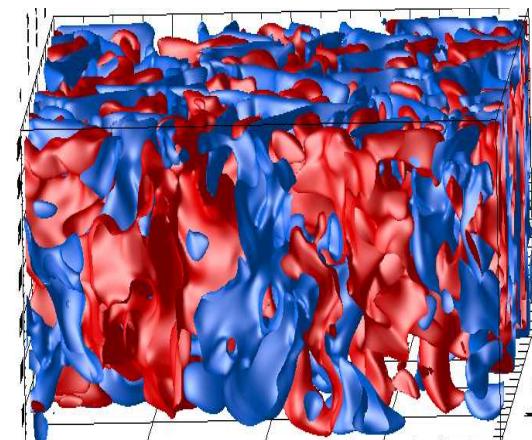
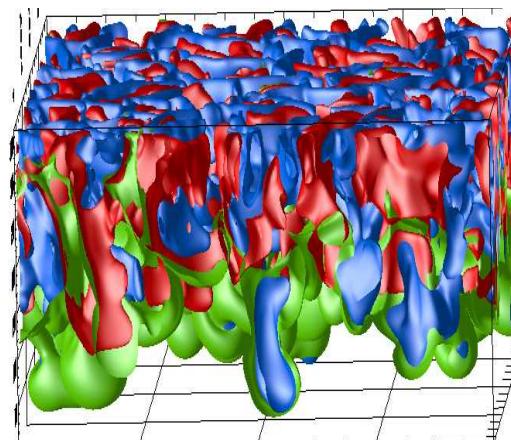
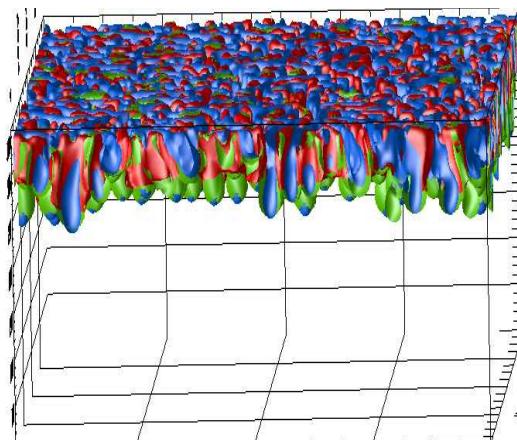


Ocean Deep Convection

Achim Wirth

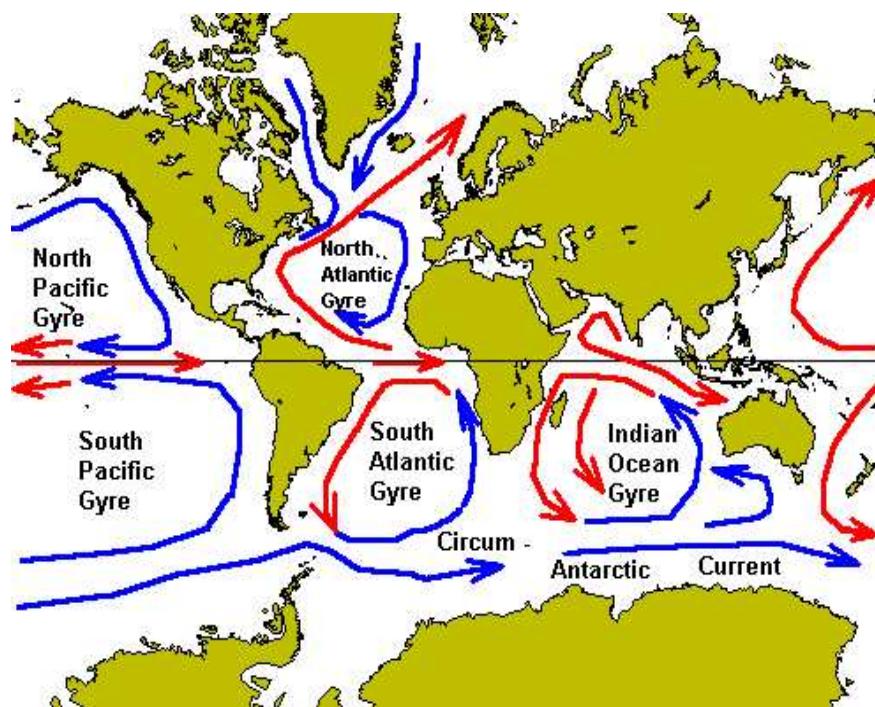
MEOM / LEGI Grenoble



Ocean Circulation

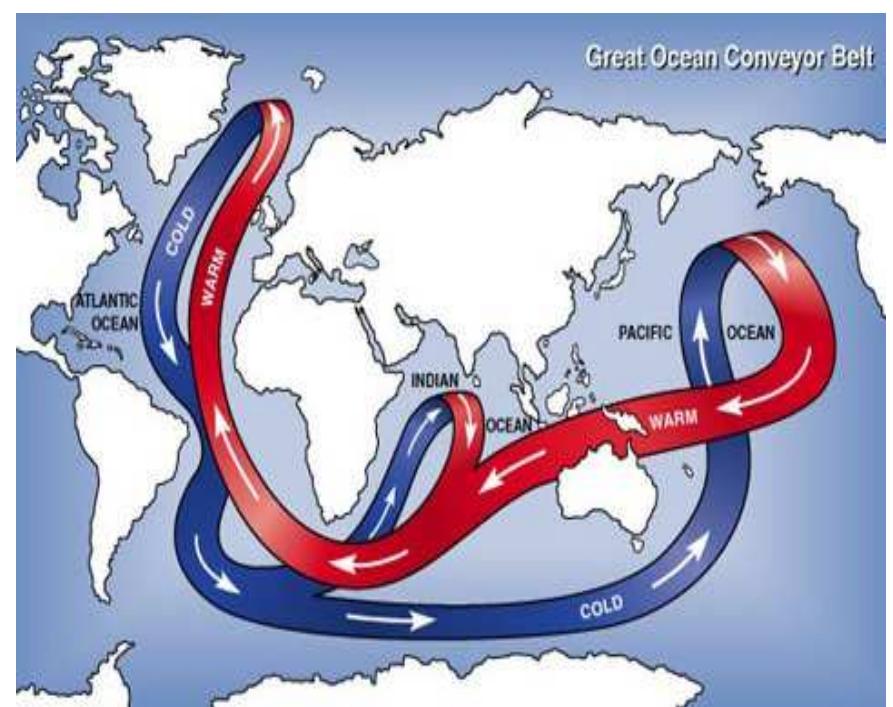
Gyre

“weather”

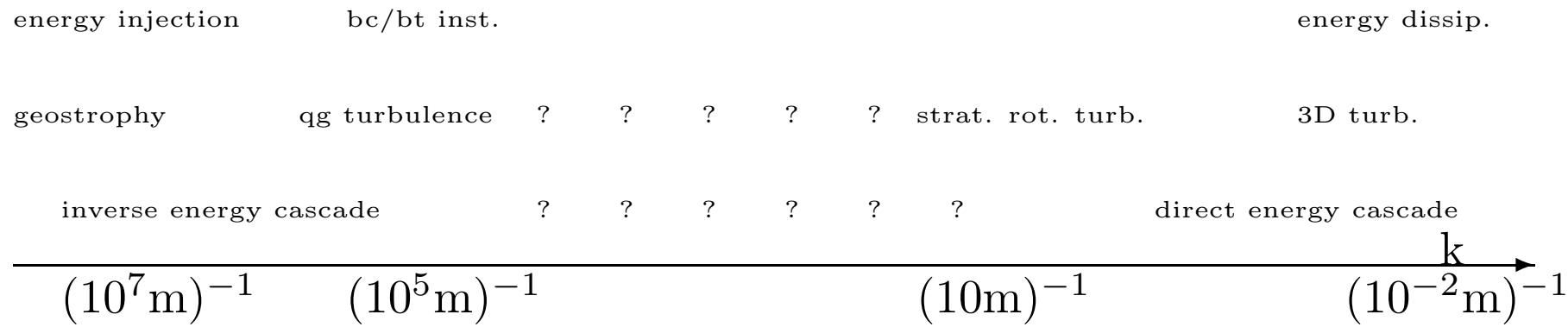


Overturning

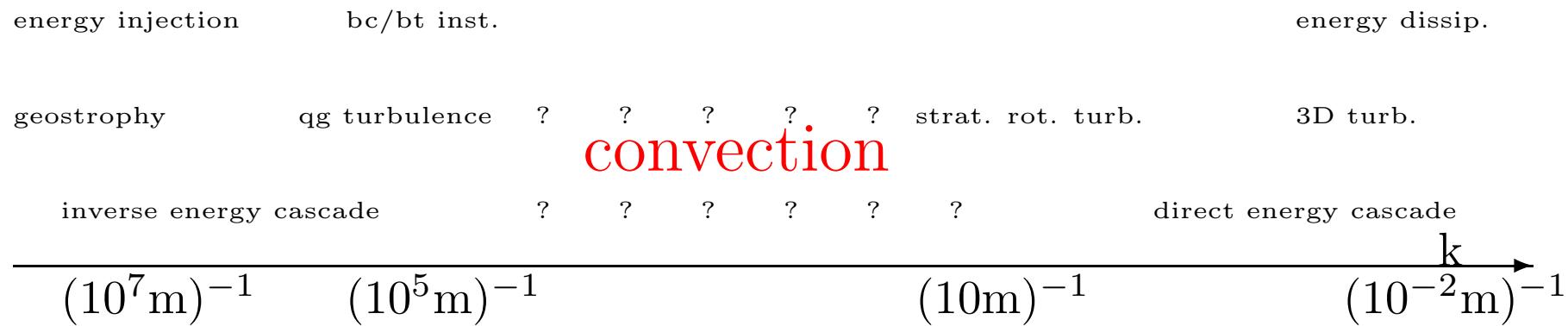
“climat”



