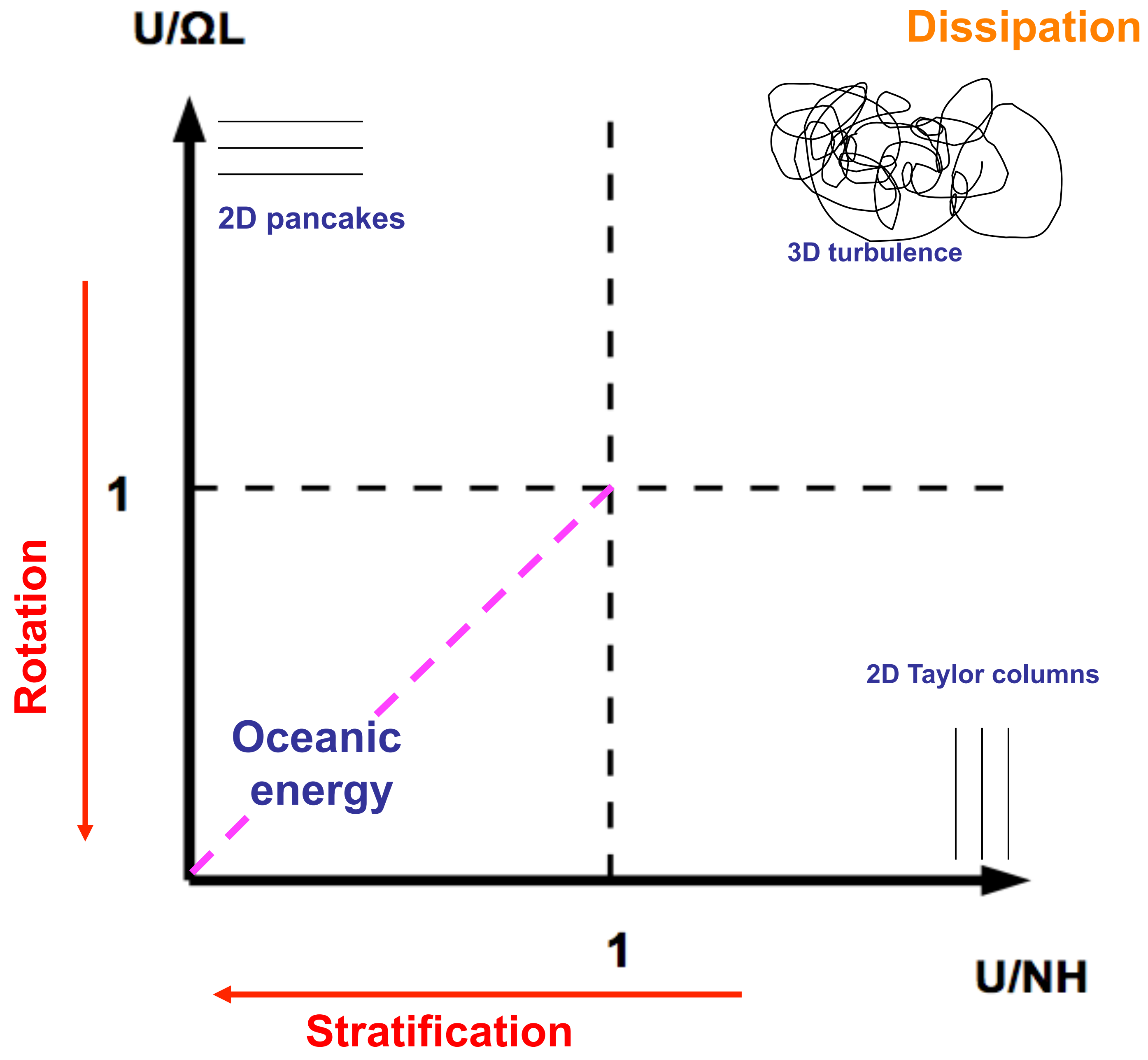
Lien’s scientific choices

- A **GFD** approach to Oceanography
- The nonlinear properties of **oceanic eddies** and **equatorial jets**
- Stirring properties of oceanic turbulence

GFD: Geophysical Fluid Dynamics



U/ΩL
Dissipation
2D pancakes
3D turbulence
1
Rotation
2D Taylor columns
Oceanic
energy
1
U/NH
Stratification

Numerical simulation of the ocean?

Landau's estimate gives the required number of model points to reach dissipation scales:

$$N = \mathbf{Re}^{9/4} \sim \mathbf{10}^{25}$$

with a Reynolds number Re ~ 10^{11}

Dissipation has to be **invented** to operate at the grid scale.

Physical interpretation of model results must be **independent** of the details of the dissipation operator.

Lien's advice: carry out simulations with the most spatial resolution and least dissipation you can afford!

Why is the ocean so nonlinear?

Energy in the open ocean is found at scale near R_i
with Rossby radius $R_i \sim NH/f$

Waves in the open ocean are vorticity waves and are slow

Rossby wave phase velocity $c \sim \beta R_i^2$

Waves are nonlinear if

fluid velocity $/ c \geq O(1)$

$[\sin^2(lat)/\cos(lat)]$ dependence of **c** favors nonlinearity at mid latitudes

Consequences of the nonlinearity

No way to break the problem in independent parts as in the linear case because parts interact:

$$\cos(\omega t) \times \cos(\omega t) = 1+\cos(2\omega t)$$

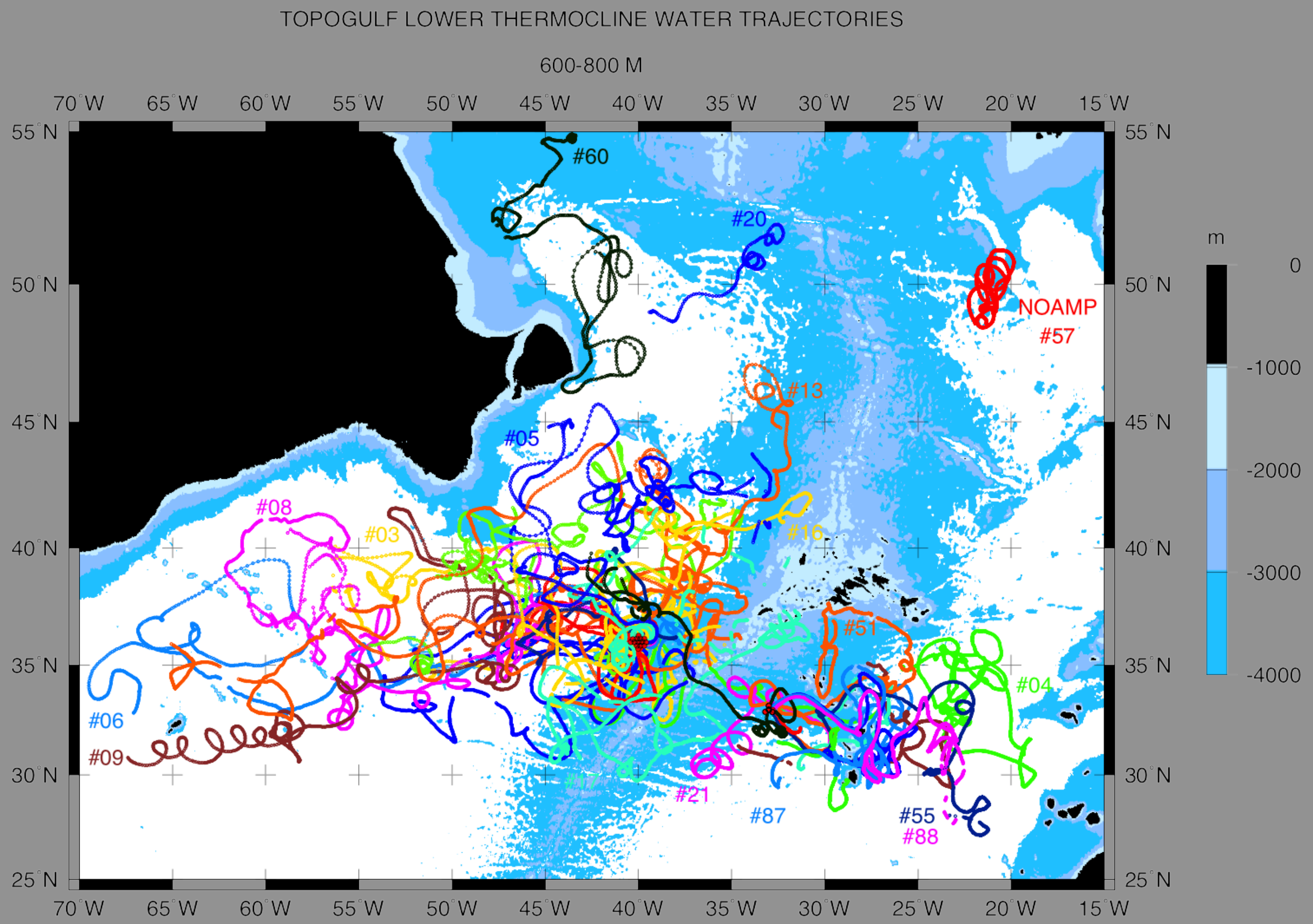
Turbulence appears and

Fluid velocity becomes random

Velocity correlation functions fall off quickly

Short memory implies lack of predictability

(and large error growth from initial conditions)



Ollitrault - Colin de Verdiere, JPO, 2002

Lien's scientific approach

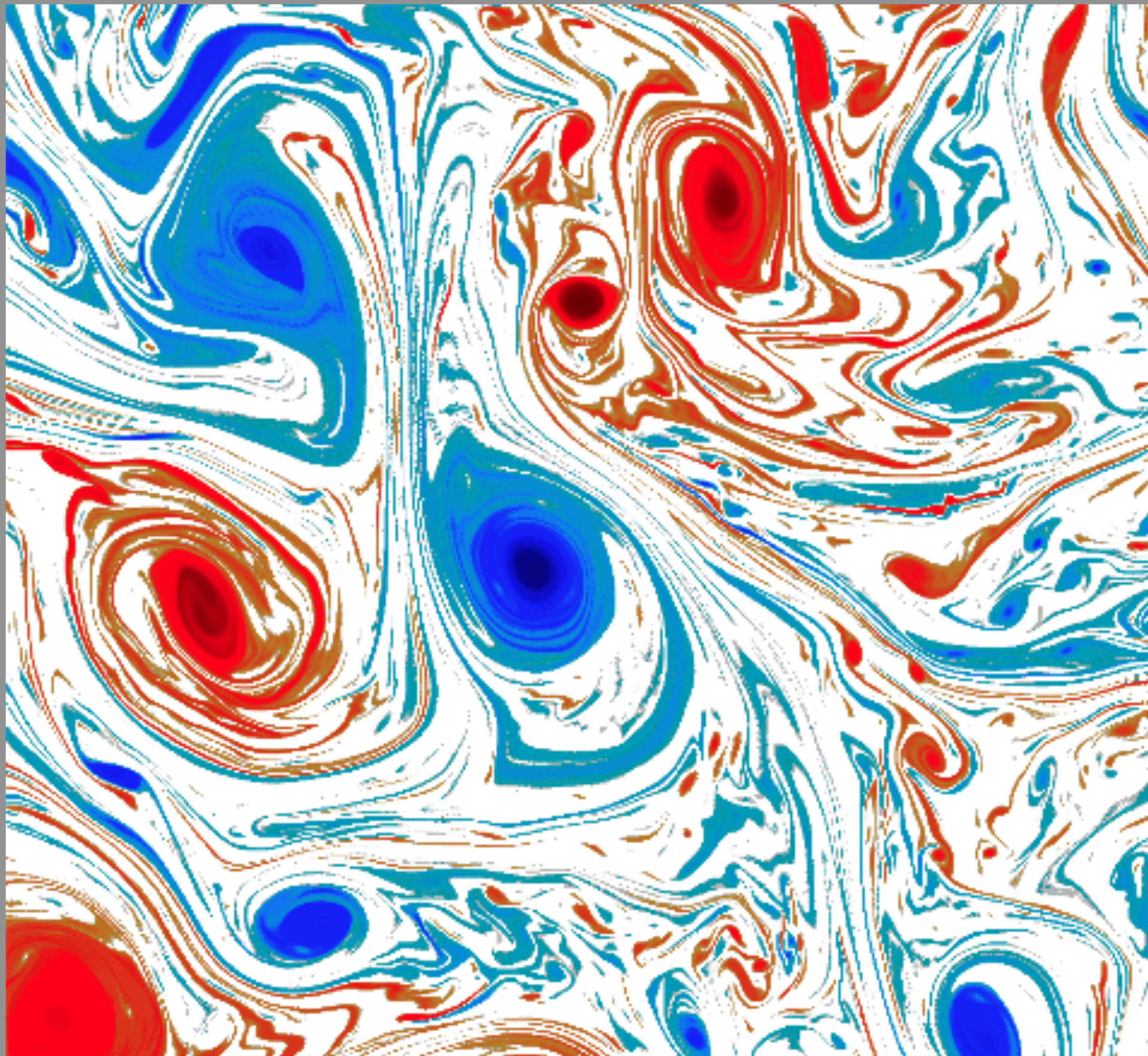
- No compromise on the energy level of the oceanic eddies
- Use of GFD thinking to write up codes, prepare and analyse full blown numerical solutions

Lien's early paintings

- Tools: computers + codes
- The paint: **vorticity** = ∇x**u**
- The paintings: look like material tracers in a fluid

