Upper ocean turbulence

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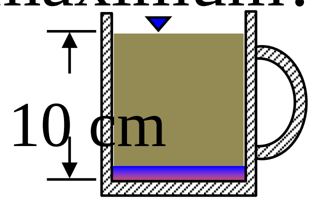
CARTHE
CONSORTIUM
for ADVANCED RESEARCH on TRANSPORT of HYDROCARBON in the ENVIRONMENT

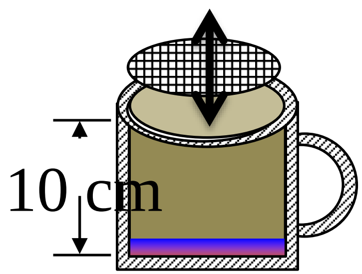
Turbulence – why we care?

- How long does it take for a slug of sugar to spread so that the concentration 10 cm away is 10% of the maximum?



Molecular:
Almost three weeks

$$D_m = 0.673 \, x \, 10^{-5} \, cm^2/s$$



Turbulent:
A few seconds

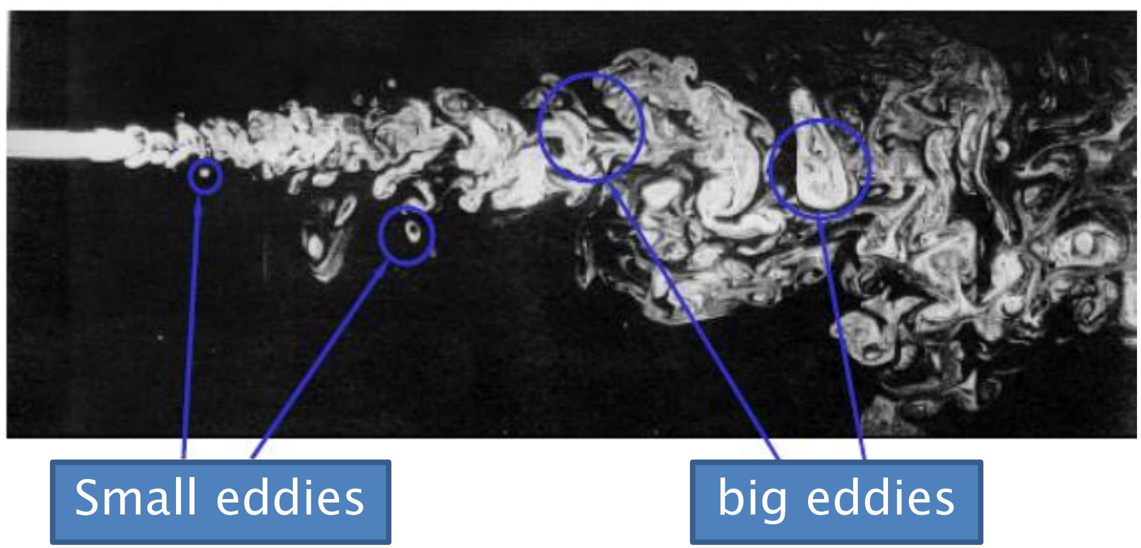
Stir it:
Energy dissipation of a few **W/kg** mixes it in few seconds !

- Turbulence is responsible for horizontal and vertical dispersion
- Oceanic implications for pollutants, heat, gas transport in ocean.

Turbulent eddy – what was going on in our cup experiment?

- The picture shows a smoke jet emerging from a circular tube into air at high Reynolds number. There is a small laminar region close to the orifice. Downstream, the jet changes to turbulent state in which the eddy patterns are complex.

- Turbulent eddies are characterized by a wide range of length scales.



Turbulence ‘age’ →

Turbulent Kinetic Energy Dissipation Rate, ε

- Energy dissipation rate (m^2/s^3):

$$\varepsilon = 2\nu \overline{S_{ij}S_{ij}}$$

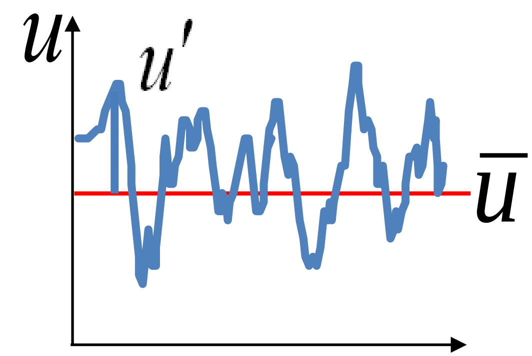
- ν- kinematic viscosity (m^2/s)
- S_{ij}-(symmetric part) strain rate tensor:

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

- Assume isotropy, then TKE or ε is the rate of dissipation.

$$\varepsilon = \frac{15}{2}\nu\left(\frac{du'}{dz}\right)^2.$$

- Temperature dissipation rate- start with: T=<T>+T' and similar to momentum

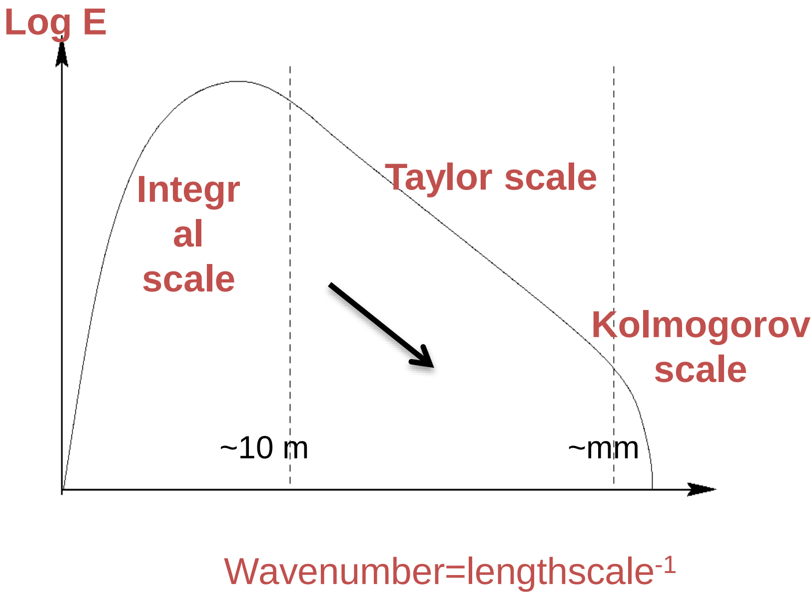


$$u = \overline{u} + u'$$

instantaneous velocity — mean velocity — velocity fluctuation

Kolmogorov energy spectrum

- **Energy cascade, from large scales to small scales.**
- **E** is energy contained in eddies of wavenumber $k=1/\lambda$.
- Length scales:
  - *Largest eddies*. (~10m) Integral length scale ($k^{3/2}/\varepsilon$).
  - Length scales at which *turbulence is isotropic*. Taylor microscale
  - $(15\nu u'^2/\varepsilon)^{1/2}$.
  - *Smallest eddies*.(<1mm) Kolmogorov lengthscale $(\nu^3/\varepsilon)^{1/4}$. These eddies have a velocity scale $(\nu\,\varepsilon)^{1/4}$ and a time scale $(\nu/\varepsilon)^{1/2}$ (~0.1sec).



$$\varepsilon = 6\nu \int_0^\infty k^2 E(k)\,dk$$

ε is the energy dissipation rate (m^2/s^3)