Scales of Ocean dynamics



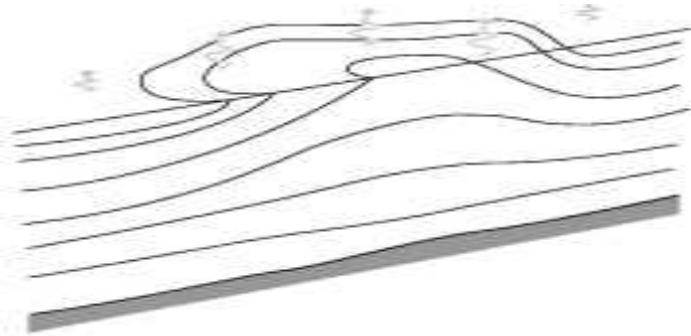
Scales of Ocean dynamics



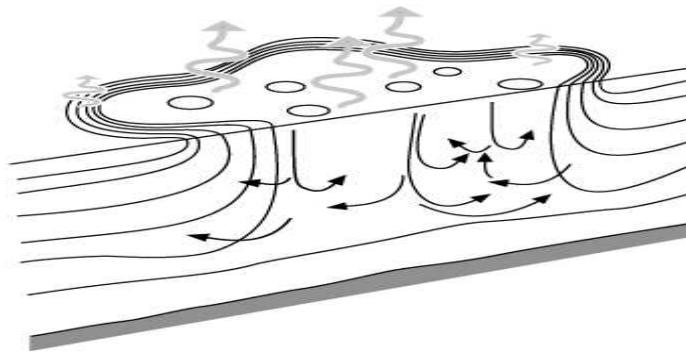
Known Ocean Deep Convection Sites



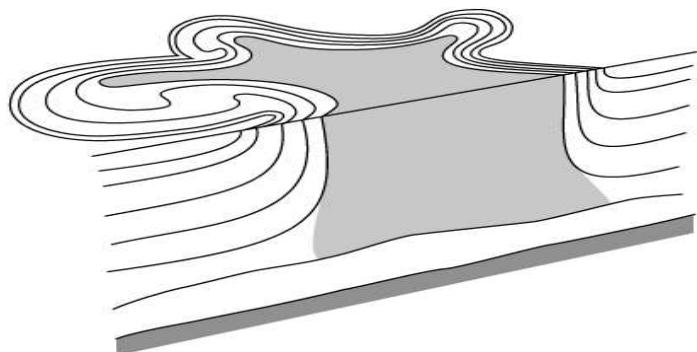
Convection



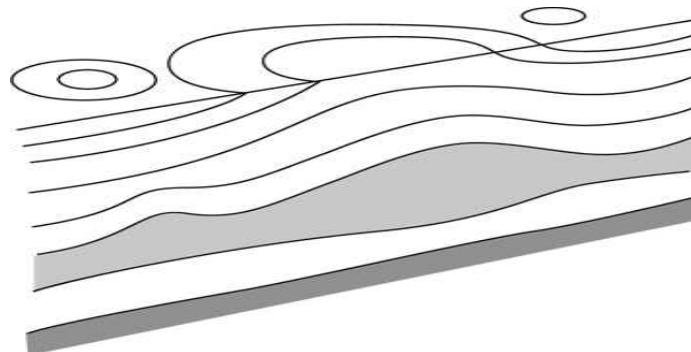
preconditioning



convection



restratification 1

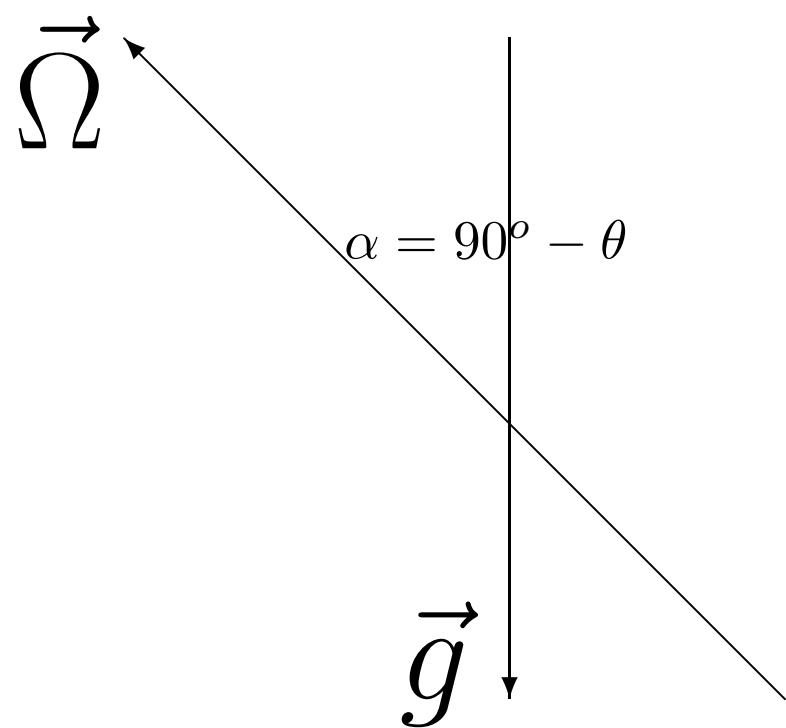


restratification 2

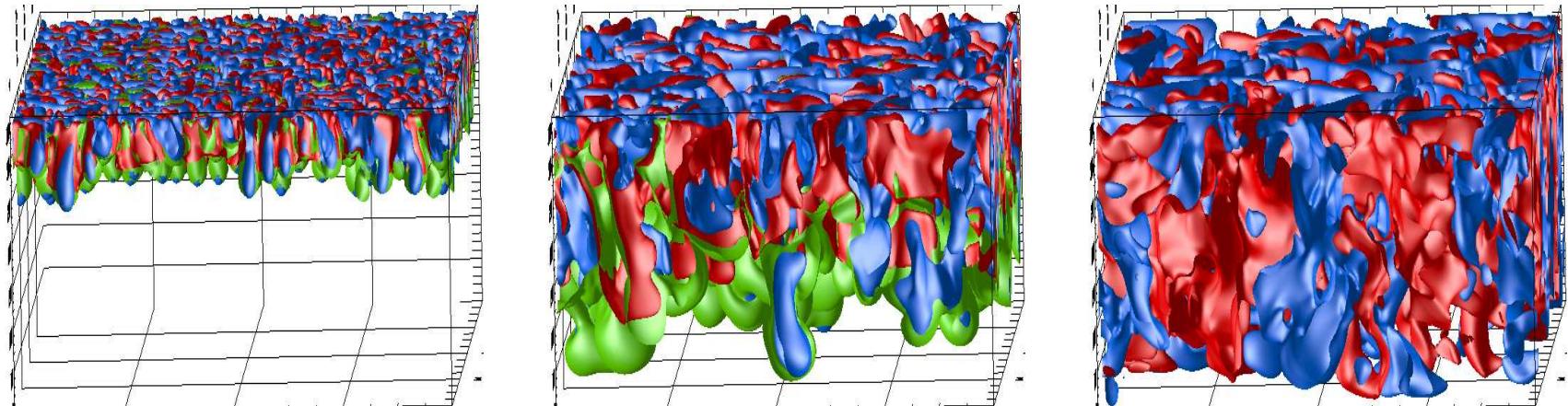
Plan :

- The numerical model (HAROMOD)
- The experiment
- Which régime (2.5D vs. 3D) ?
- Signature of the Taylor-Proudman-Poincaré theorem
- First order effects
- Second order effects
- Stratification
- Conclusions/Perspectives

Non-vertical Axis of Rotation



The Experience



Bi-periodic domain ($8\text{km} \times 8\text{km} \times 3.5\text{km}$)

Isothermal ocean

Forcing: 250, 500, 1000 W/m^2

Latitude: North pole, Gulf of Lions (45°N)