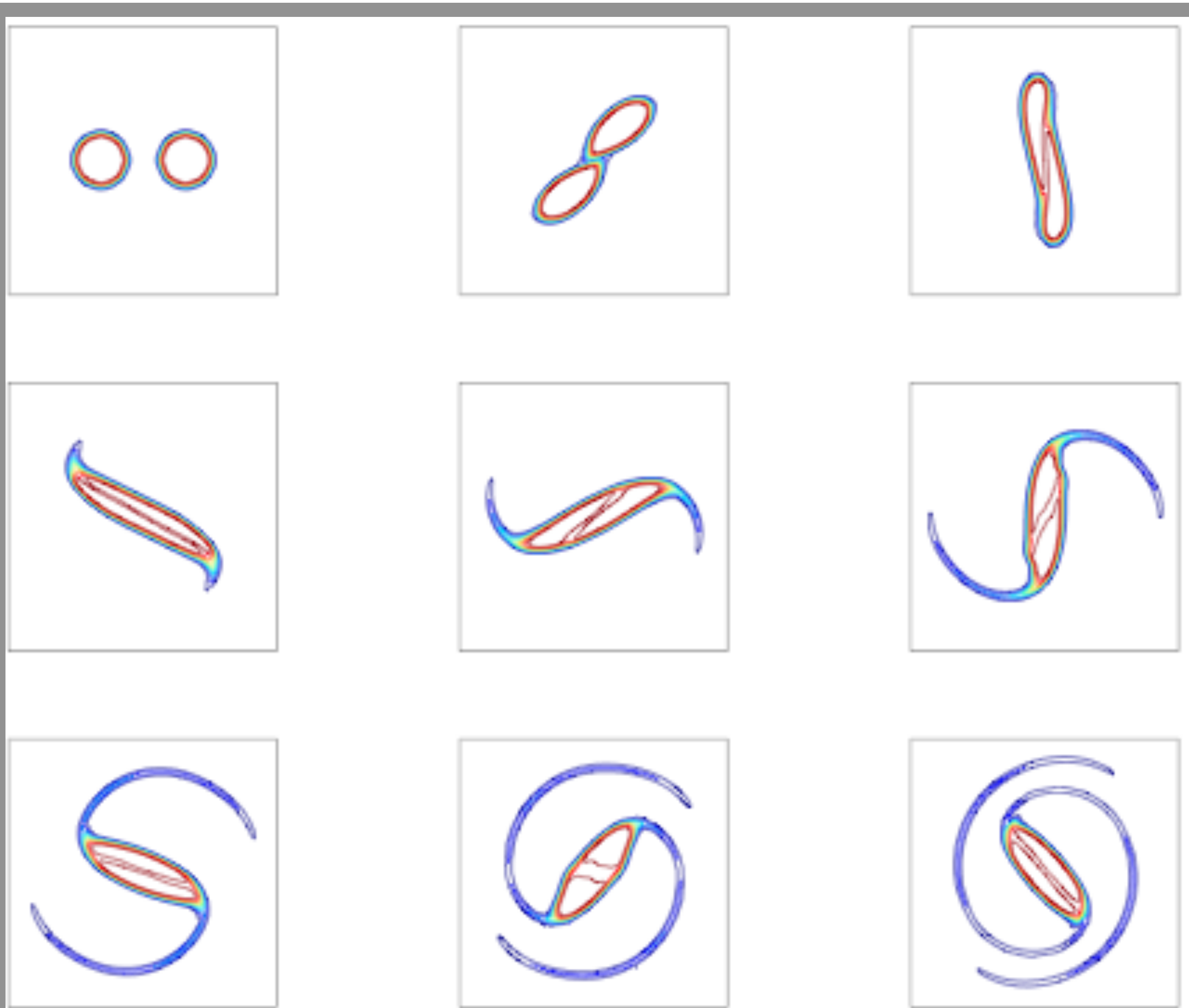
  D/Dt (vorticity) = 0
- Originality: the paint is **active** and can modify the flow [because $\Delta\psi$ = vorticity and u=k x ∇ ψ]

```
do  j=3,jsfm2
       do  i=3,isfm2
         r(i,j)=(p(i,j-1)+p(i+1,j-1)-p(i
+1,j+1)-p(i,j+1))*q(i+1,j)
     +       -(p(i-1,j-1)+p(i,j-1)-p(i-1,j
+1)-p(i,j+1))*q(i-1,j)
       enddo
     enddo
     do  j=3,jsfm2
       do  i=3,isfm2
         r(i,j)=r(i,j)+
     +        (p(i+1,j)+p(i+1,j+1)-
p(i-1,j)-p(i-1,j+1))*q(i,j+1)
     +       -(p(i+1,j-1)+p(i+1,j)-
p(i-1,j-1)-p(i-1,j))*q(i,j-1)
       enddo
     enddo
```



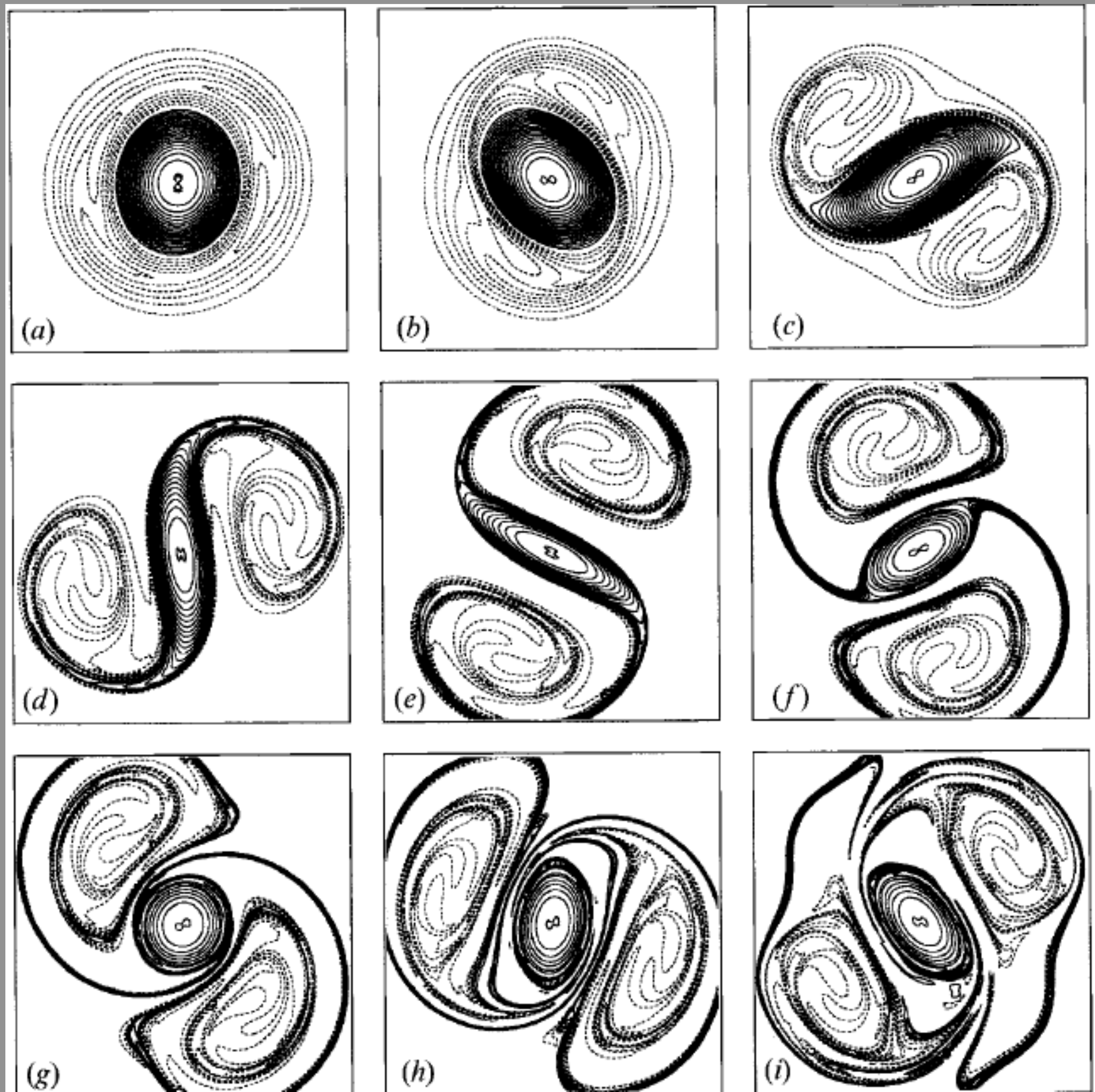
Hua - Klein, Physica D, 1998

Active paint: vortex fusion



Maze-Carton-Lapeyre, Chaos, 2004

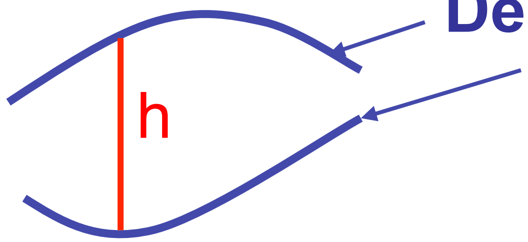
Active paint: vortex break up



Carton-Legras,
JFM, 1994

Part I The vertical structure of oceanic eddies

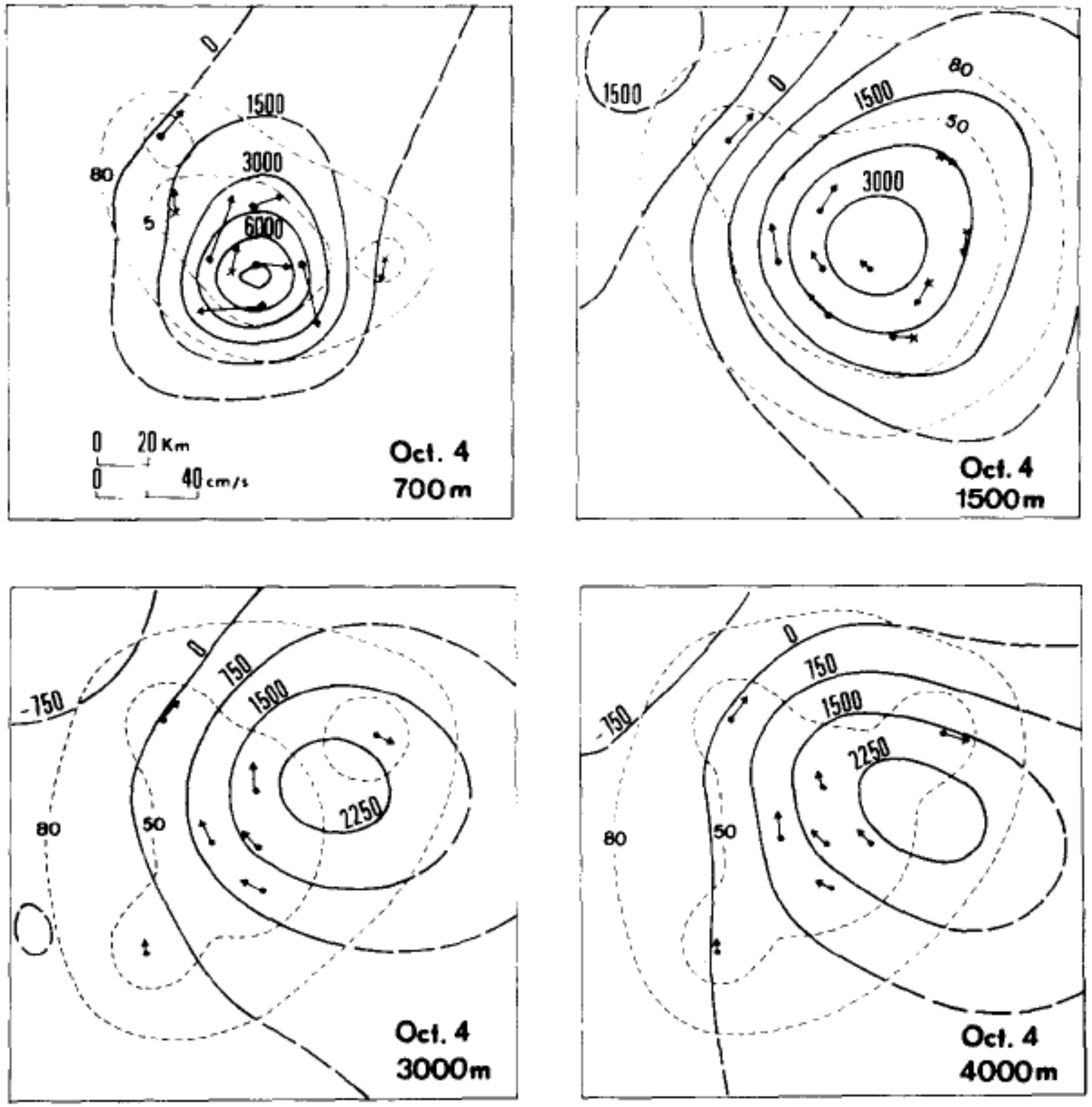
- From vorticity to potential vorticity…
  q=vorticity-f.h/H



- Burger number = U/ΩL : U/NH= **NH/ΩL**

- Leads to her recommandation for high vertical resolution: $N\,\Delta z\,/\,f\,\Delta x \sim O(1)$

Eddies in the Eastern North Atlantic: the 1979 Tourbillon experiment



Le Groupe Tourbillon, DSR,1983

Internal Barotropic instability [for scale < R_i]