χ is the temperature dissipation rate ($degC^2/s$)

ν, κ is the kinematic viscosity, thermal diffusivity (m^2/s)

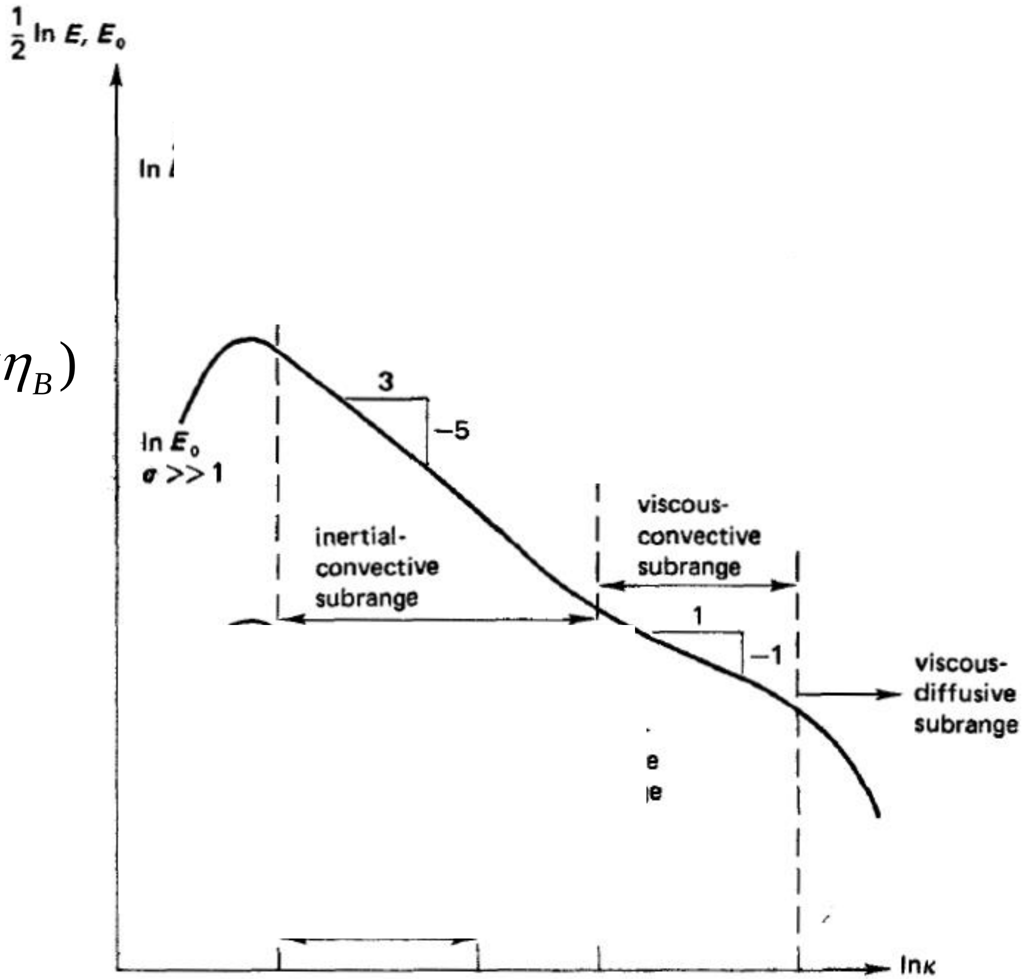
Temperature spectrum

- Physical space

$$\chi = 2\kappa\langle(\nabla\theta)^2\rangle$$

- Spectral form

$$\frac{E_\Theta(k)}{\chi(\nu/\varepsilon)^{1/2}\eta_B} = \frac{q_K}{k\eta_B}(1+(6q_K)^{1/2}k\eta_B)$$
$$\exp(-\sqrt{6q_K}k\eta_B)$$

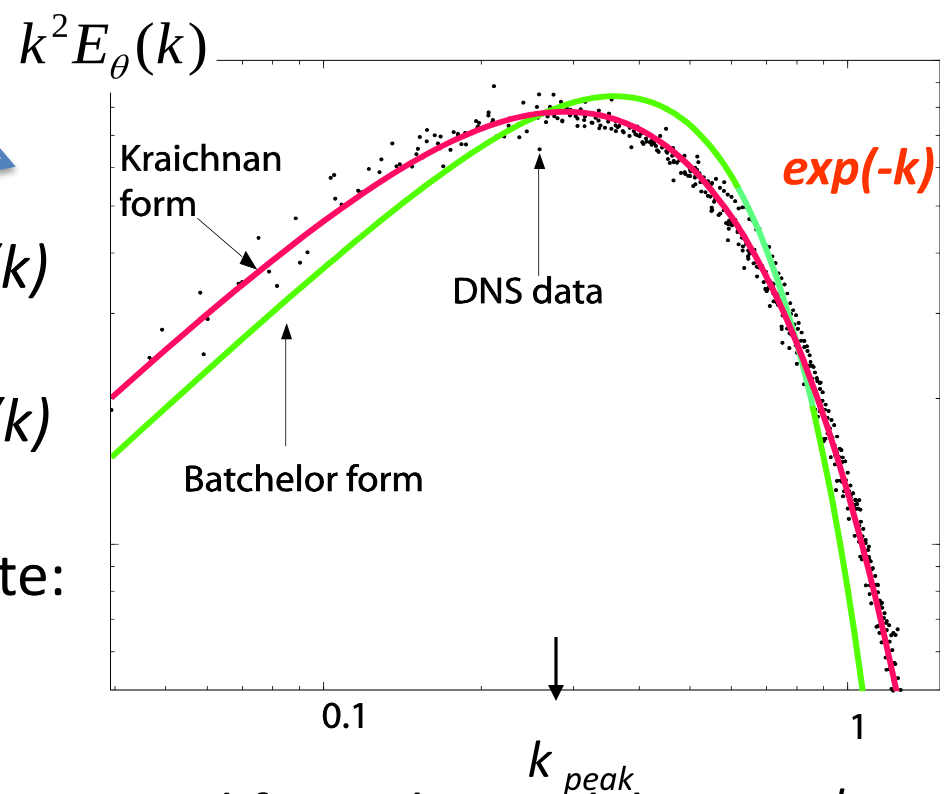


- Temperature variance dissipation rate

$$\chi = 2\kappa\int_0^\infty k^2 E_\theta(k)dk$$

Temperature dissipation spectrum-the model

$$\frac{E_{\Theta}(k)}{\chi(\nu/\varepsilon)^{1/2}\eta_B} = \frac{q_K}{k\eta_B}(1+(6q_K)^{1/2}k\eta_B)$$
$$\exp(-\sqrt{6q_K}\,k\eta_B)$$



- Temperature spectrum: $E_\theta(k)$
- Dissipation spectrum: $k^2E_\theta(k)$
- Temperature dissipation rate:

$$\chi = 2\kappa\int_0^\infty k^2E_\theta(k)dk$$

- Energy dissipation can be estimated from the peak location rate (eg. OTS):

$$k_{peak}\left(\frac{\nu\kappa^2}{\varepsilon}\right)^{1/4} = k_{univ} \approx 0.29$$

Bogucki et. al; 1997

Turbulence application:

- Estimates of the vertical turbulent fluxes in the ocean can be obtained from assumed relations between these fluxes and the dissipation rate of turbulent kinetic energy - **ε** and of temperature - **χ**.
- How do we measure it ?

