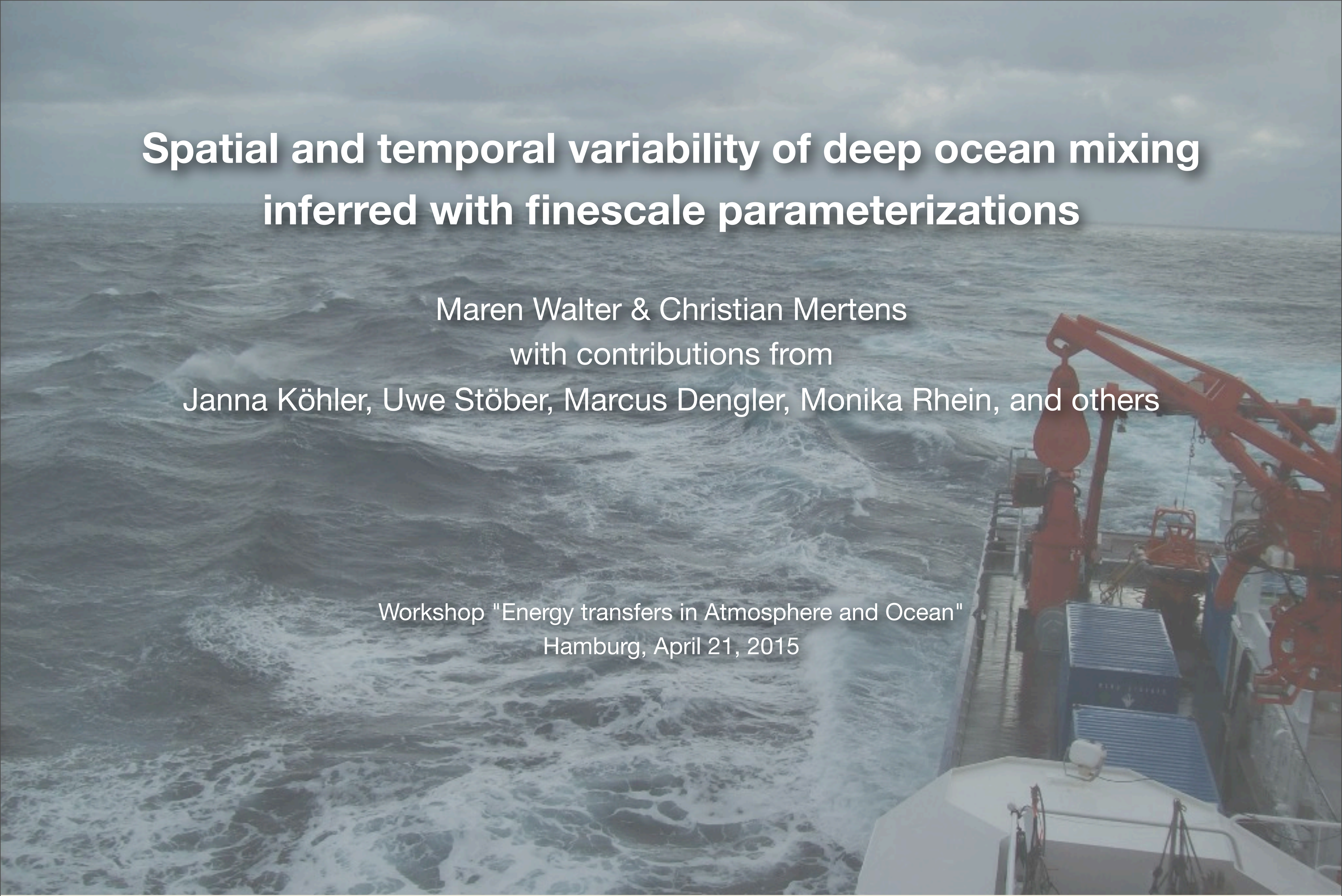

Spatial and temporal variability of deep ocean mixing inferred with finescale parameterizations

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with contributions from
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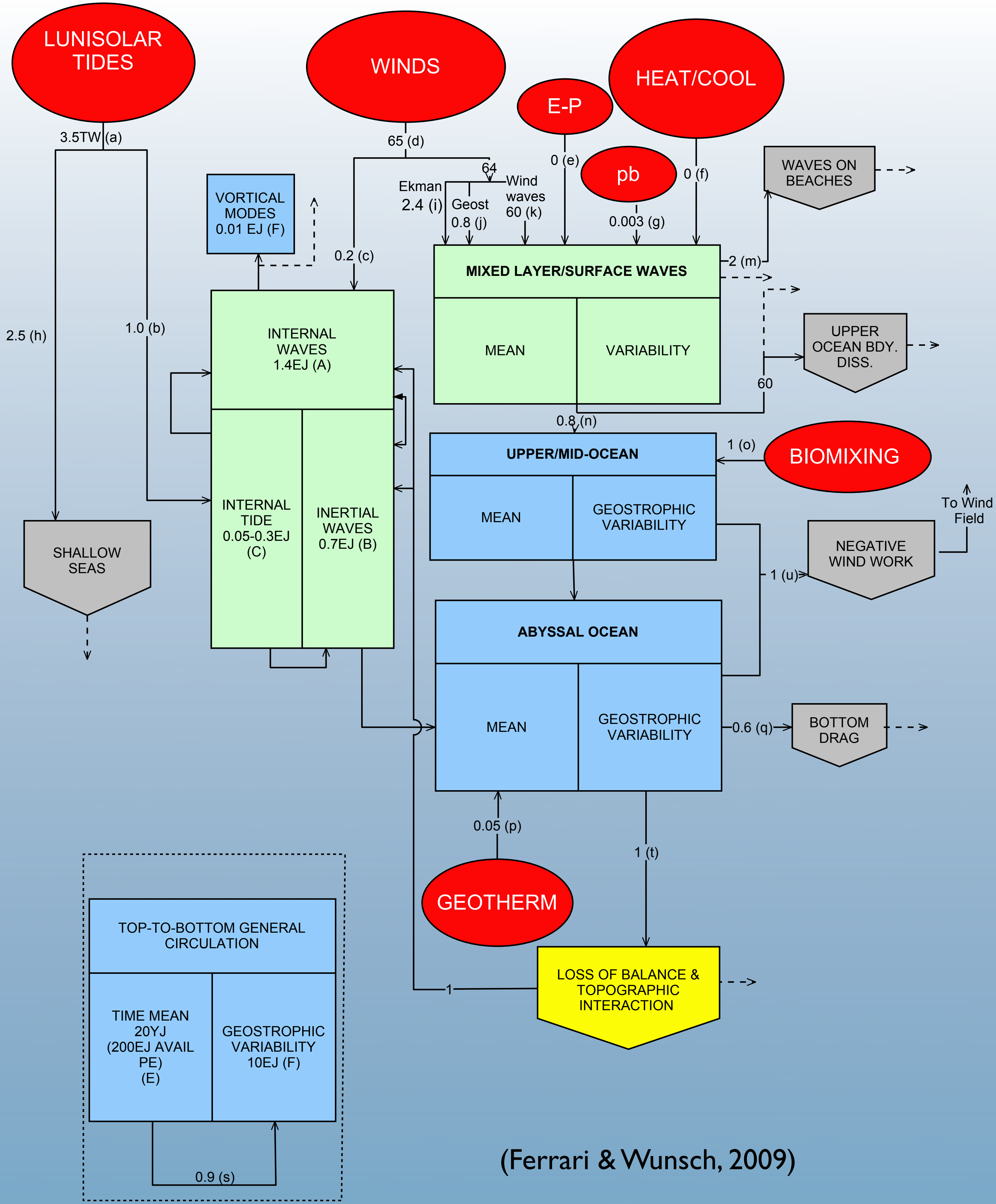
Workshop "Energy transfers in Atmosphere and Ocean"
Hamburg, April 21, 2015

Universität Bremen

Outline

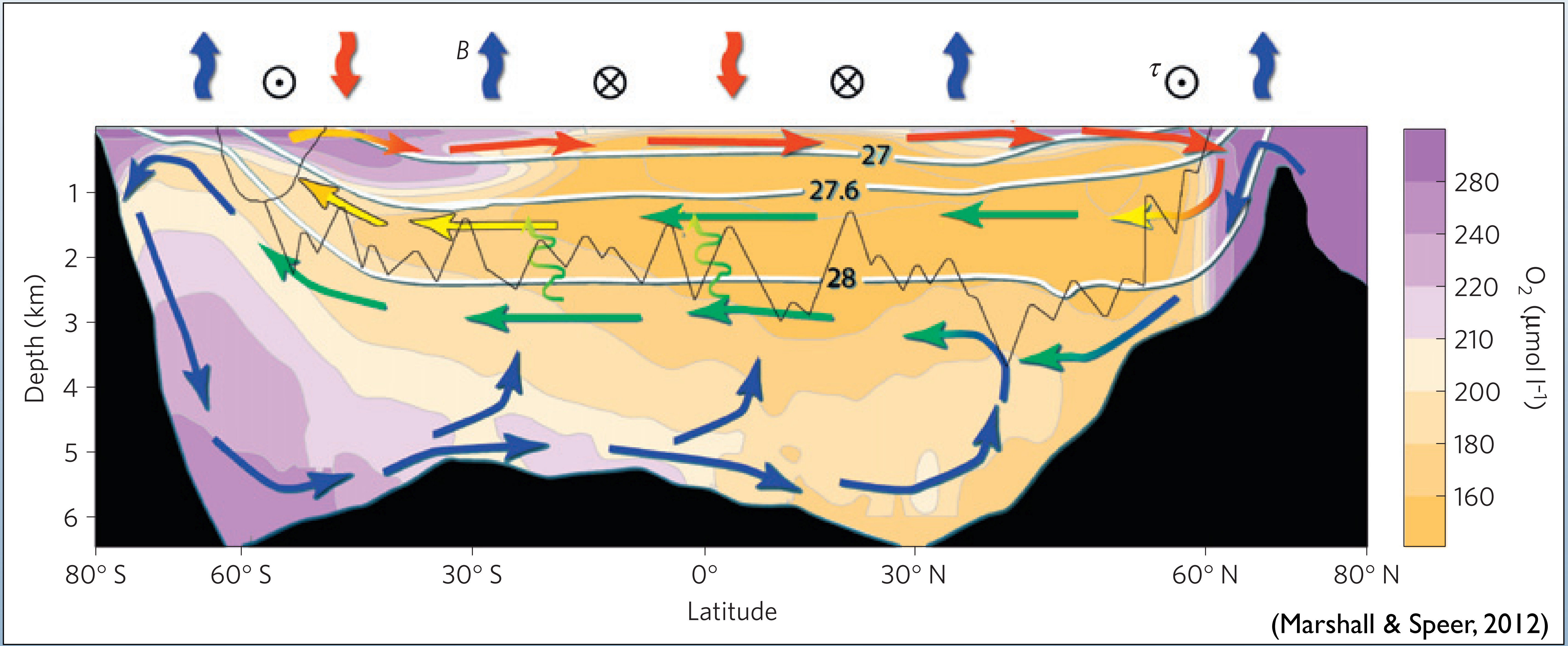
1. Deep ocean mixing
2. Finescale parameterizations: why are they useful, how do they work, what are the limits
3. What can we learn from finescale parameterizations? (local processes, global distributions/budgets)
4. Insights from existing data: temporal + spatial variability; (North Atlantic, South Atlantic, etc)
5. Outlook: what might be possible in the future?

Energy cycle in the (deep) ocean



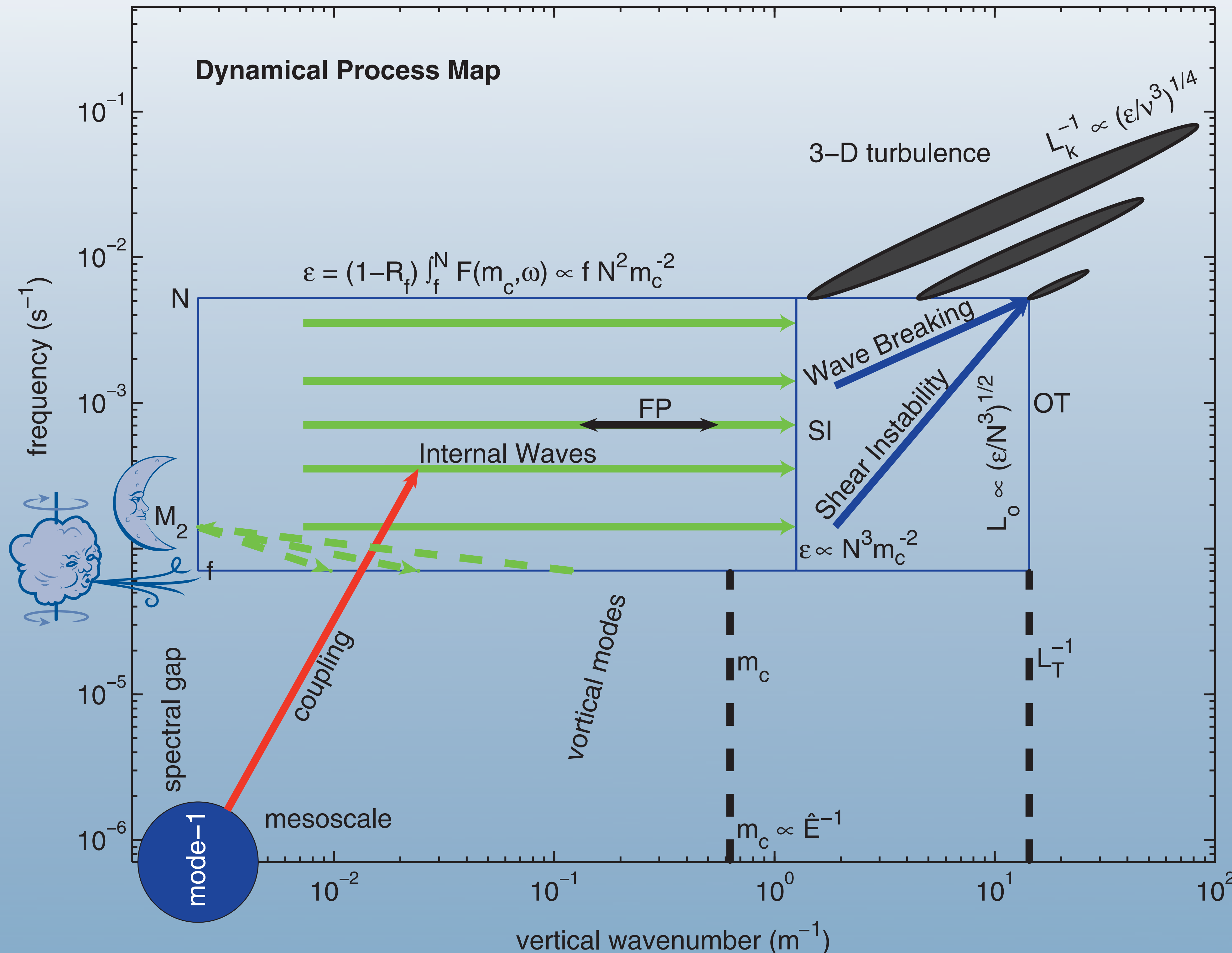
(Ferrari & Wunsch, 2009)

Overturning, bathymetry, and mixing



- Schematic of upper & lower cell of the global MOC

Processes in the vertical wave number/frequency domain



(Polzin et al., 2014)

Parameterizations:

FP: Finescale; SI: Shear Instability; OT: Thorpe scale/Overturn

Mixing/Diapycnal diffusivity K_ρ:

$$\overline{u'u'}\frac{\partial \overline{u}}{\partial x} + \overline{u'v'}\frac{\partial \overline{u}}{\partial y} + ... + \overline{v'w'}\frac{\partial \overline{w}}{\partial y} + \overline{w'w'}\frac{\partial \overline{w}}{\partial z} = \varepsilon + K_\rho N^2$$

$$\text{turbulent production } (\overline{u'_i u'_j}\frac{\partial \overline{u_i}}{\partial x_j}) = \text{dissipation} + \text{buoyancy flux}$$

local production of current shear is balanced by dissipation and buoyancy flux (i.e. homogenization of the water column)

$$\text{flux Richardson number} R_f = \frac{\text{buoyancy flux}}{\text{turbulent production}} \leq 0.15$$

