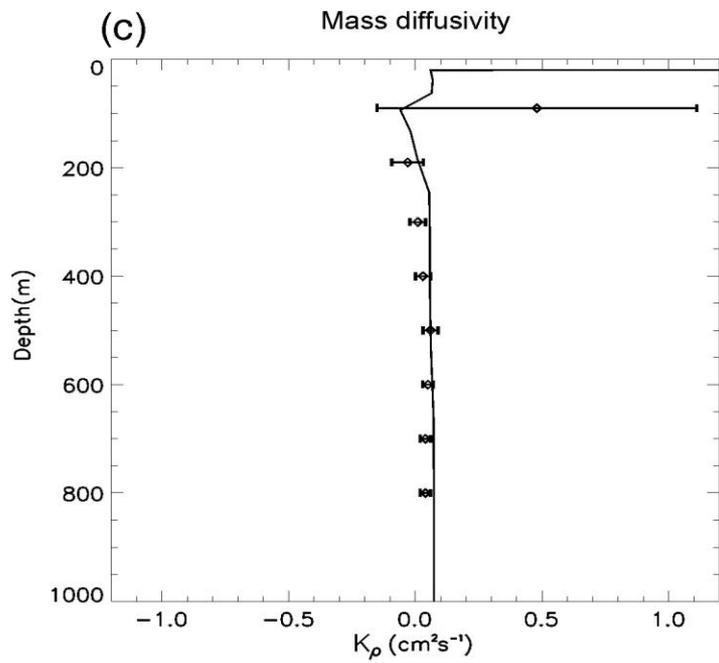
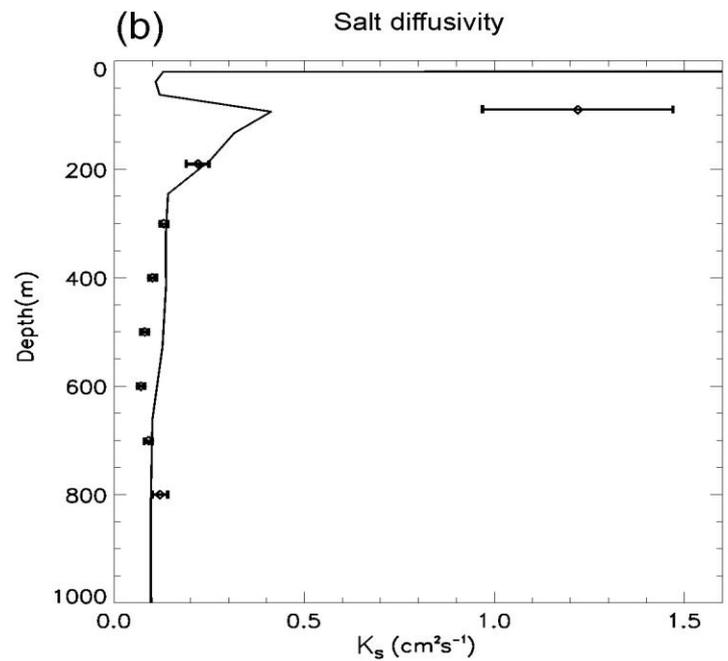
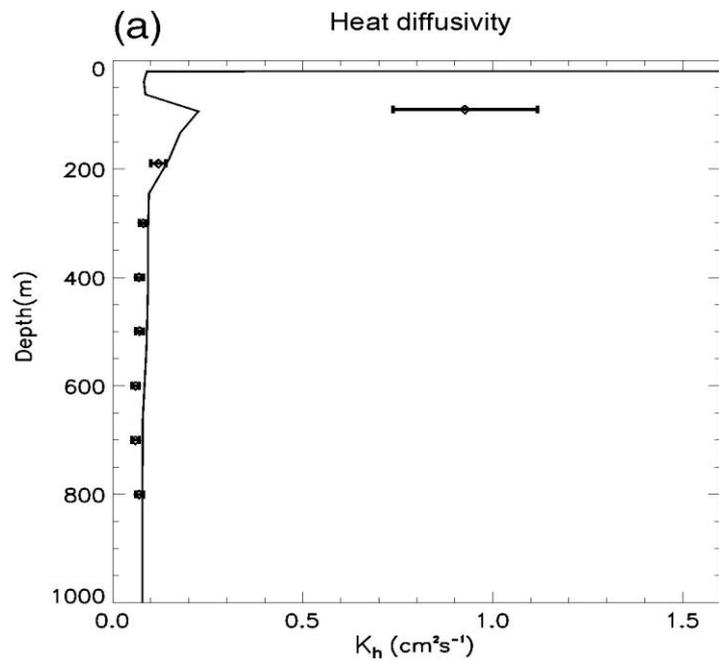
DC



SF

$$K_h = \Gamma \varepsilon N^{-2}$$



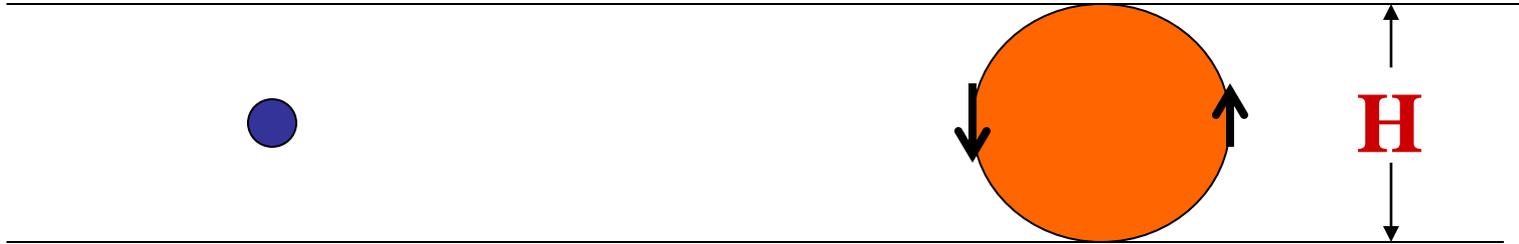


# DEEP CONVECTION

- Labrador Sea, Gulf of Lyon, Waddle Sea
- Strong winds lower the temperature
- Loss of Buoyancy
- Cooling from above
- Fast Process: Days, 1-2km,  $w \sim$  a few cm/sec
- Labrador Data on the Depth of the Mixed layer
- **Rotation ??**