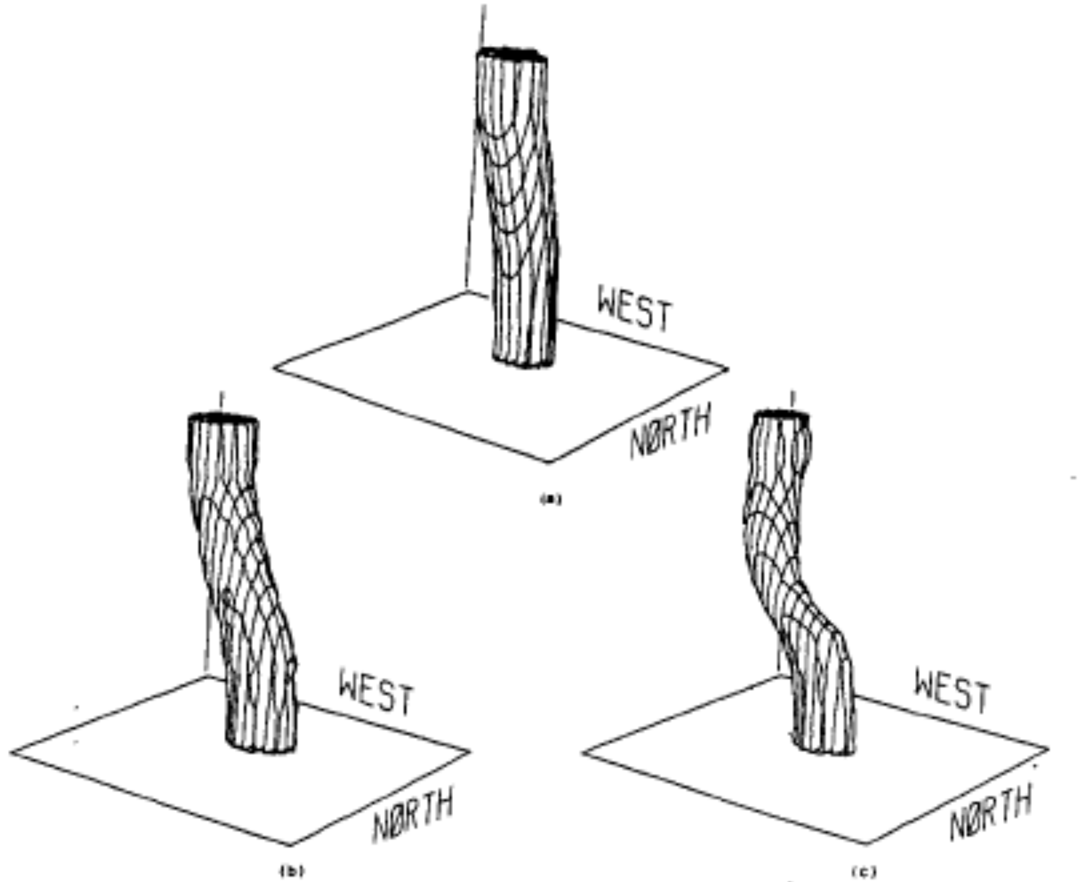
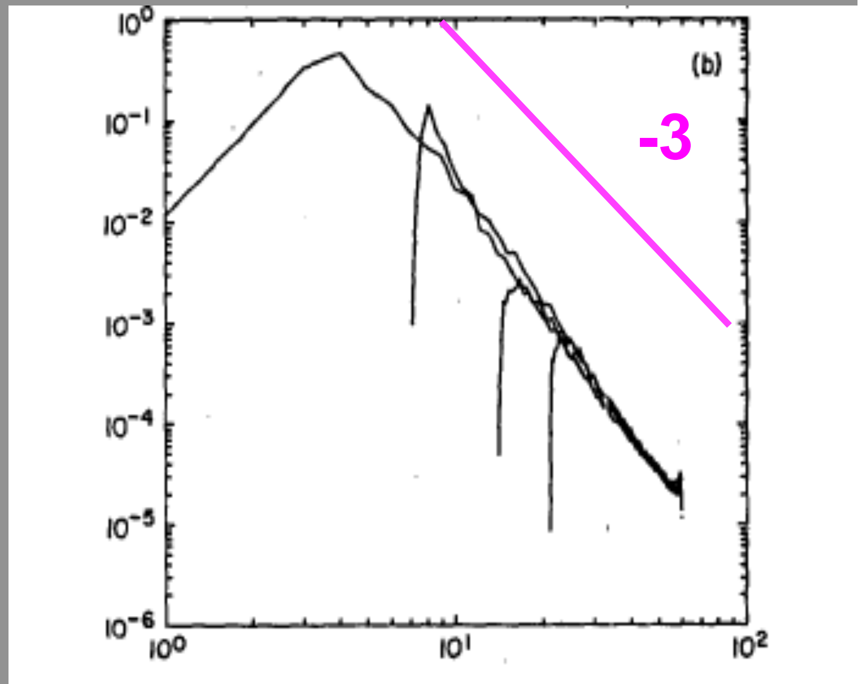


FIG. 9. Three-dimensional view of the best-fit Tourbillon case, at time $t = 0$ (a) and $t = 7.5$, i.e., roughly 32 days later (b) for case II6 of Table 2. For comparison, the same view is given for run II7 also at $t = 7.5$ (c). The isosurface plotted is 0.85 times the maximum of the streamfunction field at *each depth*.

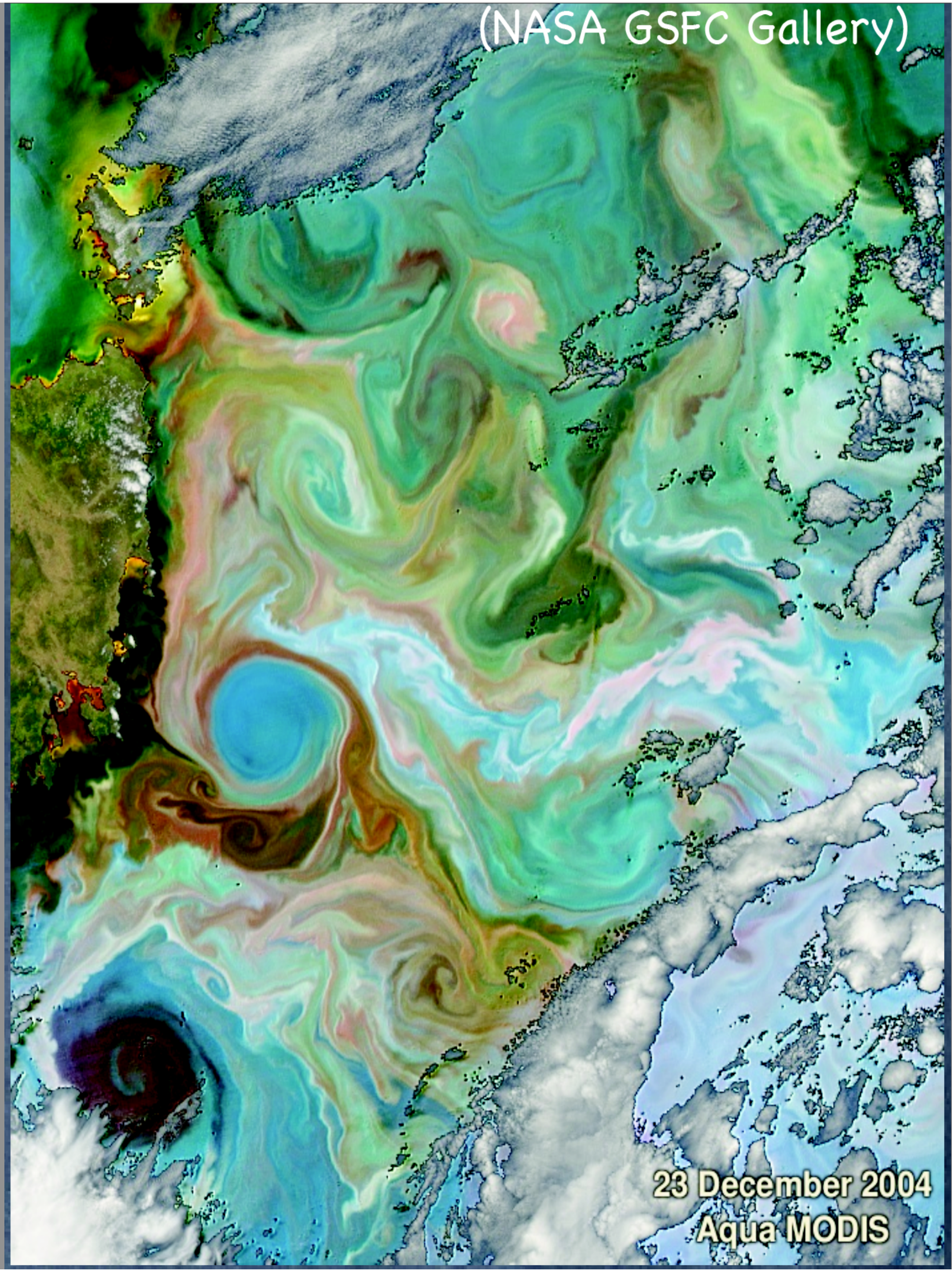
Hua, JPO, 1988

Test of Charney's 1971 predictions

- 2D turbulence: direct enstrophy cascade leads to k^{-3} kinetic energy spectrum
- Charney's predictions of a k^{-3} energy spectrum in quasi-geostrophic turbulence (k is now 3D wavenumber)



Hua-Haidvogel, JAS, 1986



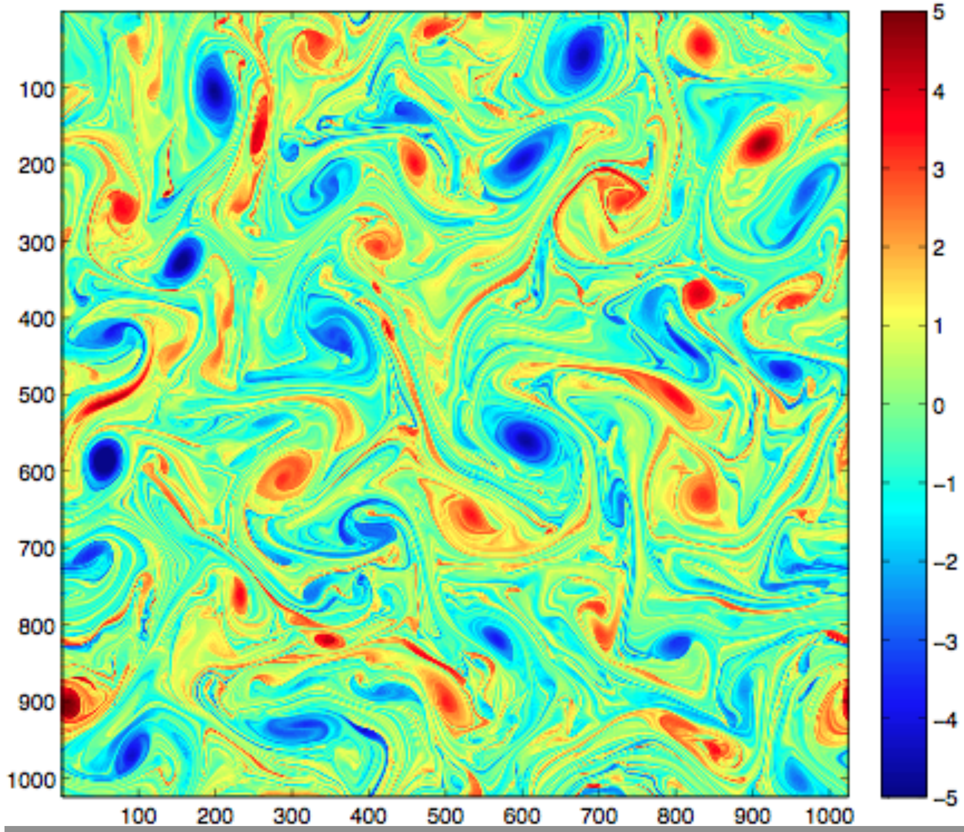
Observing smaller
and
smaller scales

From QG models to SQG

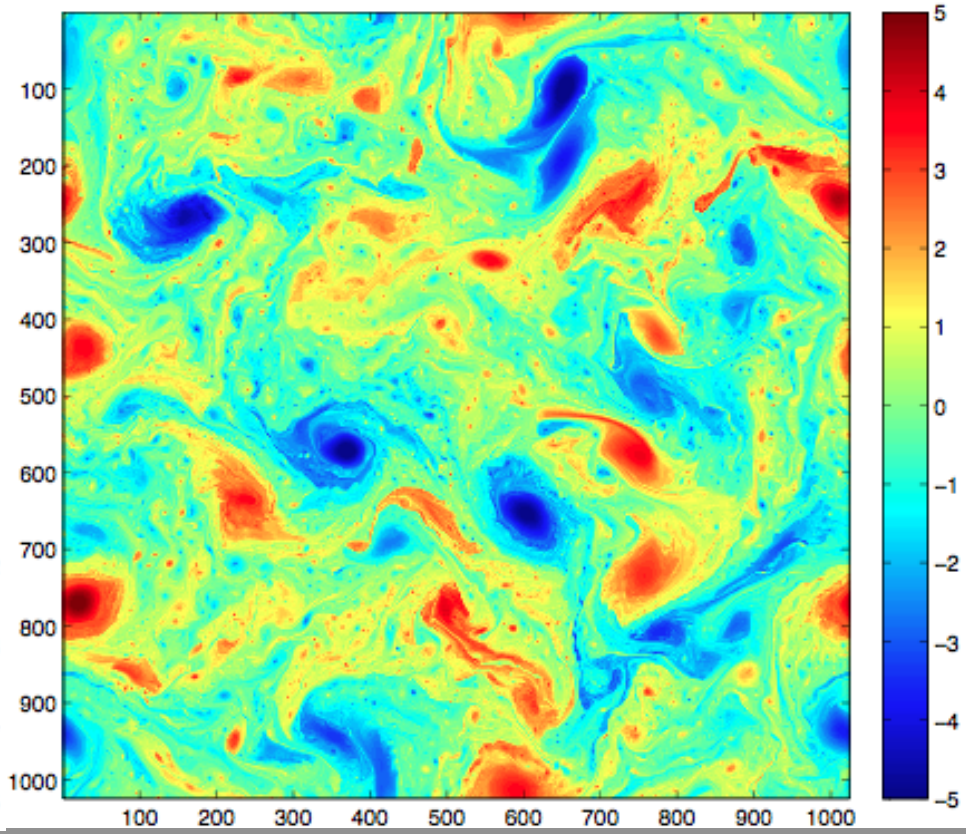
(interior) Quasi-Geostrophy	Surface Quasi-Geostrophy
Sea surface θ_S=constant	D/Dt θ_S=0
D/Dt q = 0	q = 0