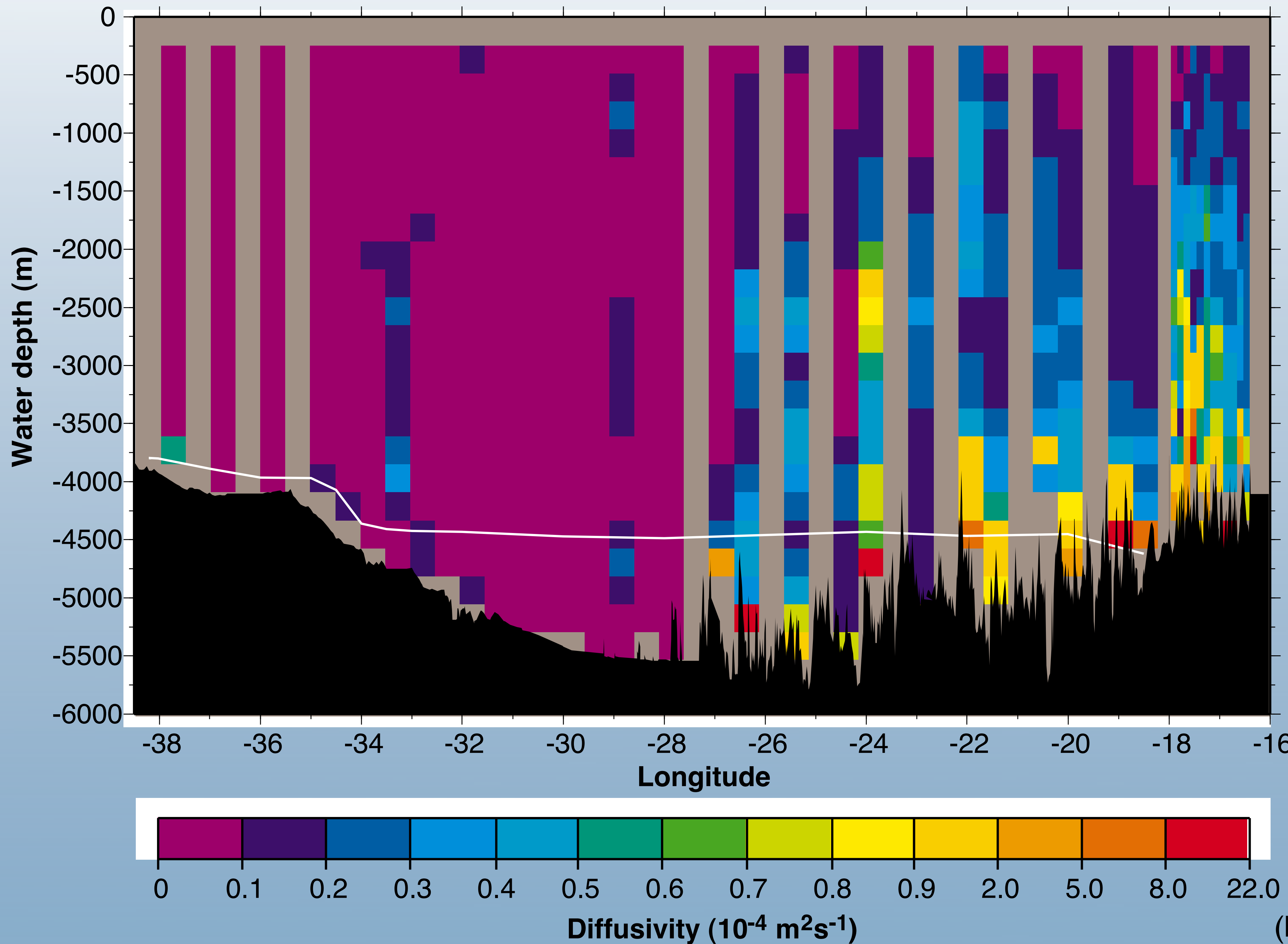
$$\Rightarrow K_\rho = \frac{R_f}{1 - R_f}\frac{\varepsilon}{N^2} \leq \Gamma\frac{\varepsilon}{N^2} \qquad \text{mixing efficiency: } \Gamma = 0.2$$

(Osborn, 1980)

Mixing observations

1. Integral: Tracer spreading (e.g. SF_6)
2. Direct: Microstructure measurements of temperature & velocity fluctuations
3. Parametric:
   a. Inversions in temperature or density (overturn method)
   b. Finestructure variance of velocity shear and density strain

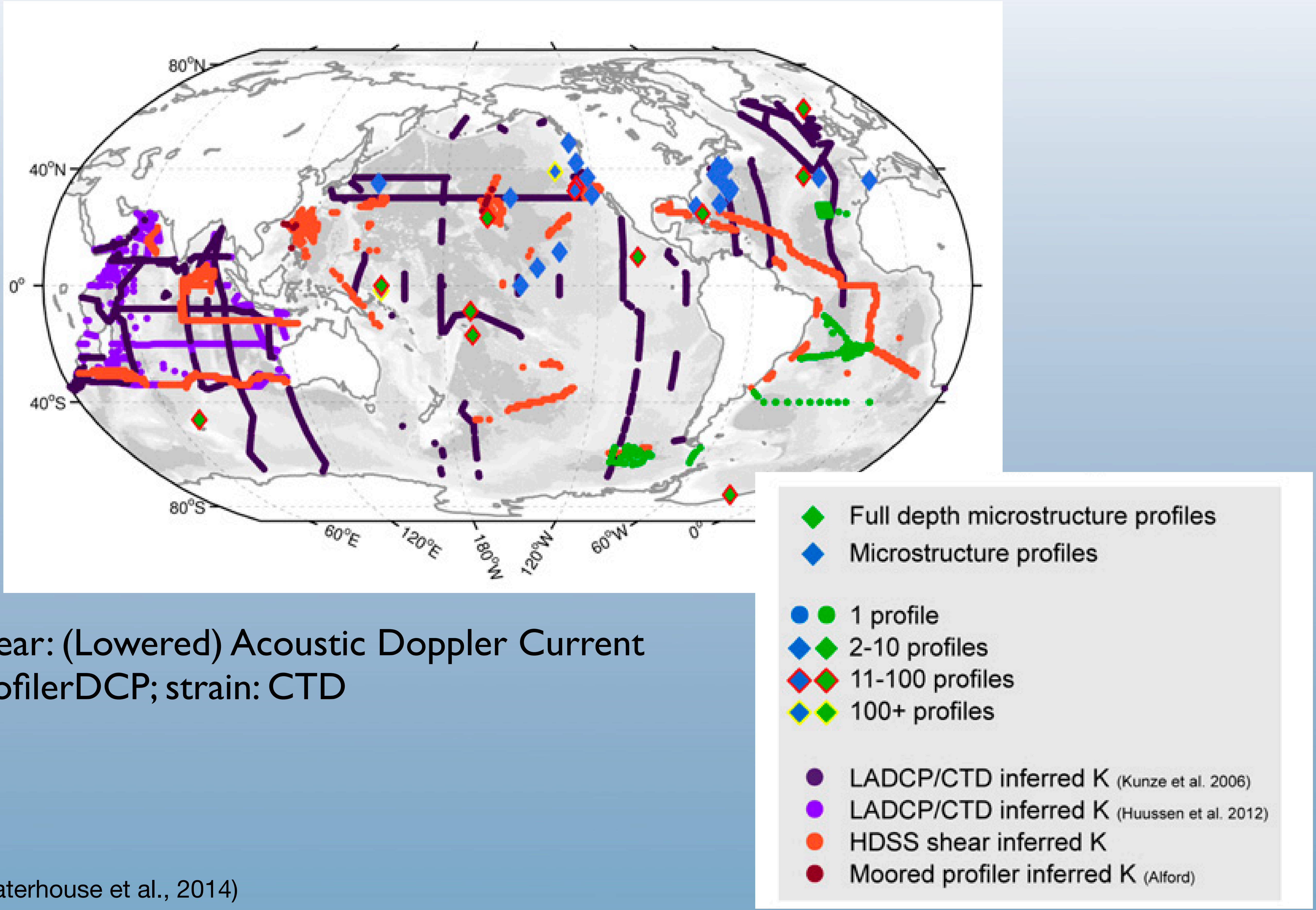
Mixing over rough topography, microstructure



(Polzin et. al, 1997)

Diapycnal diffusivity in the Brazil Basin from HRP microstructure measurements

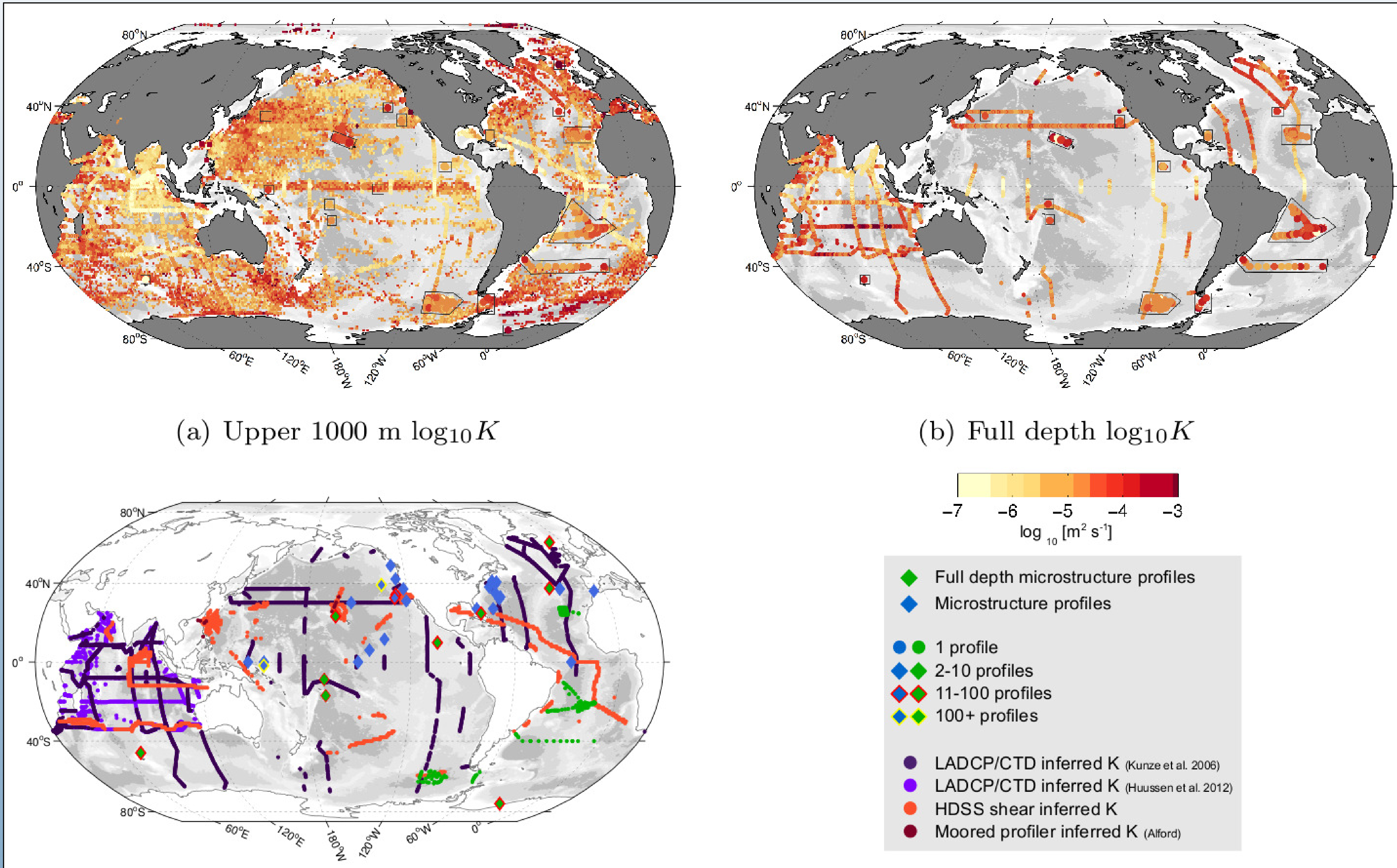
Finescale parameterizations of mixing - why



Shear: (Lowered) Acoustic Doppler Current ProfilerDCP; strain: CTD

(Waterhouse et al., 2014)

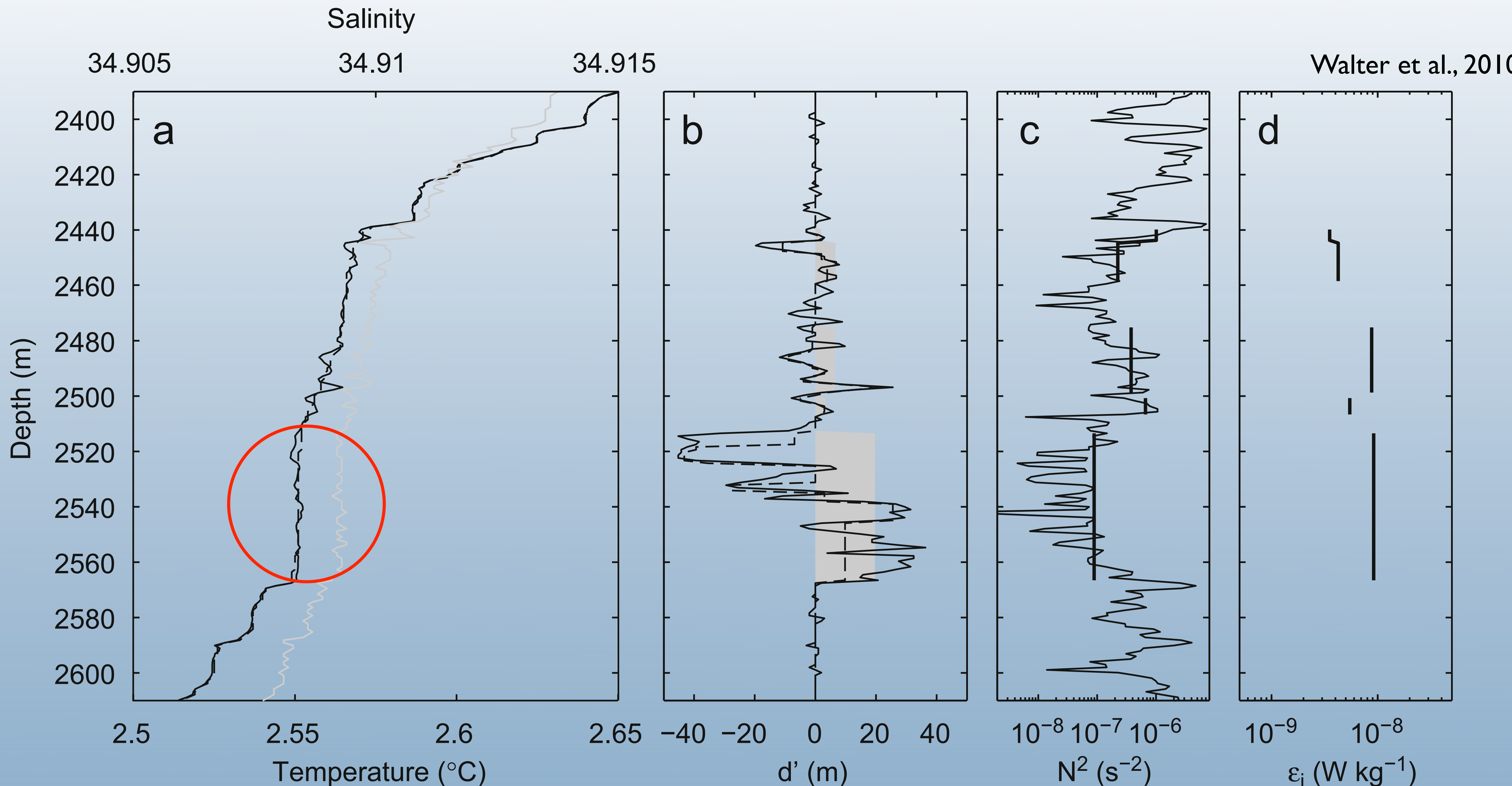
Finescale parameterizations of mixing - why