Calculated from ***microstructure*** observations →

$$3\kappa_{mol}\overline{\left(\frac{\partial T'}{\partial z}\right)^2} = \frac{\chi}{2} = \kappa_{turb}\left(\frac{\partial \overline{T}}{\partial z}\right)^2$$

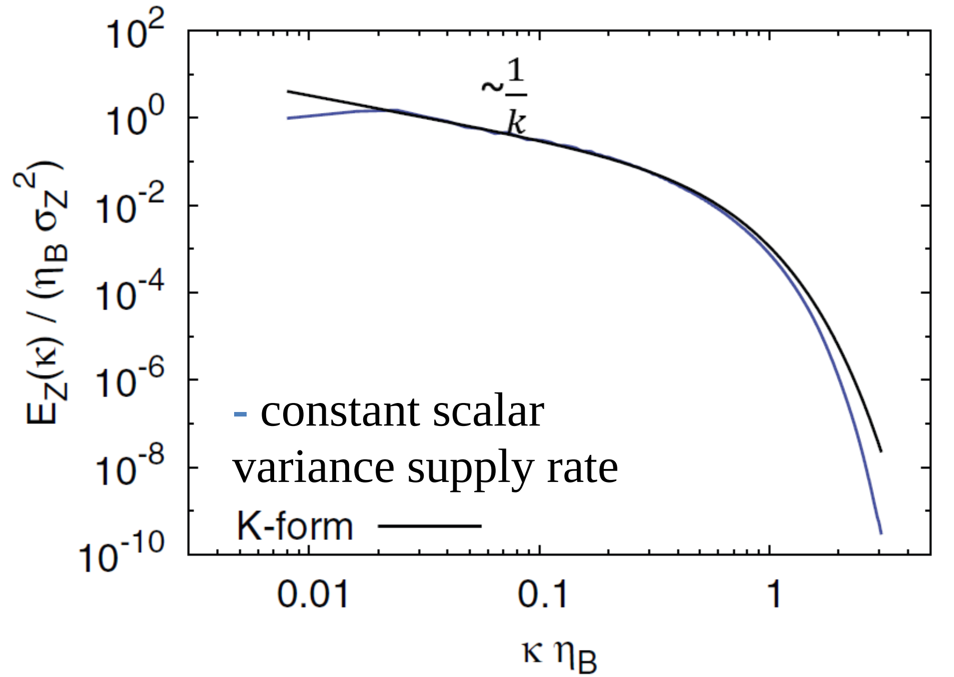
← Inferred from large scale gradients via.: ***eddy diffusivity***

$$K_{momentum} \sim \frac{\varepsilon}{(\partial \overline{U} / \partial z)^2}, \quad K_{heat} \sim \frac{\chi}{(\partial \overline{T} / \partial z)^2}$$

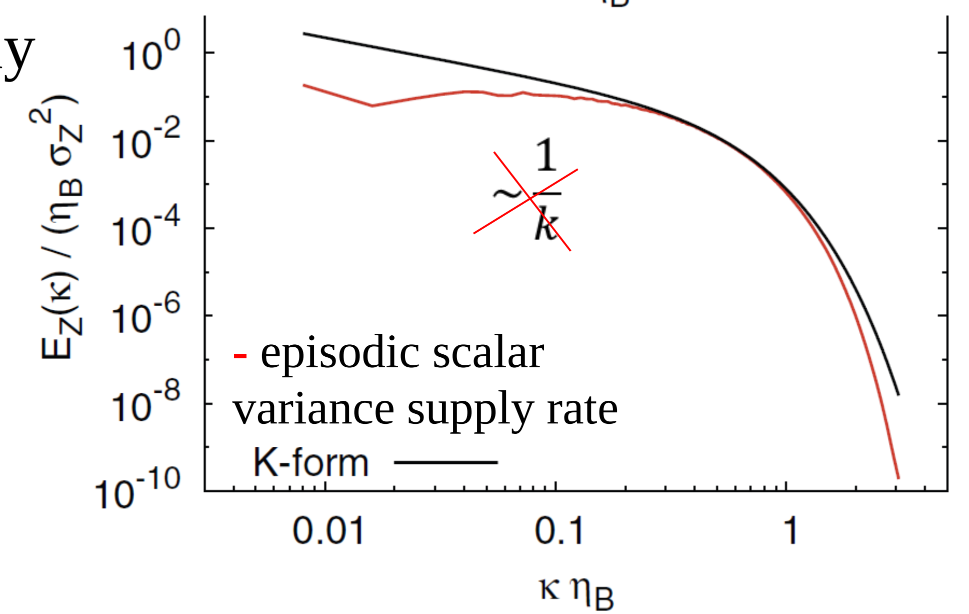
How universal is the temperature dissipation spectrum ?

•Kraichnan form derived with assumption of constant scalar variance supply rate

$$\frac{E_\Theta(k)}{\chi(\nu/\varepsilon)^{1/2}\eta_B} = \frac{q_K}{k\eta_B}\left(1+(6q_K)^{1/2}k\eta_B\right)\exp(-\sqrt{6q_K}\,k\eta_B)$$



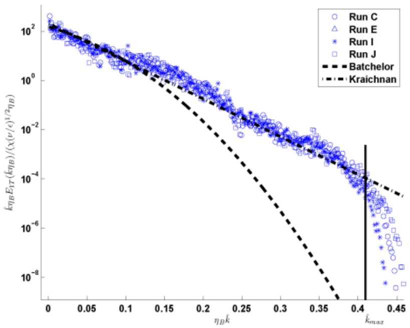
•If episodic scalar variance supply rate – we loose k^{-1} range scalar spectra. Carroll et. al.

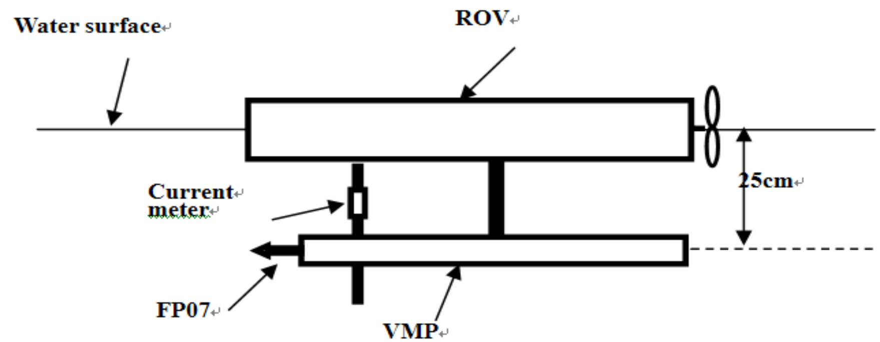


Phys. Fluids **25**, 095102 (2013)