⊕ **Atmospheric analogy:** Cloud Capped PBL

★ **Stellar analogy:** cooling from the top due to change in opacity



**Small eddies**

**Large eddies**

**Local**

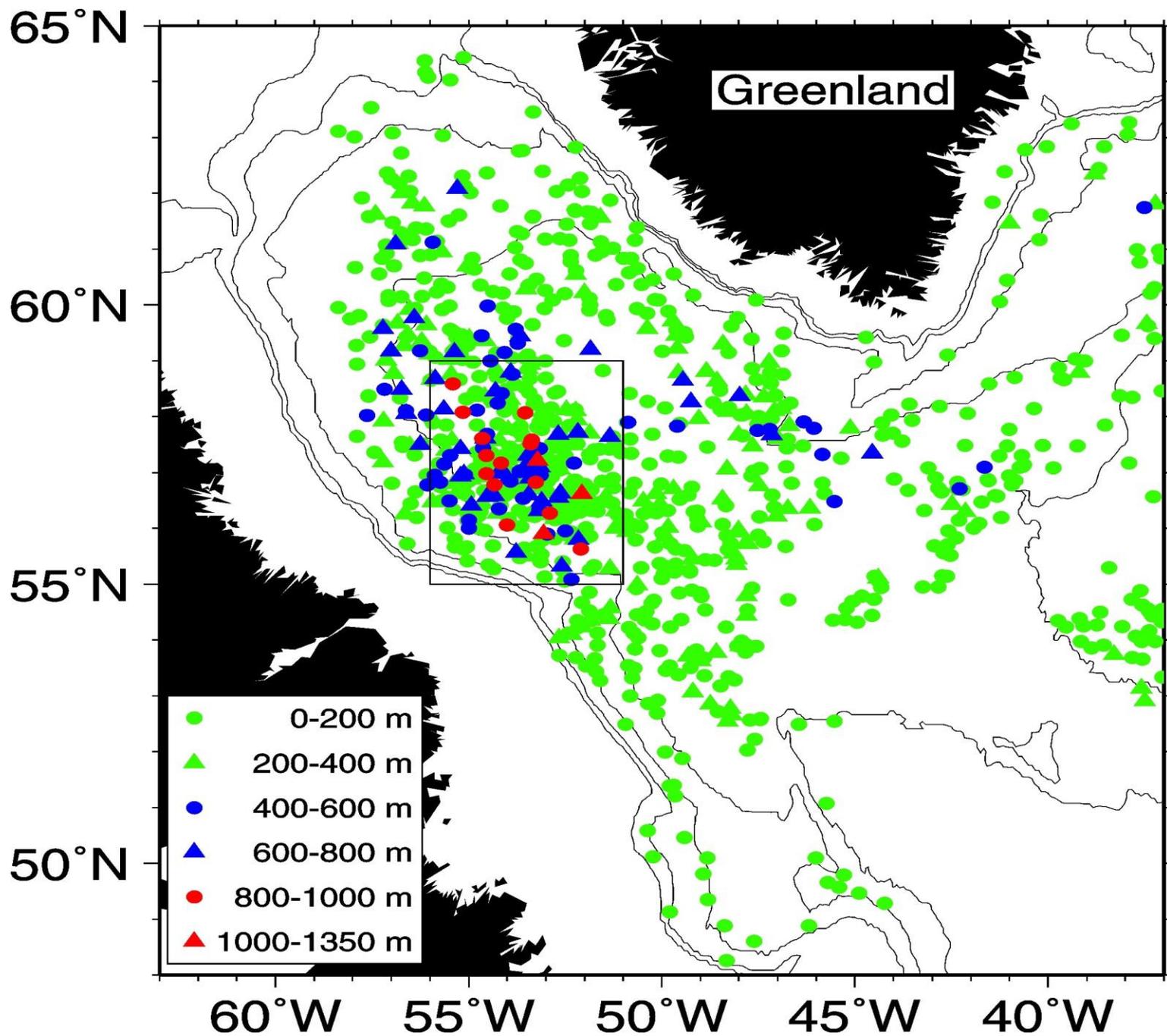
**Non-Local**

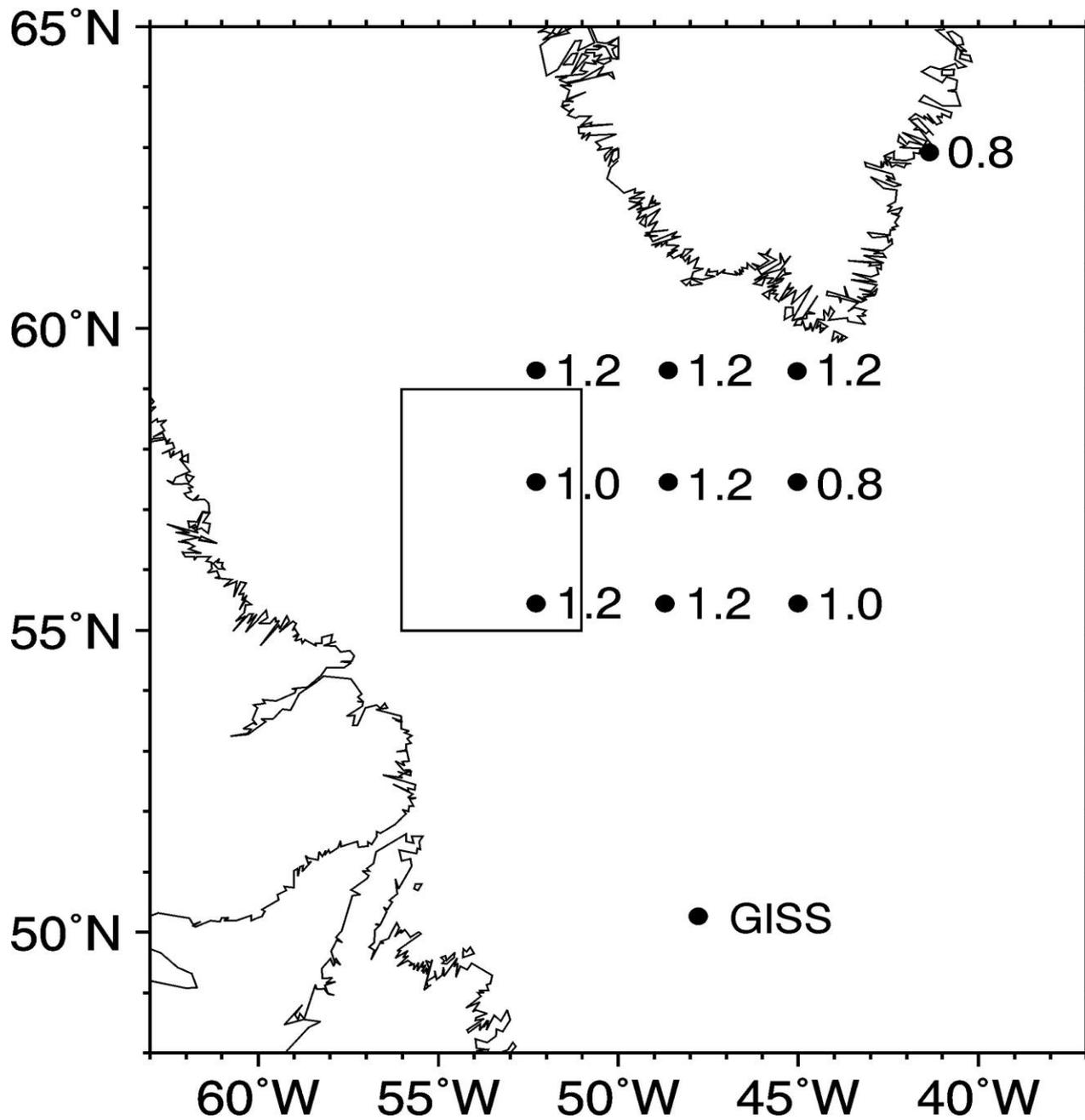
$$J(z) = -K_h \frac{\partial T}{\partial z}$$