(Waterhouse et al., 2014)

- Large data sets with good (better) spatial & temporal resolution

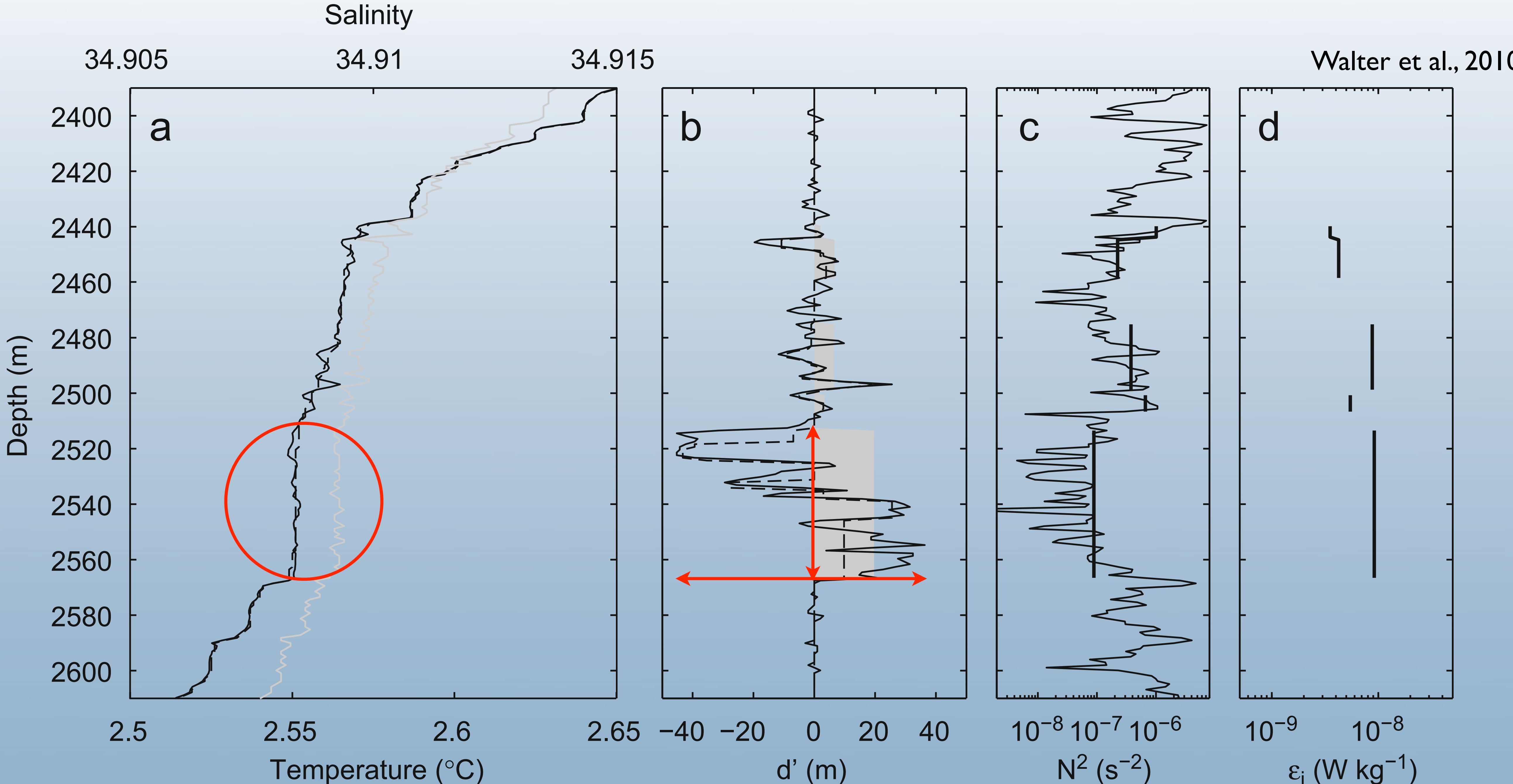
Thorpe scale (Overturn) method



- Breaking internal waves generate overturns visible as instabilities in density/temperature profiles

- Size of overturns is proxy for strength of turbulence
- Dissipation ε can be estimated from density/temperature displacements

Thorpe scale (Overturn) method

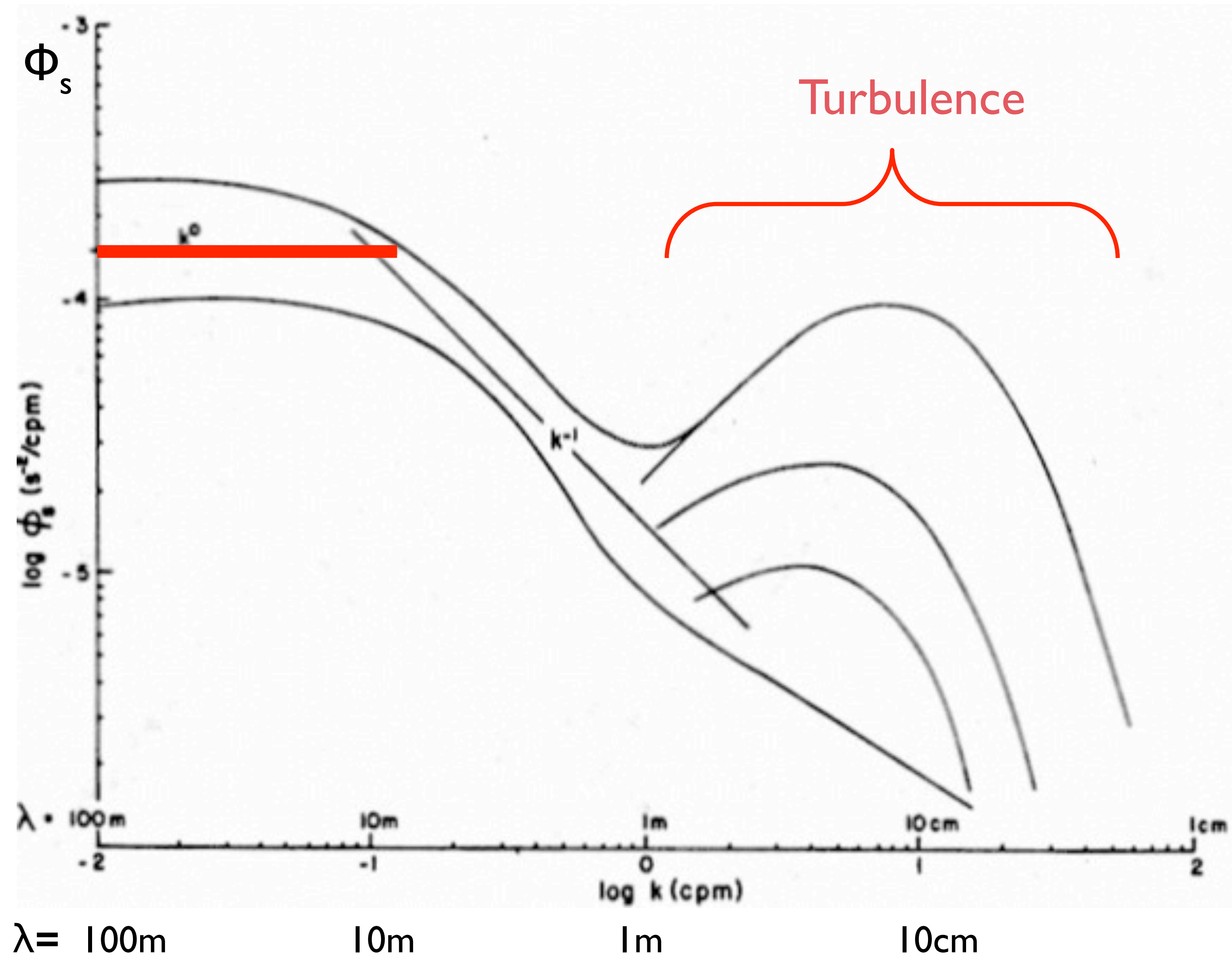


- Breaking internal waves generate overturns visible as instabilities in density/temperature profiles
- Size of overturns is proxy for strength of turbulence
- Dissipation ε can be estimated from density/temperature displacements

Finescale shear and strain

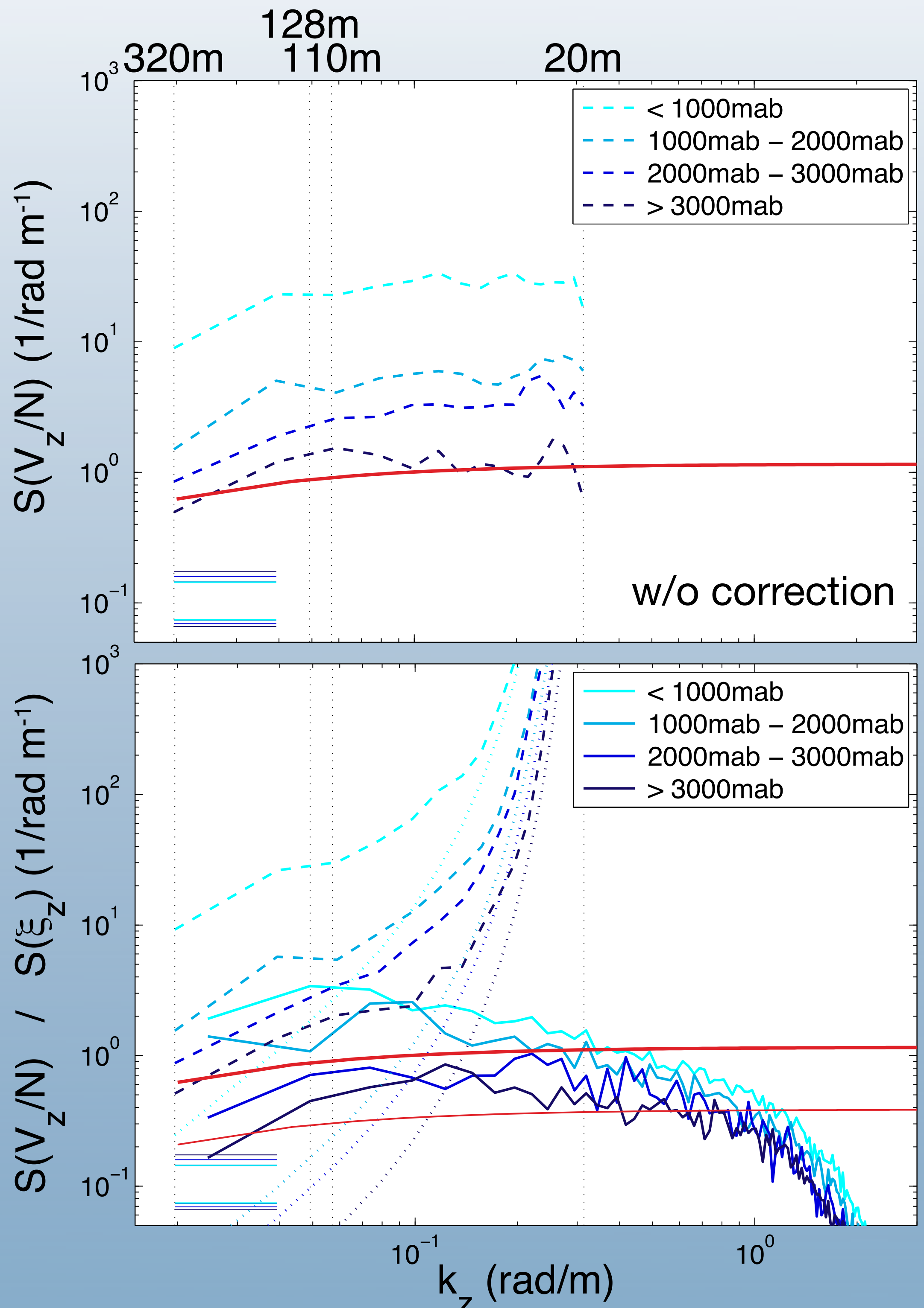
- Assumption: dissipation of energy by turbulence is in equilibrium with energy production by internal waves
- Dissipation ε is proportional to the energy level of the spectrum of vertical current shear for wavelengths > 10m
- Analogous: strain of the density field

vertical shear of horizontal velocitiy



(Gargett et al., 1981)

Practical application:



Köhler et al., 2014

Shear: LADCP; strain: CTD

Diffusivity from shear & strain:

$$K = K_0 \frac{\langle V_z^2 \rangle^2}{_{\mathrm{GM}}\langle V_z^2 \rangle^2} h_1(R_\omega) j\left(\frac{f}{N}\right)$$

Shear/strain variance ratio R_ω - a measure of the aspect ratio and frequency content of the IW field; for a single wave:

$$R_\omega = \frac{\langle V_z^2 \rangle}{\overline{N}^2 \langle \xi_z^2 \rangle} = \frac{\mathrm{HKE}}{\mathrm{APE}} = \frac{\omega^2 + f^2}{\omega^2 - f^2} \cong 1 + \frac{2f^2 k_z^2}{\overline{N}^2 k_h^2}.$$

For strain-only use

$$K = K_0 \frac{\langle \xi_z^2 \rangle^2}{_{\mathrm{GM}}\langle \xi_z^2 \rangle^2} h_2(R_\omega) j(f/N),$$

with fixed R_ω.