Direct Numerical Simulation, Pr>>1

Near surface temperature dissipation spectra

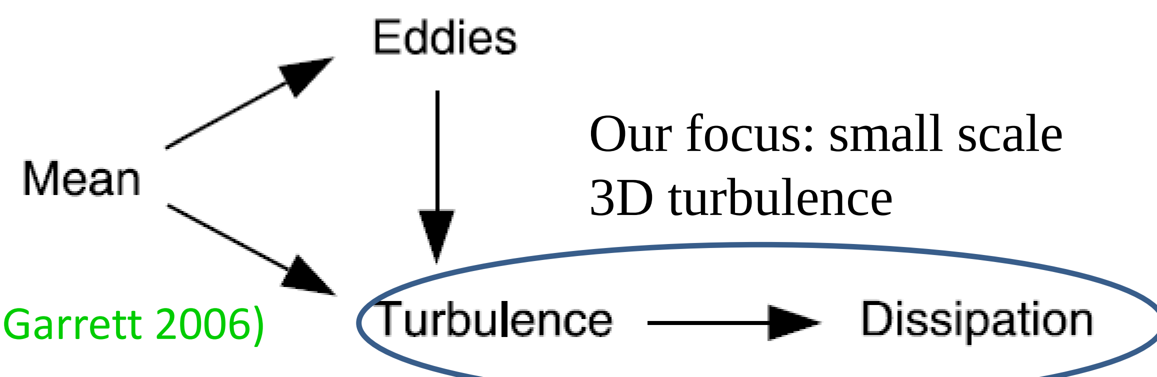




- The near surface measurements of temperature microstructure in the presence of 5*m/s* wind, (Bogucki et al. 2012 at 0.2*m* below air-sea interface the temperature spectra at the follow the Kraichnan formula.
- This is a remarkable! as the near surface layer was subject to a concurrent forcing mechanisms yet it follows the homogenous isotropic form.
- If near surface flow fielded approximates homogenous isotropic turbulence – effect of waves? (intermittent scalar supply..)

Stirring + diffusion = mixing

- *Stirring tends to sharpen gradients* to the point where molecular diffusion takes over and provides the ultimate mixing.
- Two pathways to generate scalar fluctuations:
- (1) the eddy-scale fluctuations in the scalar are acted upon by the turbulence to produce scalar fluctuations which, along with
- (2) those produced by the turbulence acting on the mean scalar field, are then cascaded to small enough scales that they can be dissipated by molecular processes.



Our focus: small scale 3D turbulence

. (Garrett 2006)

Small scale forcing - the first m of the ocean: buoyancy vs. shear

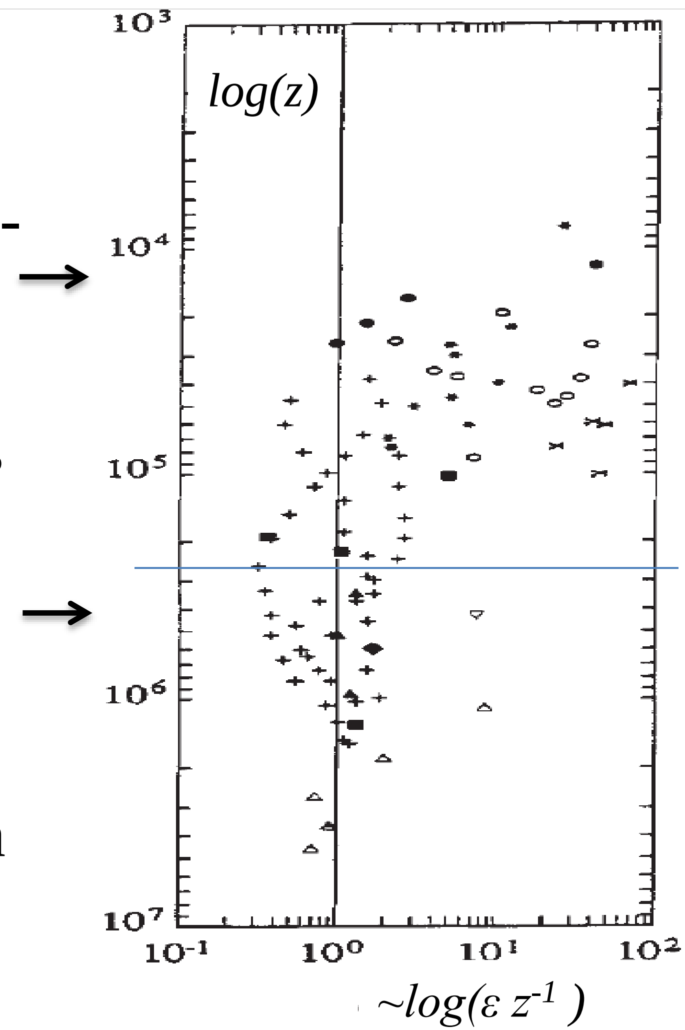
- Typically within the mixed layer and *at night*, the rate of turbulent kinetic energy (TKE) production is controlled by the *convection* while during *the day* the TKE production within ML is dominated by *wind stresses*. (LASER December 17, 2013 ?)

- Estimates carried by (Soloviev 2009) demonstrate that under *average night global* conditions i.e.: ocean surface is cooling, the globally averaged shear-driven turbulent layer is confined to a 1.5m thick near-surface layer with the rest of mixed layer TKE dissipation driven by turbulent convection.

- **Typically the first upper 1 m day/night is shear dominated**

Physics of energy dissipation below wavy interface -summary

- Values of **ε immediately below wavy interface** are enhanced relative to the wall-layer estimates where energy **ε** varies as a distance away from the wall –**z** as: **$\varepsilon \sim z^{-1}$**.
- Below that layer (here around 1m) follows constant stress scaling i.e. **$\varepsilon \sim z^{-1}$** as expected within the constant stress layer (eg below solid wall).
- In both cases, turbulence is produced via shear production, but immediately beneath the wind-driven interface, **turbulence is also produced by wave breaking** and possibly **via wave–turbulence interactions**



Soloviev et. al. 1988,
Agrawal et. al., 1992

Mass and temperature effective horizontal diffusivities

- The temperature vertical diffusivity κ:

$$K_h = \frac{1}{2}\chi\left(\frac{\partial T}{\partial z}\right)^{-2}$$

- Vertical diffusivity for density κ:

$$K_\rho = 0.2\,\varepsilon\,N^{-2}.$$

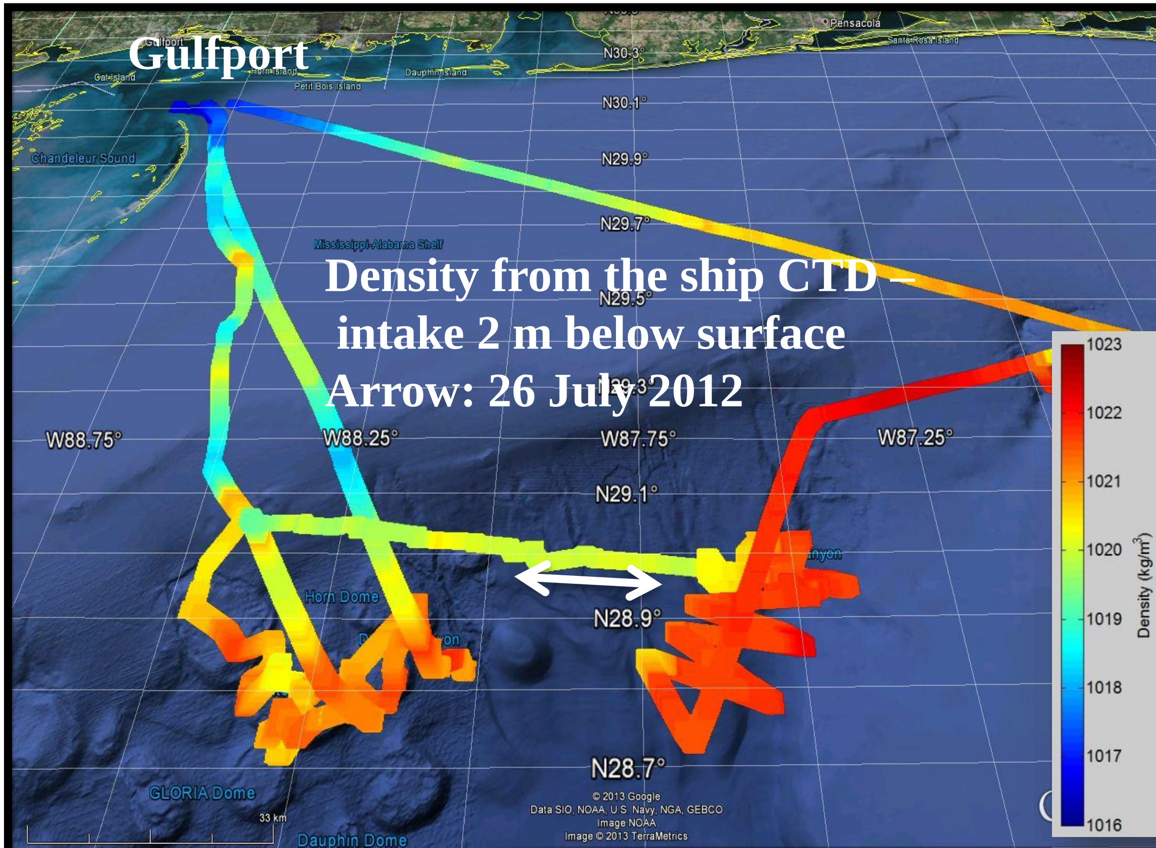
- We measure near surface ε and χ

Experiment location

- The GLAD was experiment, planned and executed by the CARTHE consortium – July 2012 Gulf of Mexico.

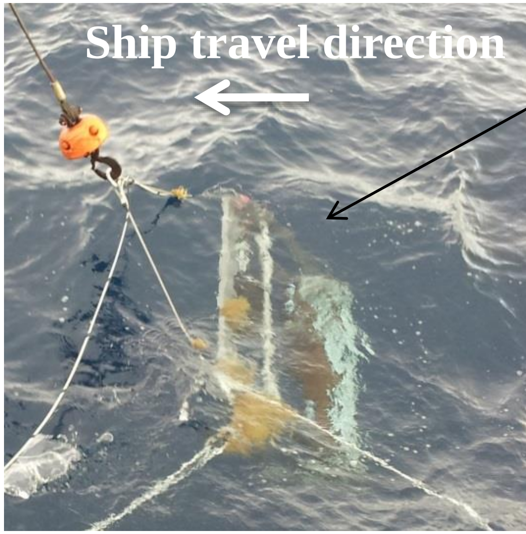
- The one week long ship track →

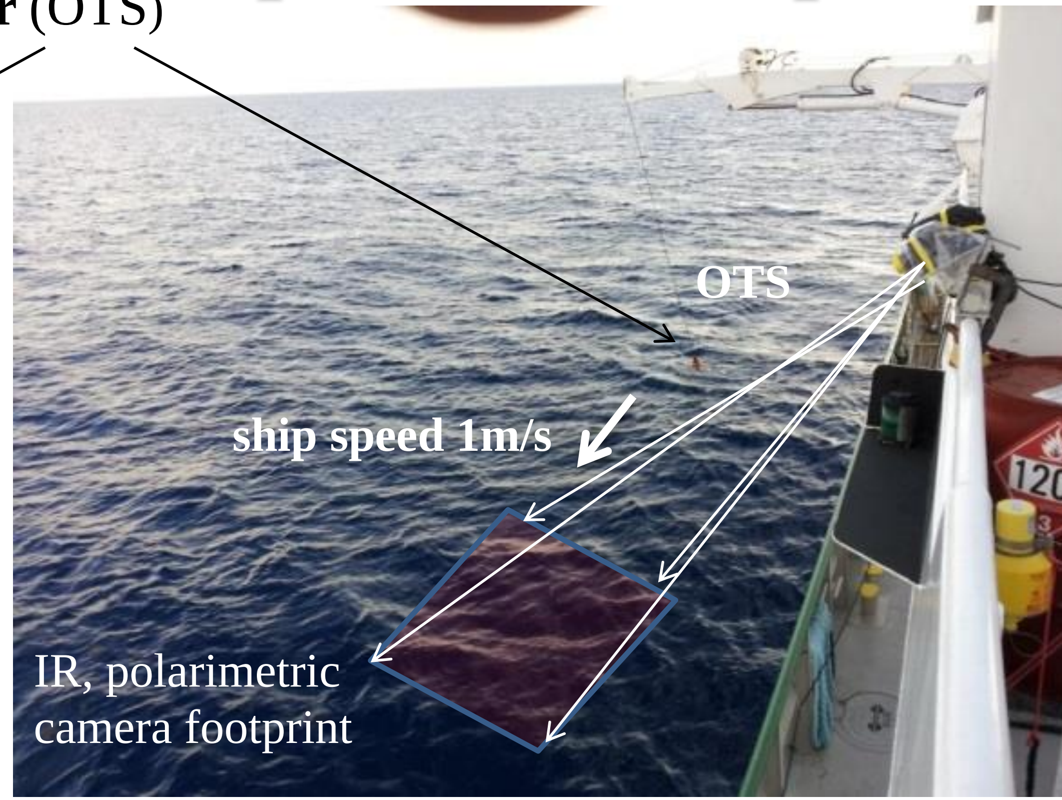
- The data presented here were collected on July 26 in vicinity of the Deep Water Horizon disaster site 1 hour long data set collected at 1 m/s tow speed.



Experiment setup

Towed **Optical Turbulence Sensor** (OTS)

