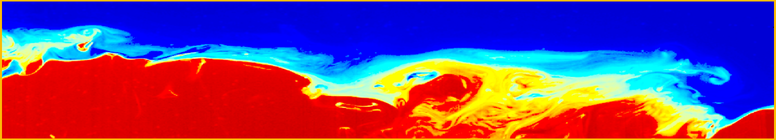
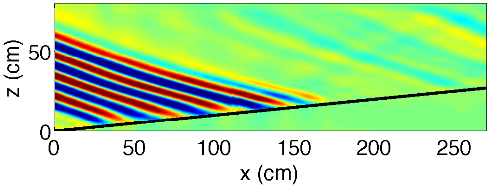
Length scales of stratified turbulence : new insight on Thorpe displacements statistics



L. Gostiaux, A. Delache, E. Horne, *LMFA, CNRS, EC Lyon, France*
H. van Haren, *NIOZ, Texel, The Netherlands*
A. Cimatoribus, *EPFL, Lausanne, Switzerland*
A. Venaille, *ENS de Lyon* - Joel Sommeria, *LEGI*

Emil Hopfinger Colloquium
11-13th May 2016, LEGI, Grenoble, France

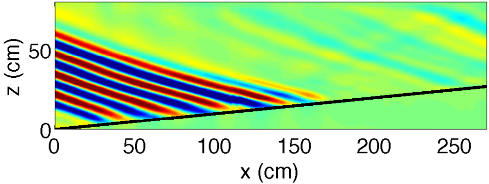
From linear internal waves to stratified turbulence



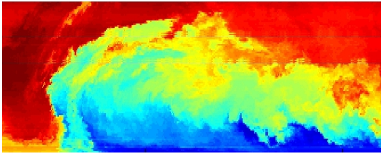
Plane waves emitted by a sinusoidal wave maker at the Coriolis Platform LEGI

T. Dauxois, J. Sommeria, C. Saquet, H. Didelle, S. Viboud

From linear internal waves to stratified turbulence

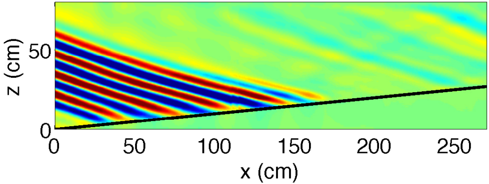


Plane waves emitted by a sinusoidal wave maker at the Coriolis Platform LEGI
T. Dauxois, J. Sommeria, C. Saquet, H. Didelle, S. Viboud

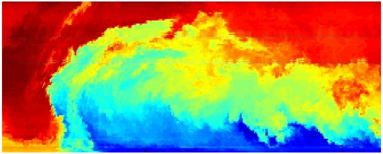


Internal wave breaking over a deep seamount, NIOZ
H. van Haren, A. Cimatoribus

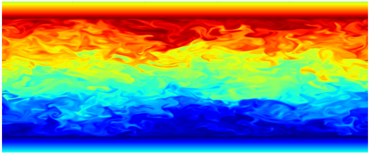
From linear internal waves to stratified turbulence



Plane waves emitted by a sinusoidal wave maker at the Coriolis Platform LEGI
T. Dauxois, J. Sommeria, C. Saquet, H. Didelle, S. Viboud



Internal wave breaking over a deep seamount, NIOZ
H. van Haren, A. Cimatoribus



Numerical stratified turbulence at LMFA
C. Cambon, F. Godeferd, A. Delache

From linear internal waves to stratified turbulence

2009 version of
Hopfinger and Toly experiment.

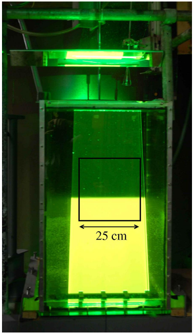
A. Venaille, J. Sommeria LEGI

From linear internal waves to stratified turbulence

2009 version of
Hopfinger and Toly experiment.