Numerical resolution: $256 \times 256 \times 224$ points

Dimensionless Parameters

$$\text{Rayleigh } \text{Ra}_f = \frac{B_0 H^4}{\nu \kappa^2}$$

$$\text{Prandtl } \text{Pr} = \frac{\nu}{\kappa}$$

$$\text{Natural Rossby } \text{Ro}^* = \sqrt{\frac{B_0}{f^3 H^2}}$$

Angle θ

Dimensionless Parameters

$$\text{Rayleigh } Ra_f = \frac{B_0 H^4}{\nu \kappa^2}$$

$$\text{Prandtl } Pr = \frac{\nu}{\kappa}$$

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Angle θ

Dimensionless Parameters

$$\text{Rayleigh } Ra_f = \frac{B_0 H^4}{\nu \kappa^2}$$

Lohse & Toschi 2003; Gibert *et al.* 2006

$$\text{Prandtl } Pr = \frac{\nu}{\kappa}$$

$$\text{Natural Rossby } Ro^* = \sqrt{\frac{B_0}{f^3 H^2}}$$

Angle θ

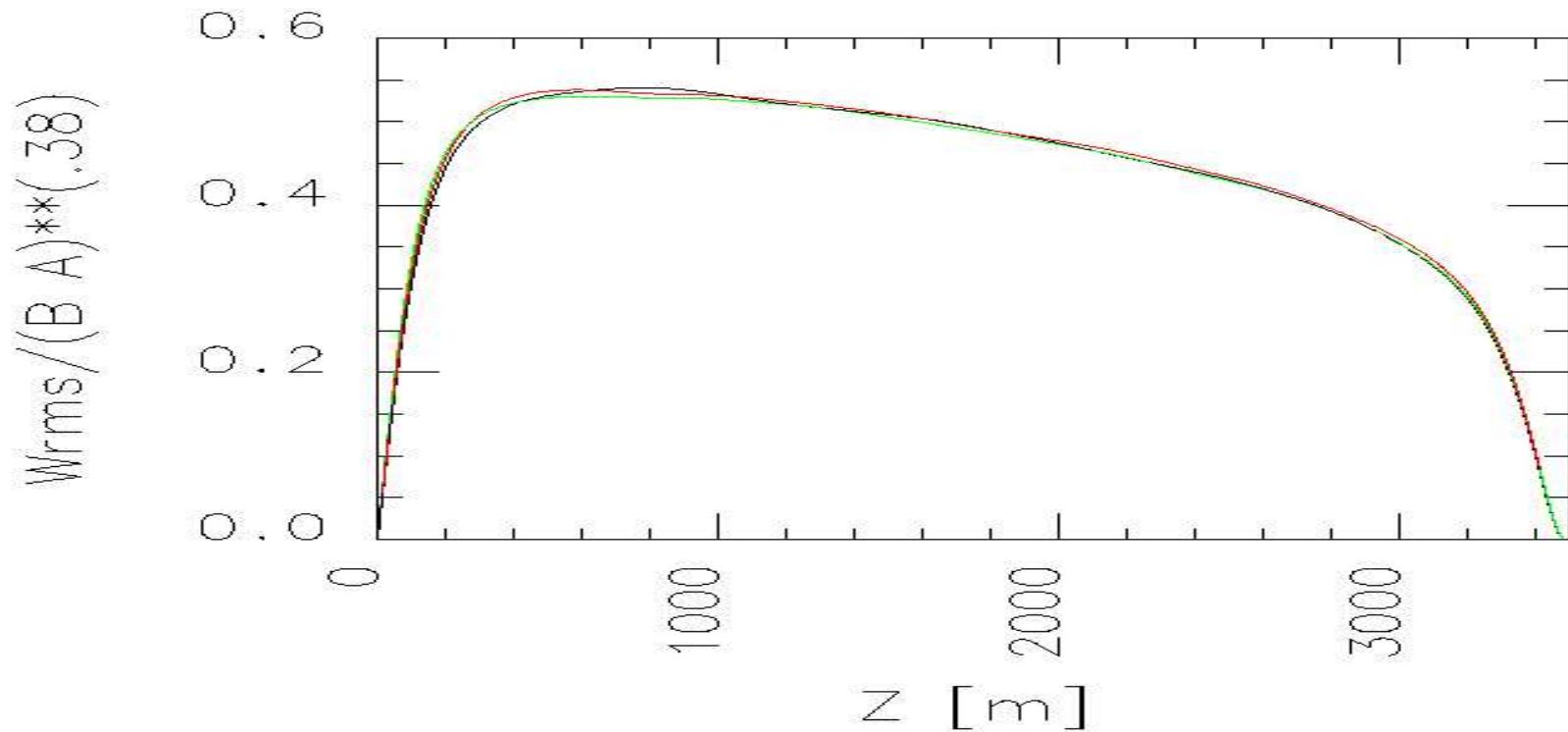
The Experiences

| exp. | surface heat flux | latitude |
|------|-----------------------|-----------------|
| E01 | 1000 W/m ² | 90 ^o |
| E03 | 500 W/m ² | 90 ^o |
| E04 | 250 W/m ² | 90 ^o |
| E31 | 1000 W/m ² | 45 ^o |
| E33 | 500 W/m ² | 45 ^o |
| E34 | 250 W/m ² | 45 ^o |

Which régime ?

Rotation (Heton) vs. 3D Turbulence ?

- $H_{rot} = \sqrt{B_0/f^3}$ \Rightarrow $u_{rot} = (B_0/f)^{1/2}$
- $H = H$ \Rightarrow $u_{3D} = (B_0 H)^{1/3}$



So, can we neglect rotation (atmospher)?