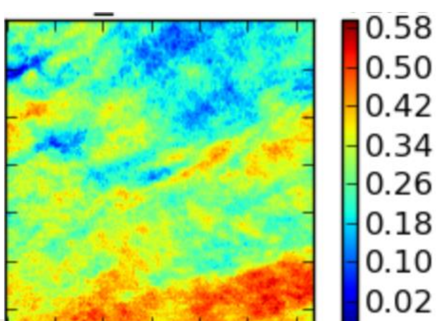




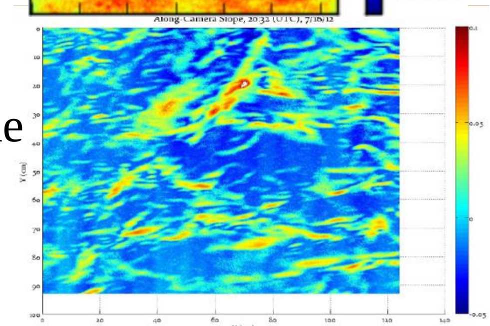
IR images provide a measure of

$\partial T / \partial x$

$\partial T / \partial y$



Polarimetric images provide a measure of short wave slopes

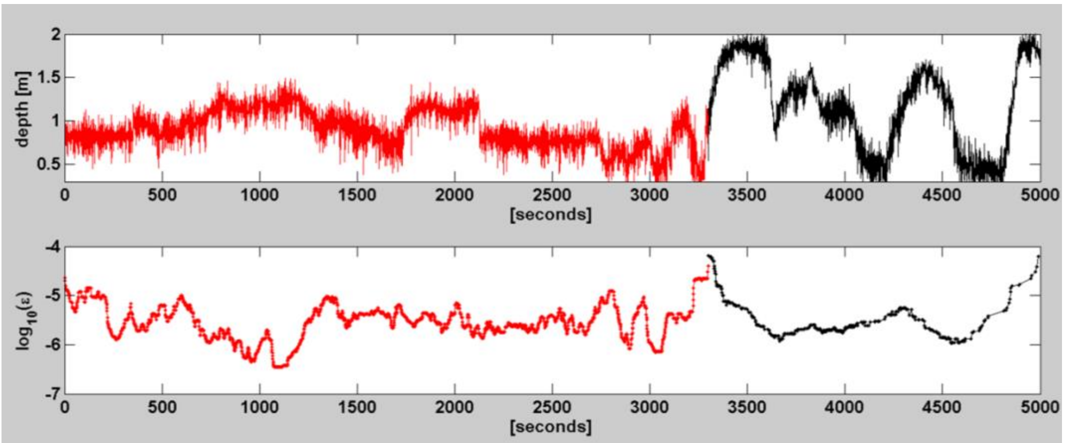


- OTS – away from RV ‘Walton Smith’ wake
- Tow – July 26, wind speed: U_{10} ~4.5m/s.
- Swell wave height <30cm.
- OTS 10cm to 200cm below surface.
- Ship traveling against wind 1m/s.
- Note: microscale breaking waves, occurs at wind speeds >4 ms−1.

OTS deployment

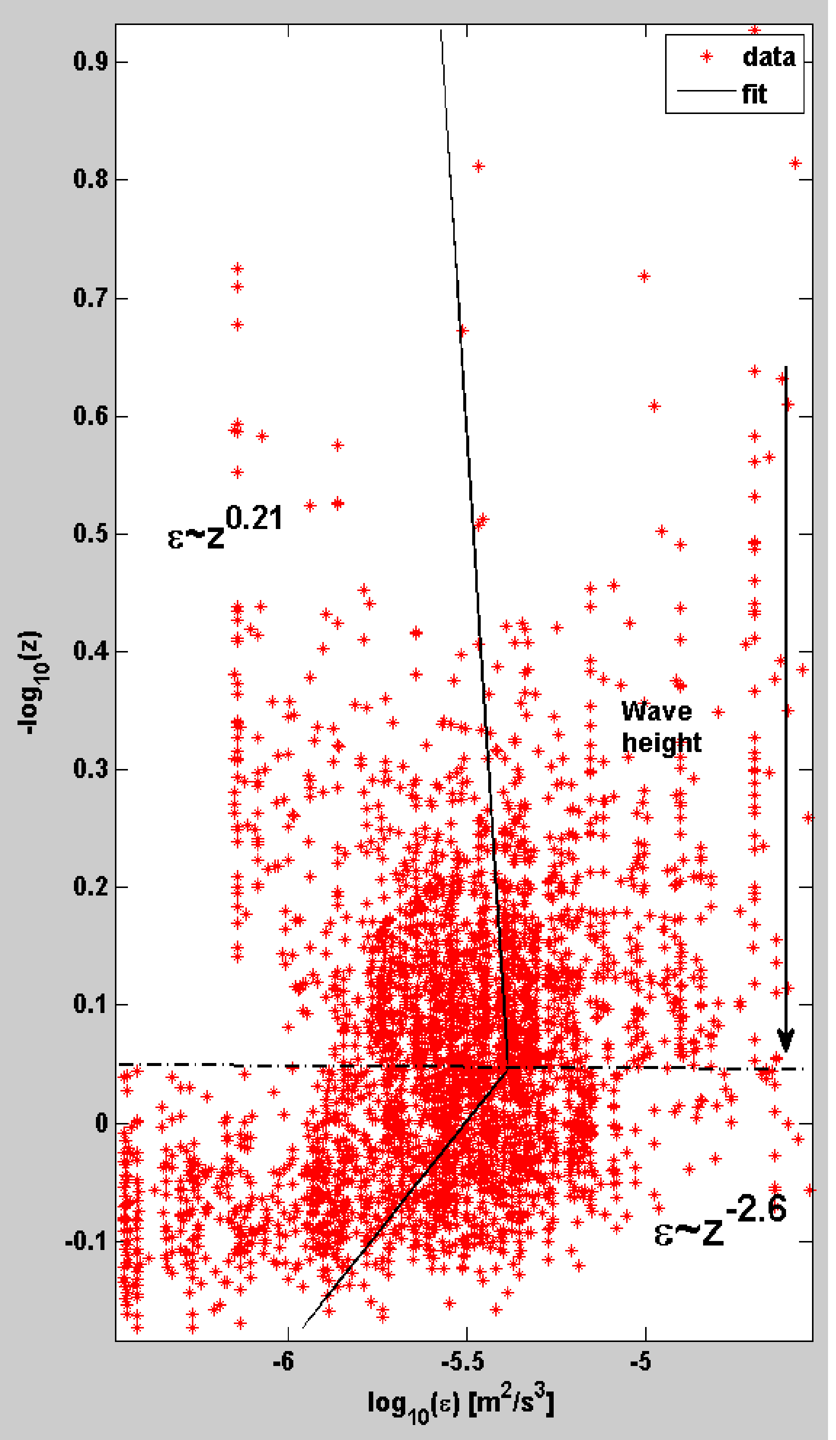
- OTS: Measures instantaneous dissipation temperature spectra
- **Approximate flow direction**
- think of an array of 110 ‘optical thermistors.
- 10000 spectra/second
- OTS laboratory verified in a grid generated turbulent flume
- ADCP with pressure sensor