Gregg et al., 2003; Kunze et al., 2006

Finescale shear and strain - problems:

- Instrumental: instrument noise, attenuation by filtering etc
- Methodological: energy content/spectral shape; non-homogeneity of internal wave field: latitudinal dependencies (PSI), distortions (vertical/horizontal wavenumber),

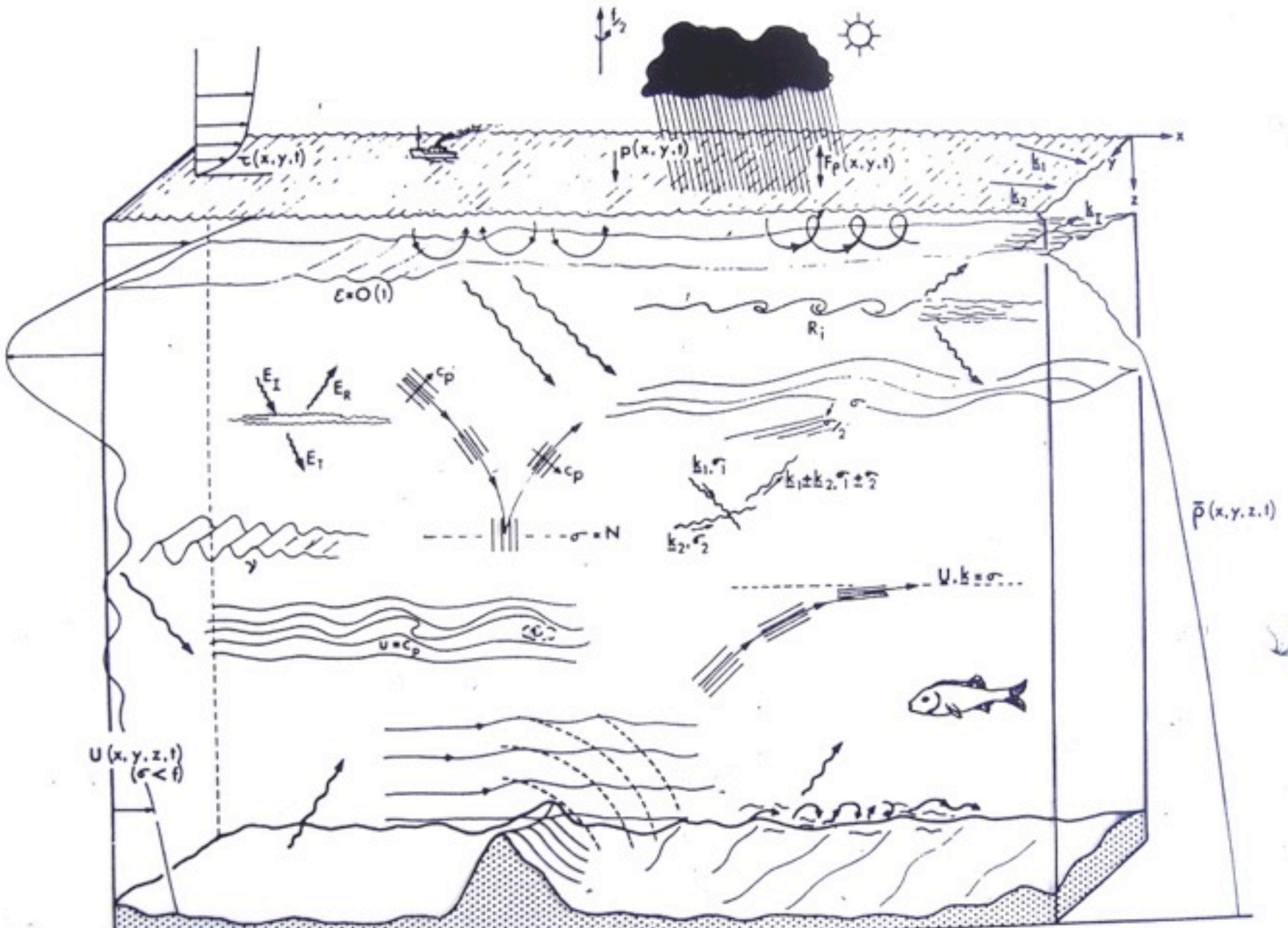
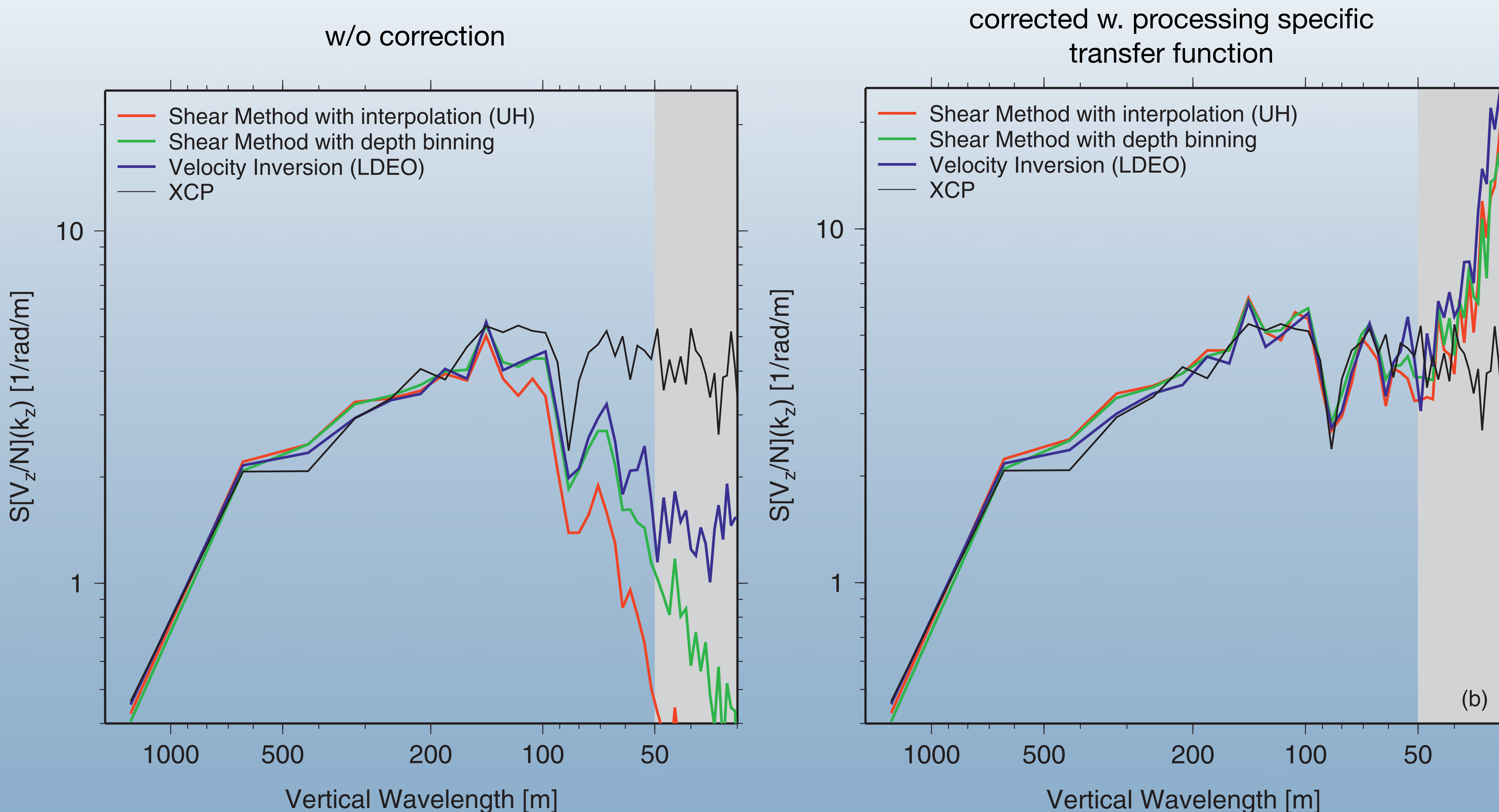


Fig. 5. Physical processes affecting internal waves.

(Thorpe, 1975)

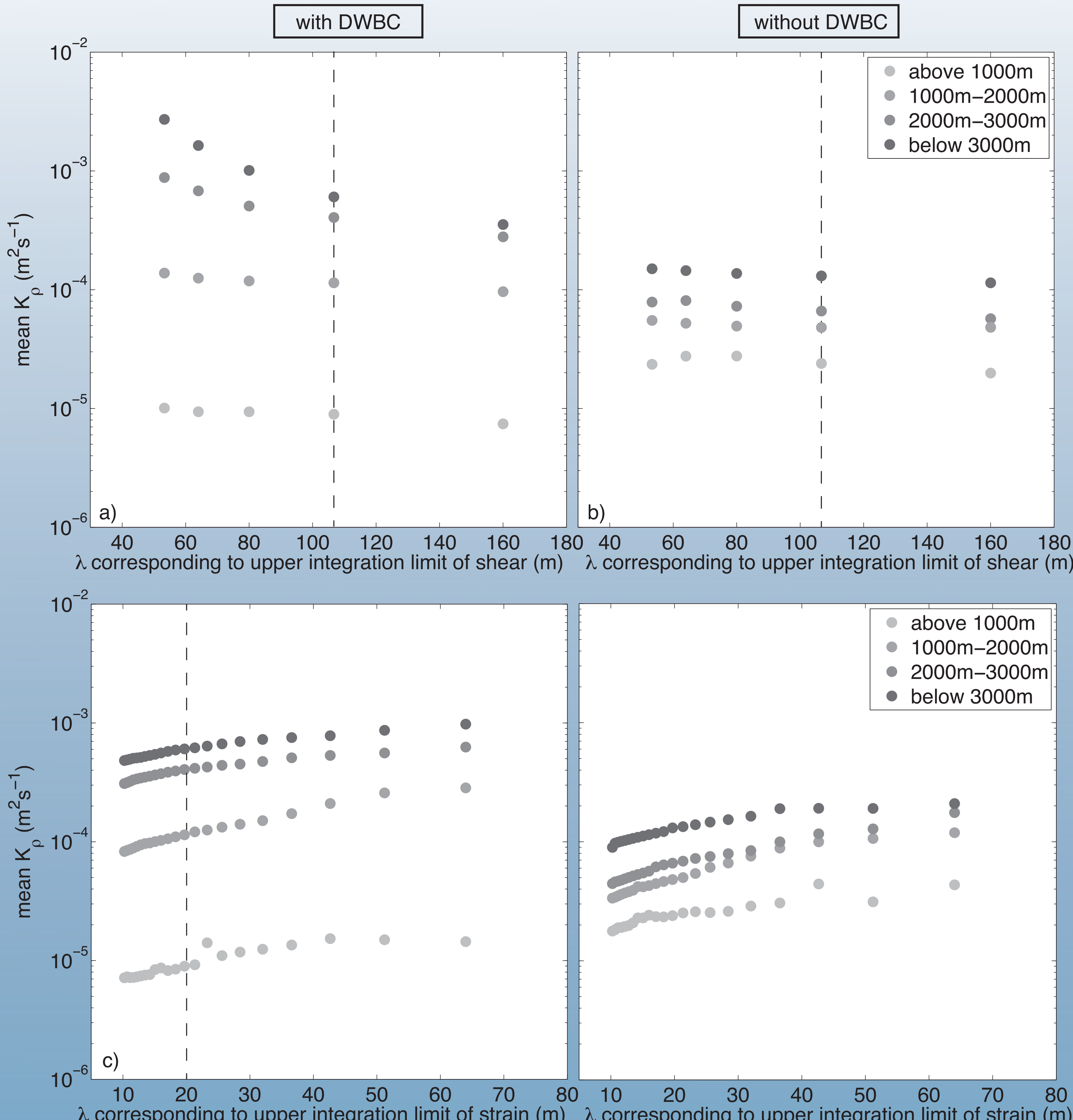
Instrument noise and and attenuation



(Thurnherr, 2012)

- Spectral level for sorter wavelengths depends on instrument settings & data processing method ➜ spectral correction needed

Sensitivity to integration limits

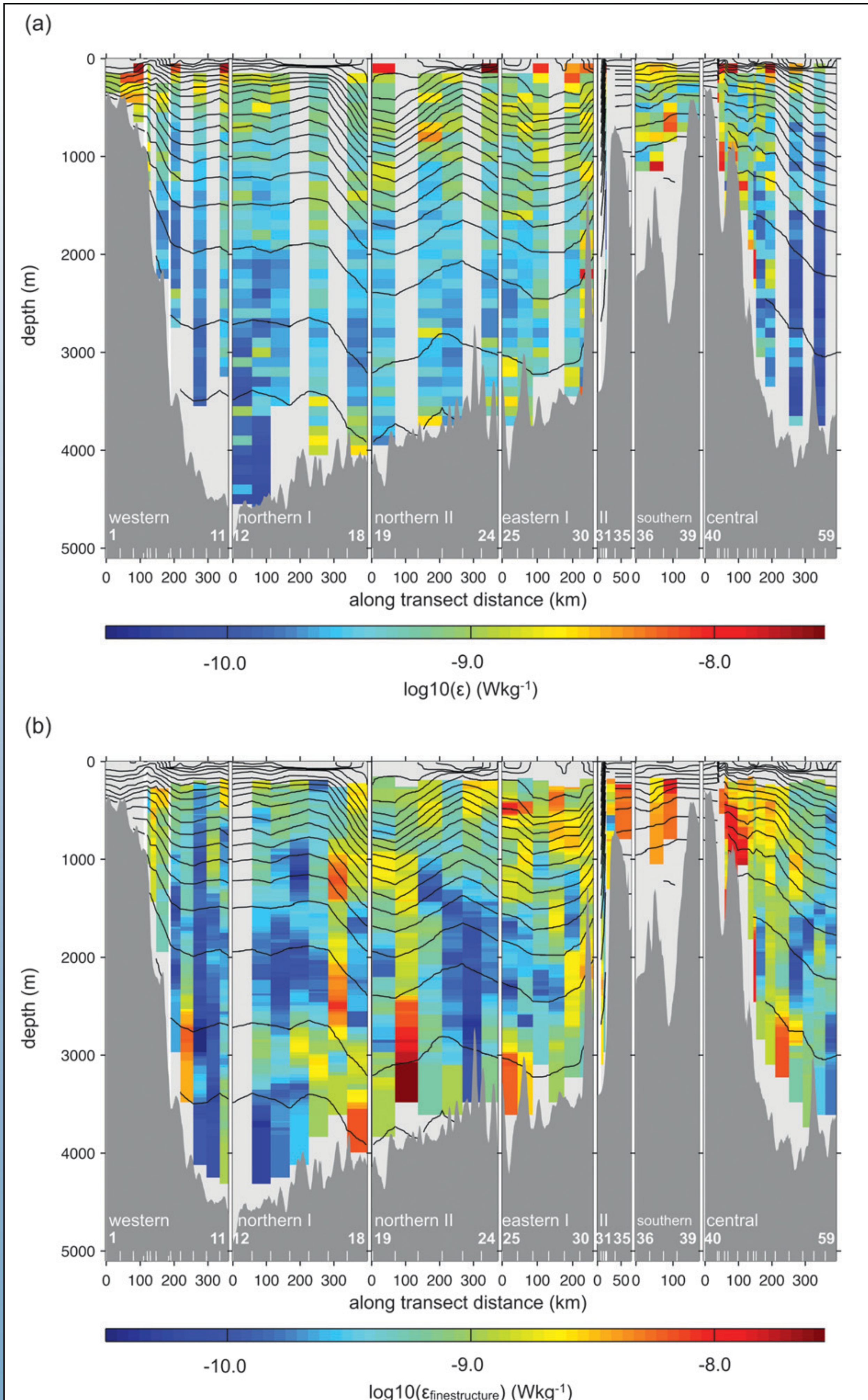


... and choice of integration limits - problems: noise, contamination by low modes, shape of spectrum for high/low shear/strain variance levels

(Köhler et al., 2014)

Microstructure

Finestructure



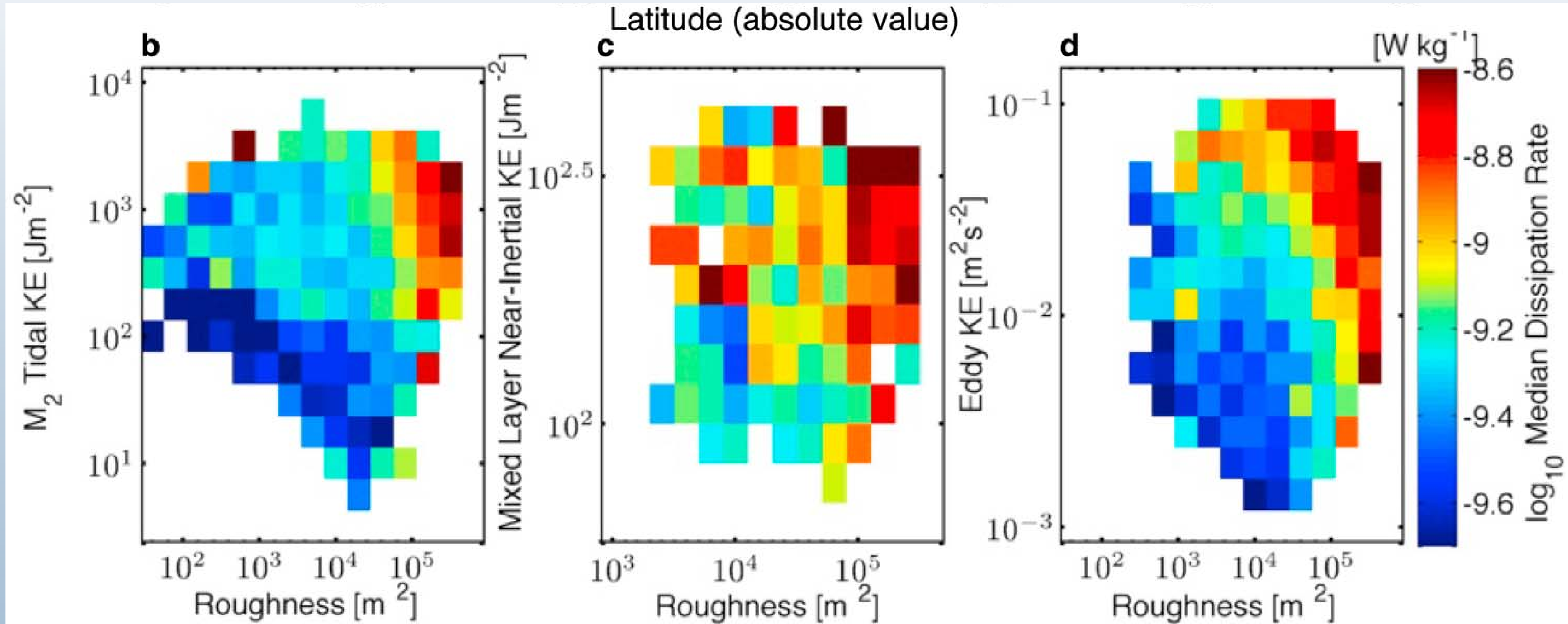
Finescale parameterizations compared to microstructure measuremen: Example from Southern Ocean