Plume Ensembles

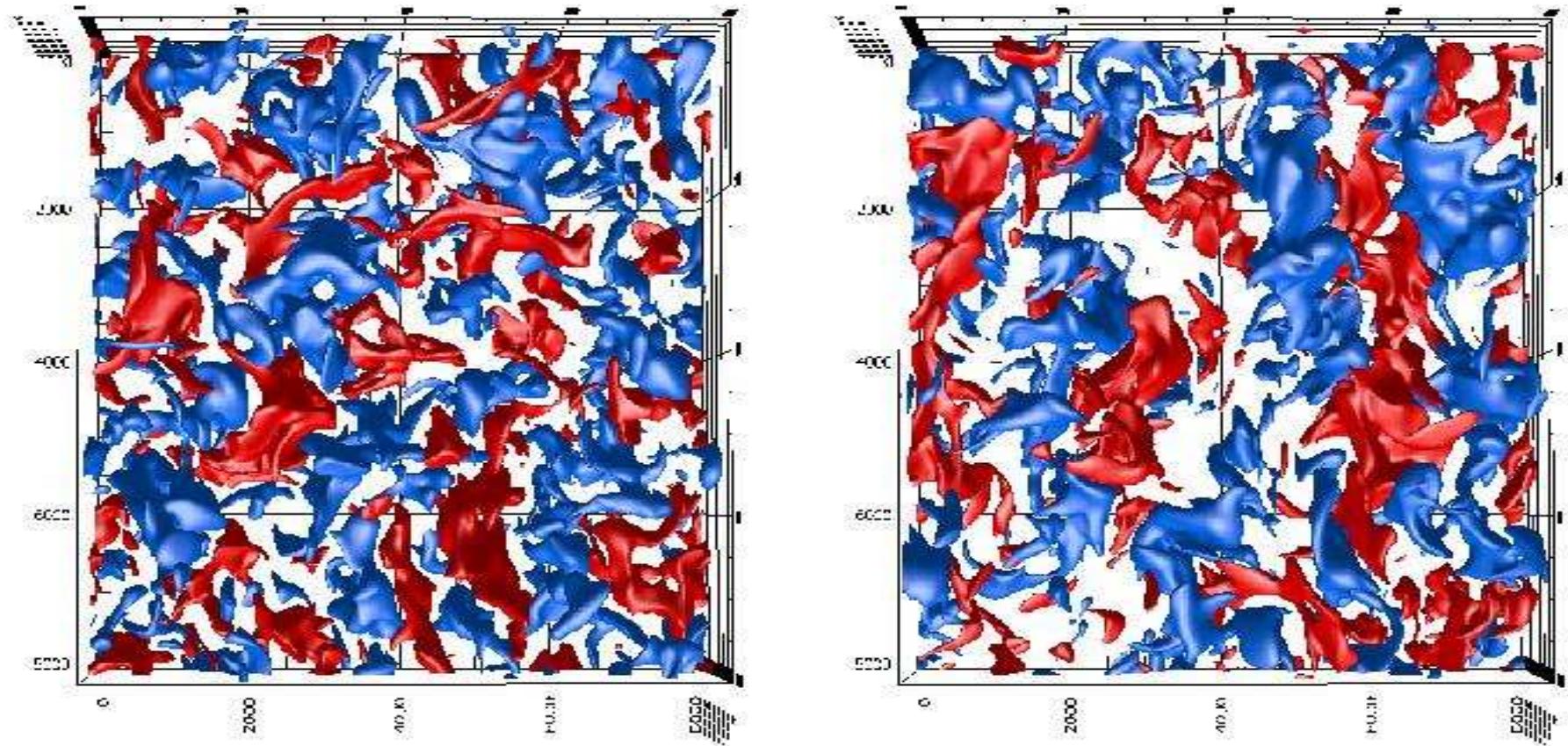


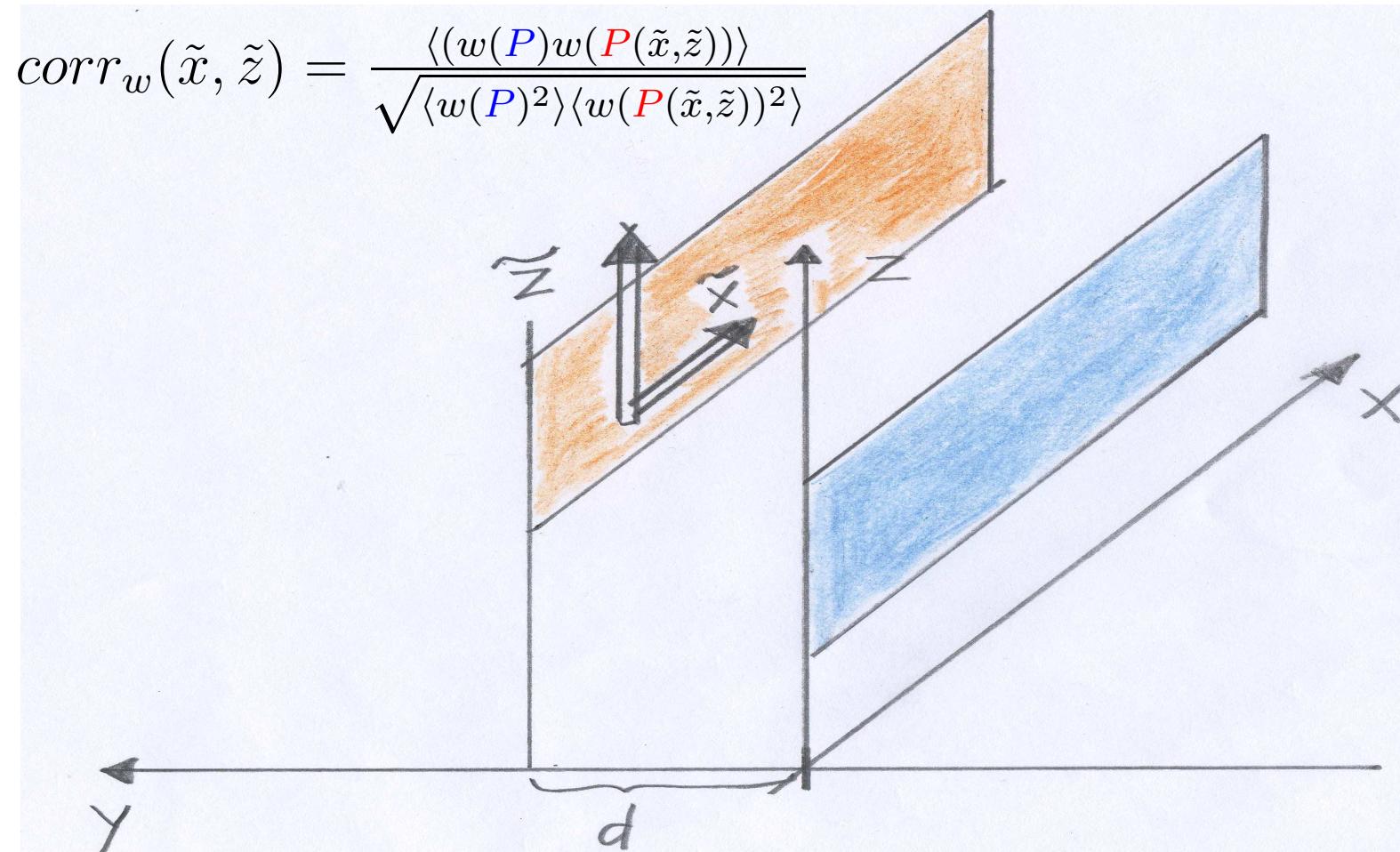
Figure 1: Isosurfaces of vertical velocity $w = \pm 0.05 \text{ m s}^{-1}$ (+ red, - blue) looking upward from the ocean floor (x to the right, y downward) at the end of the experiments $t = 168\text{h}$

Theorem of Taylor-Proudman-Poincaré

$$2(\Omega_y \partial_y + \Omega_z \partial_z) \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \frac{g}{\rho_0} \begin{pmatrix} \partial_y \rho \\ -\partial_x \rho \\ 0 \end{pmatrix}$$

(Colin de Verdière 2002, Un fluide lent entre deux sphères en rotation rapide :
les théories de la circulation océanique,
Annales Mathématiques Blaise Pascal, **9**, 245–268.)

Analysis of correlation



Signature of the Taylor-Proudman-Poincaré theorem

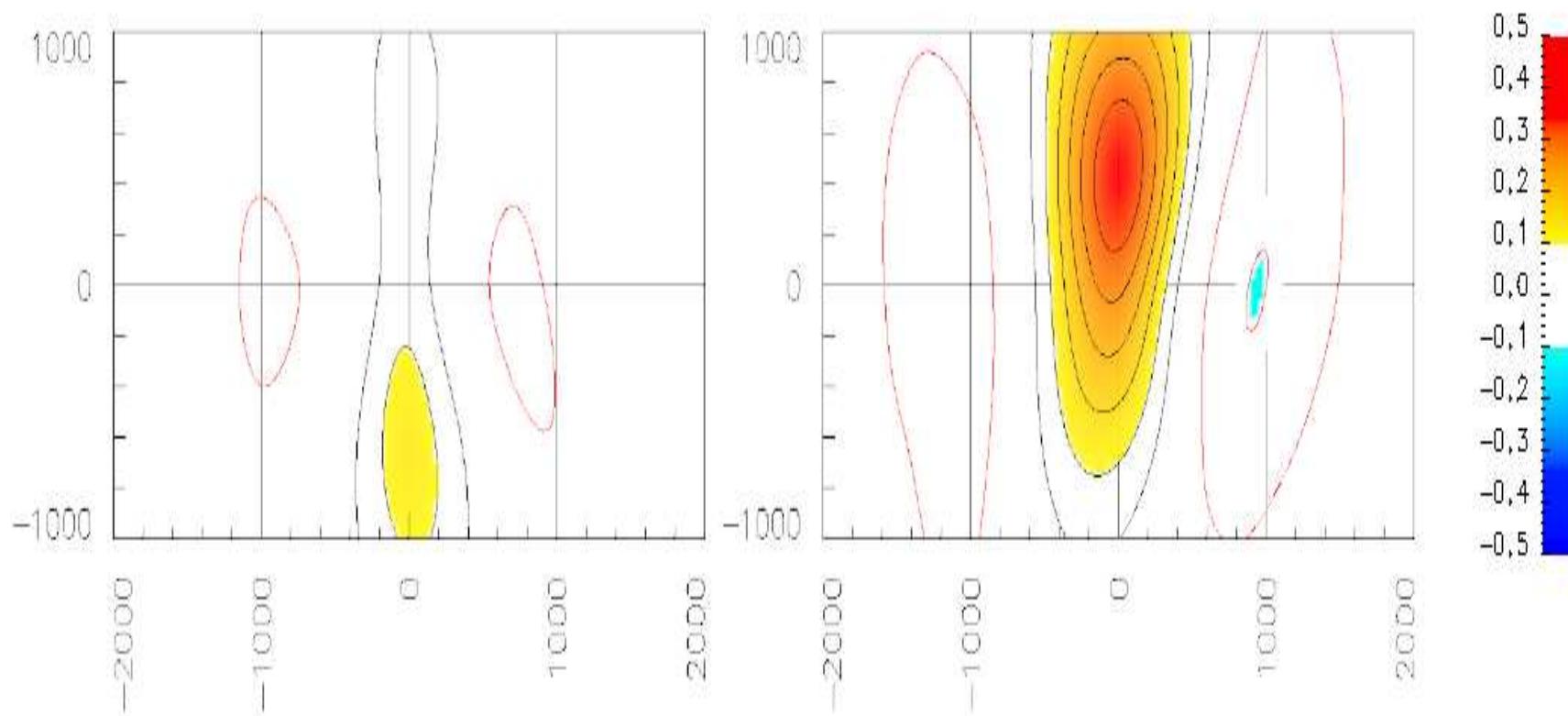


Figure 2: $C_y(500 \text{ m}, W)$ E34.