$$J(z) = \int_0^z K_h \frac{\partial T}{\partial z'} dz'$$

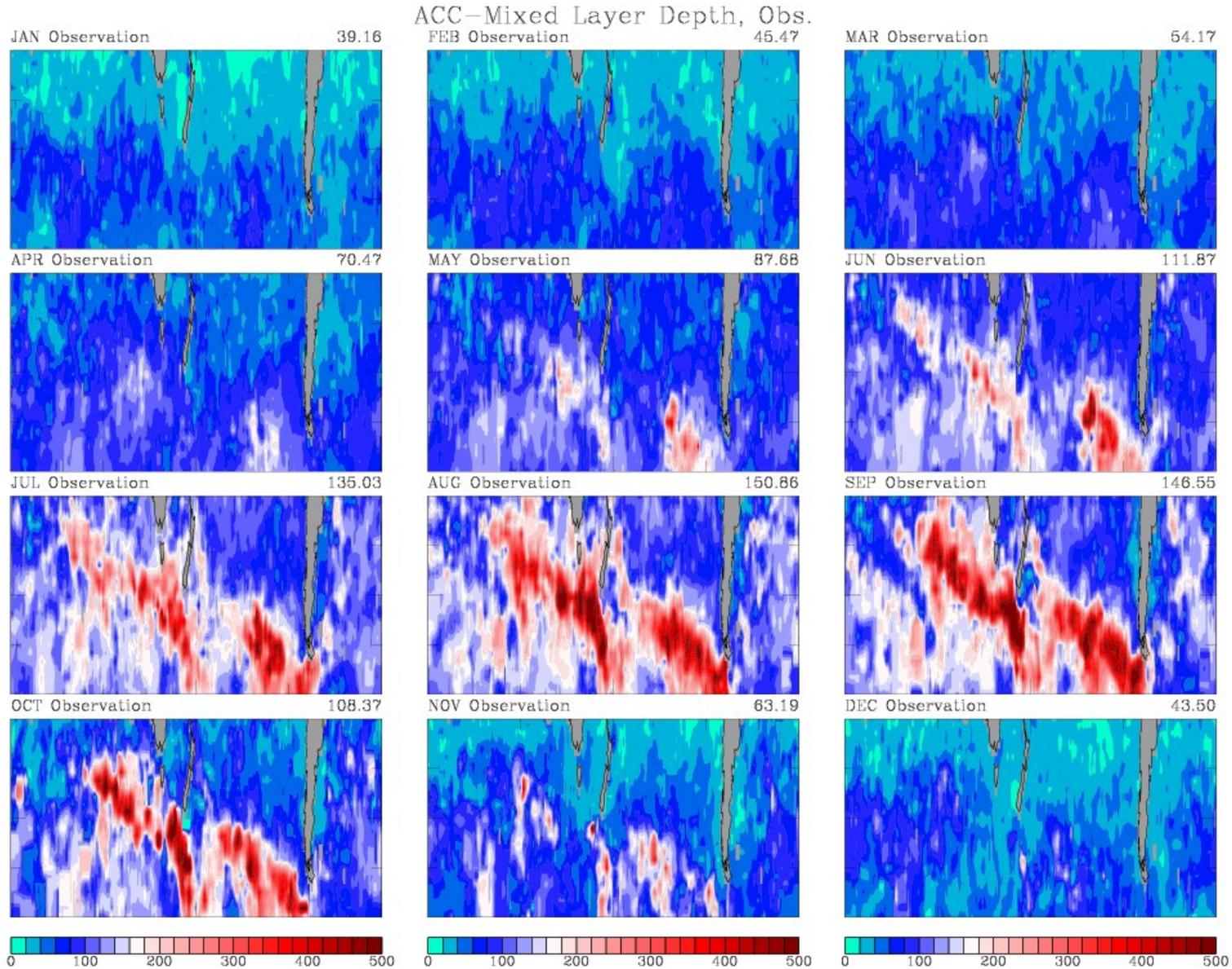
**No H**

**H**

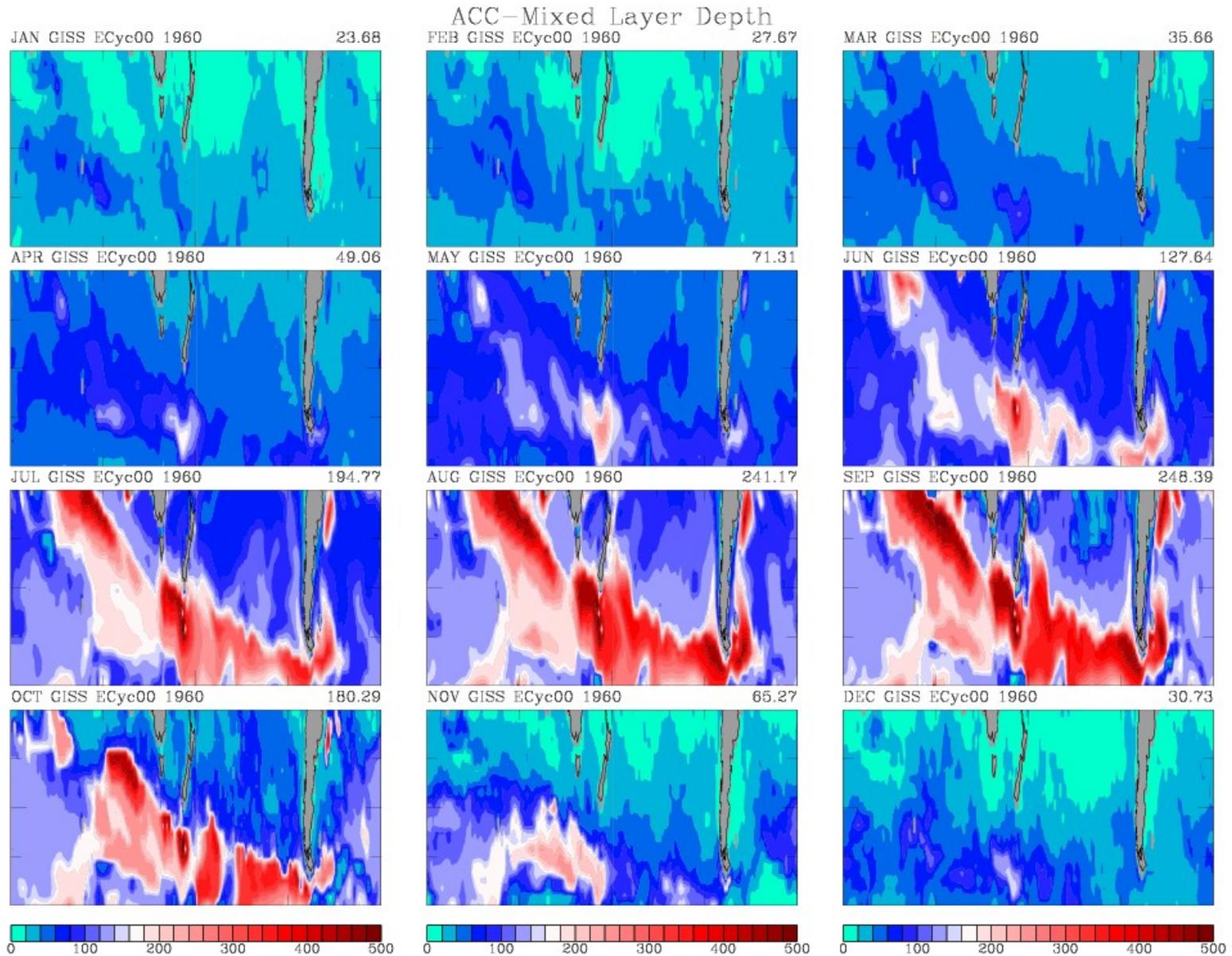




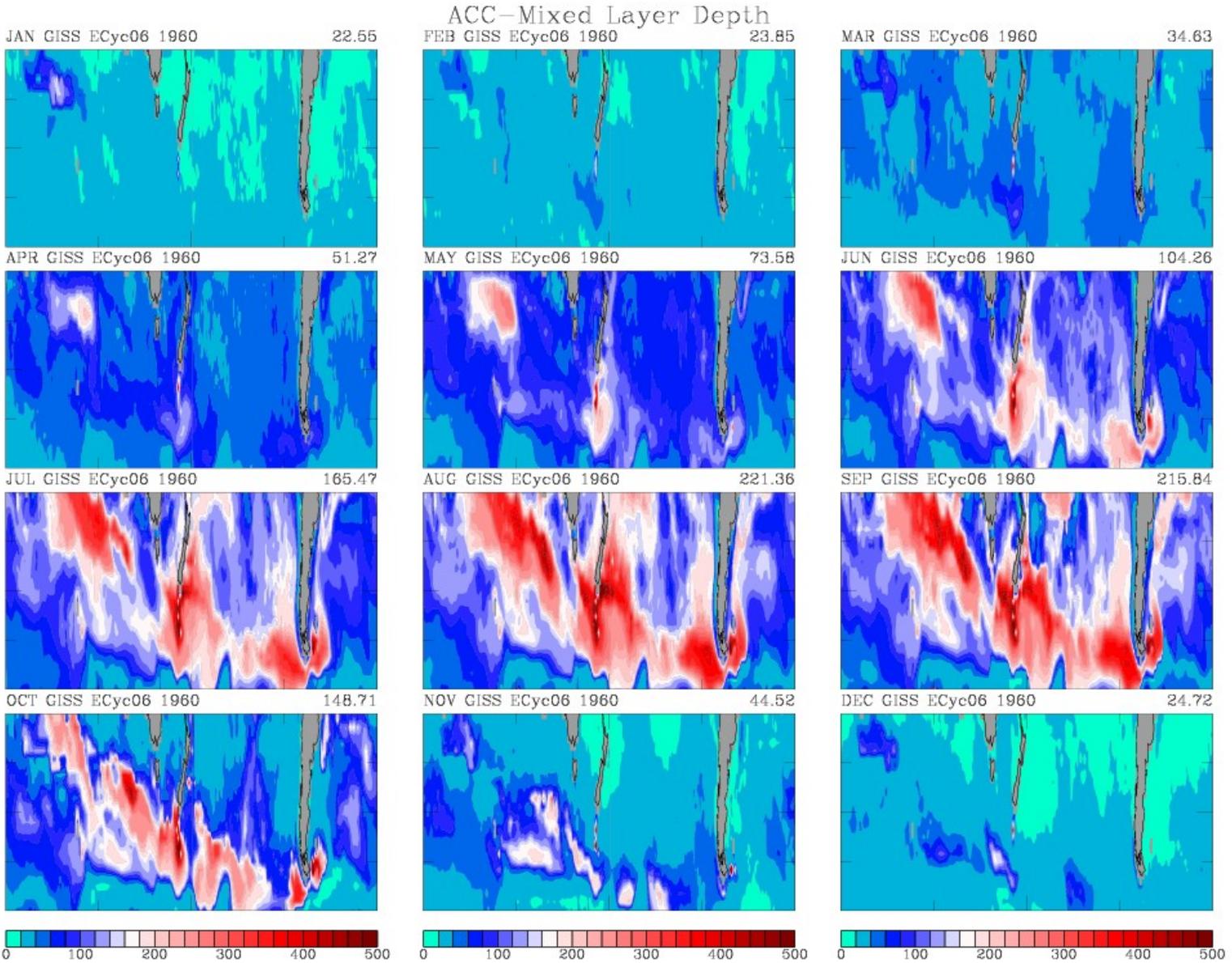
# MLD at ACC: Observations (Dong et al. 2006)