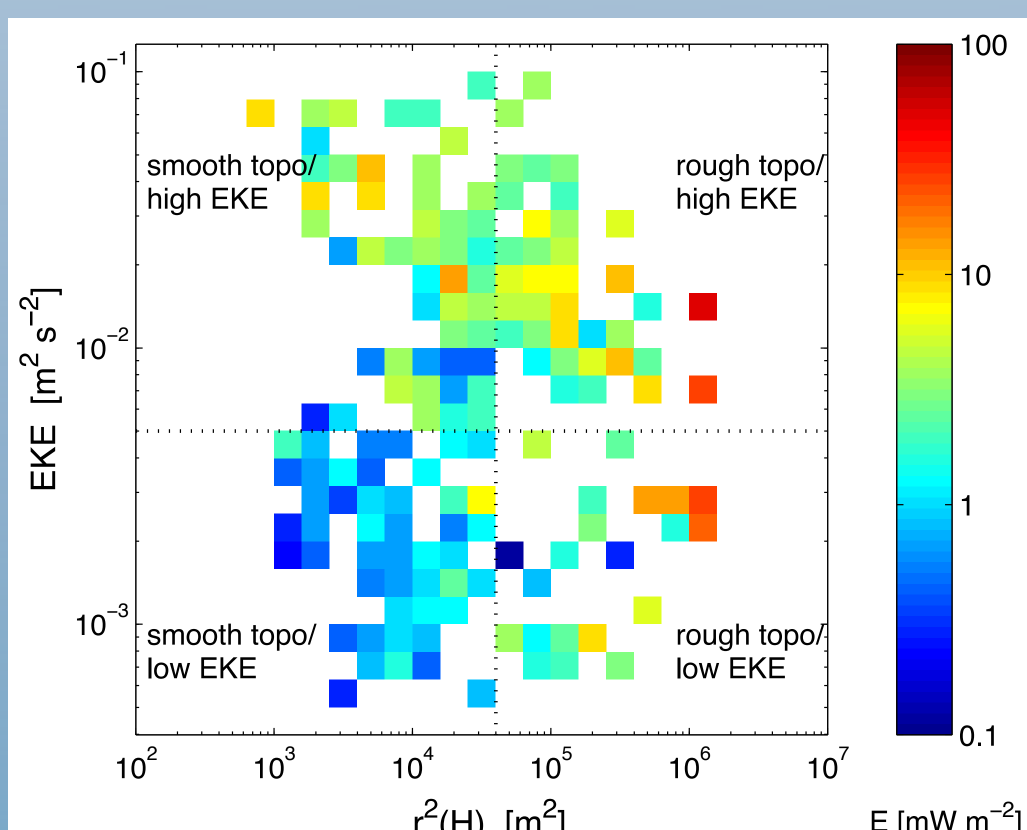
Differences may indicate

- violation of underlying assumptions, e.g. mixing not (solely) caused by breaking internal waves
- variable shear/strain ratio
- bad signal/noise ratio
- ....
- i.e. either caused by underlying physics or measurement error

(Waterman et al., 2013)

Energy dissipation

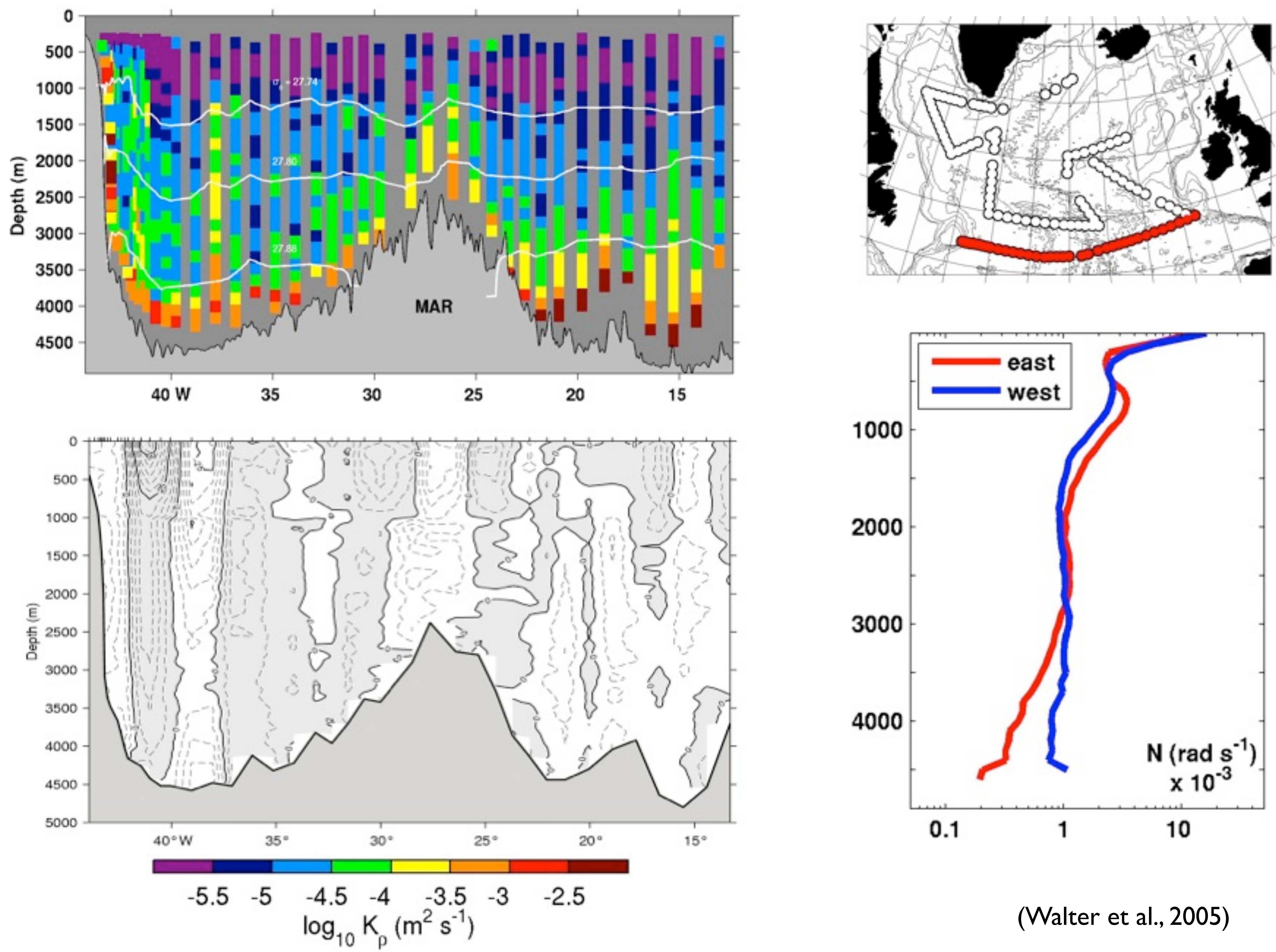




Median dissipation vs. roughness, World ocean, from ARGO floats (Whalen et al., 2012)

Integrated dissipation vs. roughness, North Atlantic, from LADCP/CTD (Li, 2013)

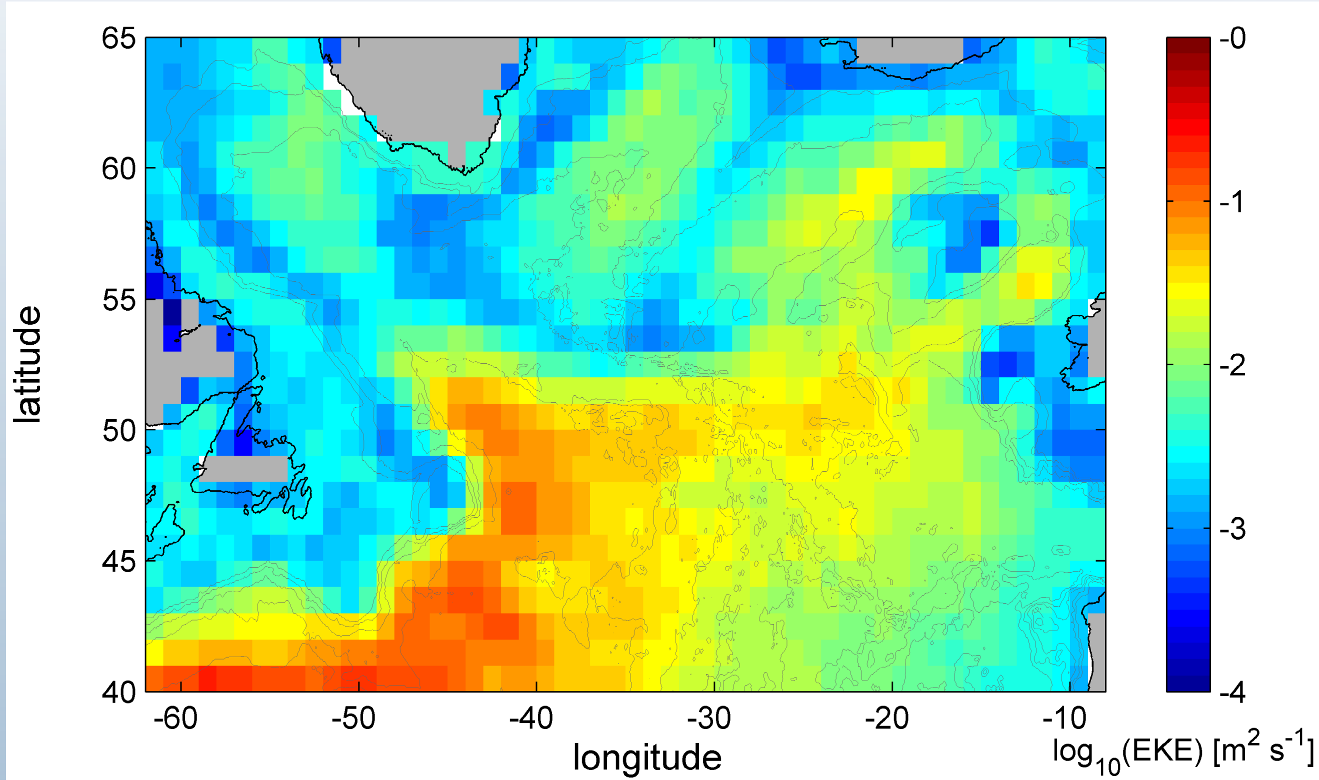
Spatial distribution of K in the North Atlantic



(Walter et al., 2005)

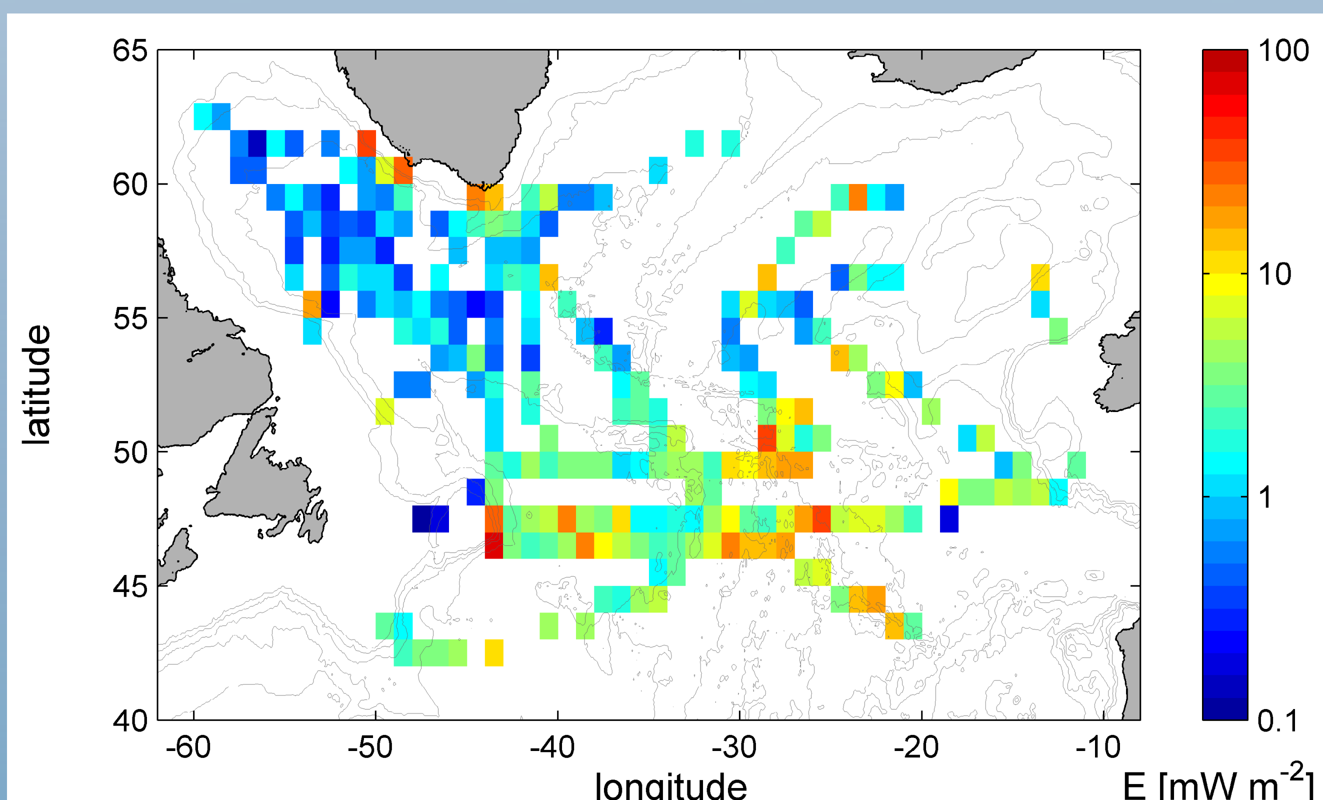
Spatial distribution of ϵ - role of EKE

EKE



(a) Eddy kinetic energy E_k

Dissipation



(b) Integrated energy dissipation rates E over whole water columns, averaged in $1° \times 1°$ boxes.