A. Venaille, J. Sommeria LEGI

- Dimension : $40 \times 40 \times 90$cm
- Grid : $L = 10cm$, 5Hz, 8cm amplitude
- Lower fluid : water + salt + rhodamine
- Upper fluid : water + ethanol
- $\Delta\rho$ =0.1, 0.3, 0.8 & 1.1%
- 1024×1024, 10Hz, $25 \times 25cm$



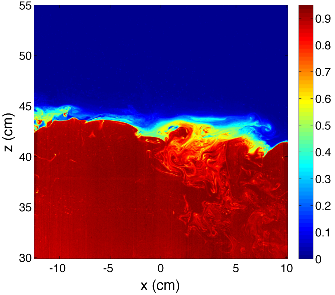
Hopfinger, E. J. & Toly, J.-A. Spatially decaying turbulence and its relation to mixing across density interfaces Journal of Fluid Mechanics, 1976, 78, 155-175

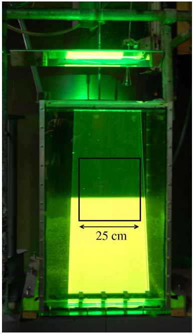
From linear internal waves to stratified turbulence

2009 version of

Hopfinger and Toly experiment.

A. Venaille, J. Sommeria LEGI



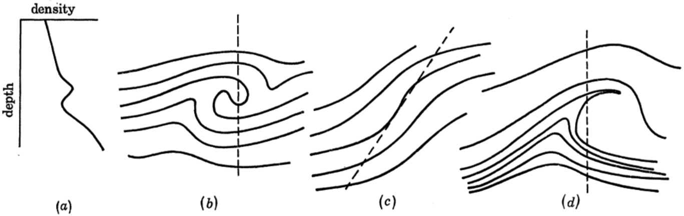


Hopfinger, E. J. & Toly, J.-A. Spatially decaying turbulence and its relation to mixing across density interfaces Journal of Fluid Mechanics, 1976, 78, 155-175

Thorpe scale mixing estimate

Thorpe 1977:

The presence of inversions may be used as a gauge of the vertical displacements which occur in the Loch.



Thorpe, S. A. Turbulence and Mixing in a Scottish Loch, Royal Society of London Philosophical Transactions Series A, 1977, 286, 125-181

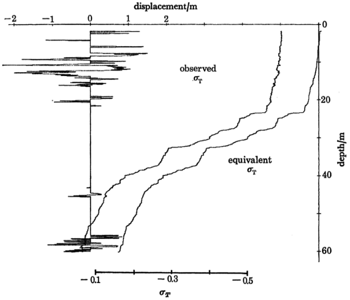
Thorpe scale mixing estimate

Re-ordering density profiles $\longrightarrow$ Thorpe displacement d.

Thorpe scale $L_T =< d^2 >^{1/2}$.
$<>$: vertical + successive profiles

In stably stratified regions, $d = 0$:
χ is the proportion of unstable fluid
(also named intermittency index)

Conditional Thorpe scale :
$L'_T =< d^2 >^{1/2} |d \neq 0$
$(L_T = \sqrt{\chi} L'_T)$

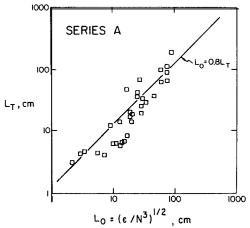


Thorpe, S. A. Turbulence and Mixing in a Scottish Loch, Royal Society of London Philosophical Transactions Series A, 1977, 286, 125-181

Oceanic Mixing recipies

Relating Thorpe scale to dissipation :

- Ozmidov Scale $L_o = \epsilon^{1/2} N^{-3/2}$
- Dillon, 1982 : $L_o = 0.8 L_T$
- Osborn 1980 : $k_z = \Gamma \epsilon / N^2$ ($\Gamma = 0.2$, mixing efficiency)



Dillon, 1982

Turbulent dissipation rate $\epsilon = 0.64 L_T^2 N^3$
Turbulent diffusivity $k_z = 0.128 L_T^2 N$

Ozmidov, R. On turbulent exchange in stable stratified ocean Izvestia Acad. Sci. USSR, Atmosphere and Ocean Physics, 1965, 8
Dillon, T. M. Vertical Overturns: A Comparison of Thorpe and Ozmidov Length Scales J. Geophys. Res., AGU, 1982, 87, 9601-9613
Osborn, T. Estimates of the local rate of vertical diffusion from dissipation measurements J. Phys. Oceanogr., 1980, 10, 83-89

On the definition of Thorpe displacement

Thorpe 77 :

"The vertical displacements are the minimum distances which fluid particles need to be moved **from the observed profile** *to produce the synthetic stable profile"*

$$\sigma(z_i) \rightarrow \sigma_s(z_i)$$

$$\sigma(z_i) = \sigma_s(z_i + d_i)$$

On the definition of Thorpe displacement

Thorpe 77 :