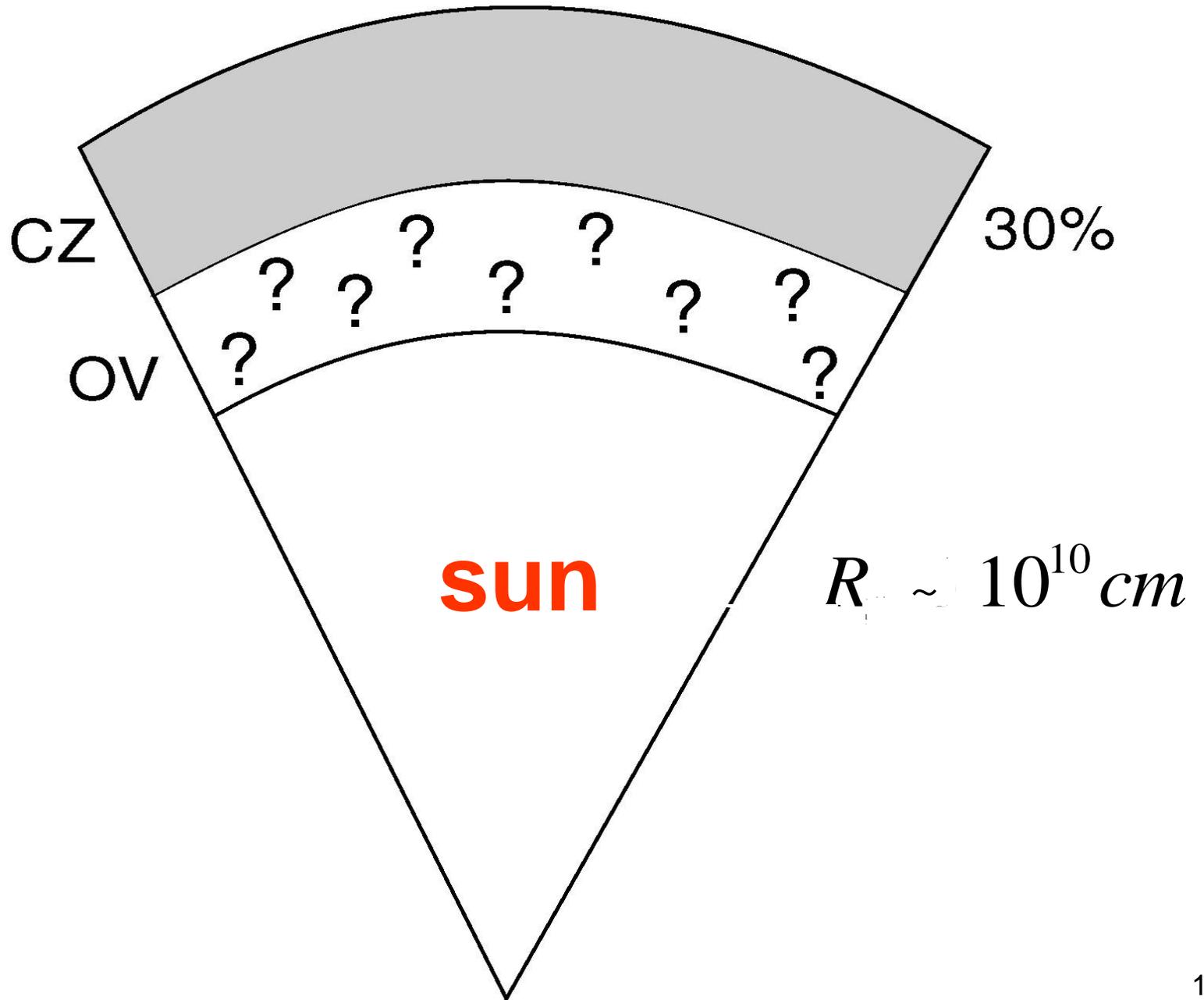


# MLD at ACC: KPP Model



# MLD at ACC: GISS Model 2011





## STARS (e.g. Sun)

- Last 30% is governed by CONVECTION
- Heated from Below, Cooled from Above
- Unstable Stratification. Large Eddies
- Non-Local Model

**OVERSHOOTING.** Unsolved problem:  $OV = ?H_p$

$$\frac{\partial K}{\partial t} + \frac{\partial}{\partial z} F(K) = J - \varepsilon$$

- In the OV, stratification is stable, there is no local source of mixing
- $RHS < 0$
- $LHS < 0$
- $F(K)$ , flux of turbulent kinetic energy, acts like a Non-Local Source<sub>17</sub>

## **F(K) is a TOM (third-order moment)**

- **TOM can be derived from FOM (4-th order moments ) and so on....**
- **New aircraft measurements on FOM have changed the scenario**
- **New FOM mean new TOM and thus a Non-Local Model can be constructed**

# New FOM Model (JAS, 2005)

$$\overline{w^4} = \overline{w^4} \Big|_{QN} + p_1 \int_0^z \frac{\overline{w^3}}{\tau} dz$$

$$\overline{w^3 \theta} = \overline{w^3 \theta} \Big|_{QN} + \int_0^z (p_2 \frac{\overline{w^2 \theta}}{\tau} + d_1 \beta \overline{w^3}) dz$$

$$\overline{w \theta^3} = \overline{w \theta^3} \Big|_{QN} + \int_0^z (p_4 \frac{\overline{\theta^3}}{\tau} + d_3 \beta \overline{w \theta^2}) dz$$

$$\overline{w^2 \theta^2} = \overline{w^2 \theta^2} \Big|_{QN} + \int_0^z (p_3 \frac{\overline{w \theta^2}}{\tau} + d_2 \beta \overline{w^2 \theta}) dz$$

$$\overline{u^2 w^2} = \overline{u^2 w^2} \Big|_{QN} + p_5 \int_0^z \frac{\overline{u^2 w}}{\tau} dz$$

$$\overline{u^2 w \theta} = \overline{u^2 w \theta} \Big|_{QN} + \int_0^z (p_6 \frac{\overline{u^2 \theta}}{\tau} + d_4 \beta \overline{u^2 w}) dz$$