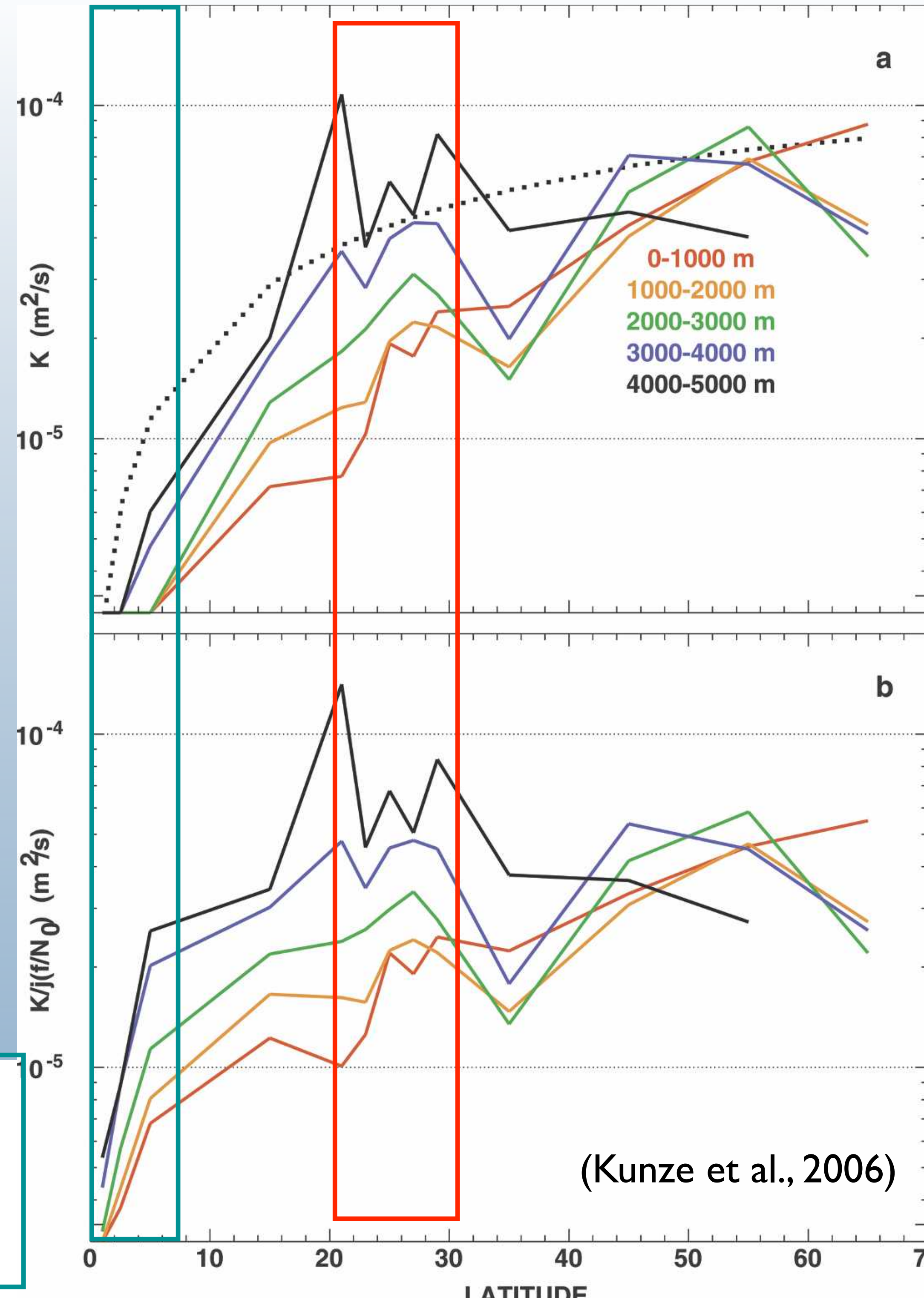
Horizontal patterns of integrated energy dissipation (from LADCP/CTD) in the North Atlantic

(Li, 2013)

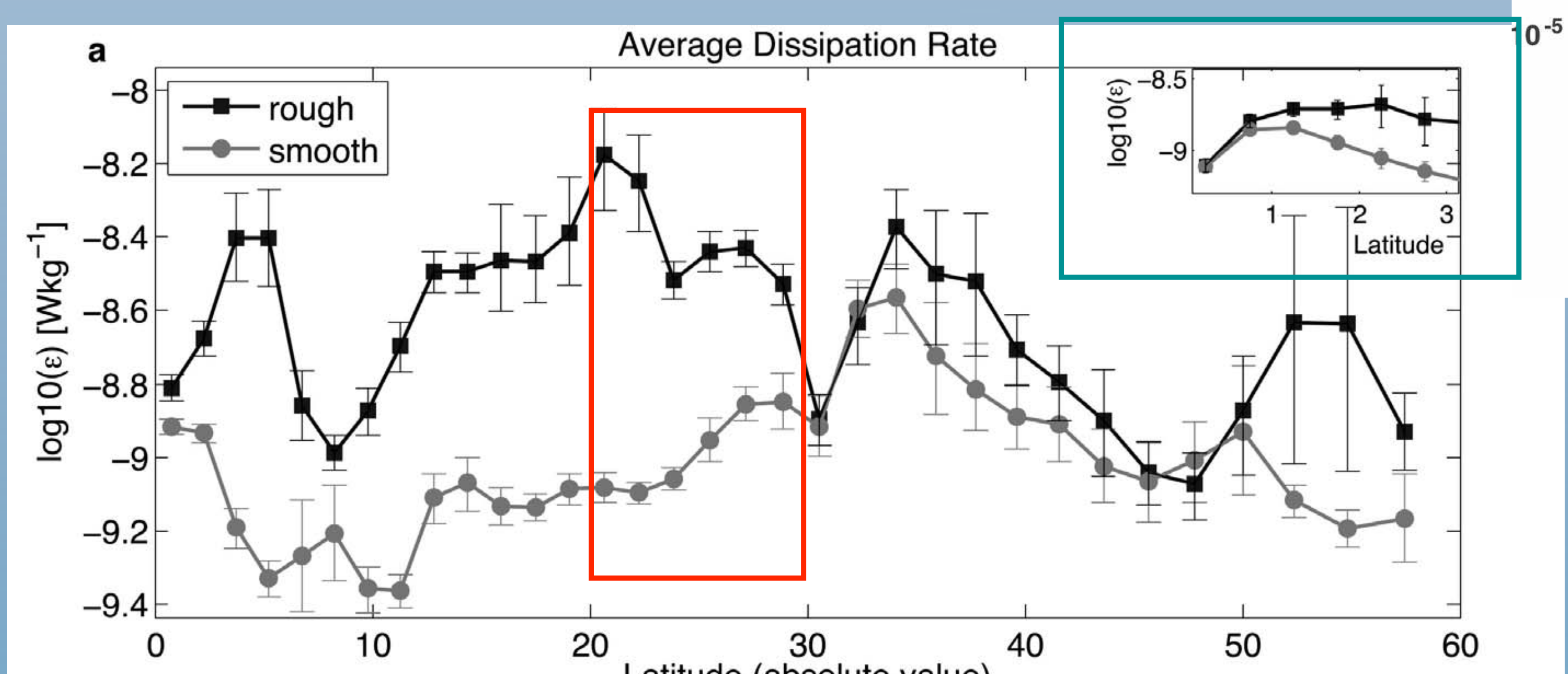
Dependence on latitude, PSI

- Diffusivity vs. latitude for different depth ranges, world ocean (WOCE lines), CTD, strain-only parameterization, w/o (upper) and with (lower) latitude correction function j(f/N)

- Energy dissipation (250-1000m) vs. latitude world ocean, ARGO floats, strain-only

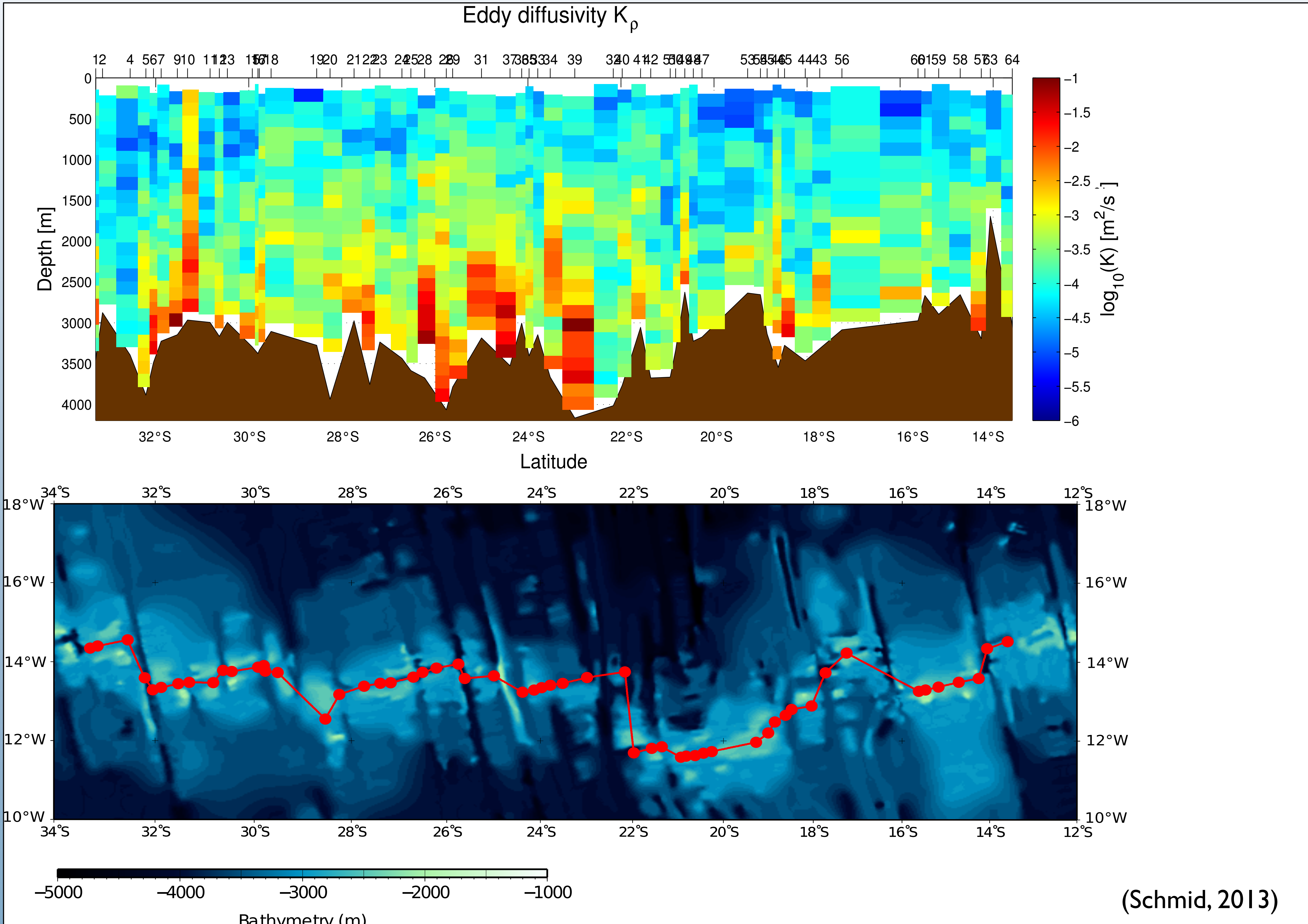


(Kunze et al., 2006)



(Whalen et al., 2012)

Latitudinal dependence, PSI

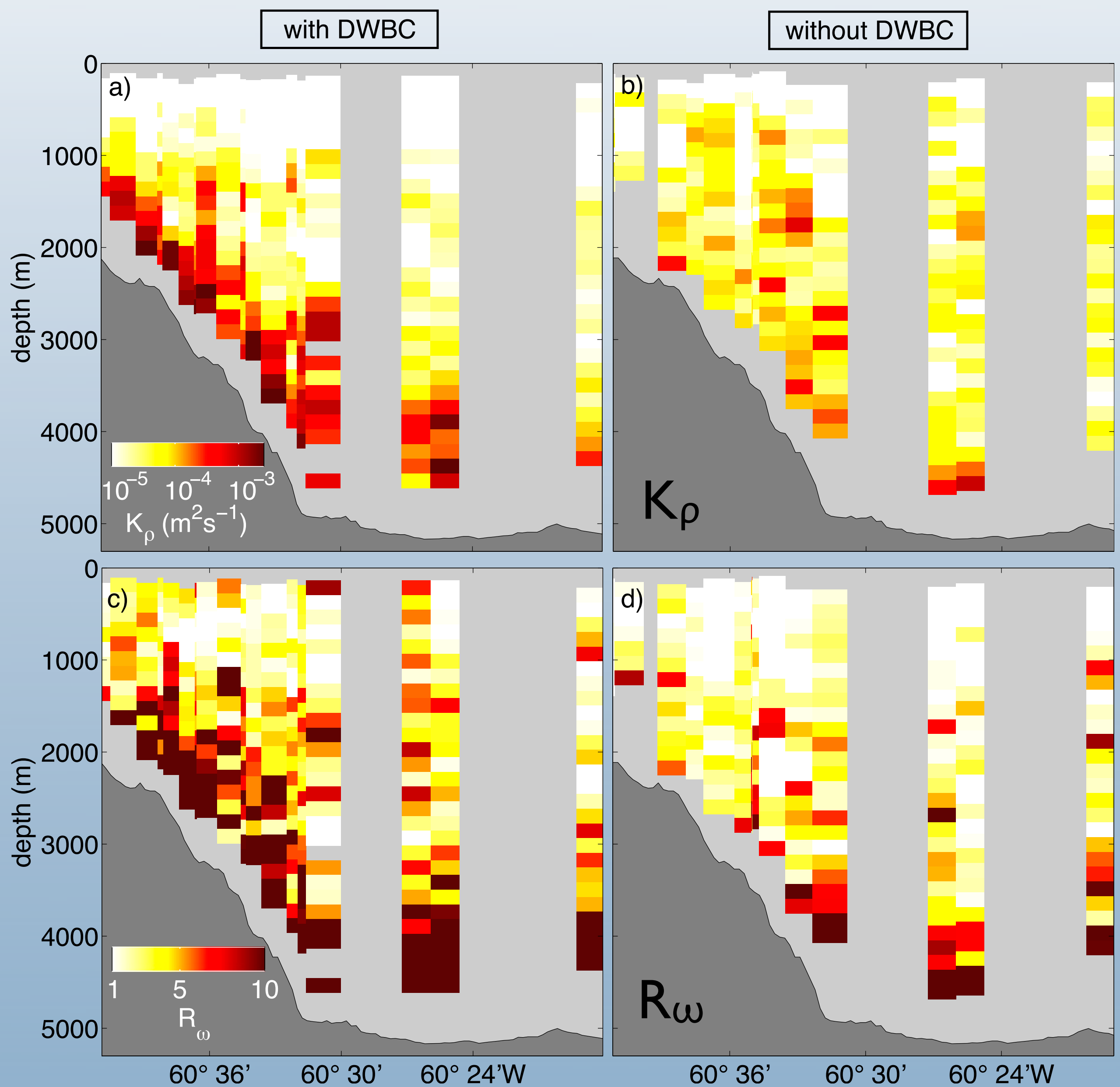


(Schmid, 2013)

- Meridional section of diffusivity along southern MAR, shear/strain /CTD/LADCP)