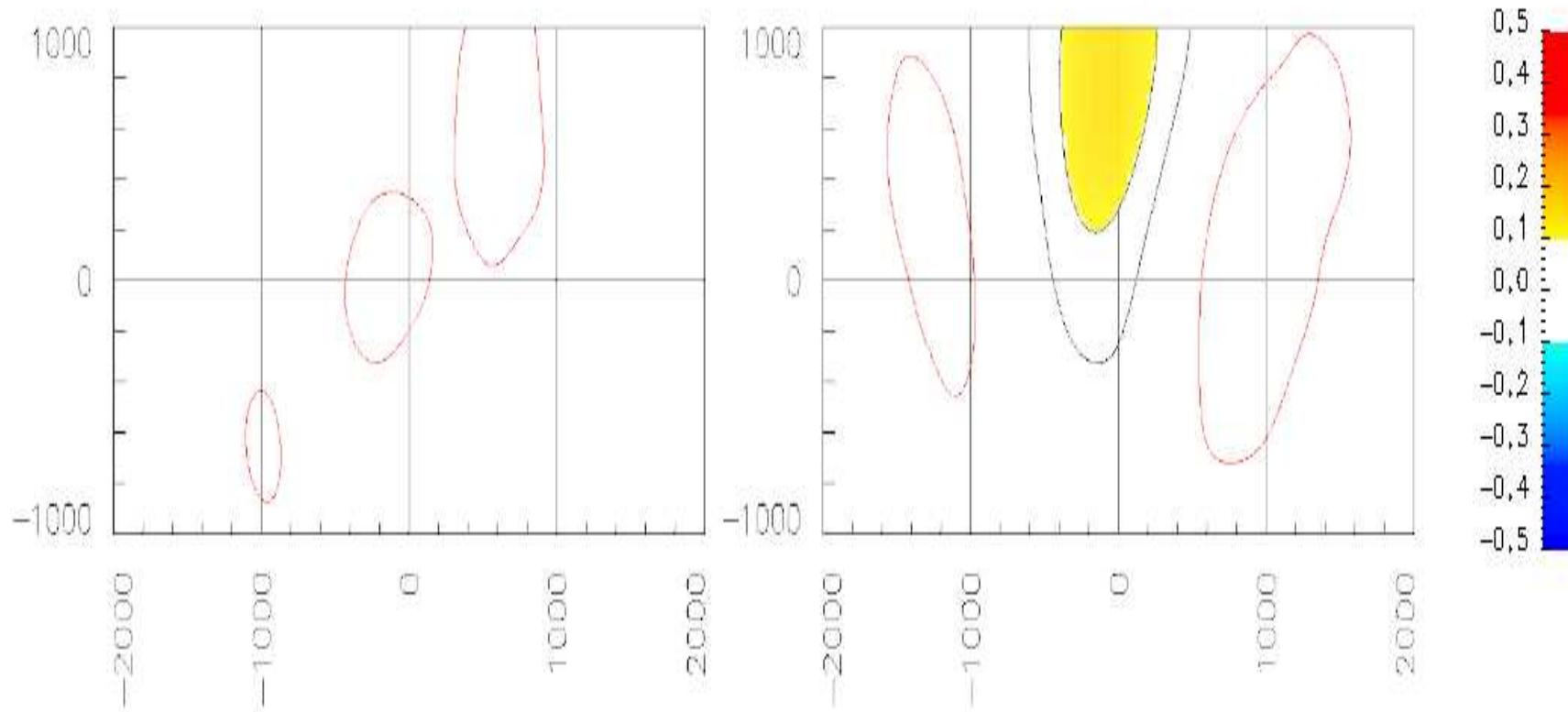


Figure 3: $C_y(1 \text{ km}, W)$ E34

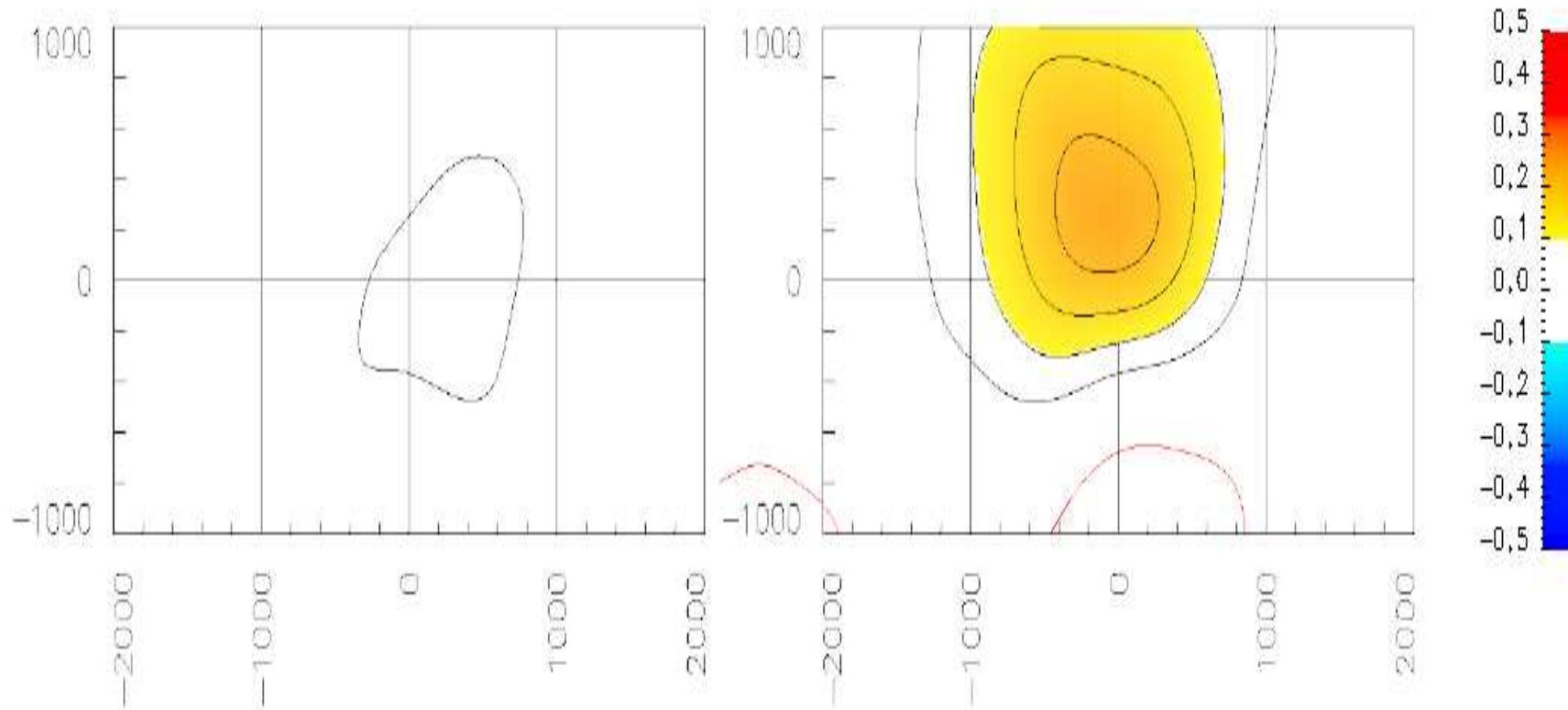


Figure 4: $C_y(500 \text{ m}, U)$ E34

Simple Plume Model

$$\begin{pmatrix} -\tau & f & -F \\ -f & -\tau & 0 \\ F & 0 & -\tau \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ g' \end{pmatrix}$$

Solution :

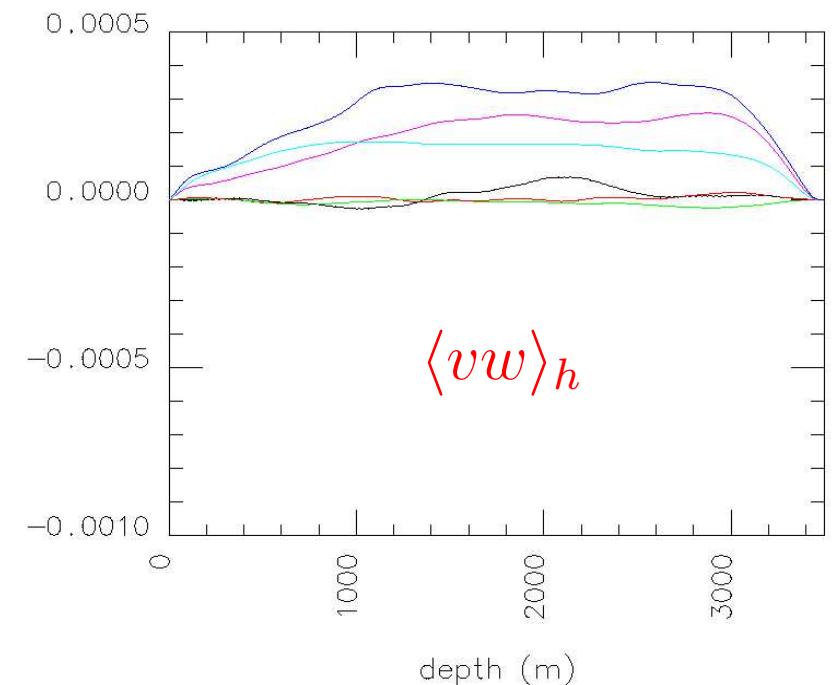
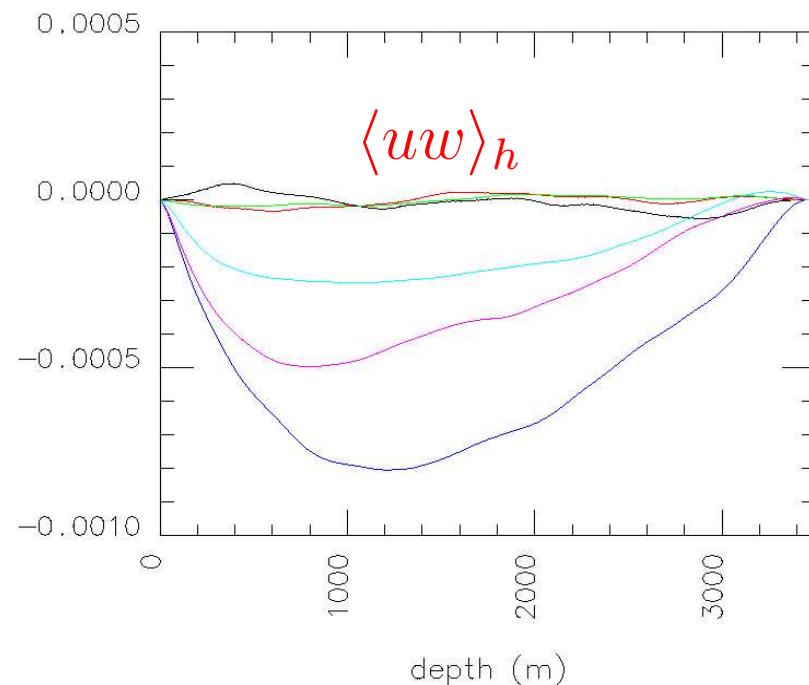
$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \tilde{c} \begin{pmatrix} \tau F/f^2 \\ -F/f \\ -1 - \tau^2/f^2 \end{pmatrix},$$

with $\tilde{c} = g'f^2/((f^2 + F^2 + \tau^2)\tau)$ plume speed,
 τ (friction time) $^{-1}$.