# Fourth order moments in a convective PBL

**Circles:** aircraft data of Hartmann et al. (1999)

**Dotted lines:** QN

**Dashed lines:** Gryanik-Hartman

**Solid lines:** New Model

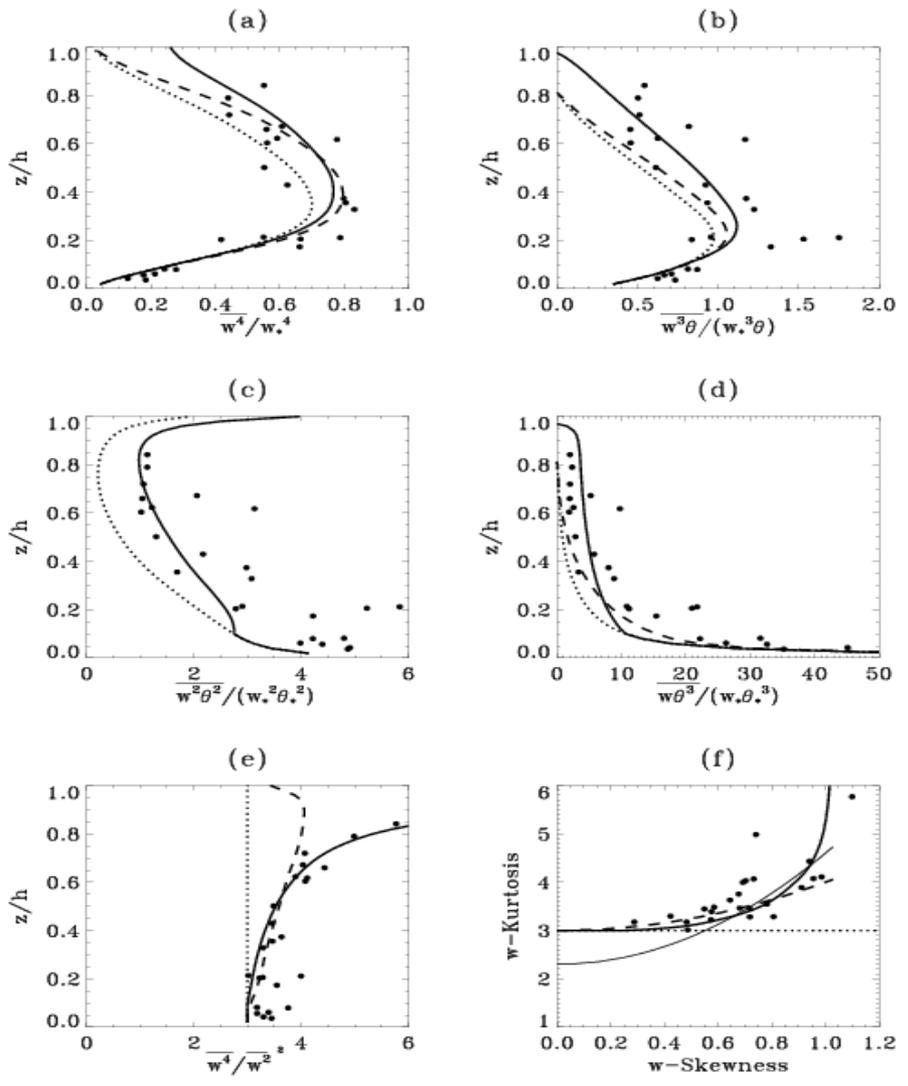


Fig.2

# Third order moments in a convective PBL

**Filled Circles:** aircraft data

**Dash-Dotted lines:** QN

**Solid lines:** New Model

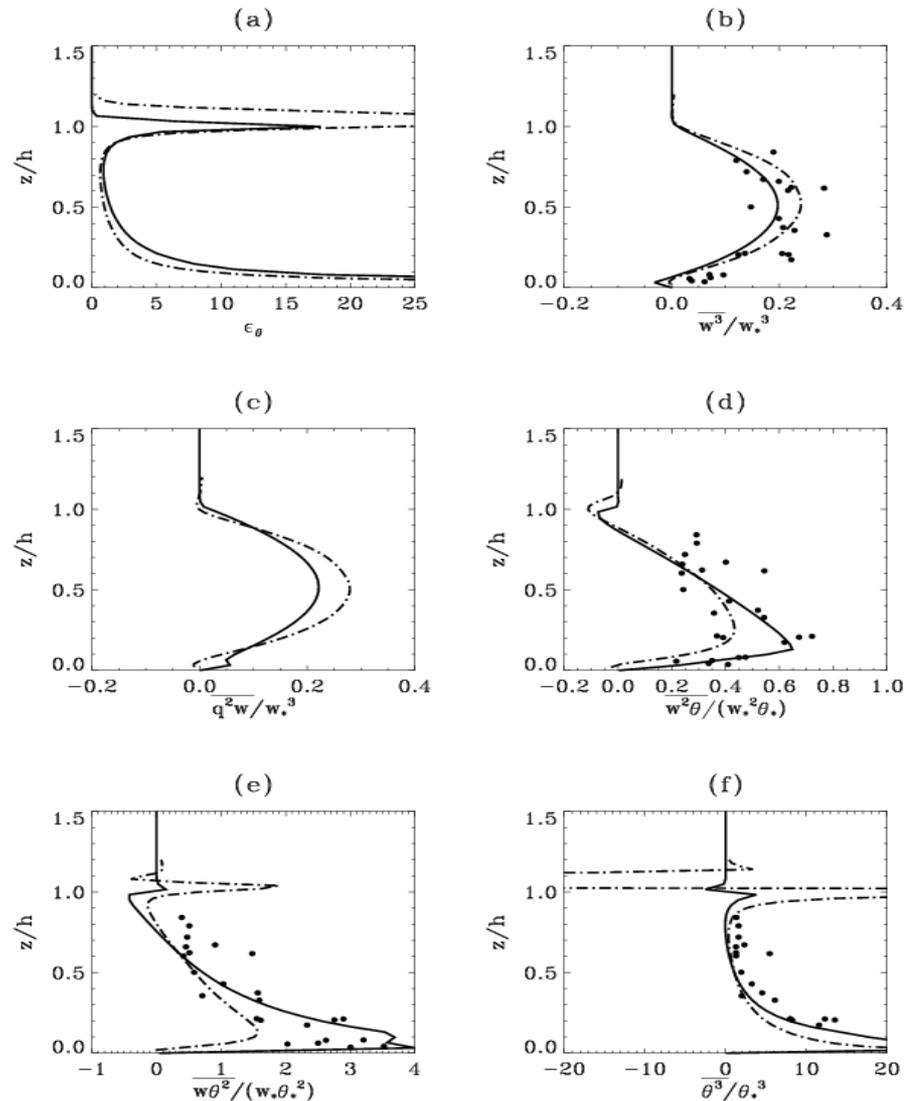
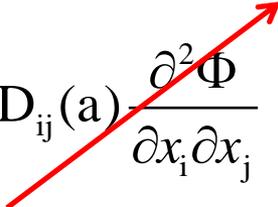


Fig.4

# MIXING AND STIRRING

$$\frac{\partial \Phi}{\partial t} + \bar{\mathbf{U}} \cdot \nabla \Phi = \frac{\partial}{\partial x_j} \left( D_{ij} \frac{\partial \Phi}{\partial x_i} \right)$$

$$D_{ij} = D_{ij}(s) + D_{ij}(a), \quad D_{ij}(s) = \frac{1}{2}(D_{ij} + D_{ji}), \quad D_{ij}(a) = \frac{1}{2}(D_{ij} - D_{ji})$$

$$\frac{\partial}{\partial x_j} \left[ D_{ij}(a) \frac{\partial \Phi}{\partial x_i} \right] = \frac{\partial D_{ij}(a)}{\partial x_j} \frac{\partial \Phi}{\partial x_i} + D_{ij}(a) \frac{\partial^2 \Phi}{\partial x_i \partial x_j}$$




$$\boxed{\frac{\partial D_{ij}(a)}{\partial x_j} = -U_{*i} \Rightarrow \partial_i U_{*i} = 0}$$

$$\boxed{\frac{\partial \Phi}{\partial t} + (\bar{\mathbf{U}} + \underbrace{\mathbf{U}_*}_{\text{stirring}}) \cdot \nabla \Phi = \frac{\partial}{\partial x_j} \left[ D_{ij}(s) \underbrace{\frac{\partial \Phi}{\partial x_i}}_{\text{mixing}} \right]}$$