"The vertical displacements are the minimum distances which fluid particles need to be moved **from the observed profile** *to produce the synthetic stable profile"*

$$\sigma(z_i) \rightarrow \sigma_s(z_i)$$

$$\sigma(z_i) = \sigma_s(z_i + d_i)$$

The **inverted** *vertical displacements are the distances which fluid particles need to be moved from the synthetic stable profile* **to produce the observed profile**

$$\sigma(z_i + d_i^*) = \sigma_s(z_i)$$

On the definition of Thorpe displacement

Thorpe 77 :
"The vertical displacements are the minimum distances which fluid particles need to be moved **from the observed profile** *to produce the synthetic stable profile"*

$$\sigma(z_i) \to \sigma_s(z_i)$$

$$\sigma(z_i) = \sigma_s(z_i + d_i)$$

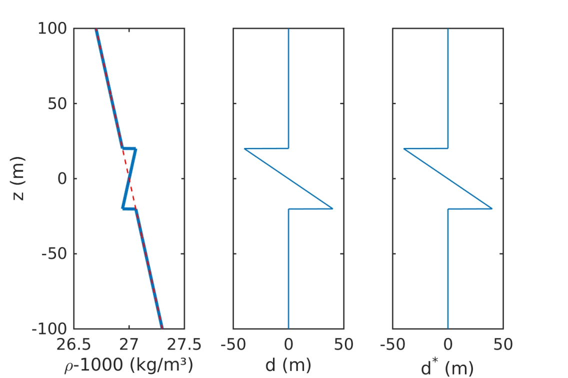
The **inverted** *vertical displacements are the distances which fluid particles need to be moved from the synthetic stable profile* **to produce the observed profile**

$$\sigma(z_i + d_i^*) = \sigma_s(z_i)$$

$d_i^* = -d_{p(i)}$ where p is a permutation operator

Direct and inverted Thorpe displacements

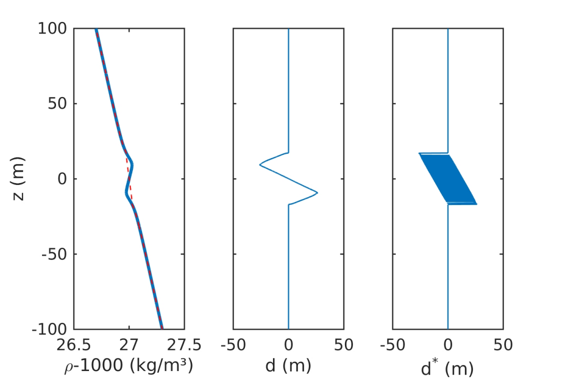
Case 1 : solid body rotation



In this case, $d_i^* = -d_{p(i)} = d_i$

Direct and inverted Thorpe displacements

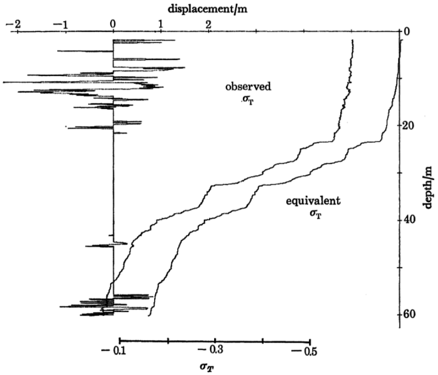
Case 2 : Rankine vortex



In this case, $d^*(z)$ is discontinuous

Direct and inverted displacements in the litterature

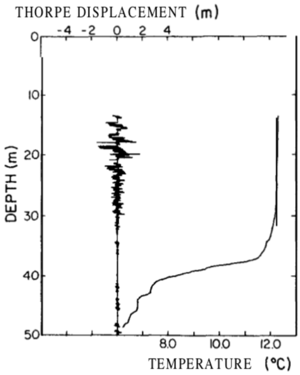
$L_T = < d^2 >^{1/2}$.
Thorpe, 1977



Thorpe, S. A. Turbulence and Mixing in a Scottish Loch, Royal Society of London Philosophical Transactions Series A, 1977, 286, 125-181

Direct and inverted displacements in the litterature

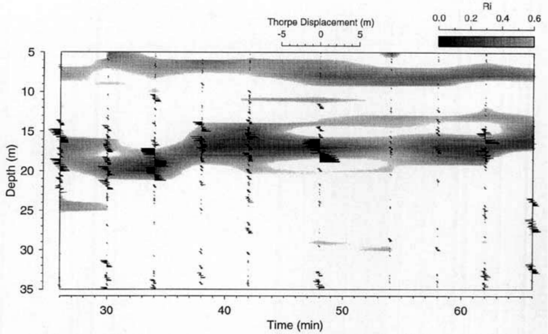
Thorpe scale
$L_T =< (-d^*)^2 >^{1/2}$.
Dillon, 1982