First Order Moments (I)

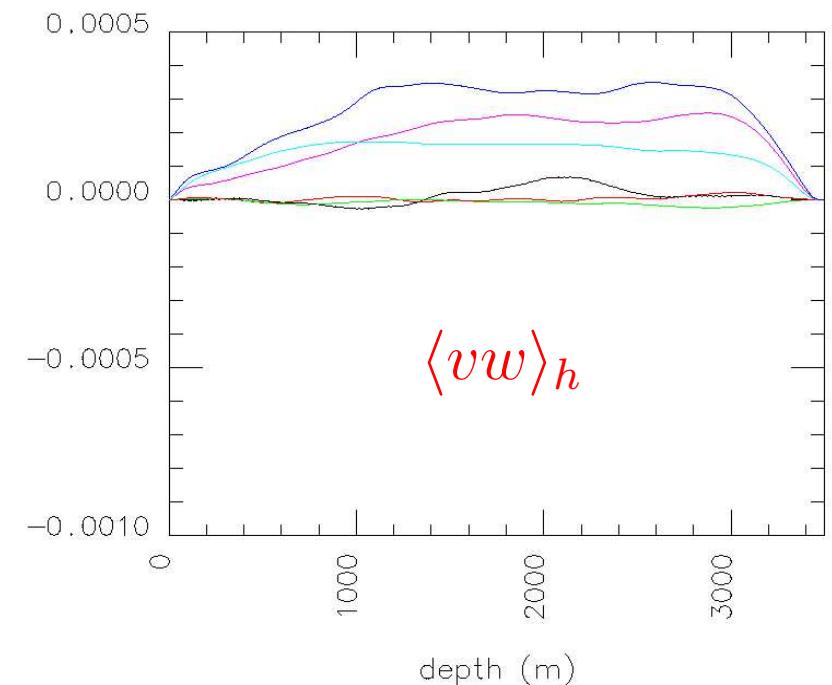
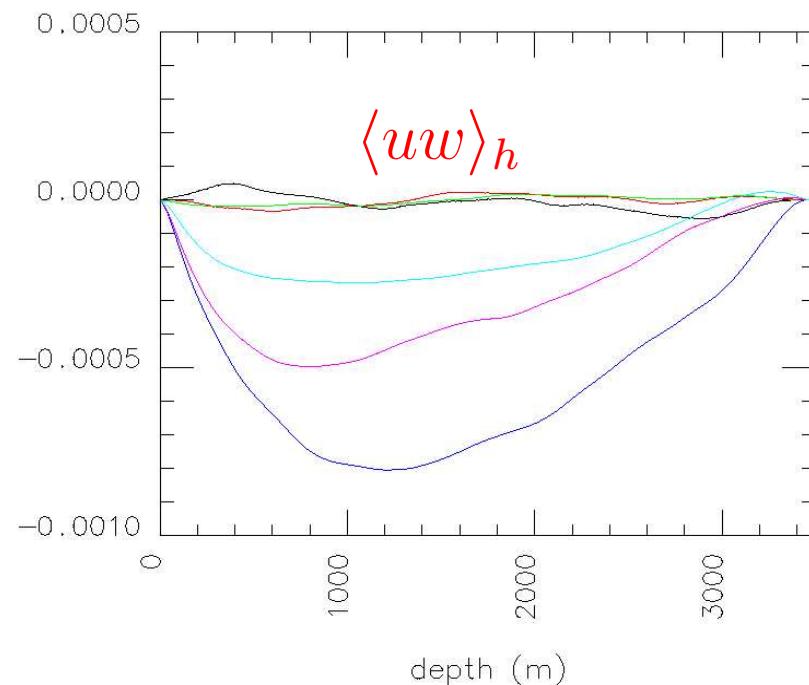
$$\partial_t \langle u \rangle_h = -\partial_z \langle uw \rangle_h + f \langle v \rangle_h + \nu \partial_z^2 \langle u \rangle_h$$

$$\partial_t \langle v \rangle_h = -\partial_z \langle vw \rangle_h - f \langle u \rangle_h + \nu \partial_z^2 \langle v \rangle_h$$



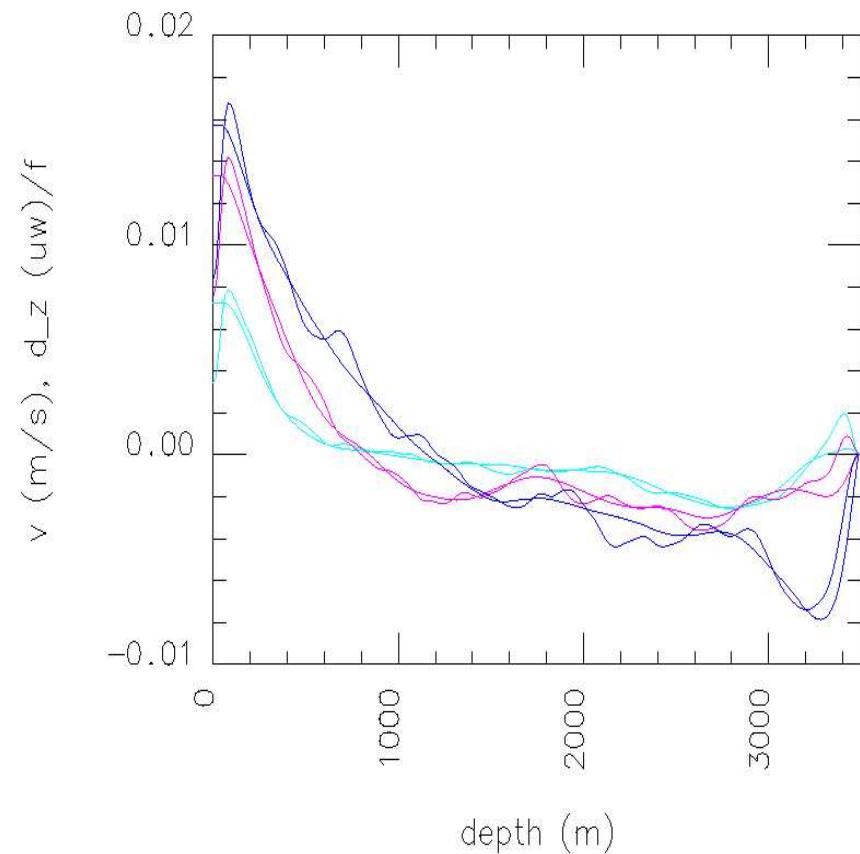
First Order Moments (II)

$$\begin{aligned}\partial_t \langle u \rangle_h &= -\partial_z \langle uw \rangle_h + f \langle v \rangle_h + \nu \partial_z^2 \langle u \rangle_h \\ \partial_t \langle v \rangle_h &= -\partial_z \langle vw \rangle_h - f \langle u \rangle_h + \nu \partial_z^2 \langle v \rangle_h\end{aligned}$$

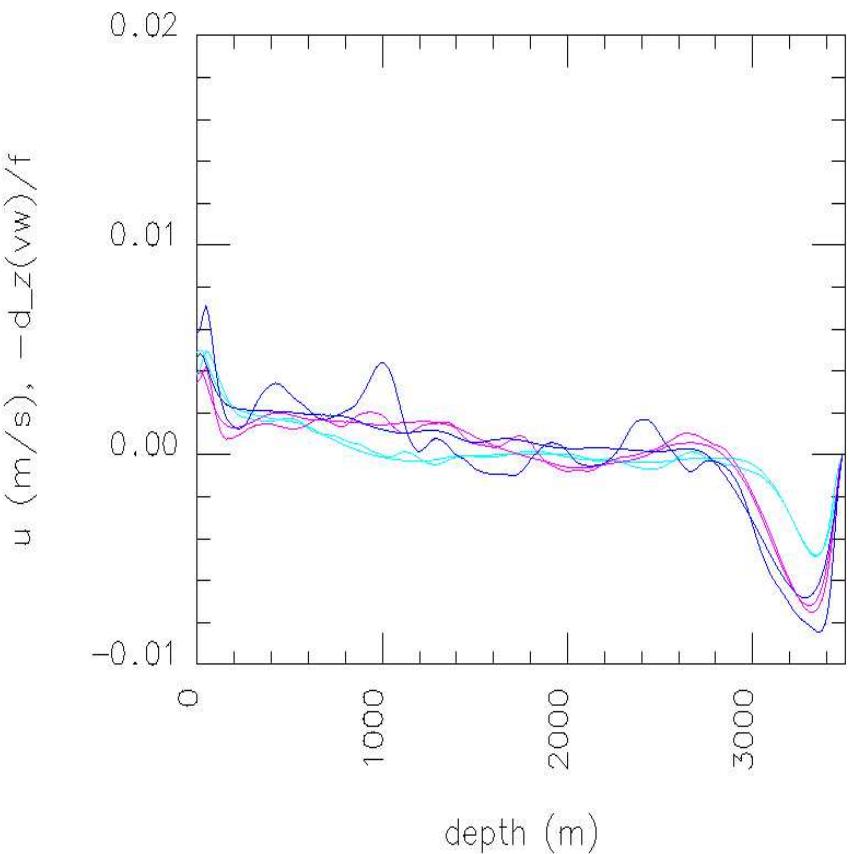


First Order Moments (III)