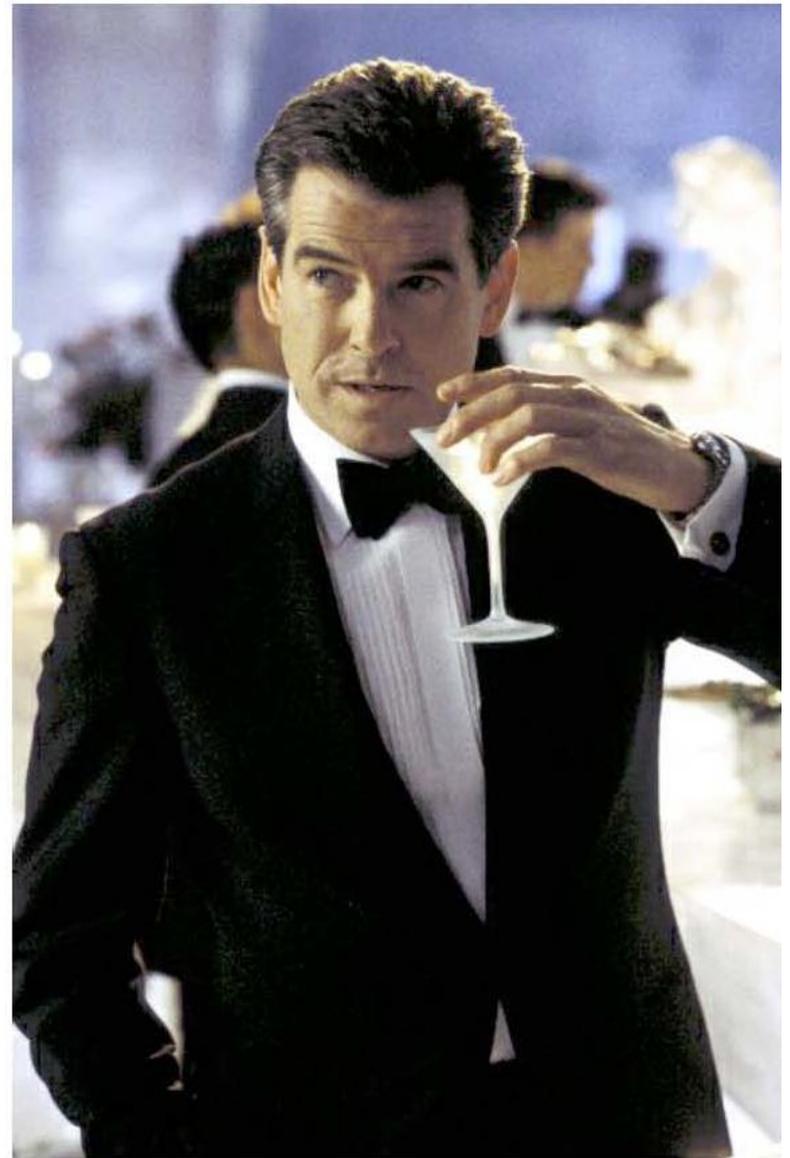
**Advection & Mixing**

**=**

**Stirring & Shaking**

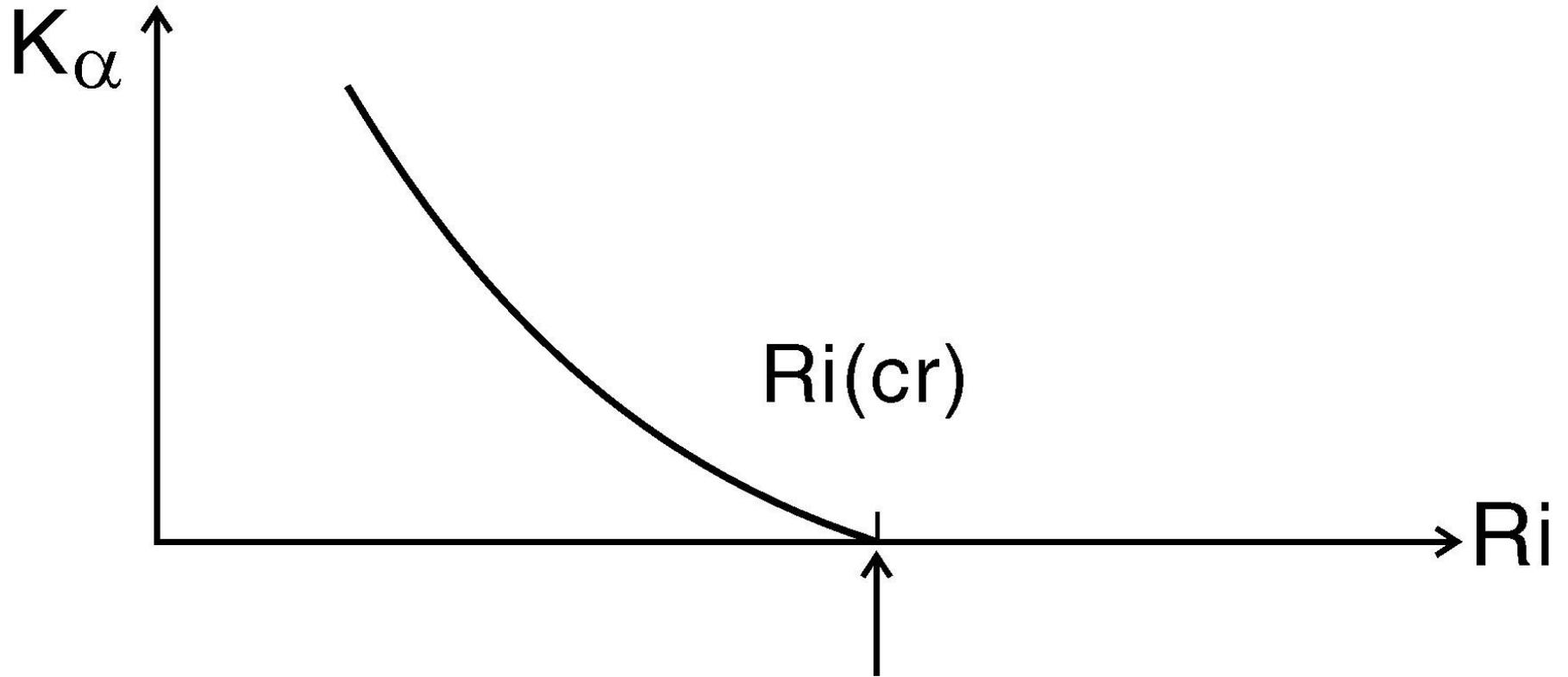


*Shaken not stirred, please.*





# Stable Stratification



# PLUME MODEL

Atmospheric LES

Skinny downflows (Twiggy-like), fat upflows

Plume Model is suggestive, **WHO's?**

Only one: Taylor, Turner and Morton. **TTM model**

Can be applied to stars?

## TTM model assumptions:

**A.** Quiescent Environment

**B.** Isolated Plume

**C.** Entrainment is an adjustable parameter

Mass conservation law:

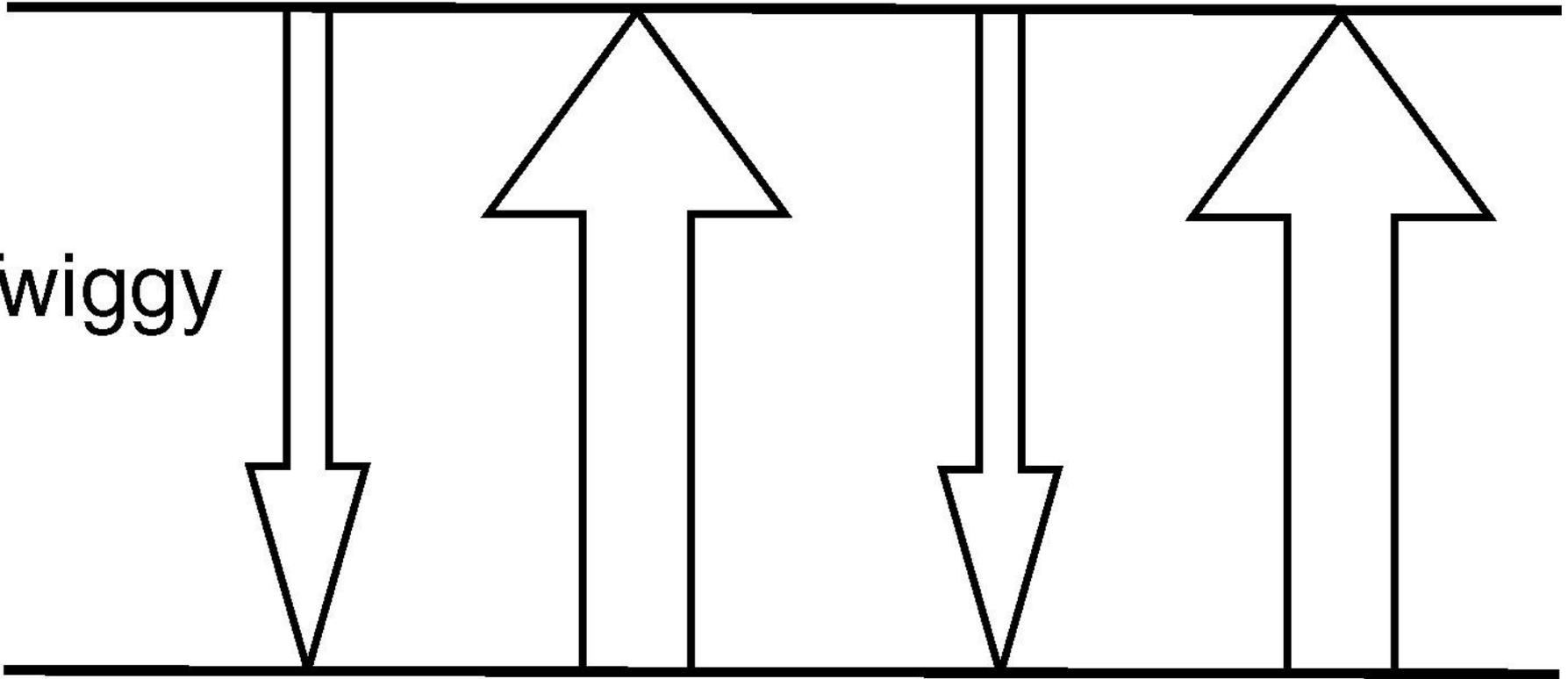
$$\lambda w_p + (1-\lambda)w_e = 0 \qquad \lambda = \frac{\Sigma_p}{\Sigma_p + \Sigma_e}$$

**A)** means that  $w_e$  tends to zero. Thus:

Isolated plume, **B)** above

$$\lambda \ll 1$$

Twiggy



Plumology

## Is this correct?

- As Twiggy descends into a stably stratified medium,  $w_p$  must slow down.
- “Entrainment” of surrounding material makes Twiggy fatter
- Thus,  $\lambda$  increases with time until the Plume merges with Environment  
 $\lambda$  and  $1 - \lambda$  become the same and thus:

$$\lambda = 1/2$$

- TTM model demands:

$$\lambda \ll 1$$

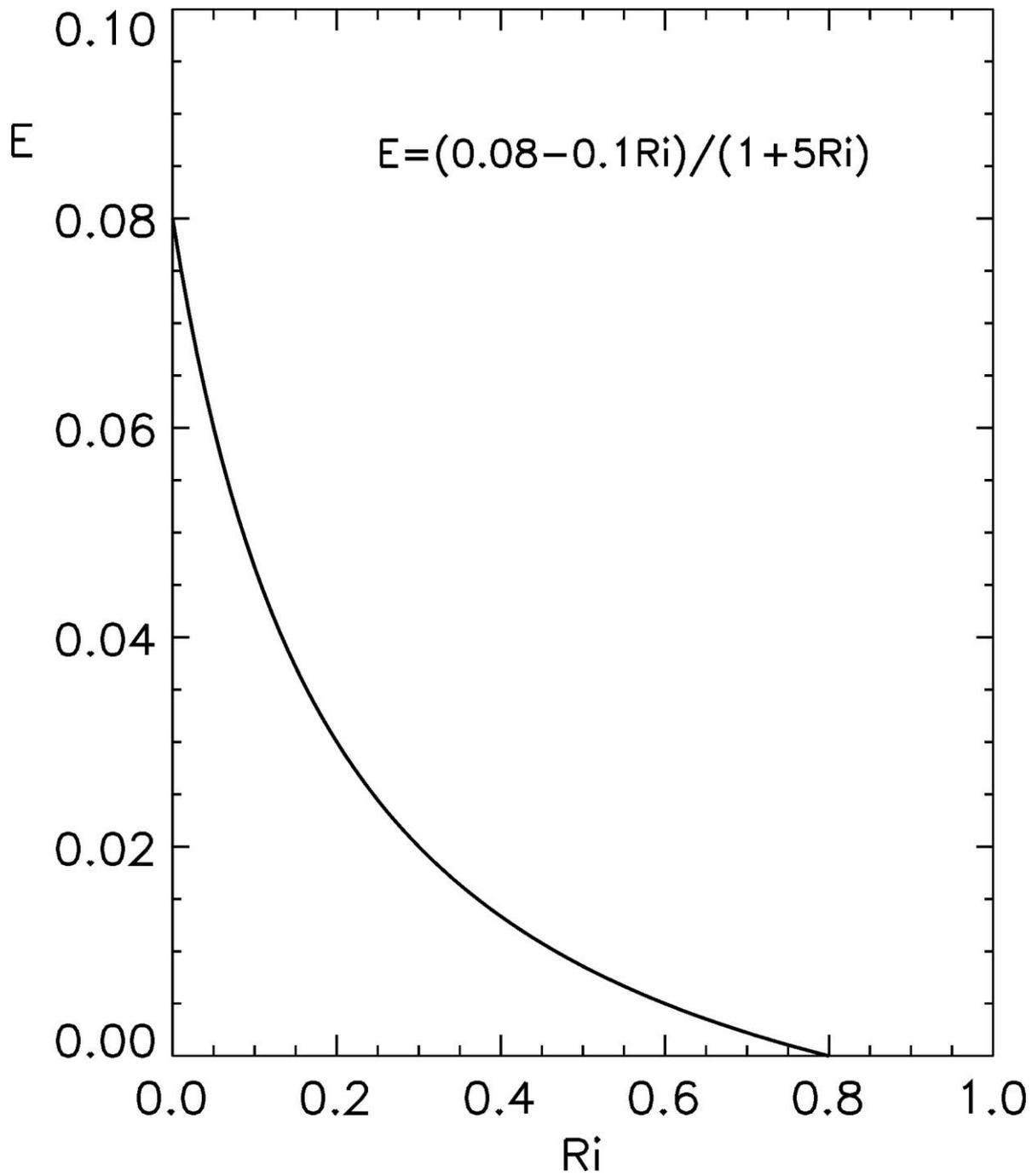
- *The TTM model is valid only for the initial phases of the Plume’s life*
- A PM must account for the whole process. It must be invariant under:

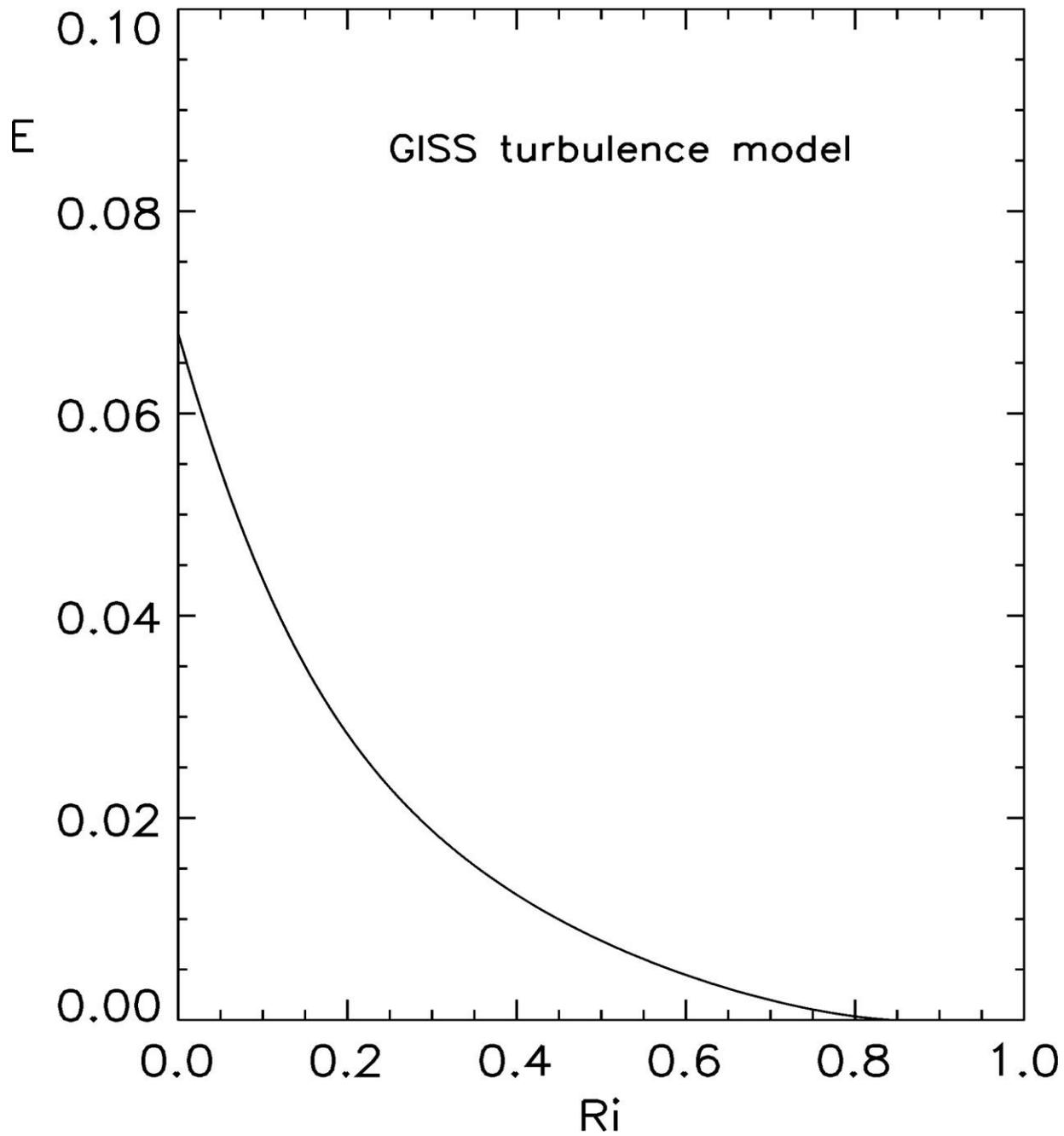
$$\lambda \rightarrow 1 - \lambda, \quad w(p) \rightarrow w(e)$$

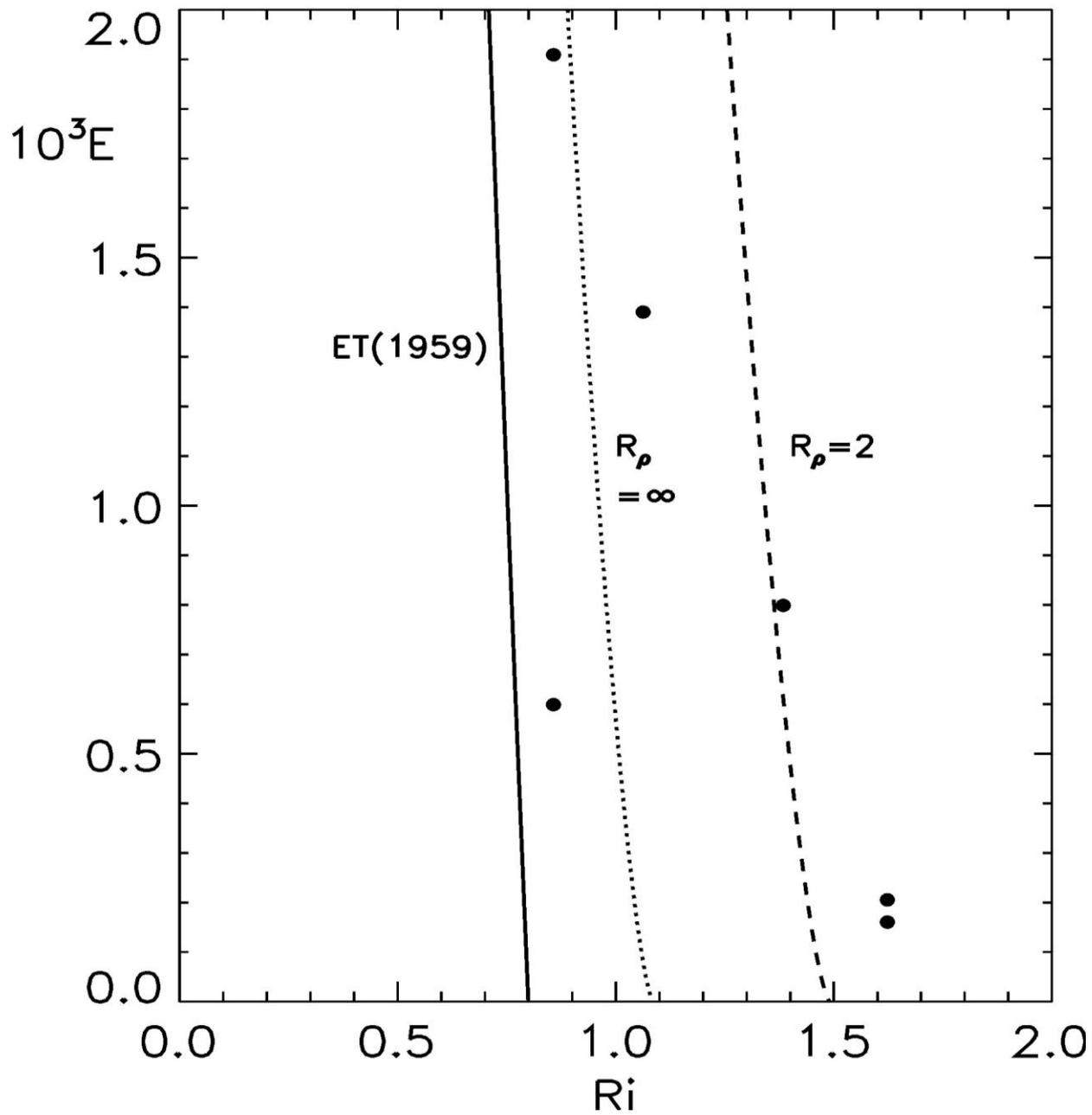
- TTM is not invariant under such transformation. *Can it be made invariant?*