Dillon, T. M. Vertical Overturns: A Comparison of Thorpe and Ozmidov Length Scales J. Geophys. Res., AGU, 1982, 87, 9601-9613

Direct and inverted displacements in the litterature

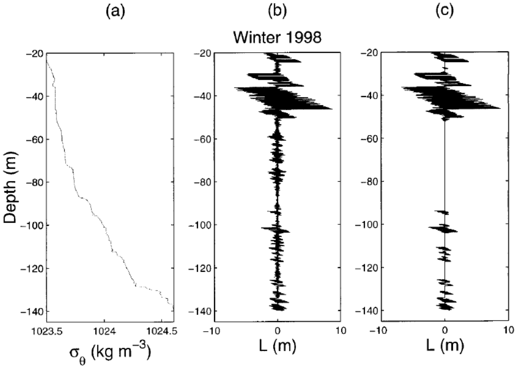
Thorpe scale
$L_T = < (-d^*)^2 >^{1/2}$.
Galbraith & Kelly, 1996



Galbraith, P. S. & Kelley, D. E. Identifying overturns in CTD profiles Journal of Physical Oceanography, 1996, 13, 688-702

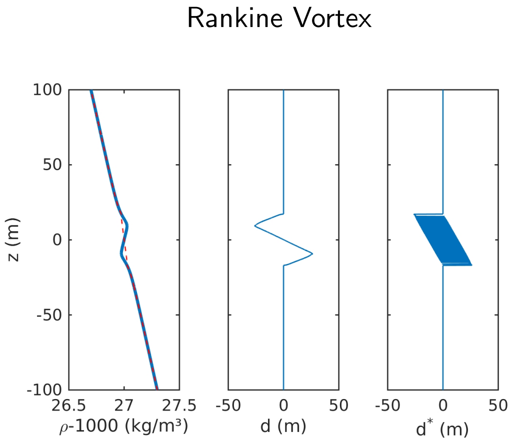
Direct and inverted displacements in the litterature

Thorpe scale
$L_T = <(d^*)^2>^{1/2}$.
Stansfield et al. 2004

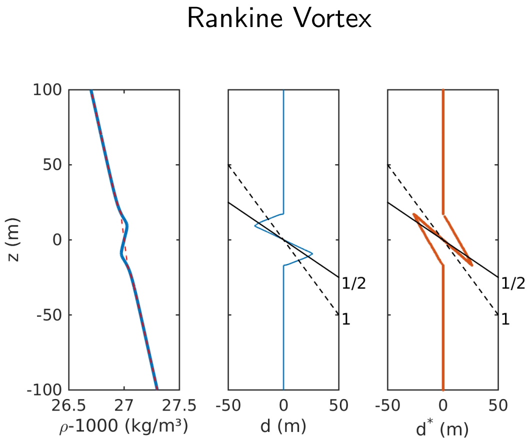


Stansfield, K.; Garrett, C. & Dewey, R. The Probability Distribution of the Thorpe Displacement within Overturns in Juan de Fuca Strait J. Phys. Oceanogr., Journal of Physical Oceanography, American Meteorological Society, 2001, 31, 3421-3434

The signature of the overturn in d^* profiles

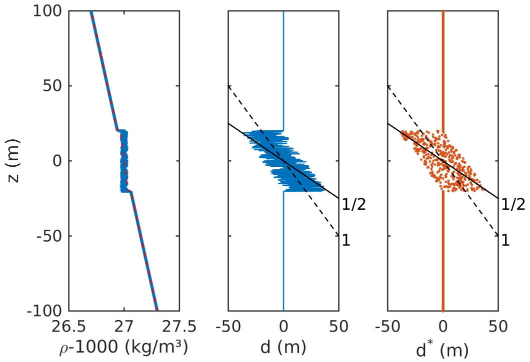


The signature of the overturn in d^* profiles

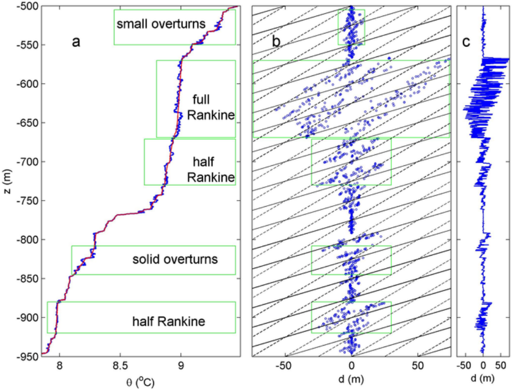


The signature of the overturn in d^* profiles

Mixed patch



Distinguishing overturns on in situ data

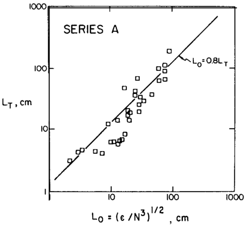


van Haren, H. & Gostiaux, L. Characterizing turbulent overturns in CTD-data Dynamics of Atmospheres and Oceans , 2014, 66, 58 - 76