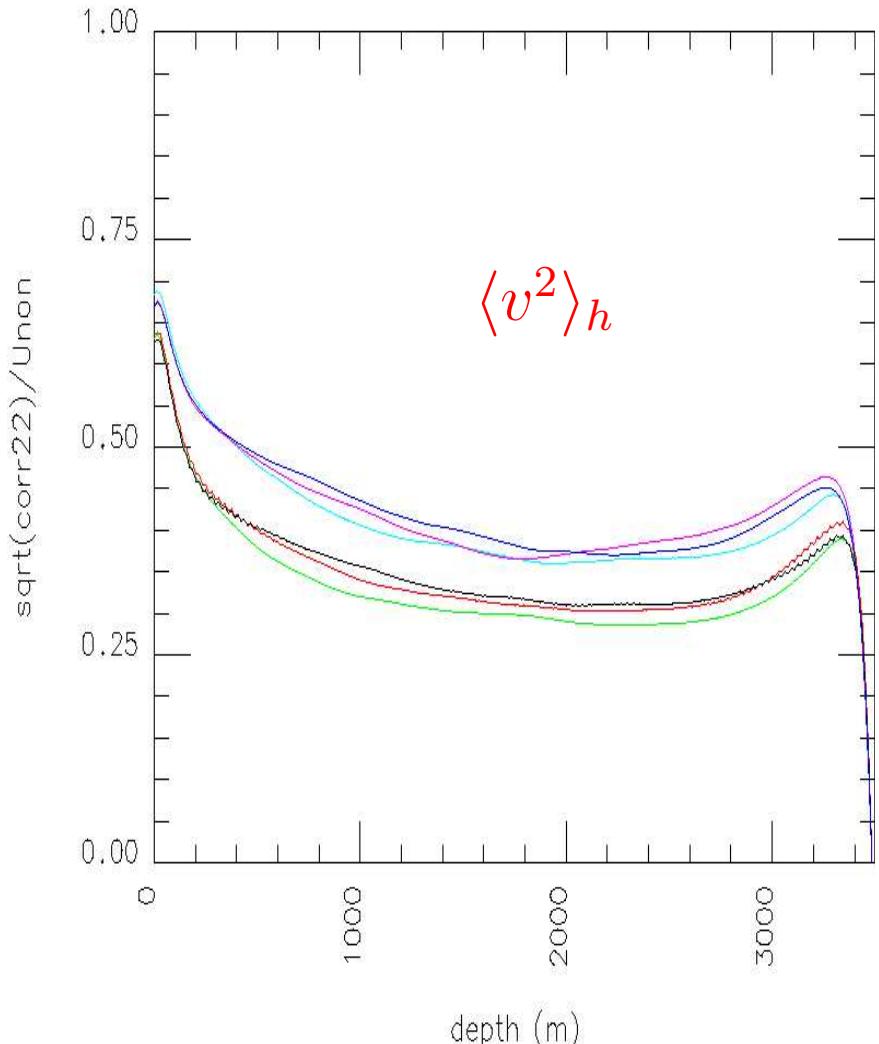
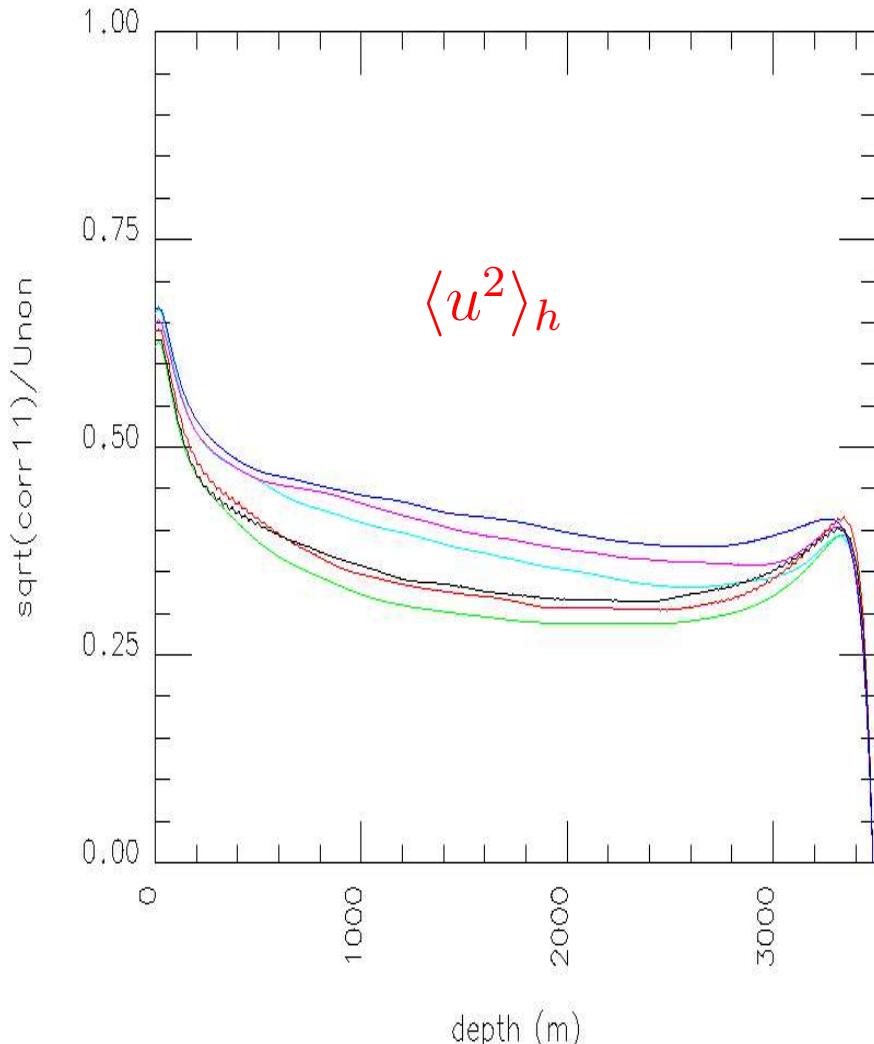
$$f\langle v \rangle_{h,t} = \partial_z \langle uw \rangle_{h,t}$$



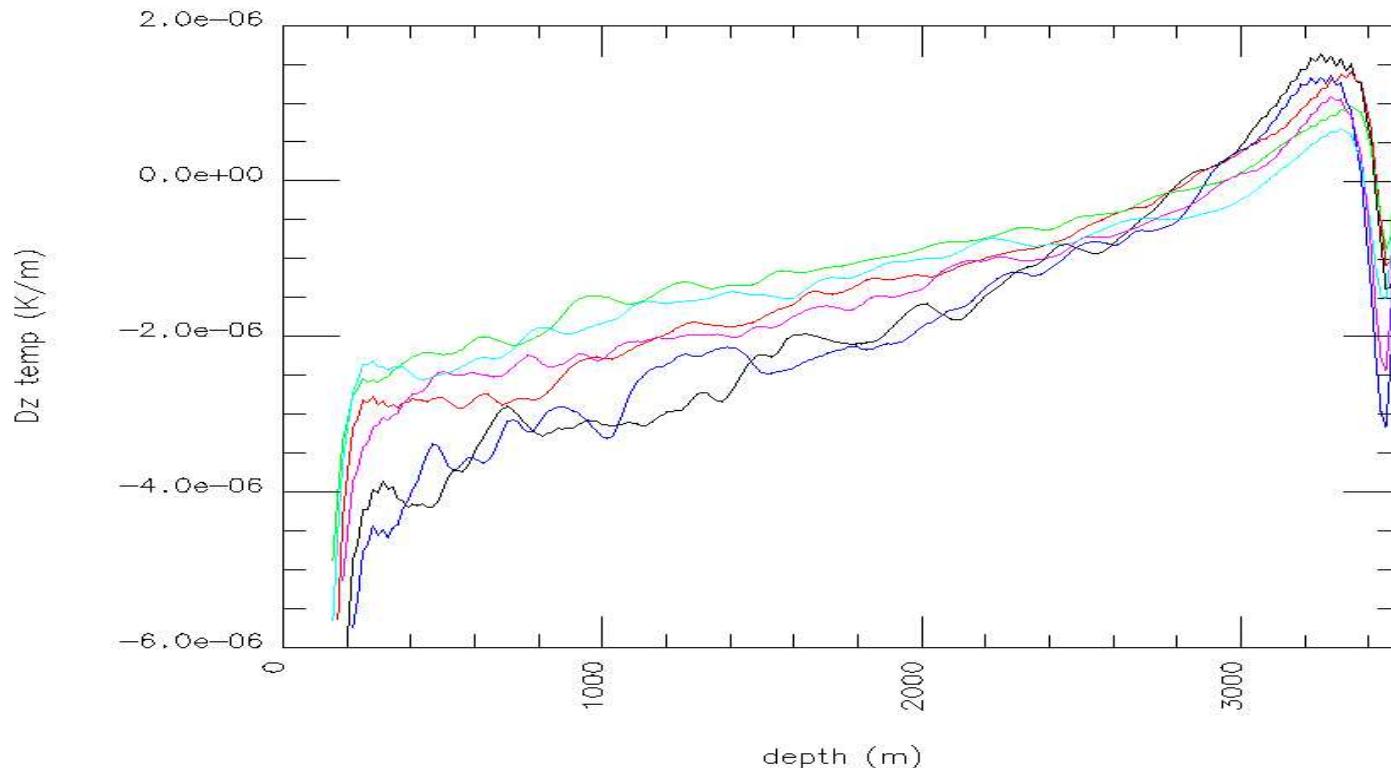
$$f\langle u \rangle_{h,t} = -\partial_z \langle vw \rangle_{h,t}$$