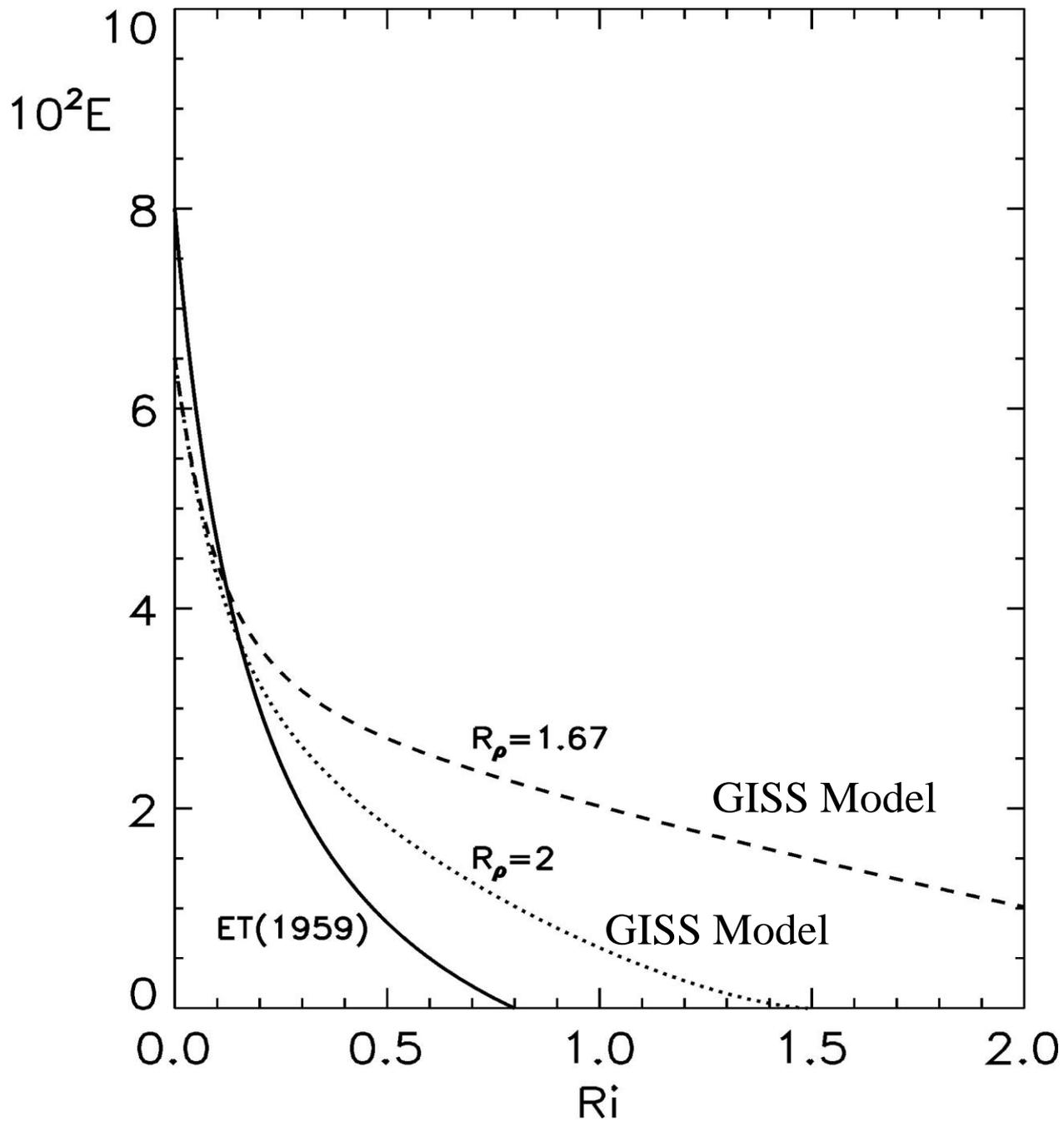
## Entrainment, $E$

- TTM:  $E$  is an adjustable parameter
- Ellison-Turner (1959):  $E = E(R_i)$ , lab experiment
- GISS Model (2004): reproduced it
- Comparison with the data: Rather poor
- ✓ GISS Model:  $E = E(R_i, R_\rho)$
- ✓ Better fit to the data









## Back to the OV Problem

- How do you define the extent of the OV?
- $J(z)$  vanishes
- $w(z)$  vanishes,  $w(p)$  vanishes

$$\lambda w_p + (1-\lambda)w_e = 0, \quad \lambda \rightarrow 1$$

Plumes take up the whole space. *Not very likely*

- Suggestion for the OV extent:

$$\lambda \rightarrow 1/2$$

- ✓ Plumes and Environment become indistinguishable

$$\mathbf{OV}(\lambda=1/2) < \mathbf{OV}(\lambda=1)$$

- **TTM: only *Advective*; Local TM: only *Diffusive***
- **How about having both Advection and Diffusion?**
- **A Non-Local Turbulence Model? Automatically invariant**
- **Can be written in Plume language assuming: up and down flows.**

$$\begin{array}{c}
 \boxed{\boxed{\text{Diffusion}}\boxed{\boxed{\quad}}\quad} \qquad \boxed{\boxed{\text{Advection}}\boxed{\boxed{\quad}}\quad} \\
 \mathbf{B} = -\underbrace{A_1(\lambda) K_b N^2}_{\text{LOCAL}} - A_2(\lambda) \underbrace{\ell S_w \frac{\partial \mathbf{B}}{\partial z}}_{\text{NON-LOCAL}} \\
 K_b = \ell w_p, \quad S_w = \frac{\overline{w^3}}{w^2} = (2\lambda - 1)[\lambda(1 - \lambda)]^{-1/2}
 \end{array}$$

- Buoyancy flux is contributed by both **Diffusion** and **Advection**

$$\lambda \rightarrow 1/2, \quad S_w \rightarrow 0, \quad \text{Advection} \rightarrow 0$$

$$\frac{\partial T}{\partial t} + w \frac{\partial T}{\partial z} = - \frac{\partial B}{\partial z}$$

$$\frac{\partial T}{\partial t} + (w + w_*) \frac{\partial T}{\partial z} = \frac{\partial}{\partial z} (A_1 K_b N^2)$$

$$w_* = A_1 A_2 S_w \frac{\partial K_b}{\partial z}$$

# Table

<b>Stage</b>	$\lambda$	$S_w$	<b>P vs E</b>	<b>Adv</b>	<b>Diff</b>
Initial	Small	$<0$	$w_p \gg w_e$	<b>Yes</b>	No
Final	1/2	$\approx 0$	$w_p \approx w_e$	No	<b>Yes</b>

Thus :

$TM \Rightarrow PM$

$PM \not\Rightarrow TM$

# BOTTOM

Data show an increase in diffusivity

Source of energy:

TIDES 3.75TW

Example:  $E = 1/2 I \Omega^2$

$E(\dot{\phantom{t}}) = I \Omega \dot{\Omega}$

Astronomical data  $P(\dot{\phantom{t}})/P = 1\text{-}2 \text{ millisecc/year}$

$E(\dot{\phantom{t}})$  few TW

$\epsilon$ :

$$E(\dot{\phantom{t}})/\text{mass ocean} = 10^{-2} \text{ cm}^2\text{s}^{-3}$$

$$K = \gamma \epsilon / N^2$$

Barotropic Tides transform into Baroclinic ones which then scatter  
Fragment against rough topography and generate mixing