Oceanic Mixing recipies

Relating Thorpe scale to dissipation :

- Ozmidov Scale $L_o = \epsilon^{1/2} N^{-3/2}$
- Dillon, 1982 : $L_o = 0.8 L_T$
- Osborn 1980 : $k_z = \Gamma \epsilon / N^2$
  ($\Gamma = 0.2$, mixing efficiency)



Dillon, 1982

Turbulent dissipation rate $\epsilon = 0.64 L_T^2 N^3$
Turbulent diffusivity $k_z = 0.128 L_T^2 N$

Ozmidov, R. On turbulent exchange in stable stratified ocean Izvestia Acad. Sci. USSR, Atmosphere and Ocean Physics, 1965, 8

Dillon, T. M. Vertical Overturns: A Comparison of Thorpe and Ozmidov Length Scales J. Geophys. Res., AGU, 1982, 87, 9601-9613

Osborn, T. Estimates of the local rate of vertical diffusion from dissipation measurements J. Phys. Oceanogr., 1980, 10, 83-89

Searching for mixing places

Importance of boundaries

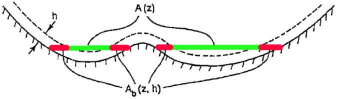


Fig. 1. Schematic of an ocean basin with a bottom boundary layer of thickness h. $A_b(z,h)$ is the horizontal area at depth z that is within the boundary layer, and $A(z)$ is the interior area at this depth.

$$K_{Vb} = K_V A(z)/A_b(z,h) \quad (45)$$

$$K_{Vb} = K_V A(z)\delta z[A_b(z,\delta z)h]^{-1} \quad (46)$$

Armi [1979*a*] cites values of about 3×10^{-4} for $A_b(z,\delta z)/A(z)\delta z$ for the abyssal ocean, so for $K_V = 10^{-4}$ m^2 s^{-1} and, say, $h = 100$ m we require $K_{Vb} = 3 \times 10^{-3}$ m^2 s^{-1}. Taking this value for κ_e and ν_e, $N = 10^{-3}$ s^{-1}, $\sin\theta = 0.1$, and $f = 10^{-4}$ s^{-1} in (3.3) gives $q = 0.15$ and $qh = 15$. On the basis of this estimate, it seems that the near-boundary mixing that might be caused by internal wave breaking is effective in that the stratification is continually restored by the secondary circulation. Taking a

Armi, L. Some evidence for boundary mixing in the deep Ocean Journal of Geophysical Research: Oceans, 1978, 83, 1971-1979
Garrett, C. The role of secondary circulation in boundary mixing Journal of Geophysical Research, 1990, 95, 3181-3188

The NIOZ High Sampling-Rate Thermistors

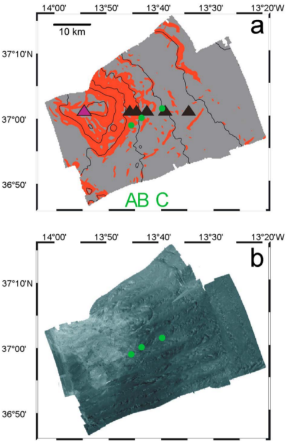
NIOZ-HST thermistors

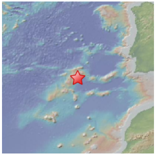
- Autonomous sensors (energy and data storage)
- Synchronized 1Hz temperature aquisition
- 1mK relative accuracy
- Duration more than one year
- Deployment depth 6000m

H. van Haren, M. Laan, D.-J. Buijsman, L. Gostiaux, M.G. Smit and E. Keijzer, NIOZ3: independent temperature sensors sampling yearlong data at a rate of 1 Hz, IEEE J. Ocean. Eng., 34, 315-322 (2009).