θ_S surface temperature
q potential vorticity

Vorticity QG barotrope



Vorticity SQG

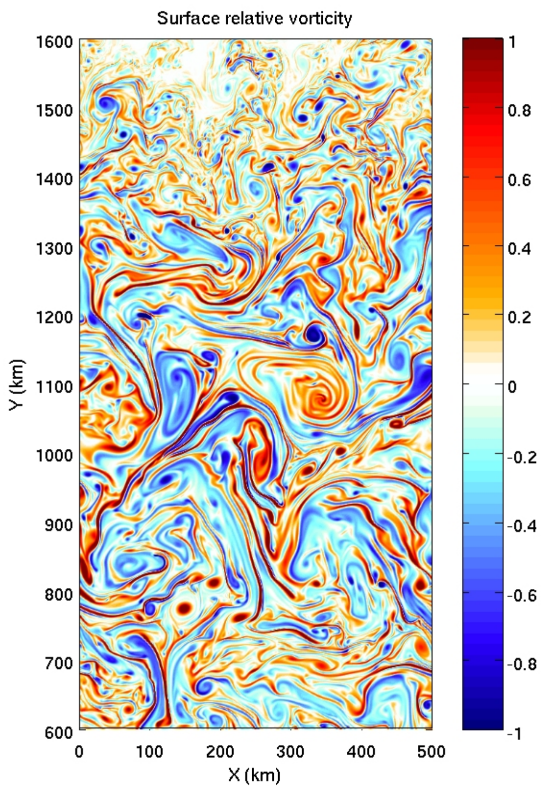


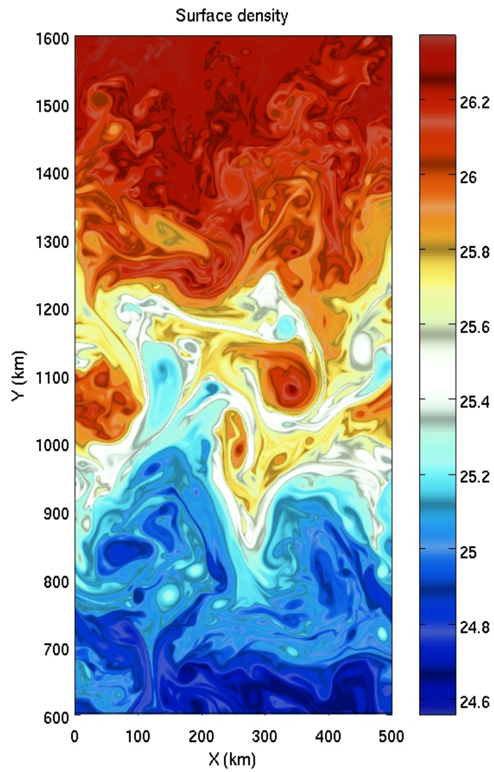
Lapeyre, pc, 2014

SQG ideas tested in high resolution primitive equations,

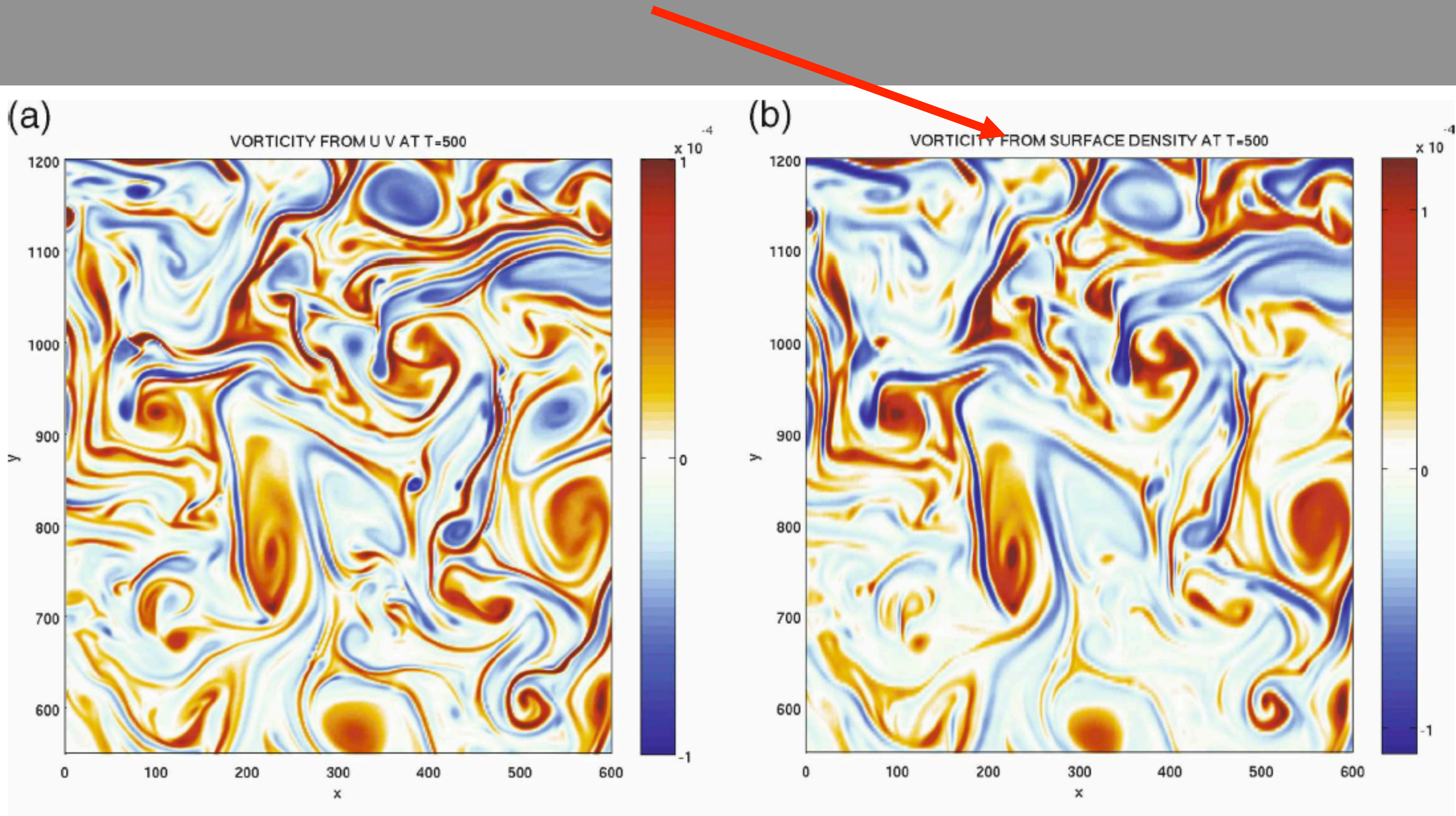
Klein, Hua, Lapeyre, Capet, LeGentil, Sasaki, JPO, 2008

Kinetic energy spectrum in k^{-2}

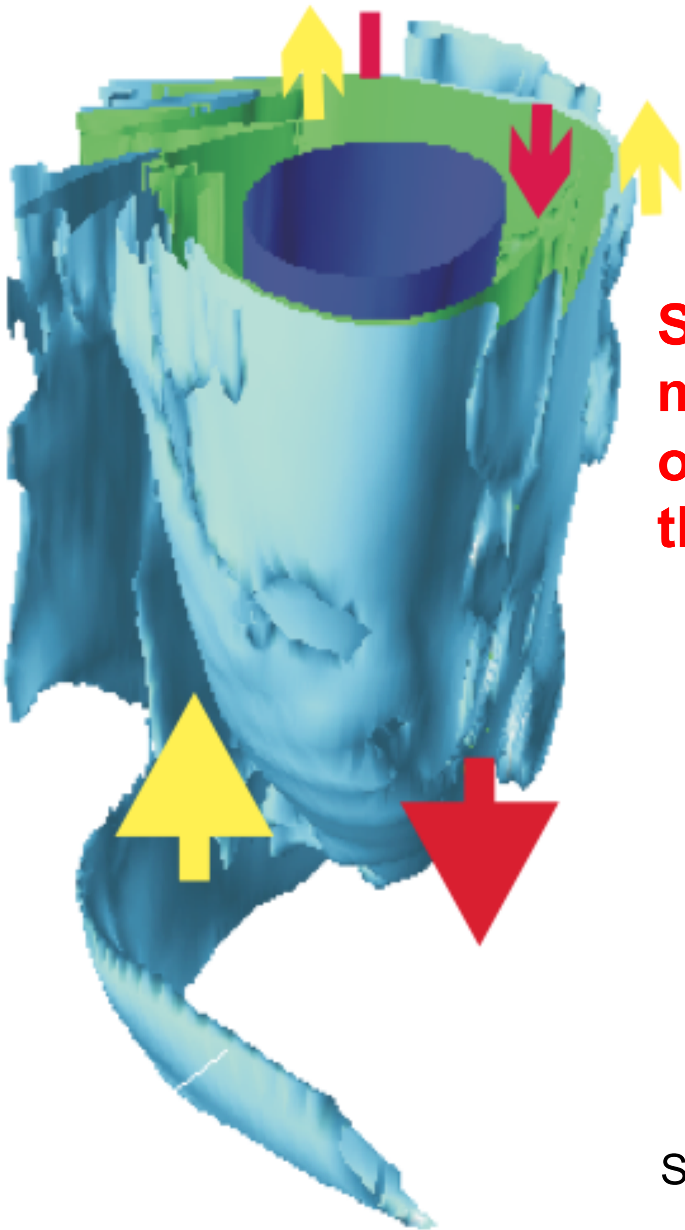




Vorticity recovered from surface density BC



Klein, Hua, Lapeyre, Capet, LeGentil, Sasaki, JPO, 2008



Strong vertical motions on the edges of the vortex

S. LeGentil, 2014

Part II Deep equatorial flows

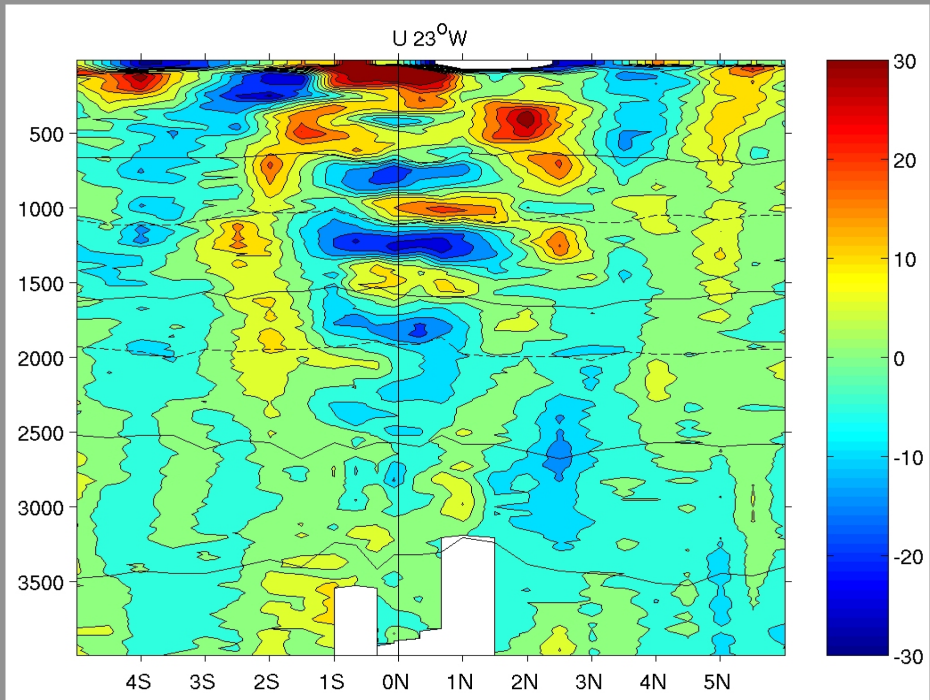
Destabilization of mixed Rossby gravity waves …

Hua, d' Orgeville, Fruman, Menesguen, Schopp, Klein, Sasaki, JFM,

2008

Oceanic Equatorial Deep jets:
East-West flows alternating with depth

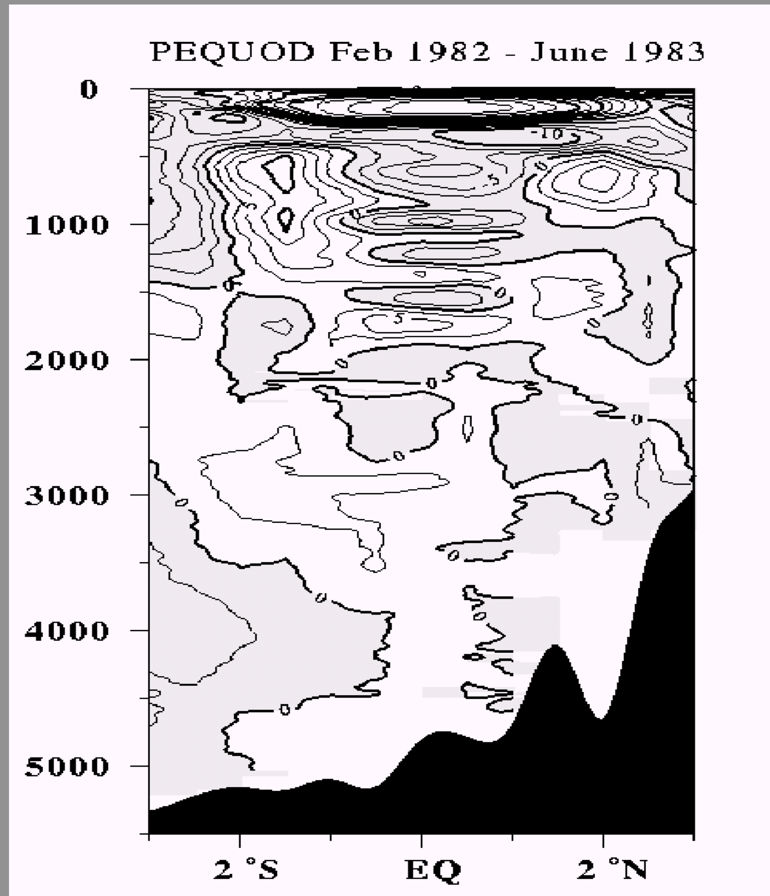
depth



latitude

Atlantic (instantaneous)