The energy dissipation rate ε within 0-2 m depth

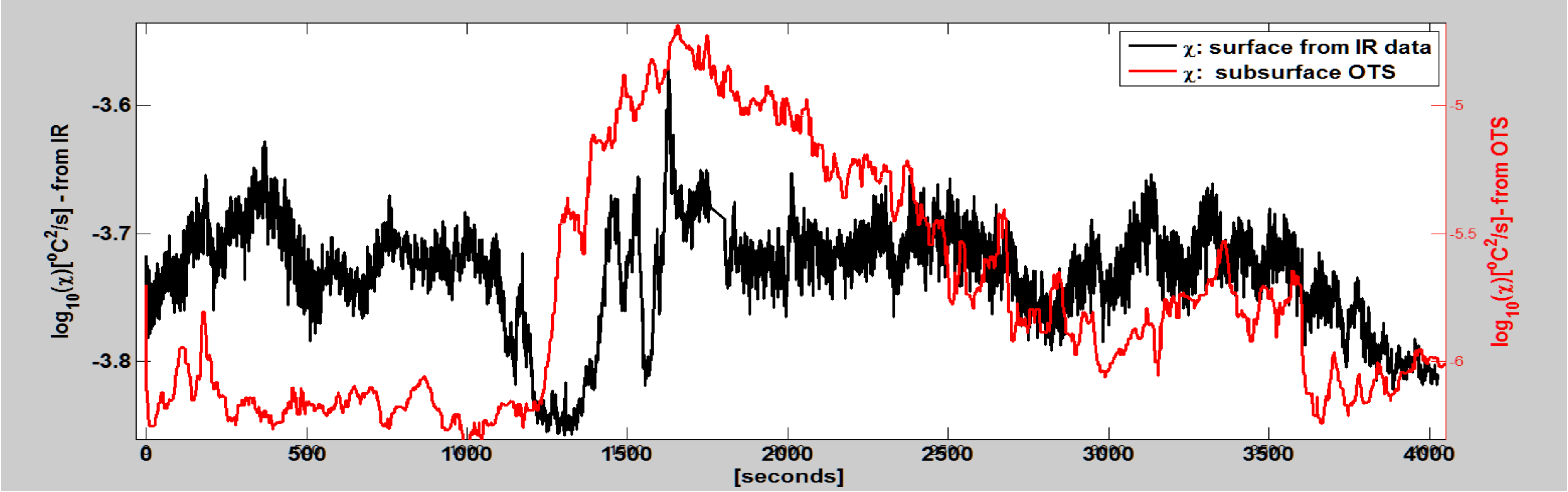


The time series of depth and temperature dissipation
The red denotes the origin of the data in ***ε(z)*** plot.

- Data are from 3250 second long tow at 1m/s
- Within the wave affected water column (0-0.9 m depth) $\varepsilon(z) \sim z^{0.21}$ i.e. weakly depends on depth.
- Below that depth $\varepsilon(z) \sim z^{-2.6}$

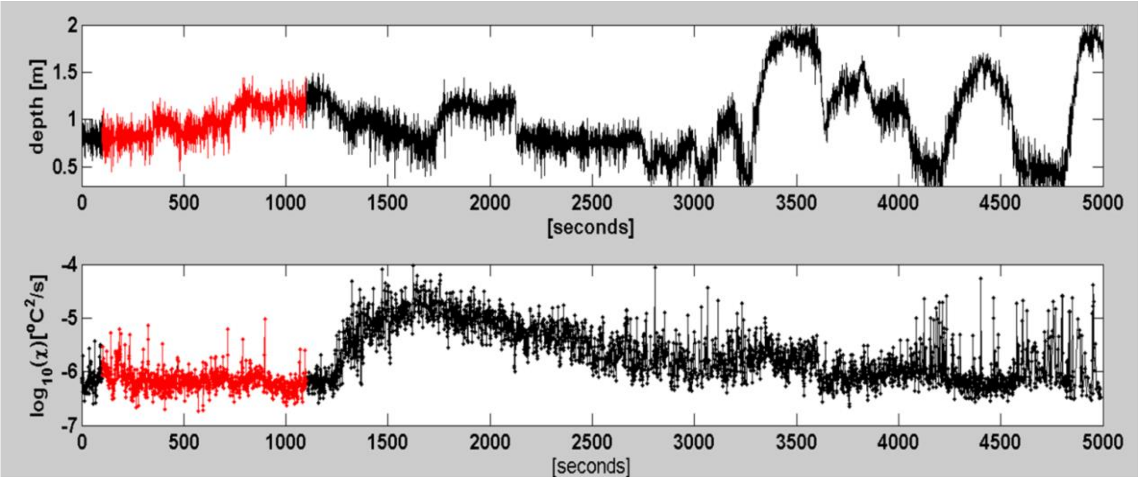


Time series of surface and subsurface temperature dissipation rate

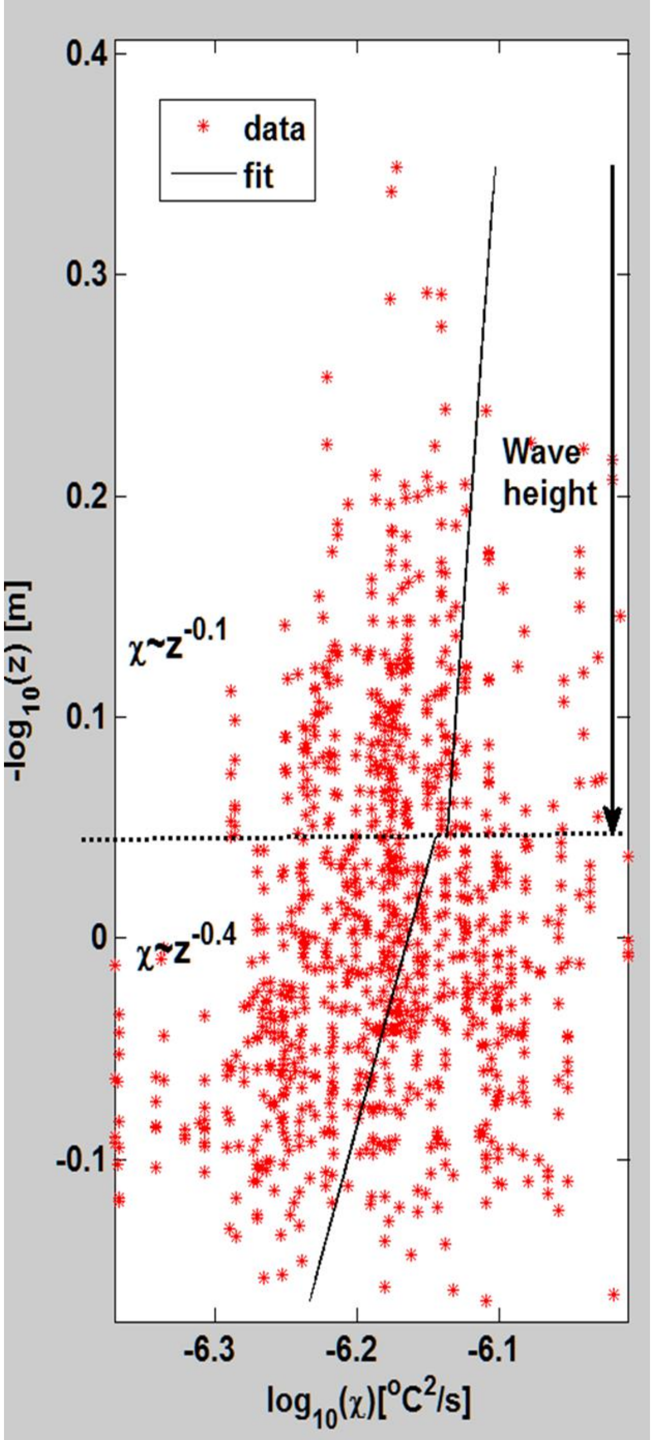


- 4000 seconds of surface and subsurface temperature dissipation rate χ collected during 1m/sec tow.
- **Surface - skin**: for each IR image we calculate $\partial T/\partial x$ and $\partial T/\partial y$ at the dissipation scale length interval – IR 10Hz rate.
- We have estimated the temperature dissipation rate from IR surface data $\chi_{z=0}$ as: $\chi_{z=0} = 2D_T[(\partial T/\partial x)^2 + (\partial T/\partial y)^2 + (\partial T/\partial z)^2] \cong 3D_T[(\partial T/\partial x)^2 + (\partial T/\partial y)^2]$
- **Subsurface (0-2 m)**: OTS temperature dissipation spectra and χ at 5000 spectra/second as 1 second average.