Hans van Haren, NIOZ, The Netherlands

Measurements at Josephine Seamount

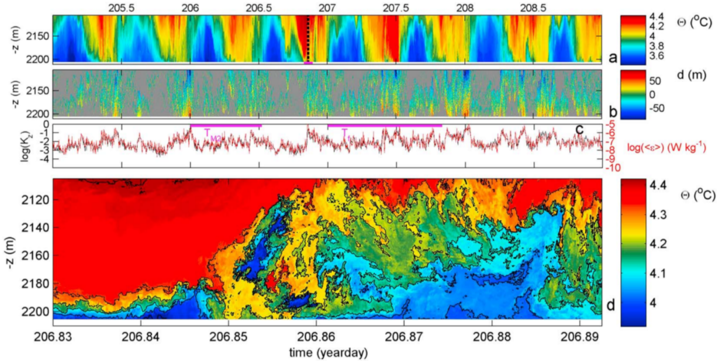




- Deep Atlantic Ocean seamount (submit at 2000m)
- Supercritical to subcritical for M2 tide
- Mooring line with 100 sensors each, 1m vertical resolution, 3 months at 1Hz
- Three different locations (supercritical to subcritical)

Measurements at Josephine Seamount

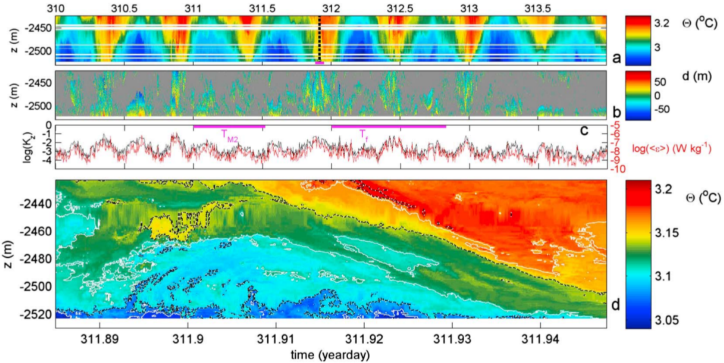
Mooring A, 2210m, $N = 1.4\,10^{-3}$rad/s



H. van Haren, A. Cimatoribus and L. Gostiaux, Where large deep-ocean waves break, Geophysical Research Letters, GL063329, 2015

Measurements at Josephine Seamount

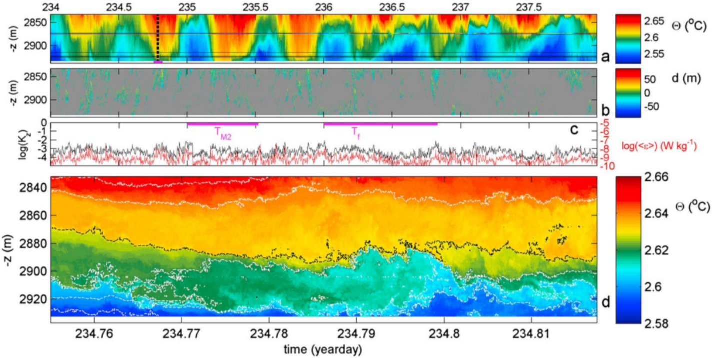
Mooring B, 2530m, $N = 1.0\,10^{-3}$rad/s



H. van Haren, A. Cimatoribus and L. Gostiaux, Where large deep-ocean waves break, Geophysical Research Letters, GL063329, 2015

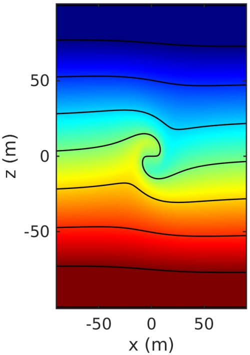
Measurements at Josephine Seamount

Mooring C, 2937m, $N = 0.7\,10^{-3}$rad/s

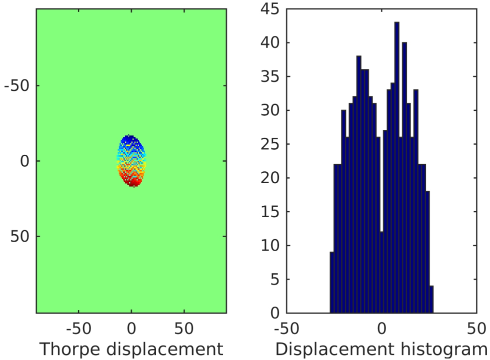


H. van Haren, A. Cimatoribus and L. Gostiaux, Where large deep-ocean waves break, Geophysical Research Letters, GL063329, 2015