depth

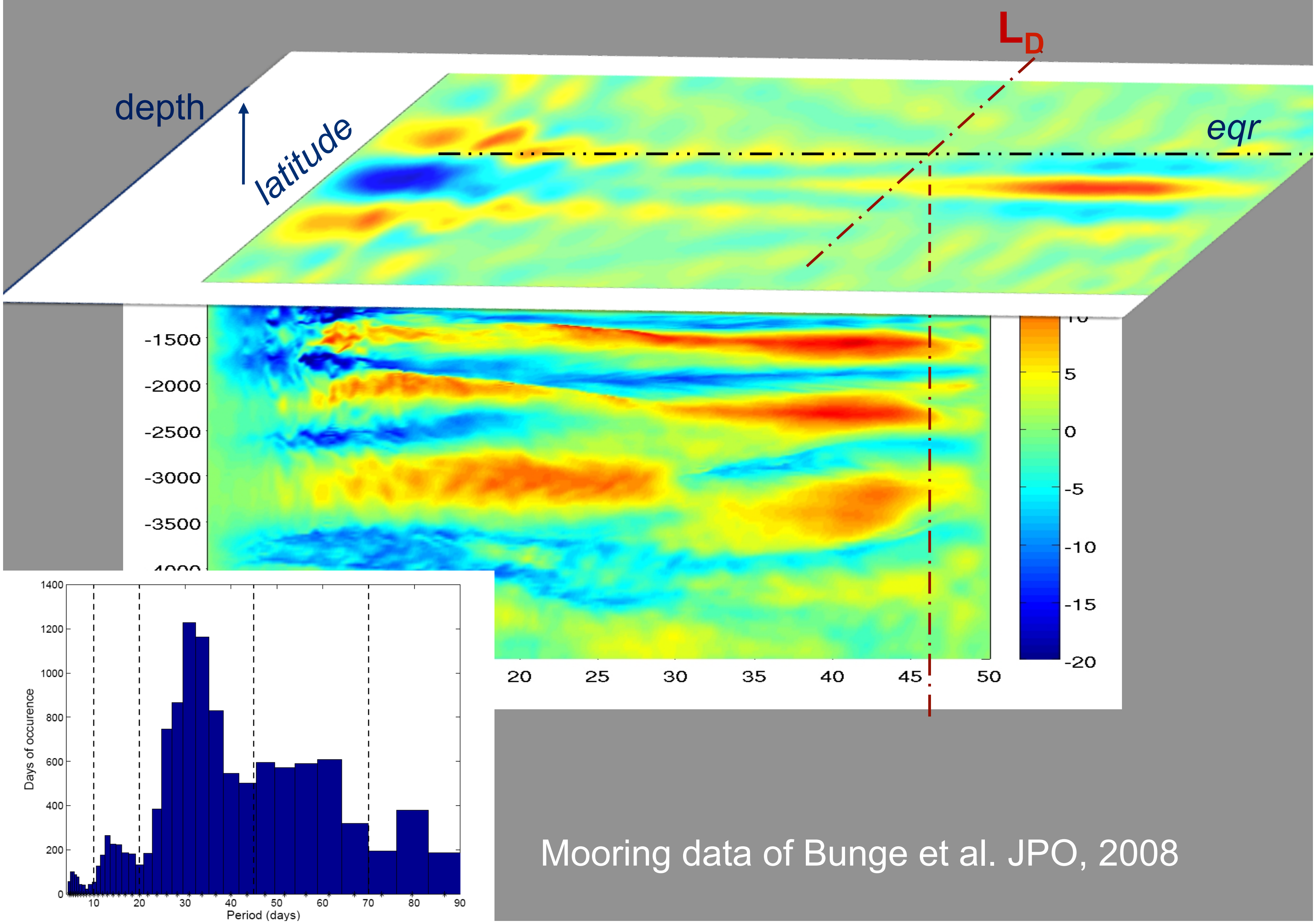


latitude

Pacific (temporal average)

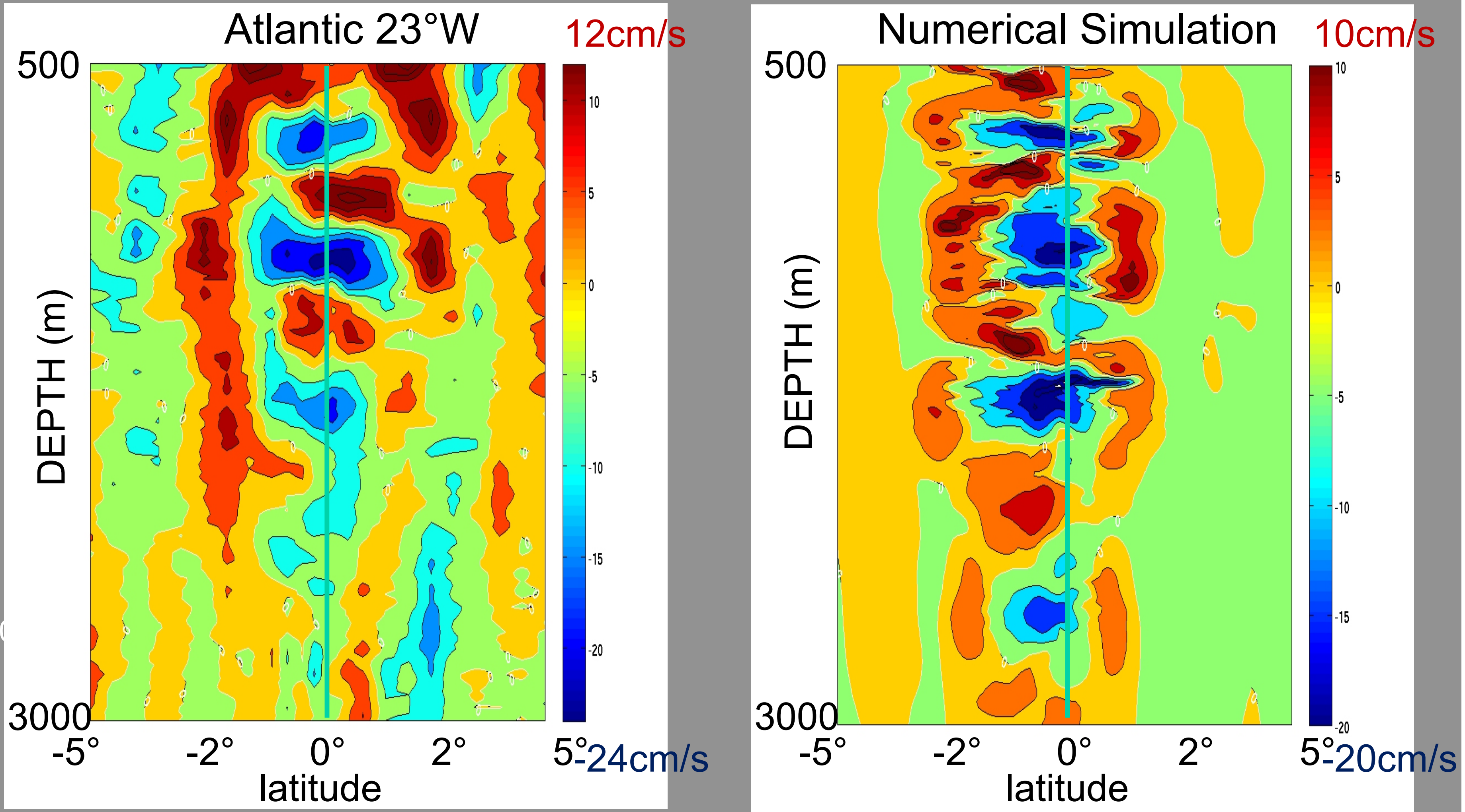
Gouriou et al , GRL,2001; Firing, JMR, 1987