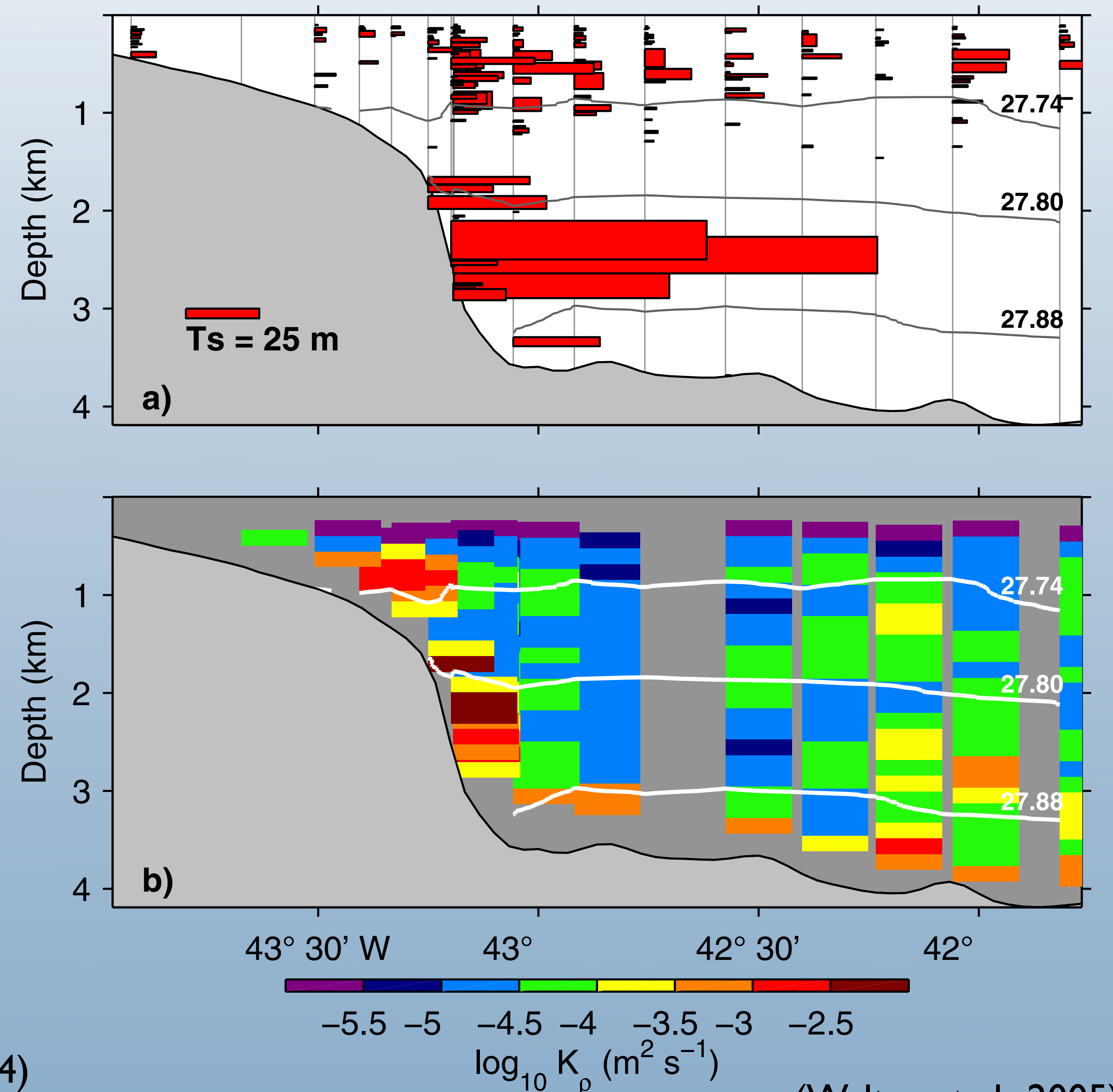
Strong mesoscale flow

Subtropical Atlantic (16°N)



(Köhler et al., 2014)

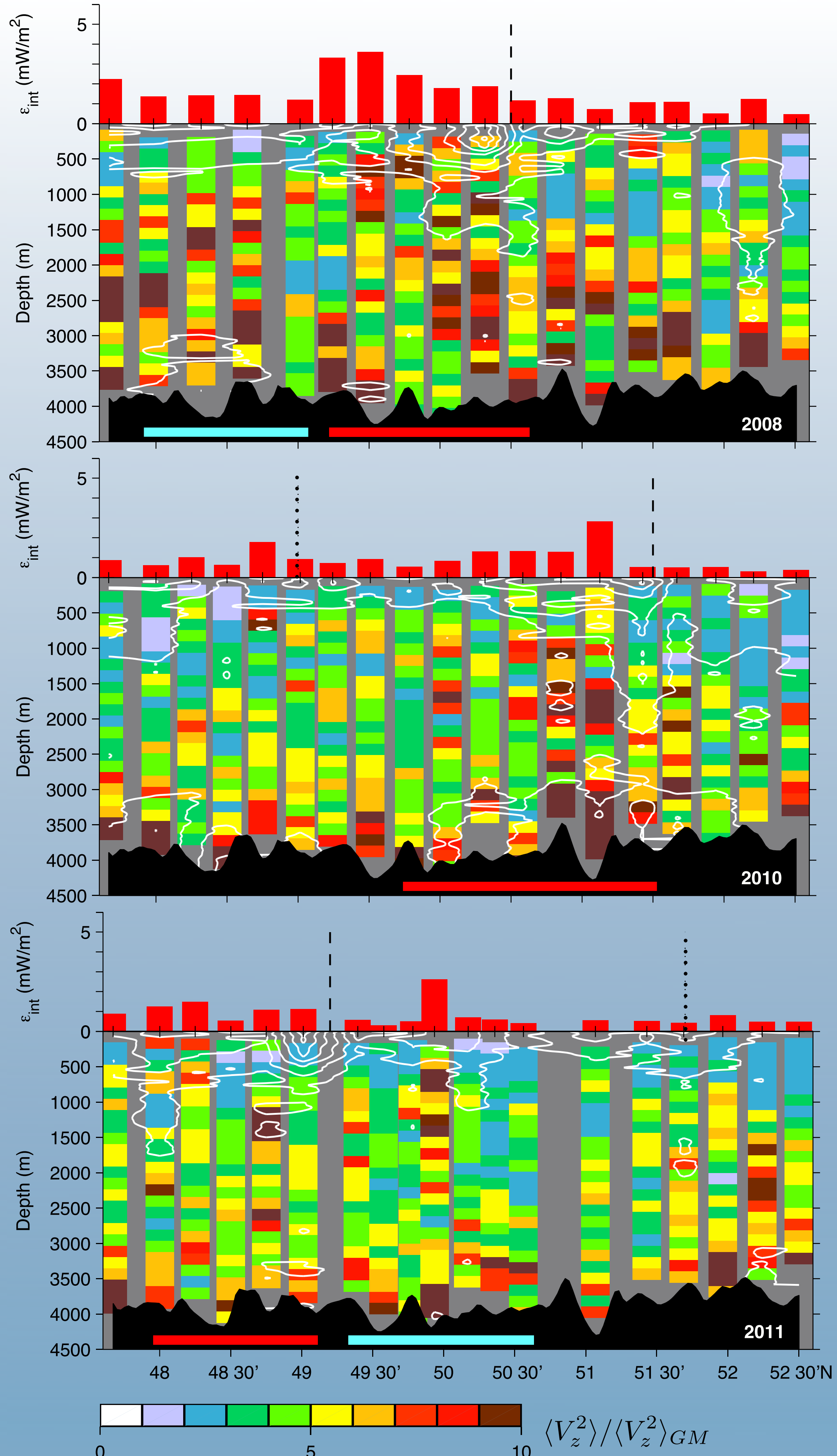
Subpolar Atlantic (48°N)



(Walter et al., 2005)

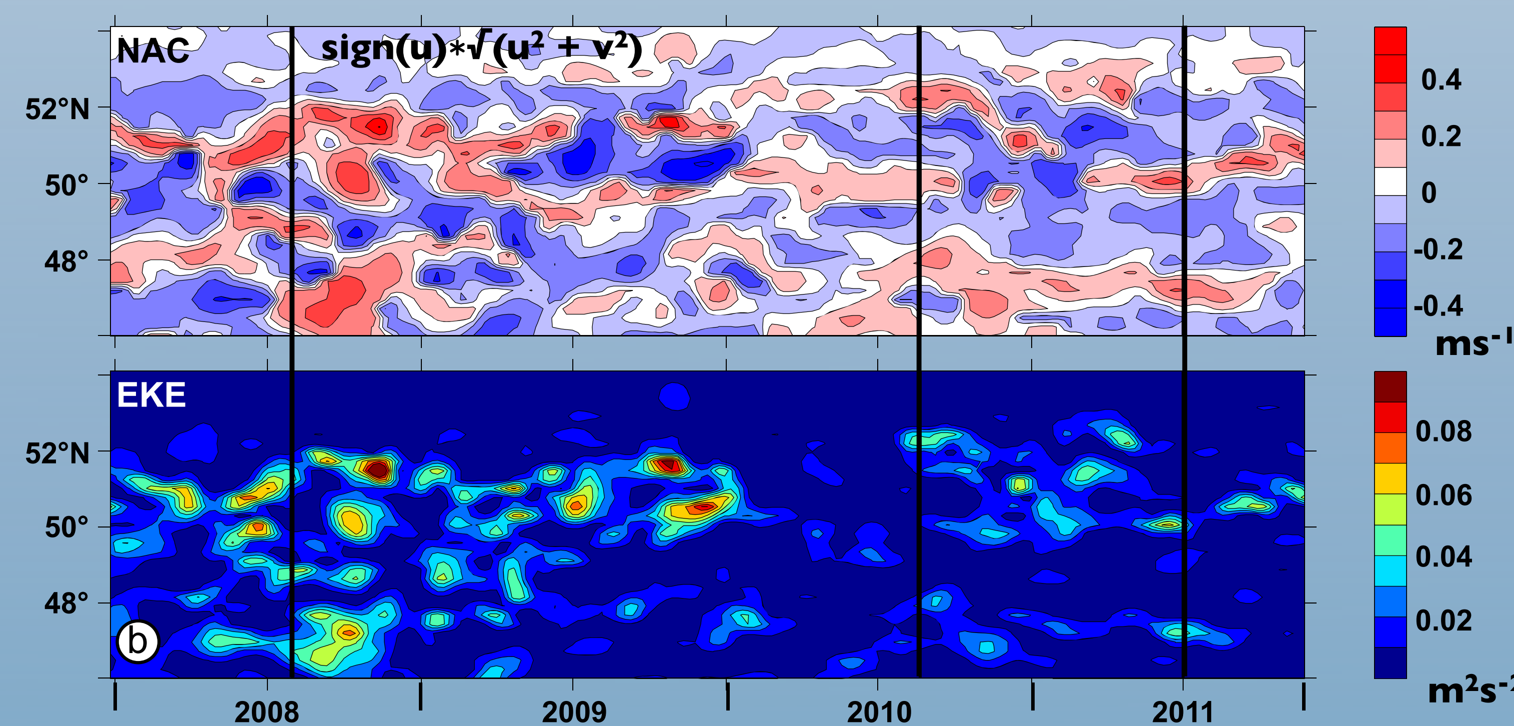
Composite diapycnal diffusivity from 3 (left) and 2 (right) sections across the DWBC position shows strongly enhanced mixing and altered shear/strain ratios when DWBC is present

Overturn size and distribution and mixing strength from shear/strains show strong mixing events in the DWBC



Mesoscale flow and temporal variability

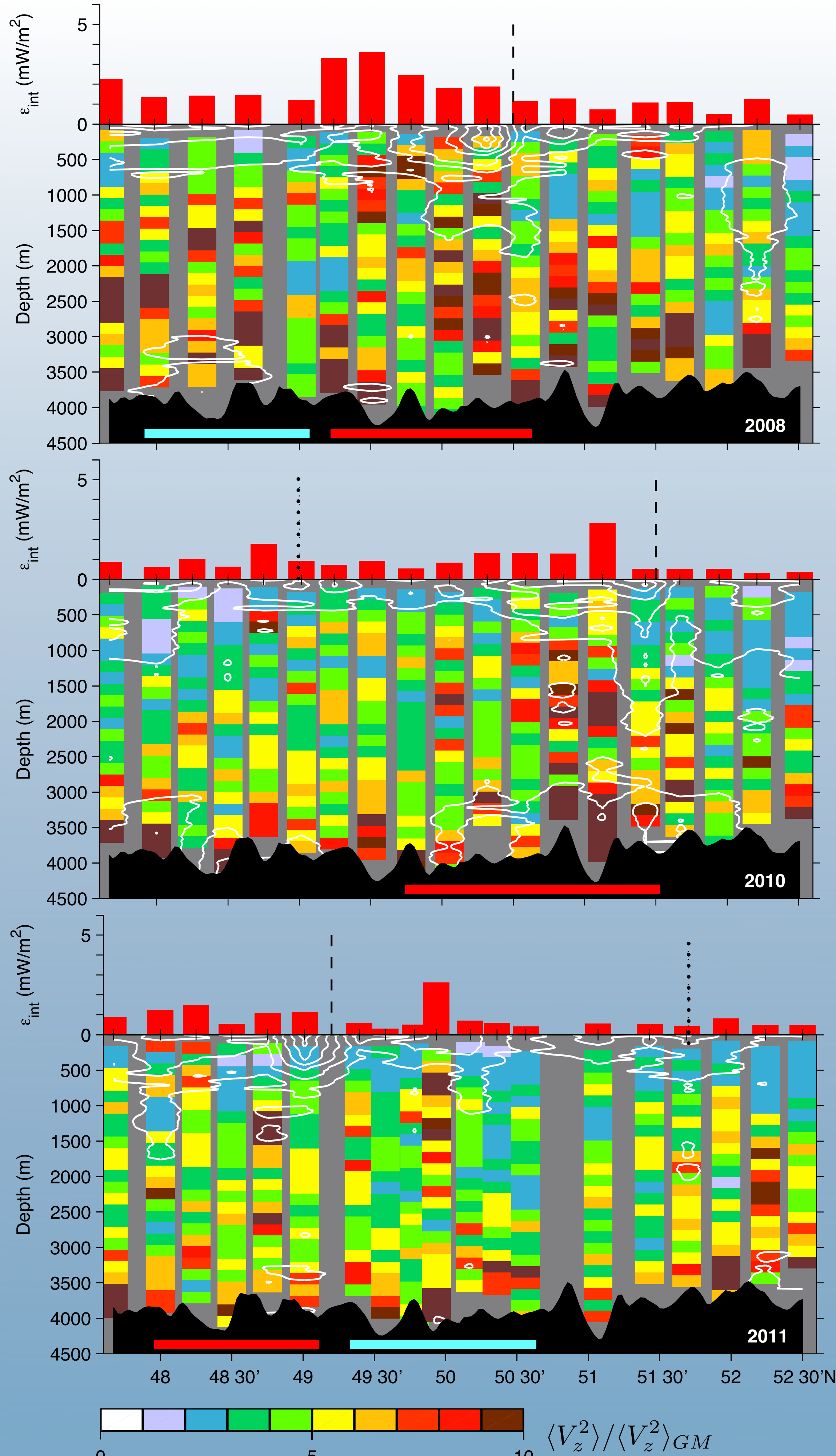
- Temporal variability of shear variance in internal wave band and integrated dissipation across NAC/SPF in the North Atlantic