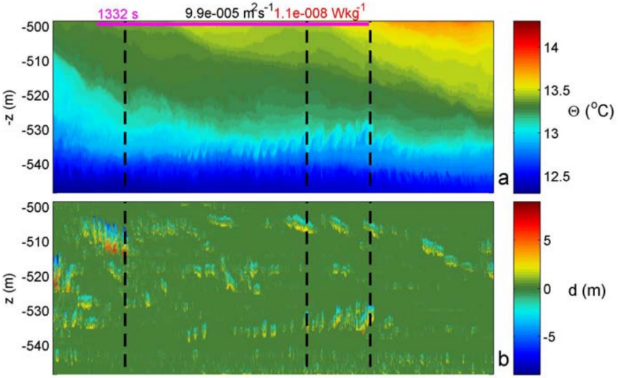
Analytical overturn



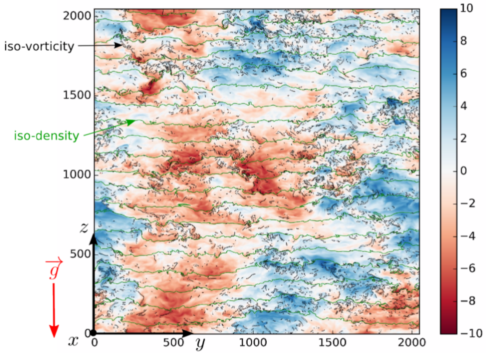
Analytical overturn



Deep ocean overturns



Numerical overturns

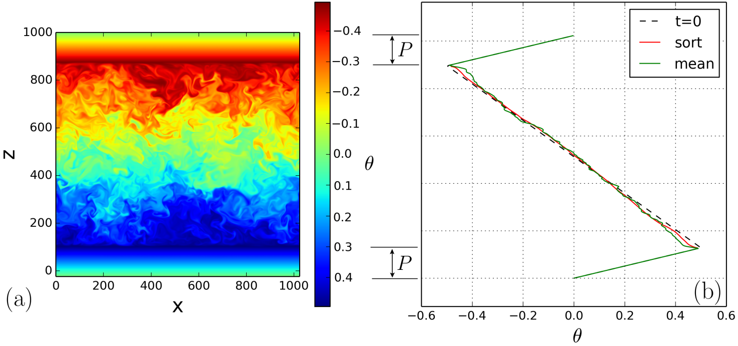


High resolution (2048^3 points, Re=1000 $k_{max}\eta \simeq 3$) with pseudospectral method, freely decaying turbulence.

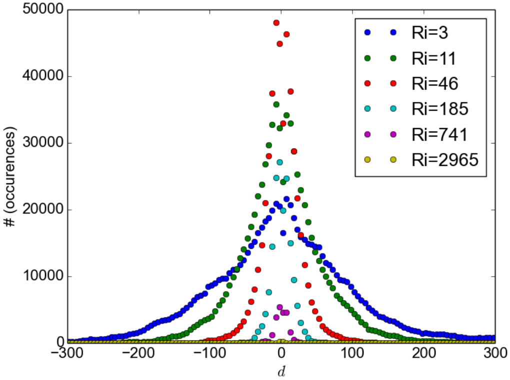
A. Delache, E. Horne, LMFA

Statistics of displacement values

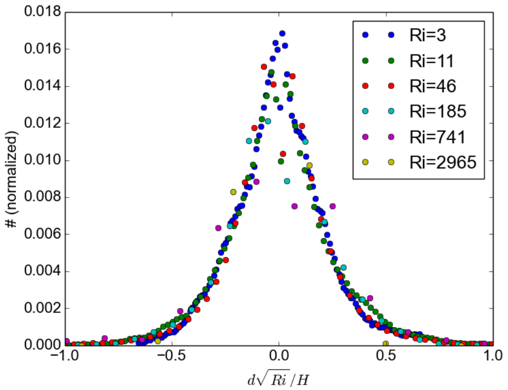
Gobal richardson number $Ri = N^2 H^2 / u^2$ with u the rms turbulent velocity and H the vertical domain size