Zonal velocity at the equator, C.Mesnesguen



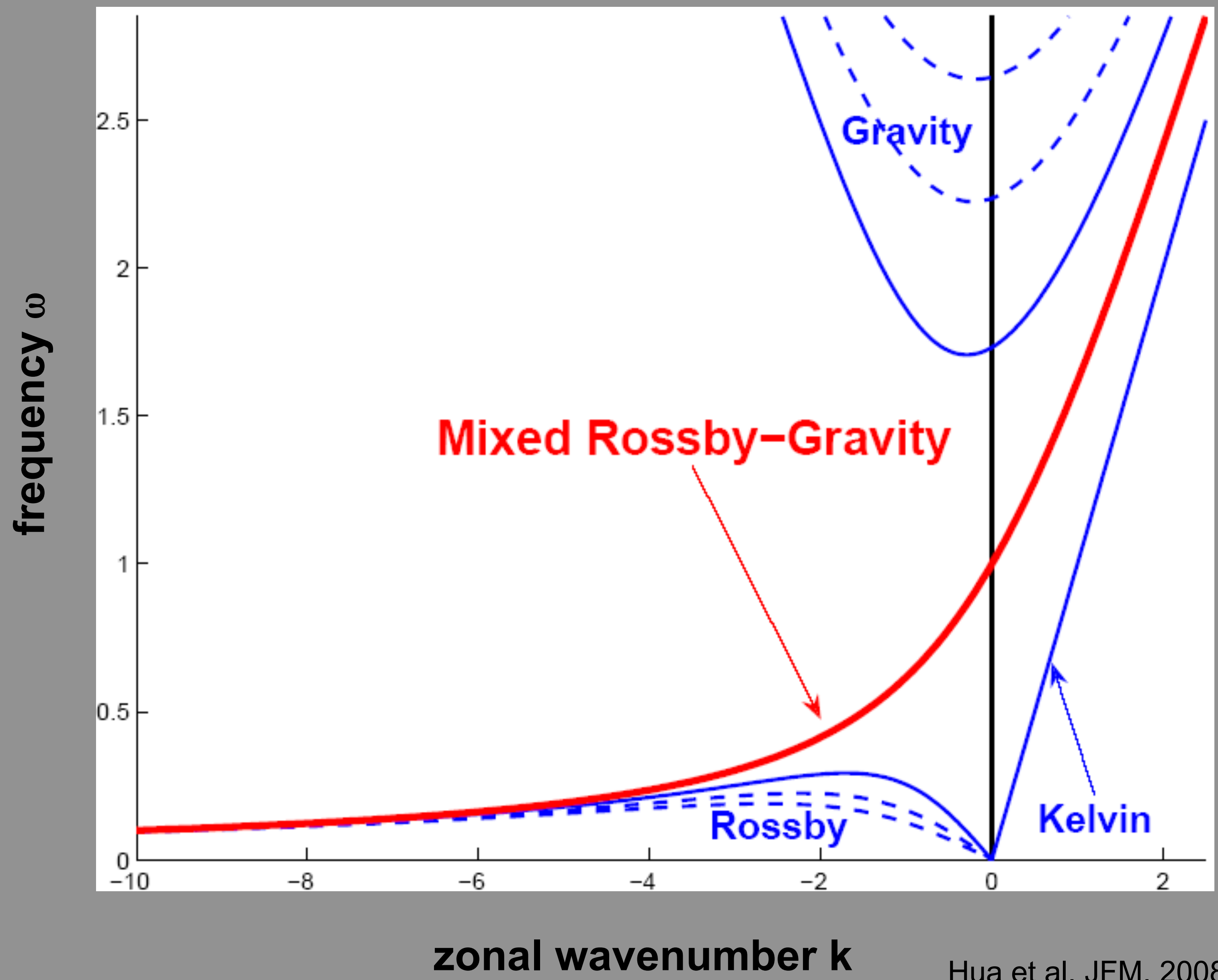
Mooring data of Bunge et al. JPO, 2008

Zonal velocity sections



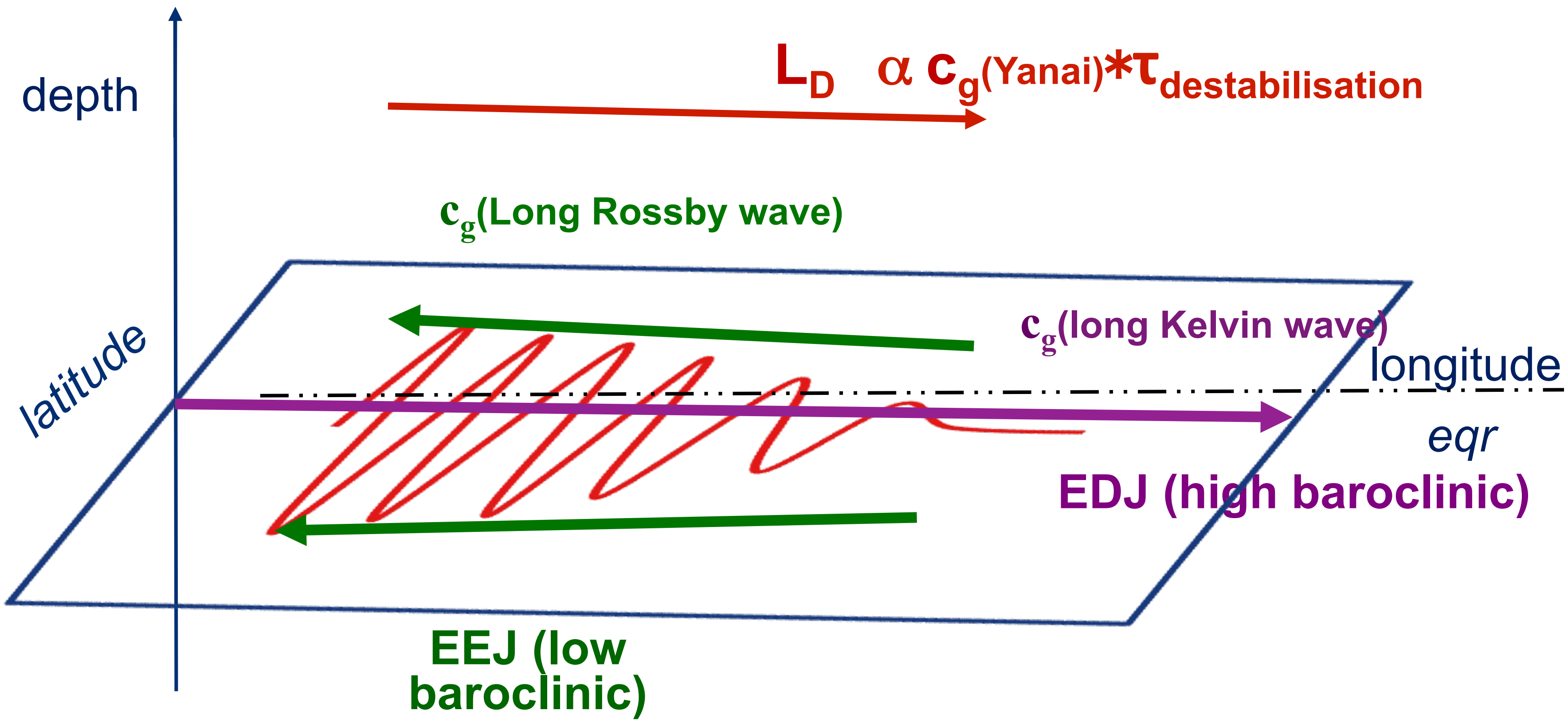
Menesguen et al, JMR, 2009

Equatorial dispersion relation



Hua et al, JFM, 2008

Zonal jets formation by equatorial meridional sheared waves



C. Menesguen, pc, 2014

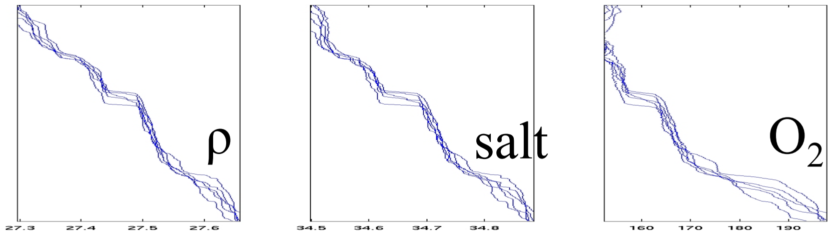
A GFD prediction

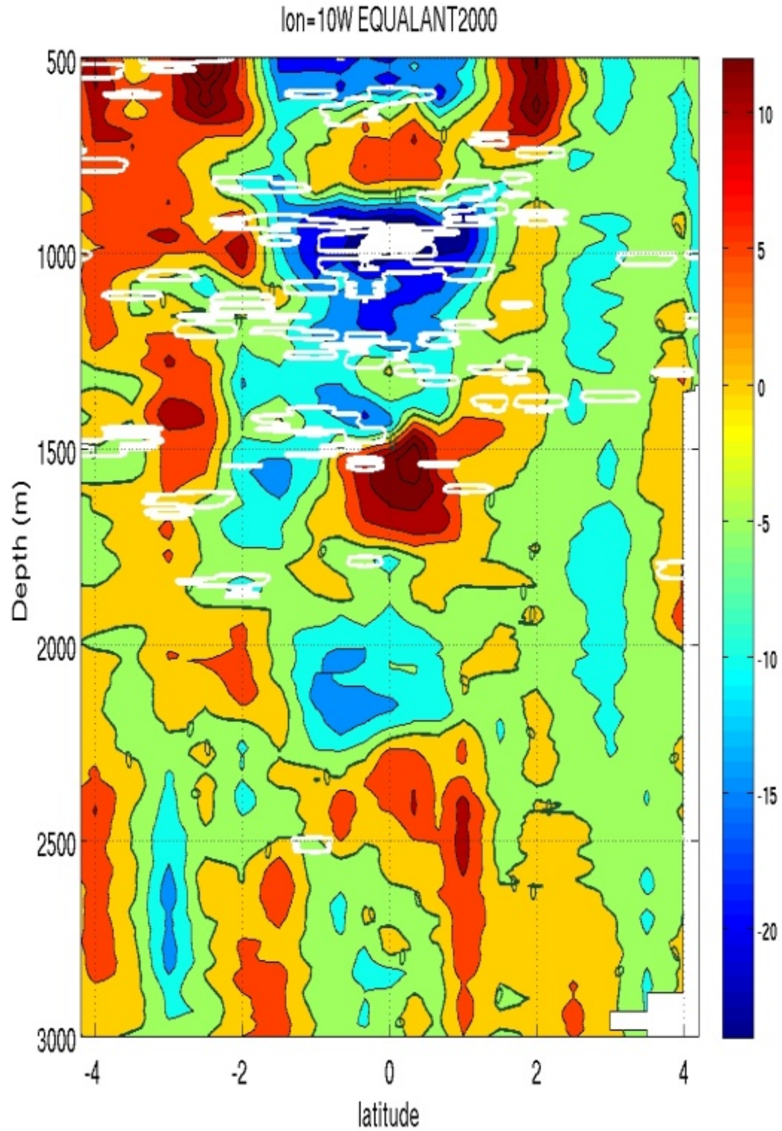
Vertical wave number m of equatorial deep jets and forcing period T