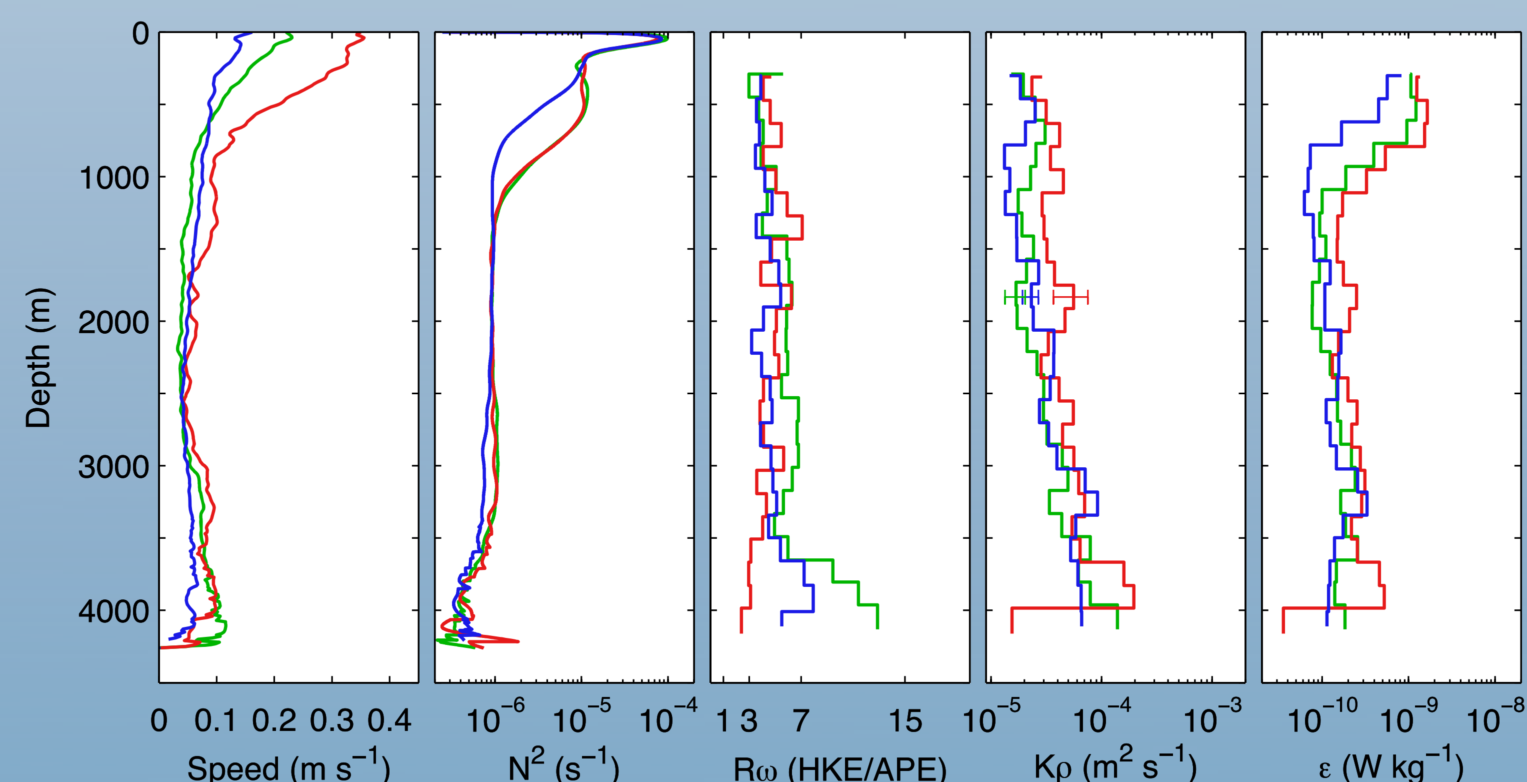


(Walter & Mertens 2013)

Mesoscale flow and temporal variability

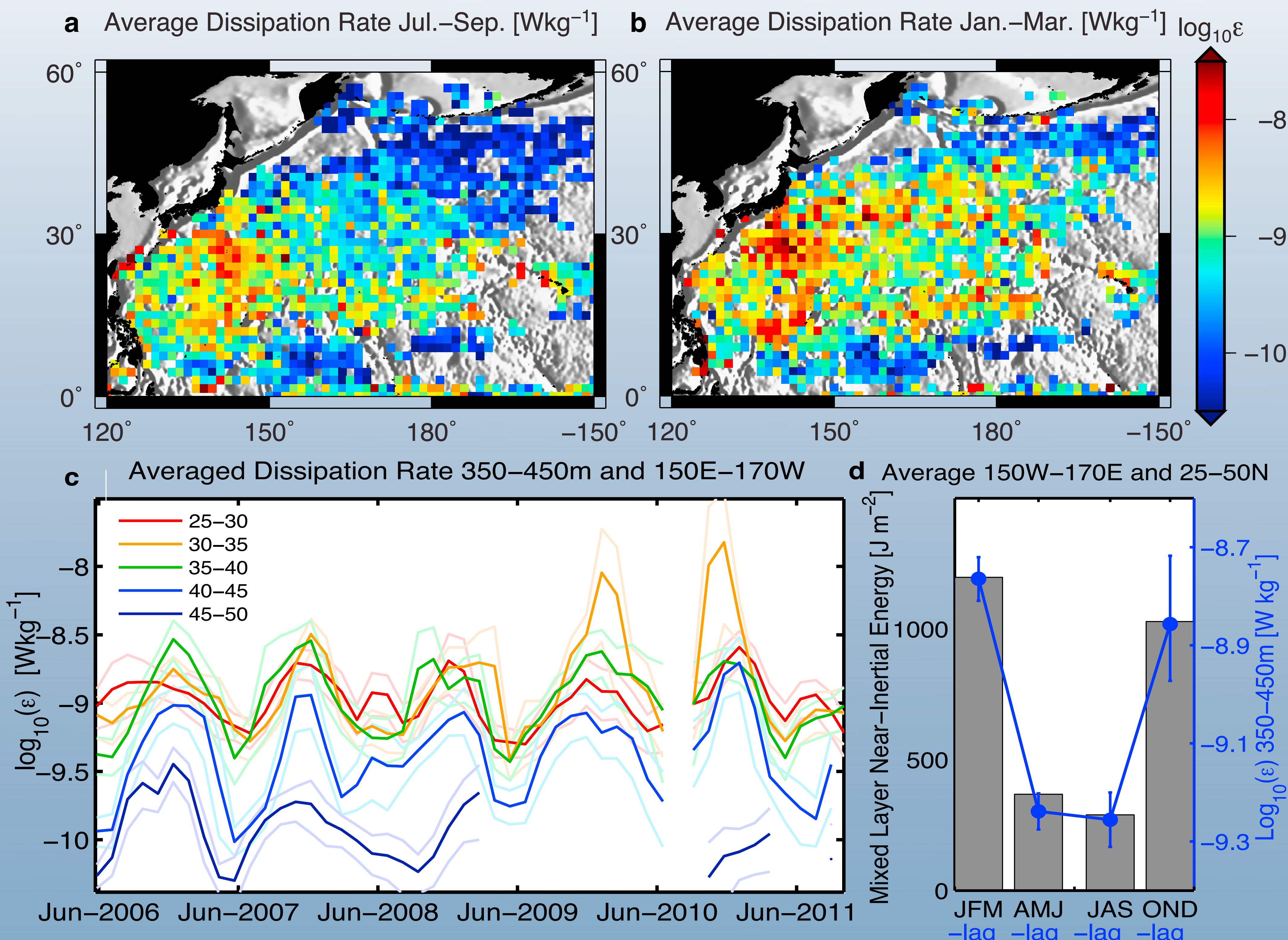
- Temporal variability of shear variance in internal wave band and integrated dissipation across NAC/SPF in the North Atlantic, resulting average profiles of diffusivity





(Walter & Mertens 2013)

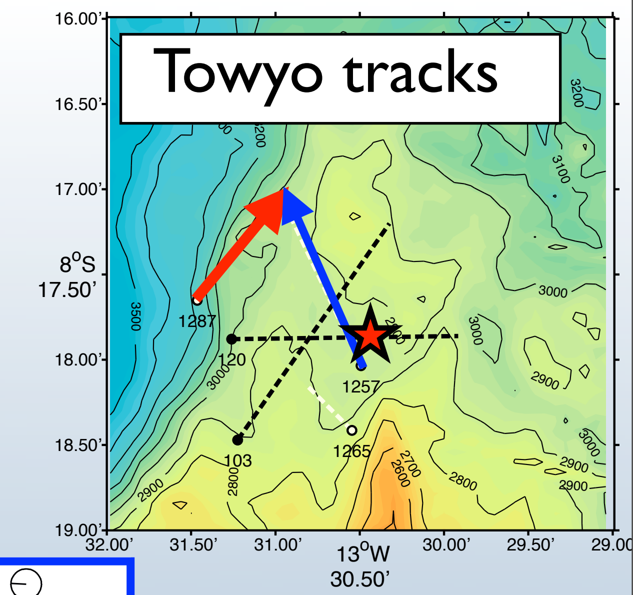
Temporal variability: seasonal cycle



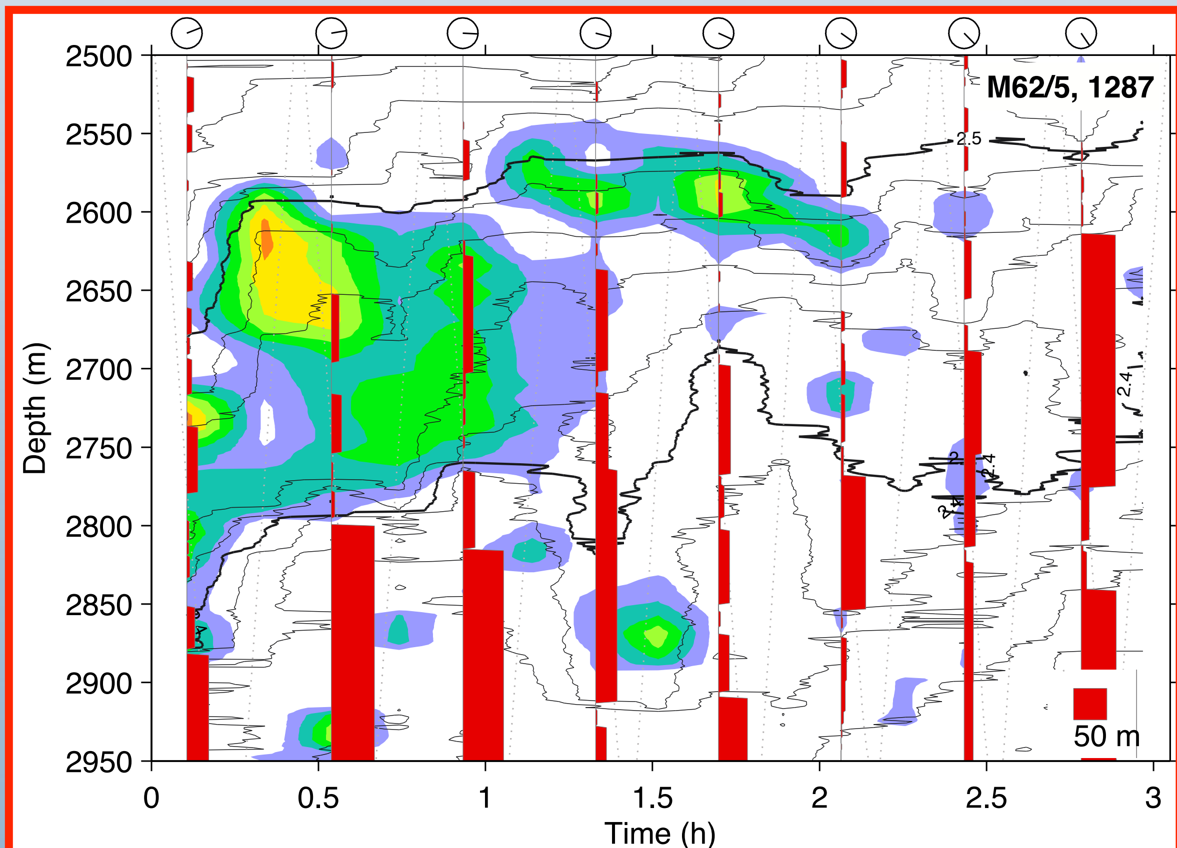
(Whalen et al., 2012)

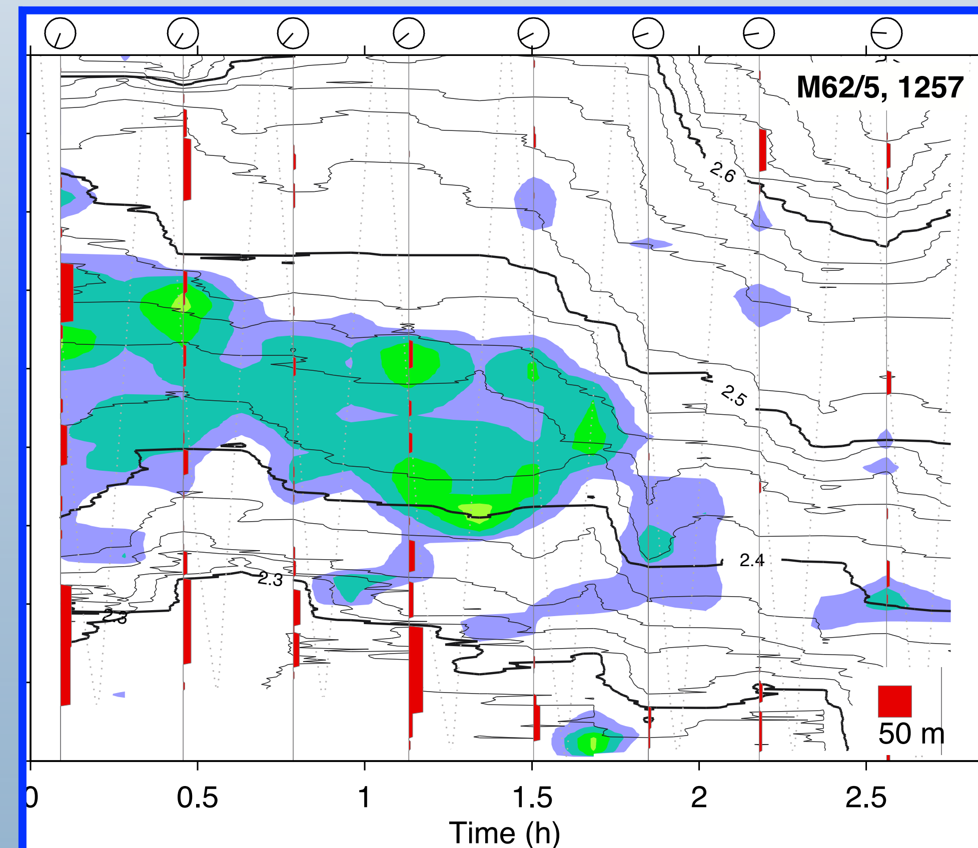
- Seasonal cycle in the Pacific from ARGO (strain only)

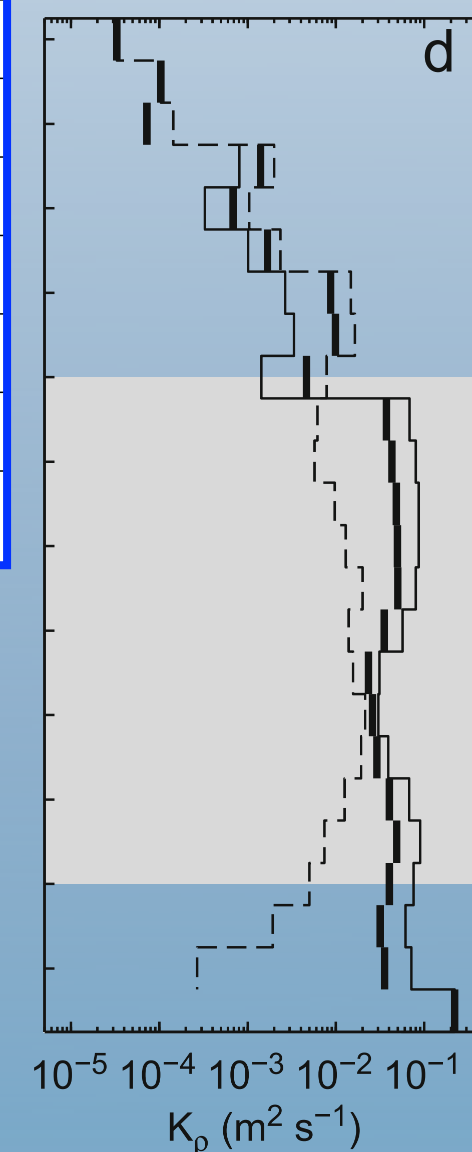
Temporal variability: tidal cycle



- Small scale mixing at rough topography, from Thorpe scale (hydrothermal vent site, southern MAR)







(Walter et al., 2010)

ebb:

- more inversions, strong mixing
- internal waves of up to 200 m amplitude and ~ 2h period

flood:

- sporadic inversions, weaker mixing

Important (open) Questions:

- What is the temporal variability of the spectral characteristics of the deep ocean internal wave field?
- What is the role of regional and temporal variability in forcing?
- How does variability in the internal wave field affect observable spectral properties used in finescale parameterizations of mixing?