Statistics of displacement values



Statistics of displacement values



Simple energetic scaling

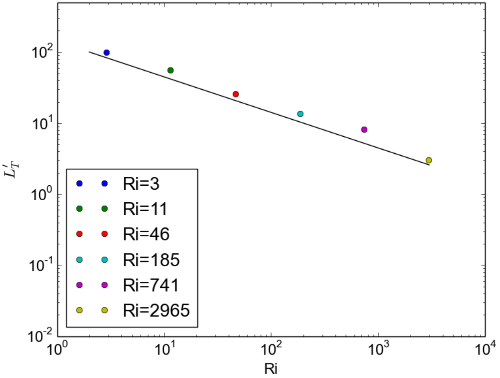
From the energetic point of view, the potential energy in an overturn is $Ep \simeq N^2 d^2$ (Thorpe 1977)
If an overturn is seen as a transfer of kinetic to potential energy, $E_c \simeq Ep$ leads to $d^2 \simeq u^2/N^2 = H^2 Ri^{-1}$

$$d \simeq H/\sqrt{Ri}$$

Conditional Thorpe scale L'_T

$$L'_T = < d^2 >^{1/2} |d \neq 0$$

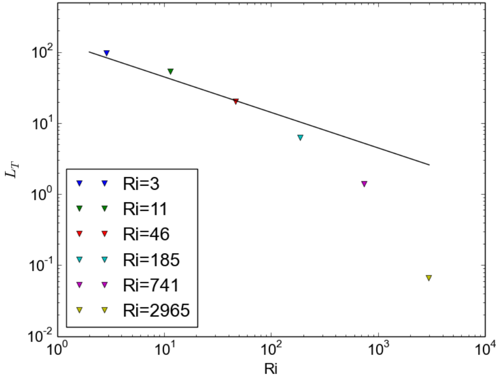
$(L_T = \sqrt{\chi} L'_T)$



Conditional Thorpe scale L'_T

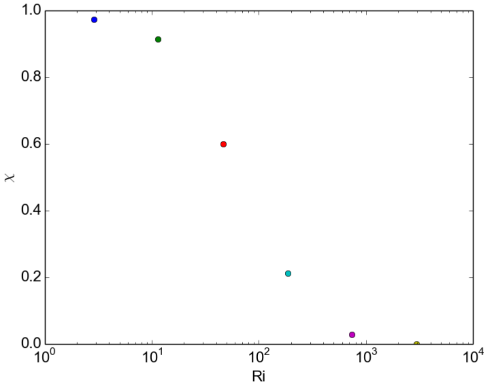
$$L'_T = < d^2 >^{1/2} |d \neq 0$$

$$(L_T = \sqrt{\chi} L'_T)$$



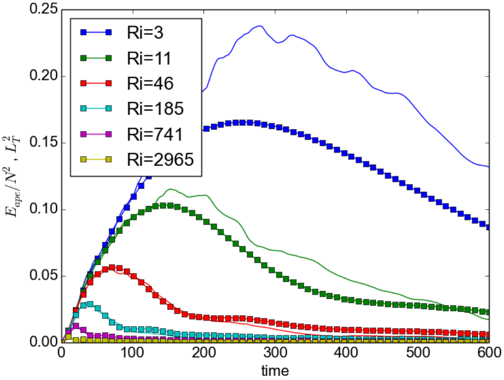
Effect of intermittency χ

The intermittency influences the Thorpe scale estimate at high Ri

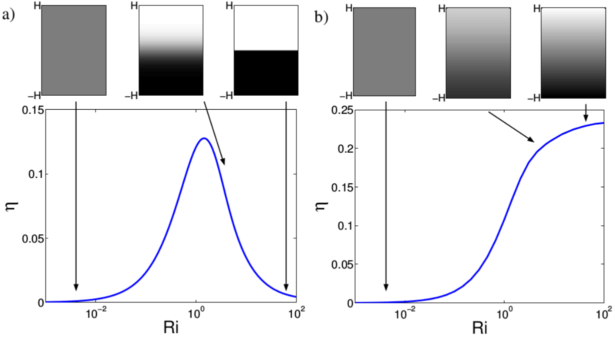


Energetic approcah

On the other hand, the energetic interpretation $Ep \simeq N^2 d^2$ is more valid with a strong intermittency



Perspectives



- Comparison with A. Venaille statistical model
- DNS in the case of two-layer stratified turbulence
- Statistics of Thorpe displacements on oceanic data

The inverted Thorpe displacement

$$\begin{cases} \sigma(z_i) = \sigma_s(z_i + d_i) \\ \sigma(z_i + d_i^*) = \sigma_s(z_i) \end{cases}$$

With $z_i^* = z_i + d_i^*$, it follows

$$\sigma(z_i^*) = \sigma_s(z_i^* - d_i^*)$$

But $[z_i^*]$ is a permutation of $[z_i]$, which can be written :

$$\begin{cases} z_i^* = z_{p(i)} \\ d_i^* = -d_{p(i)} \end{cases}$$