$$m \propto \beta N T^2$$

Hua et al, JFM, 2008

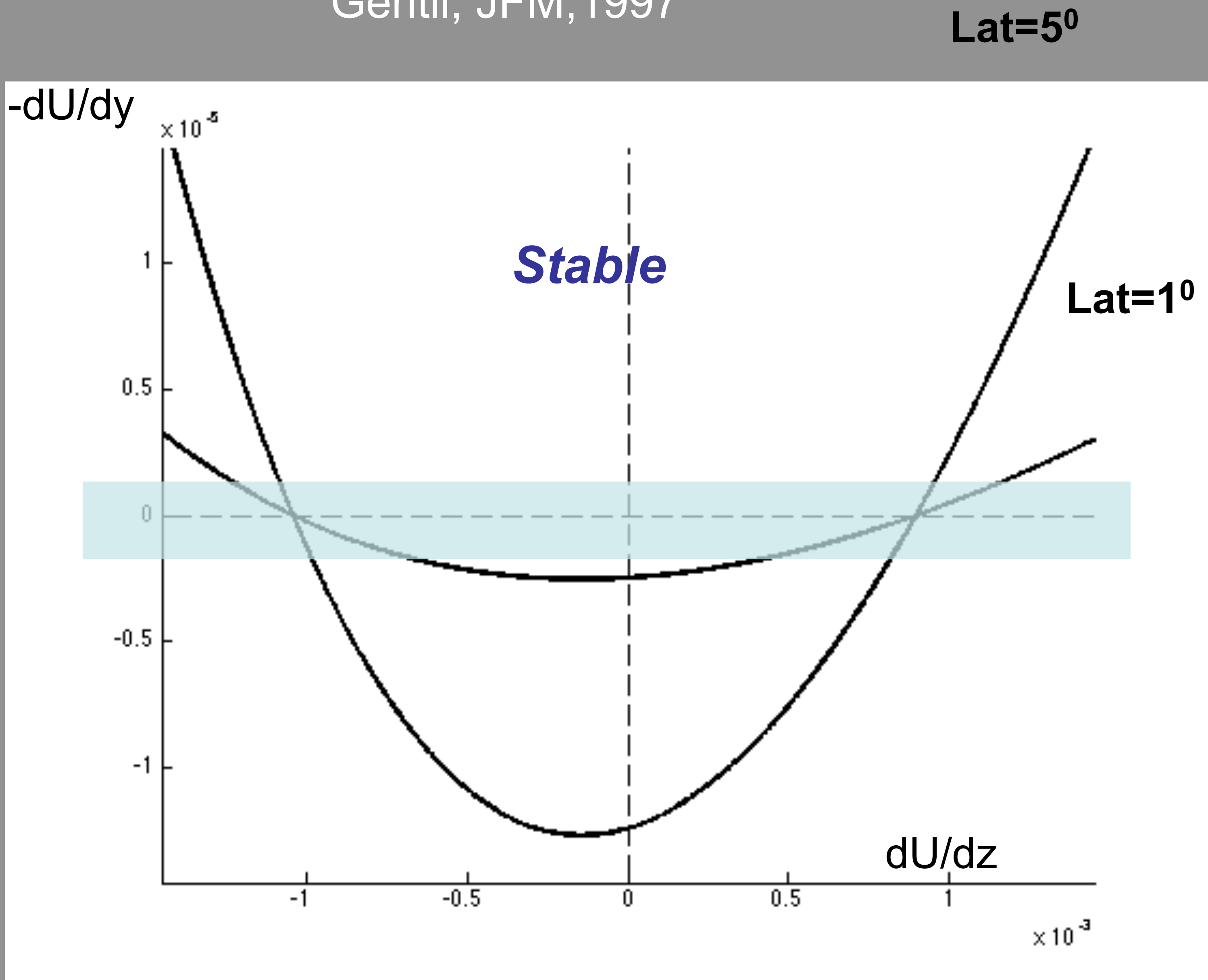
Layering



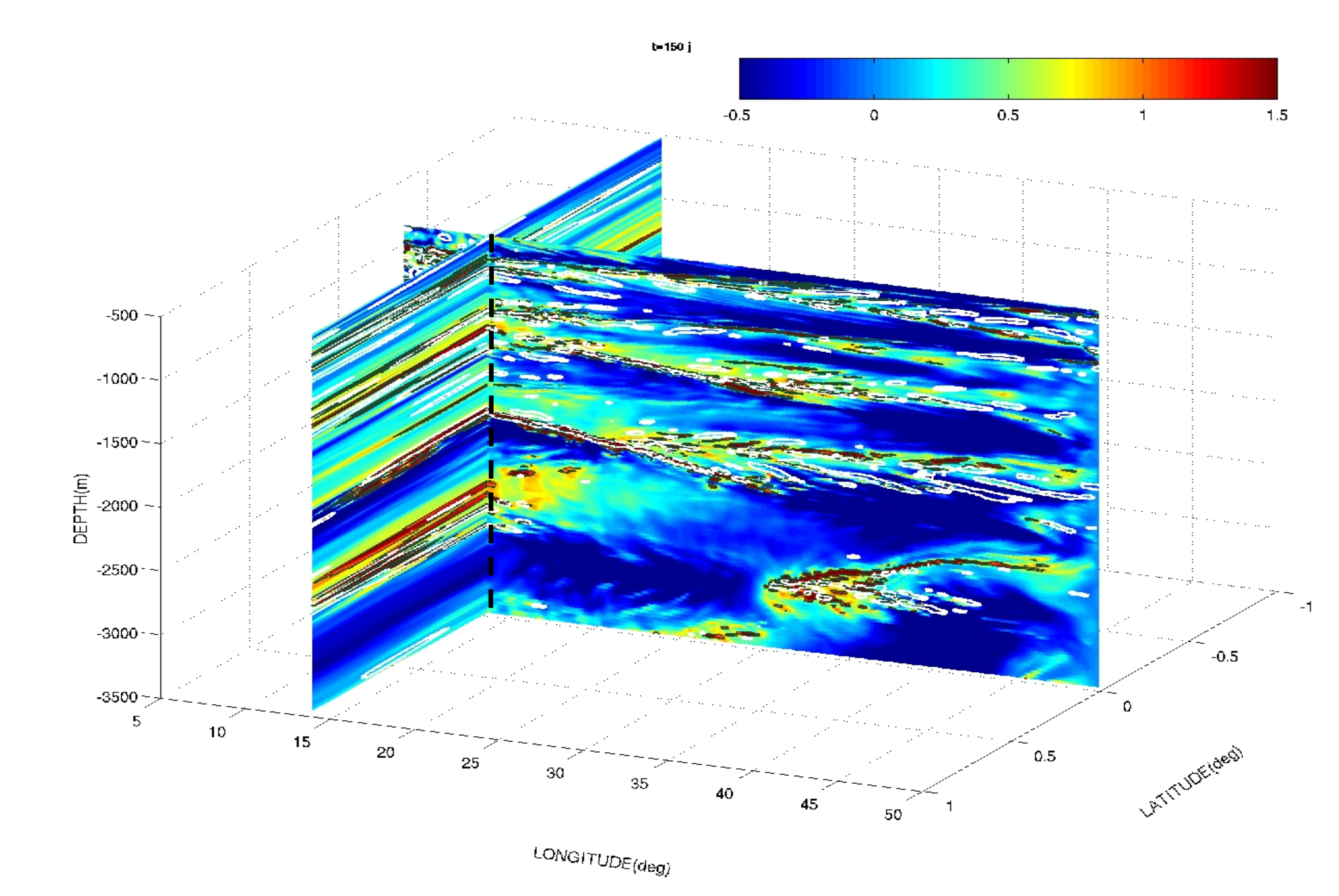


Menesguen et al, JMR, 2009

Symmetric instability from equations in Hua-Moore-Le Gentil, JFM,1997



Layering occurrence and inertial instability

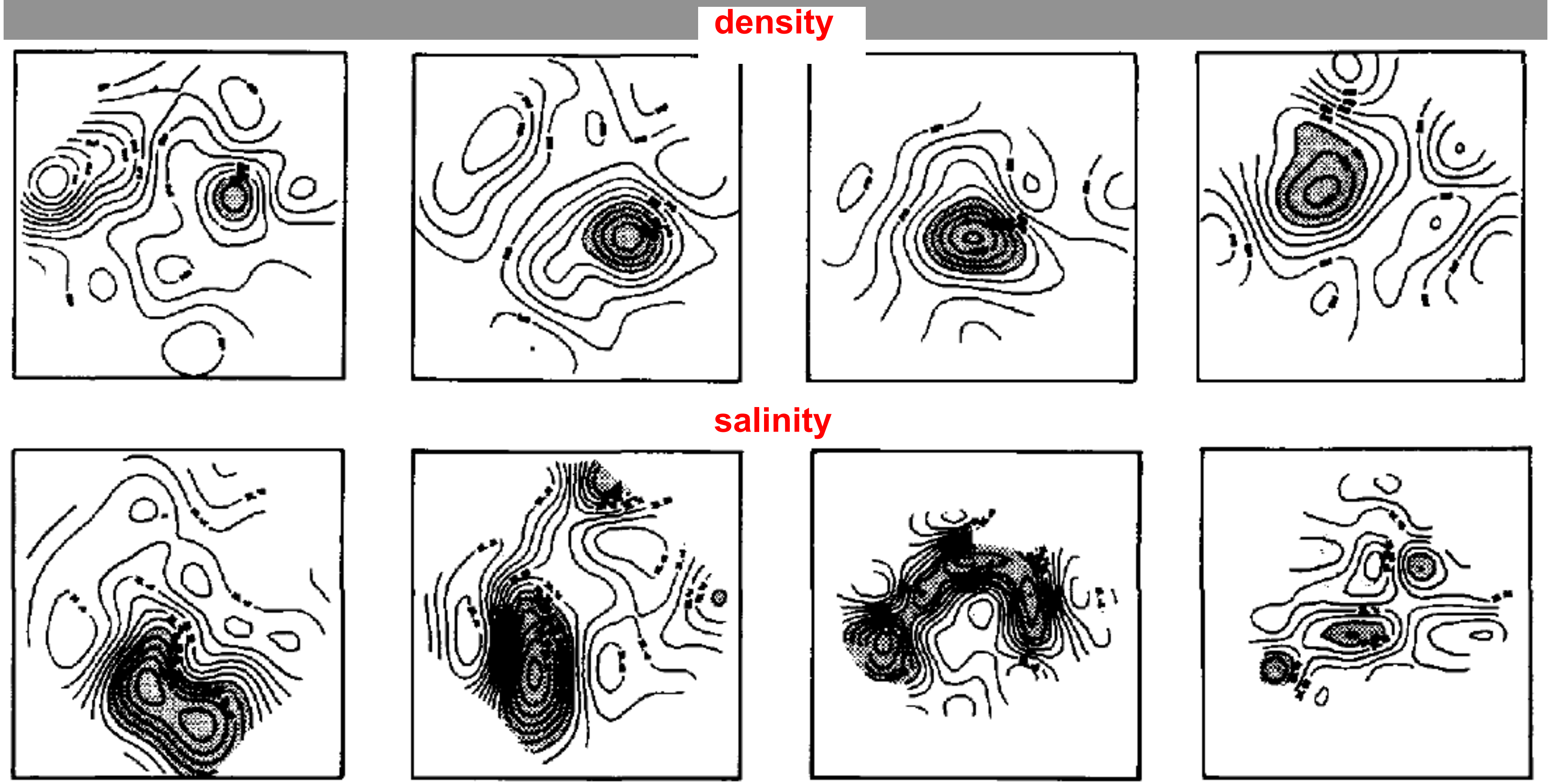


3D view of generalized Richardson number and layer contours

Menesguen et al, JMR, 2009

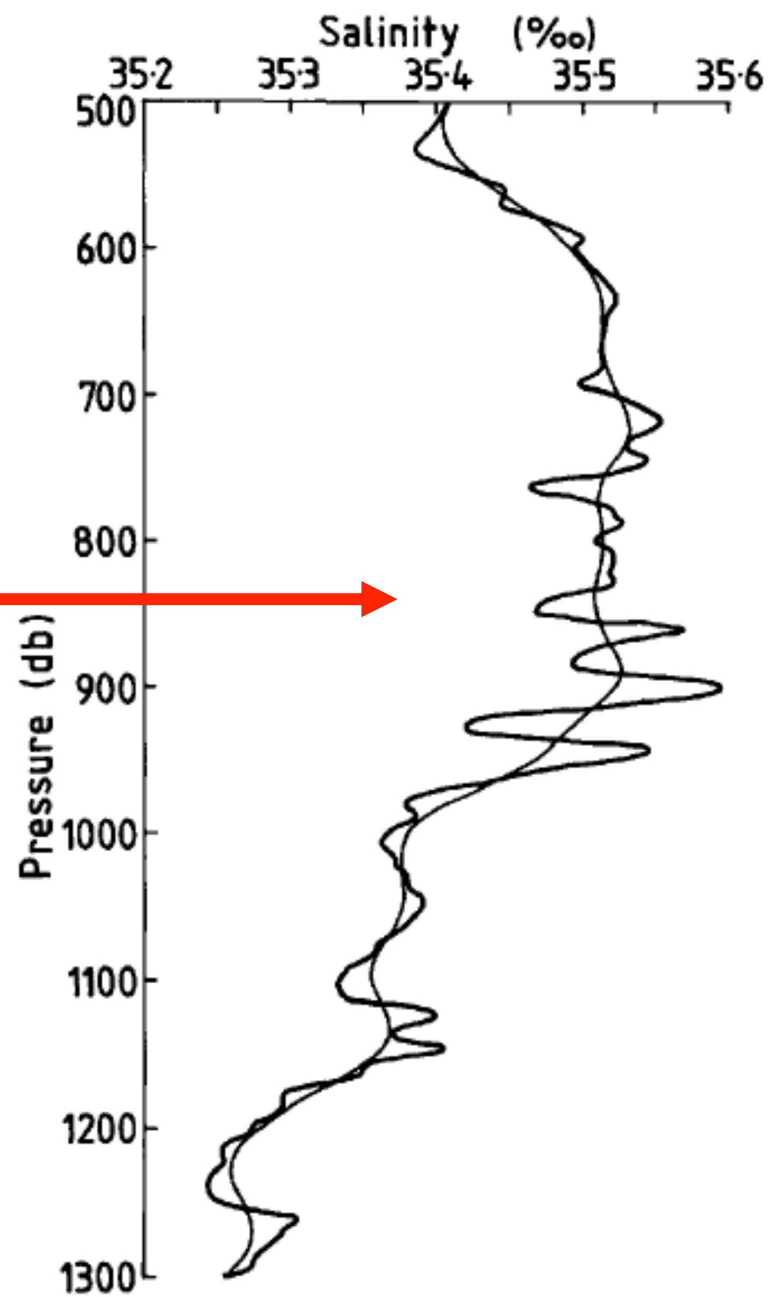
Part III
Thermohaline stirring by eddies

Thermohaline stirring by mesoscale eddies



Tourbillon experiment, Colin de Verdiere et al, JMR,1986

Salinity layers

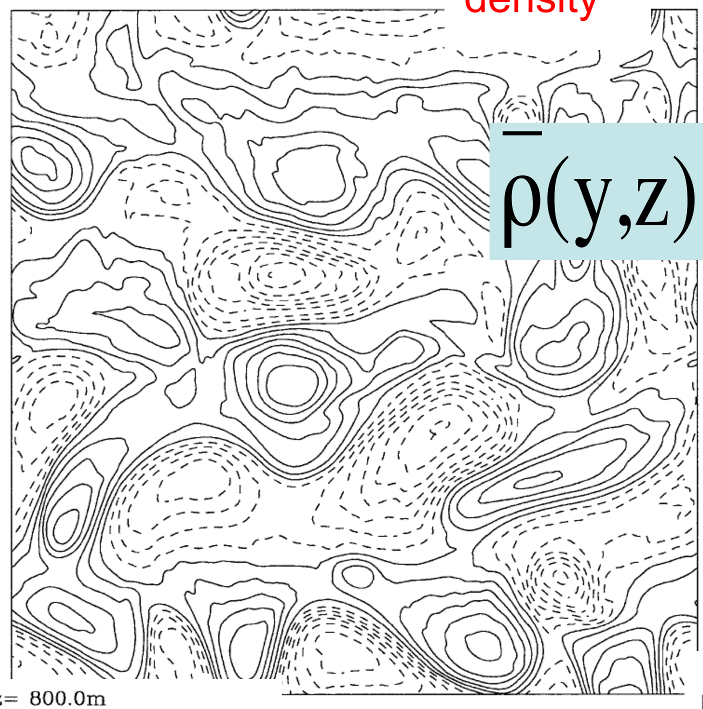


Thermohaline stirring in QG

Klein, Treguier, Hua, JMR, 1998

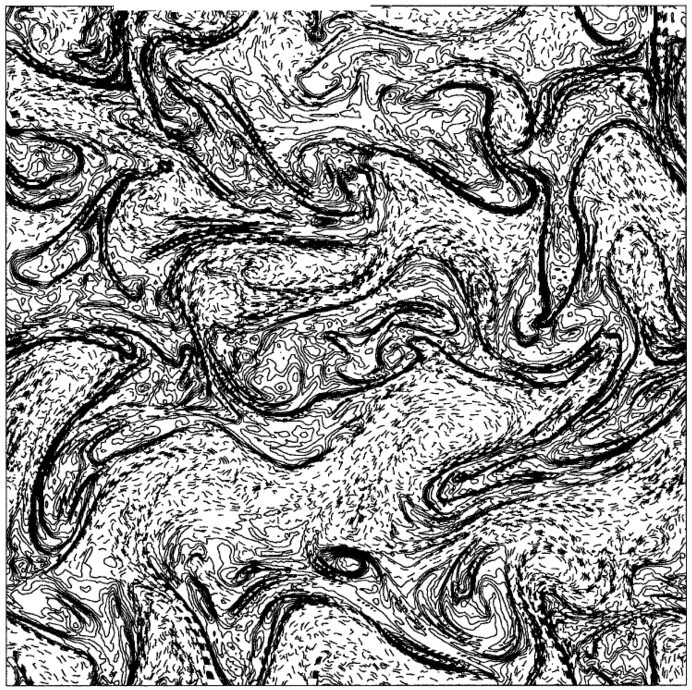
$$\bar{\rho}(y,z) = -\alpha\ \bar{T}(x,y)\ +\ \beta\ \bar{S}(z)$$