Second Order Moments



Stratification (independent of θ)

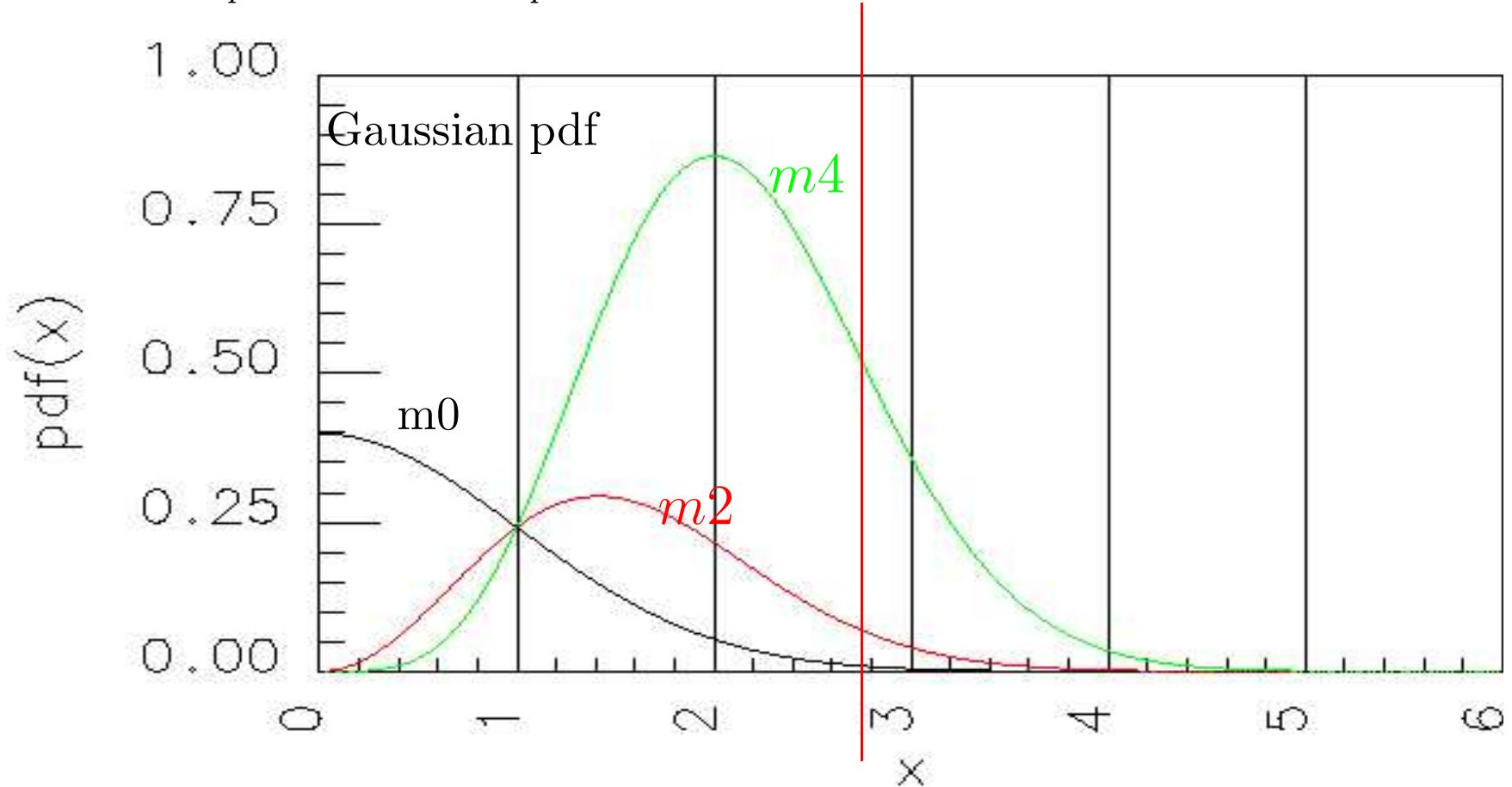


$$\kappa_Z(\alpha g \partial_z T - \gamma) = -\frac{B_0 z}{D}$$

| param. (H, B) | (3500m, 1000W/m ²) | (1000m, 500W/m ²) | (350m, 500W/m ²) |
|-------------------------------|--------------------------------|-------------------------------|------------------------------|
| $\kappa_Z \sim (H^4 B)^{1/3}$ | $40 m^2/s$ | $6 m^2/s$ | $1.5 m^2/s$ |

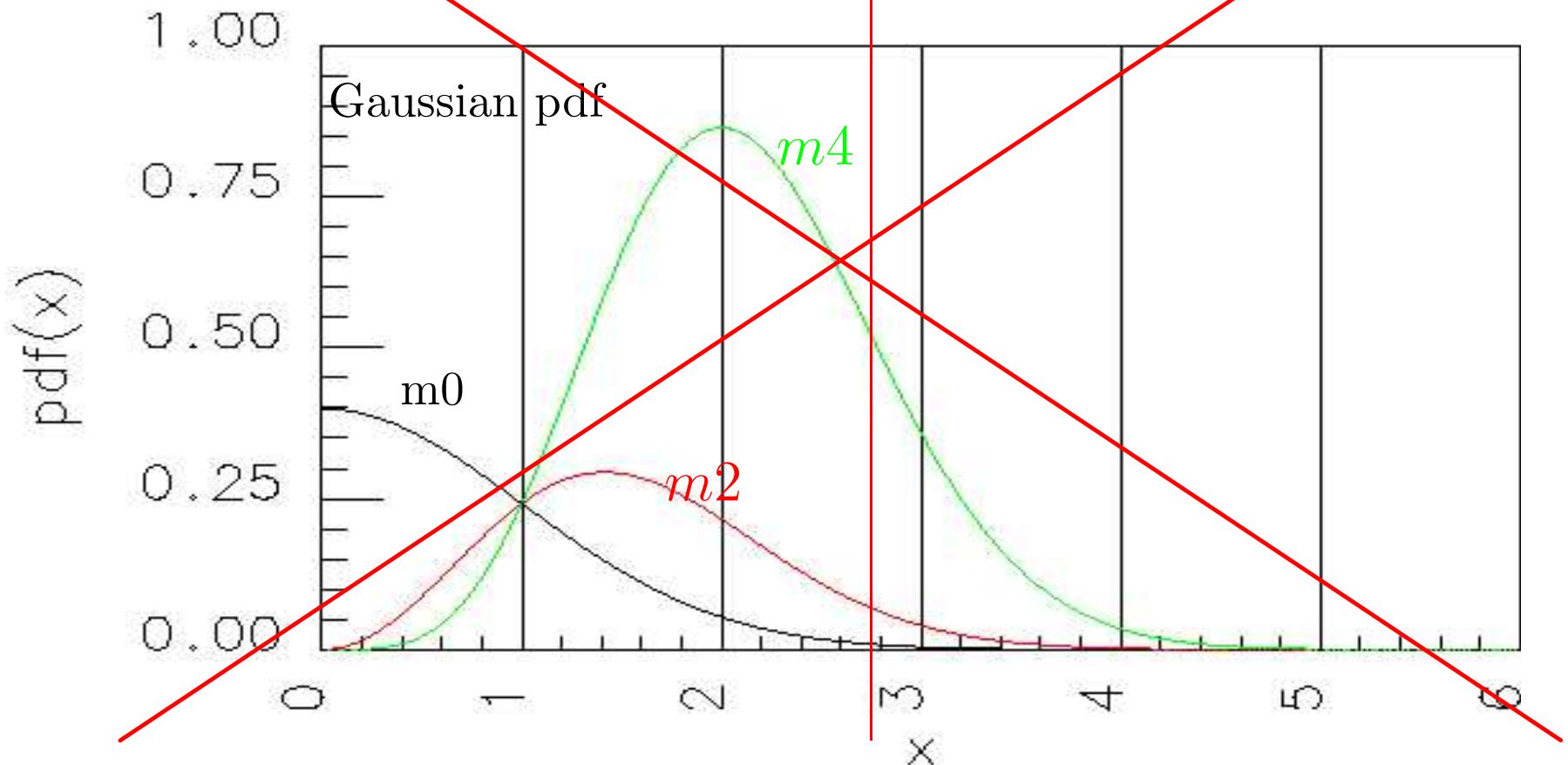
Higher Order Moments

$t_{plume} \approx 12h, x_{plume} \approx 2km \Rightarrow$ ensemble size $\approx 200.$



Higher Order Moments (HOM)

$t_{plume} \approx 12h, x_{plume} \approx 2km \Rightarrow$ ensemble size $\approx 200.$



Conclusions:

- Tilt of rotation vector more important than rotation!
- Tilt stretches structures along the axis of rotation
- Tilt generates a local overturning circulation
- Tilt increases horizontal mixing
- Tilt does NOT change stratification (allows for a param. for density structure indep. of tilt)
- Forget about HOM

Perspectives:

- Develop a parametrisation
- Observations, ~~Laboratory Experiments~~