The temperature dissipation rate $\chi(z)$ at 0.5-1.5 m below surface.

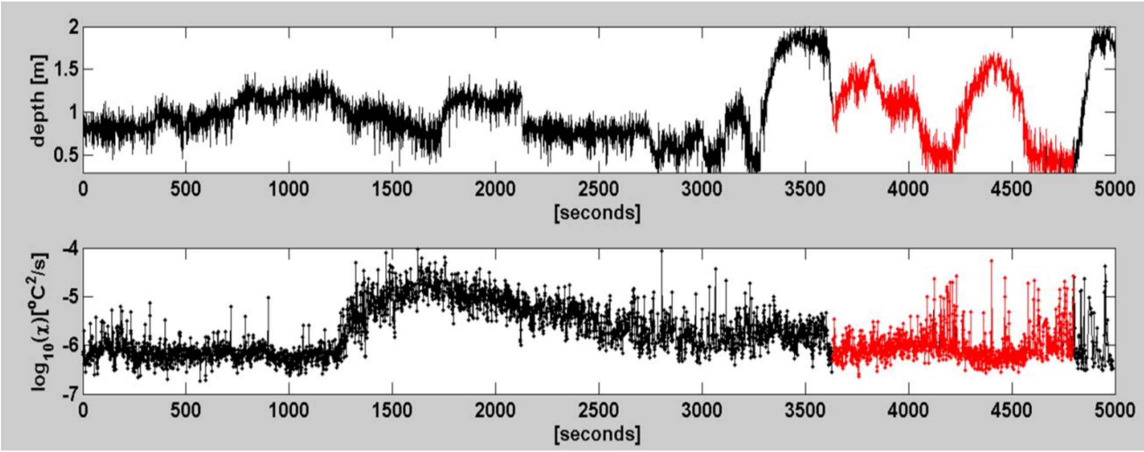


The time series of depth and temperature dissipation
The red denotes the origin of the data in $\chi(z)$ plot.



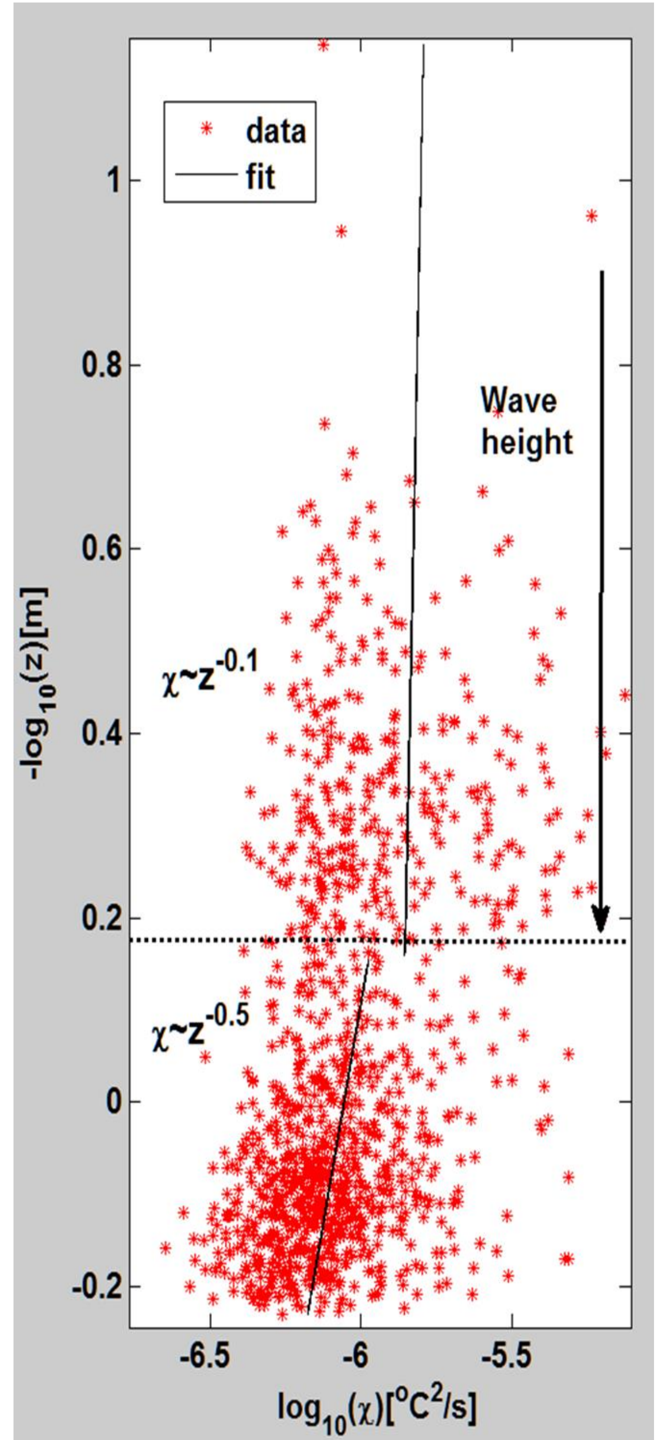
- The temperature dissipation rate χ as a function of depth (0-2 m) below surface).
- Within the wave affected water column (0-0.9 m depth) $\chi(z)$~$z^{-0.1}$ - weak depth dependence
- Below that depth $\chi(z)$~$z^{-0.4}$

The temperature dissipation rate $\chi(z)$ at 0-1.5 m below surface.



The time series of depth and temperature dissipation
The red denotes the origin of the data in $\chi(z)$ plot.

- The temperature dissipation rate **χ** as a function of depth (0-2 m)below surface.
- Within the wave affected water column (0-0.9 m depth**)** **$\chi(z)\sim z^{-0.1}$** and weakly depends on depth.
- Below that depth $\chi(z)\sim z^{-0.5}$



Simple approach: diffussion of thermal variance by background turbulent flow

- Within constant stress layer the energy dissipation ε depends on the distance from the boundary z as $\boldsymbol{\varepsilon} \cong \frac{\boldsymbol{u_*^3}}{\boldsymbol{\kappa}\,|\boldsymbol{z}|}$; $\boldsymbol{\kappa}$ -von Karman constant
- At smallest dissipative scales (Kolmogorov) the relevant time scale for scalar evolution is $\boldsymbol{t_k} = \left(\frac{\boldsymbol{v}}{\boldsymbol{\varepsilon}}\right)^{\frac{1}{2}}$;
- If the scalar variance source is localized at the surface and the upper layer is subject to a constant shear (e.g. solid wall), then the depth dependent temperature dissipation rate $\chi(z)$ becomes:

$$\boldsymbol{\chi(z)} = \frac{\Delta \boldsymbol{T_{z=0}}'^2}{\boldsymbol{t_k}} = \Delta \boldsymbol{T_{z=0}}'^2 \left[\frac{\boldsymbol{u_*^3}}{\boldsymbol{v\kappa}\,|\boldsymbol{z}|}\right]^{\frac{1}{2}} \sim \boldsymbol{z}^{-1/2}$$

- Are our observations consistent with temperature dissipation varying with depth as $\boldsymbol{\chi(z)} \sim \boldsymbol{z}^{-\frac{1}{2}}$ below wave affected layer?

Conclusions: Vertical structure of the temperature dissipation χ(z)