Density at z: density



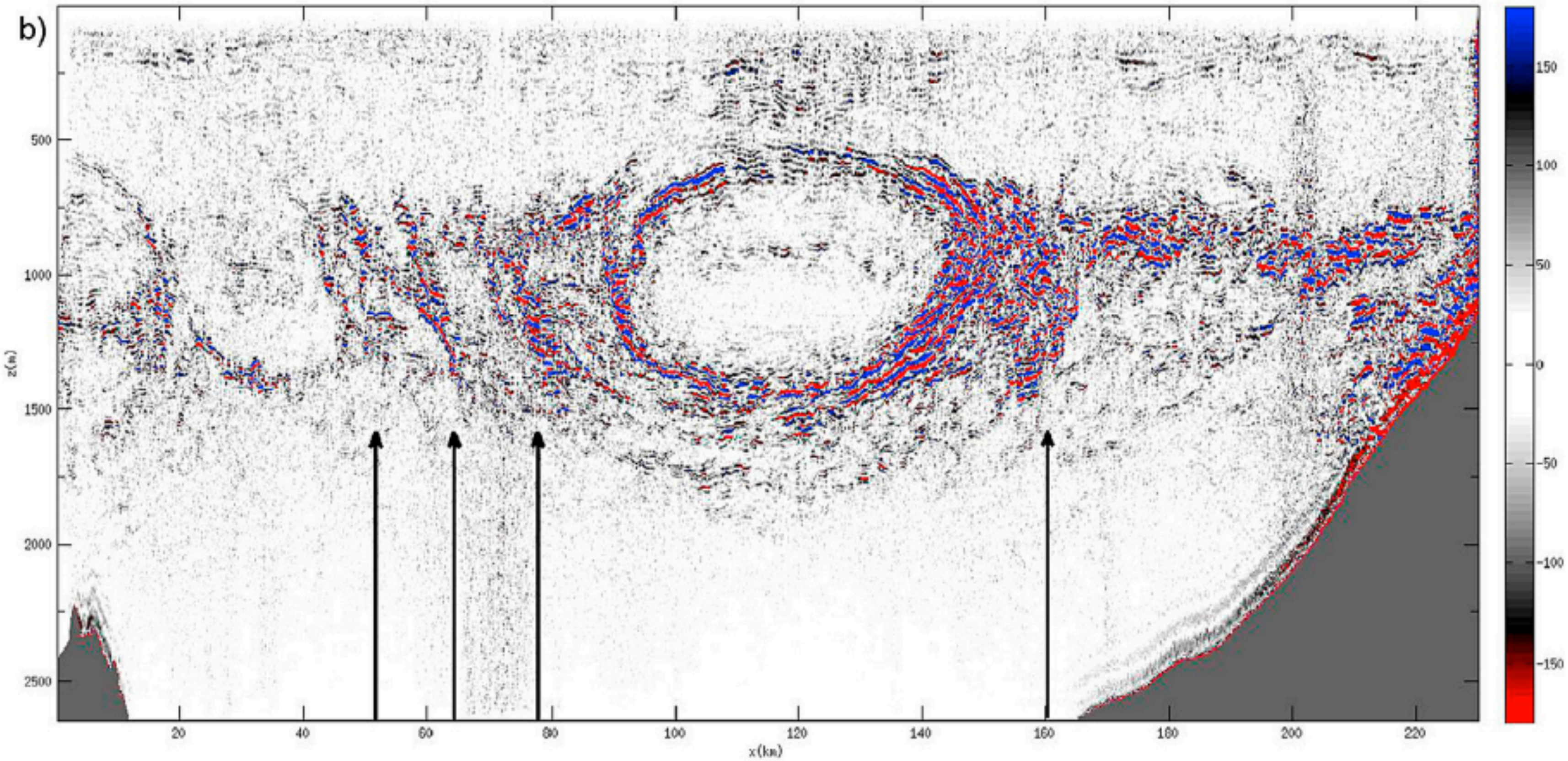
-α T

at z= 800.0m



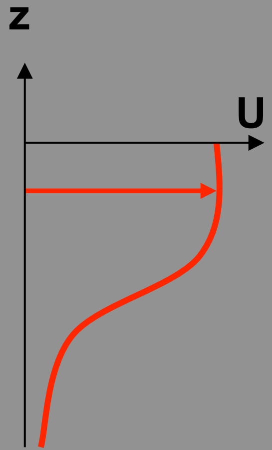
βS

Seismic image

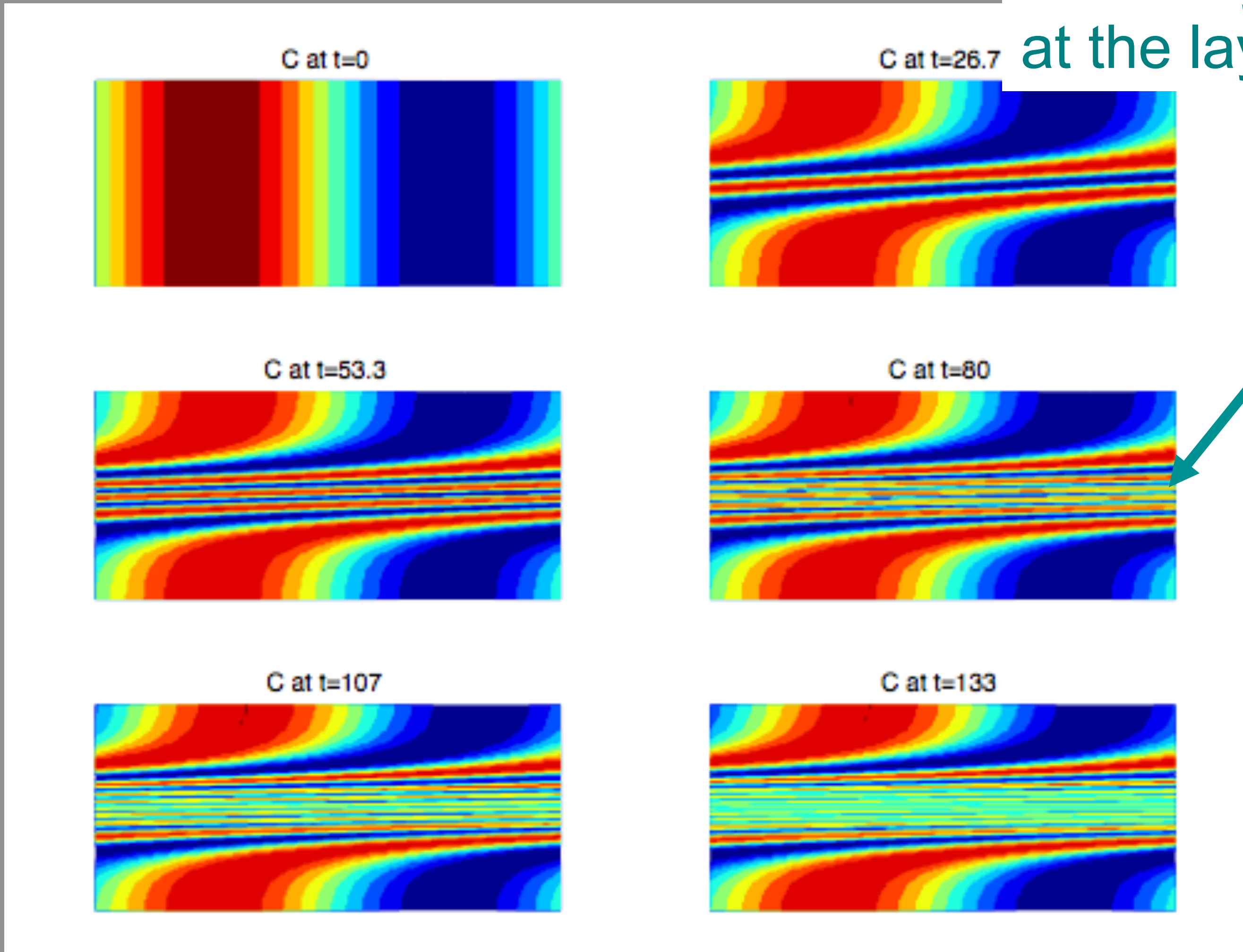


Menesguen-Hua et al GRL,2012

Stirring by the vertical shear of a Meddy



Which dynamics at the layer scale?



Perspective # 1: **modeling**

- Importance of resolving the small scales to get rid of uncertain parametrisations in numerical models.

- Can we get a physically realistic direct cascade of kinetic energy towards dissipation scales?

- Implications of eddy heat fluxes for climate models

Eddy heat transport and resolution?

(~10 km) *M. Lévy et al. / Ocean Modelling 34 (2010) 1–15* (~2km) 5

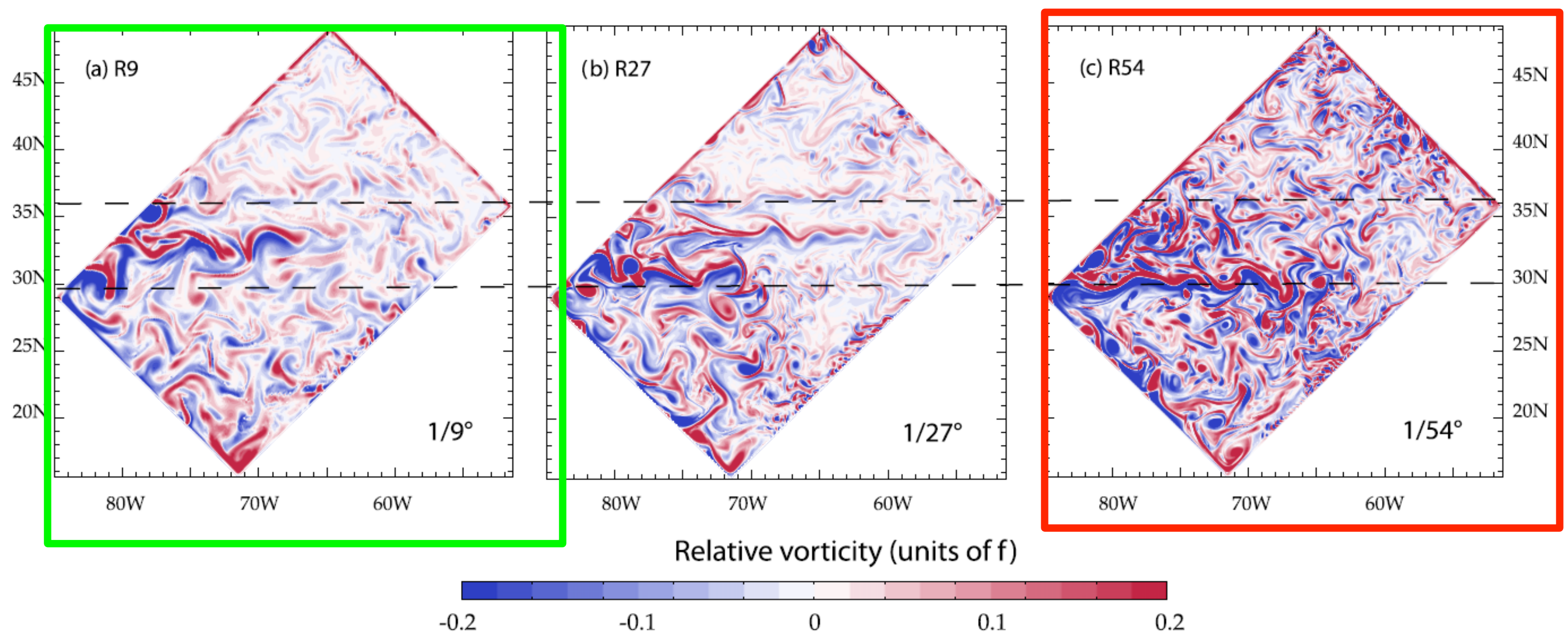


Fig. 3. Snapshot of relative vorticity at the surface of the model domain in experiments R9, R27 and R54. The color intervals are chosen to highlight the structures, but are not representative of the extremum values (see Table 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

(Levy et al., OM'10, '11)

Meridional heat transport

green curves:
~ 10 km

red curves:
~ 2 km

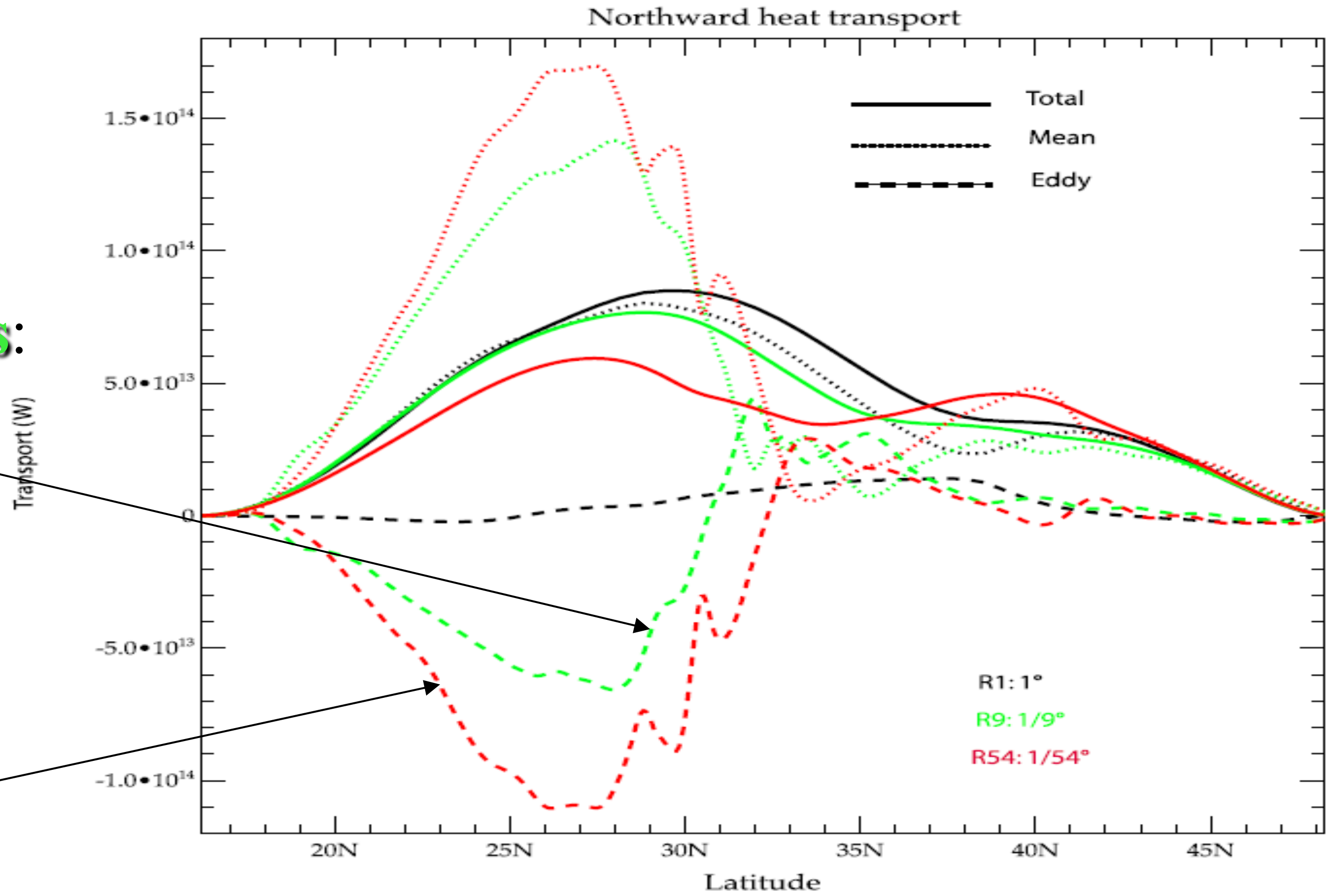


Fig. 12. One-year-mean northward heat transport (in W) in experiments R1 (black), R9 (green) and R54 (red). The plain line shows the "total" heat transport, comp the integration of 1 year-mean meridional heat fluxes. The dotted line shows the "mean" heat transport, computed from the 1 year-mean flow and 1 year-mean te distribution. The dashed line shows the "eddy" contribution, computed as the difference between the "total" and "mean" contributions. (For interpretation of the to color in this figure legend, the reader is referred to the web version of this paper.)

Impact of submesoscales to the total meridional heat transport can be up to 50% !

Perspective # 2: **Observations**

- Role of equatorial layering and the general circulation: is diapycnal mixing significant there?

- Origin of layering around eddies: inertial double diffusive…

- Need for new observations at smaller time and space scales?

Perspective # 3: **Theory**

- Importance of acceleration terms in stirring by fast evolving turbulence.
- Ideas on 3D stirring following the 2D Hua-Klein 1998 paper, the QG extension of Hua-McWilliams-Klein, 1998.

To summarize following Diderot

- « Nous avons trois moyens principaux; l'observation de la nature, la réflexion et l'expérience. L'observation recueille les faits, la réflexion les combine, l'expérience vérifie le résultat de la combinaison »

- « **recueillir** **et** **lier les faits** sont deux occupations bien pénibles; aussi les Philosophes les ont ils partagés entre eux »

Diderot, 1753, Pensées sur l'interprétation de la Nature

A possible origin for Lien ‘s choice of a GFD approach?

1979 RESEARCH VESSEL PROGRAMME

REPORT: RV CIROLANA: CRUISE 9

(Provisional: Not to be quoted without prior ref

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A Vangreishem — Centre Oceanographique de Bretagne (COB)
J-P Gouillou
L Hua, Museum National d'Histoire Naturelle, Paris.

DURATION:

Left Grimsby 0730 hours, 26 September
Arrived Immingham 0900 hours, 20 October
All times are GMT

LOCATION:

Within 30 miles of 46°59'N, 14°48'W, the centre of the Tourbillon moored current meter array.

Ideas, figures and comments given by

- B. Bourles
- X. Capet
- X. Carton
- P. Klein
- S. LeGentil
- G. Lapeyre
- G. Maze
- C. Menesguen
- M. Ollitrault
- R. Schopp
- R. Scott
- AM. Treguier