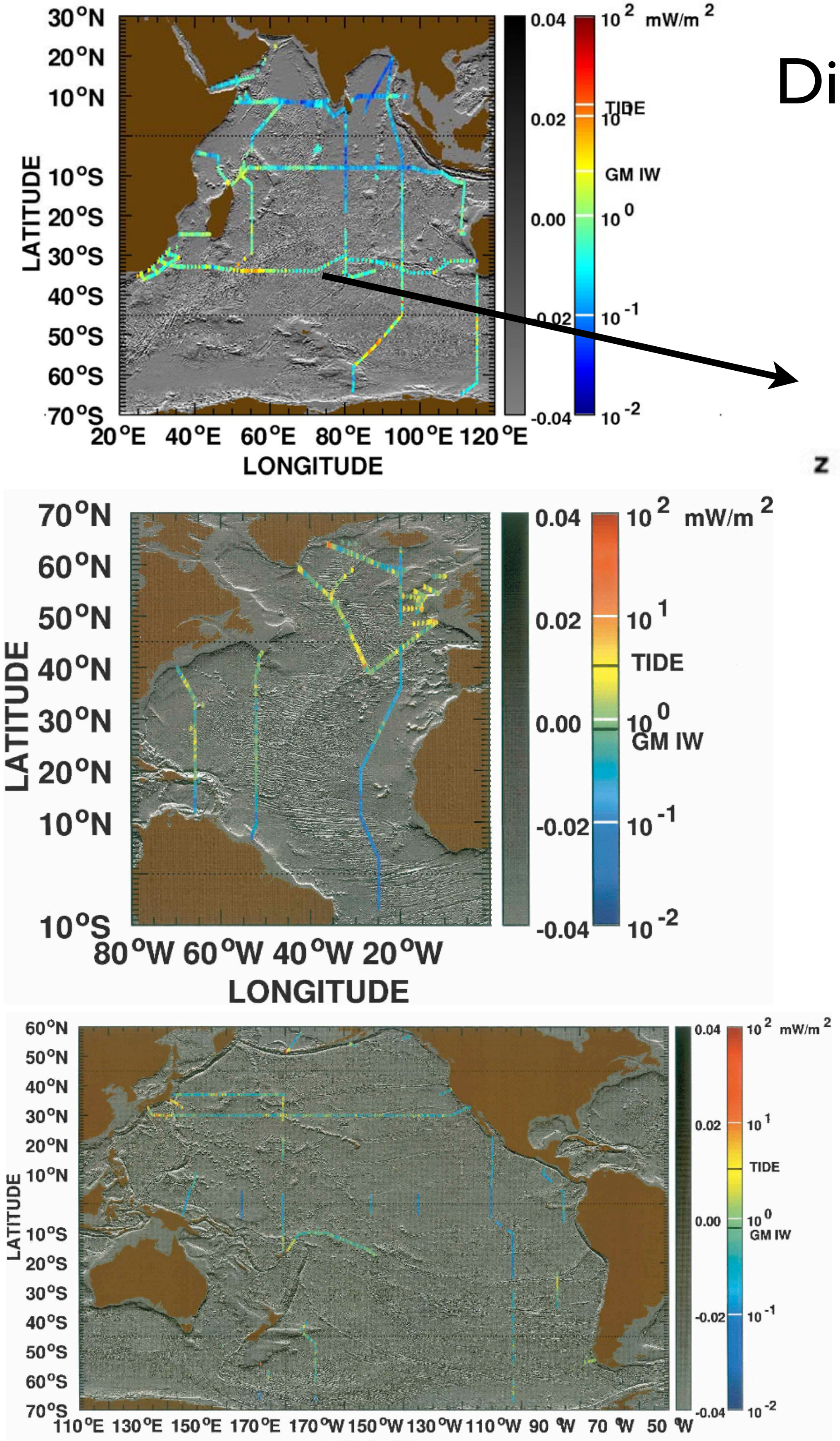
Mixing for the masses

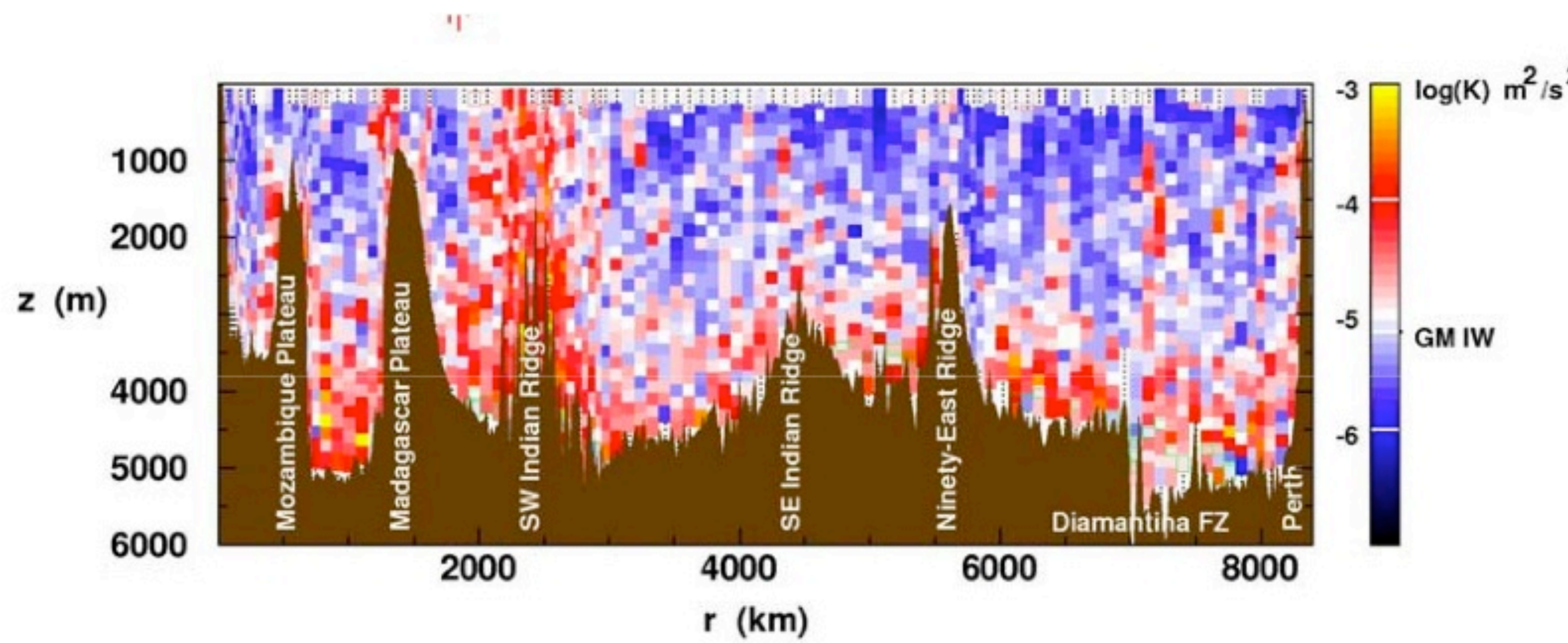
Jennifer MacKinnon

7 May 2009

Global mixing estimates



Diapycnal dissipation/diffusivity from WOCE CTD/ LADCP data

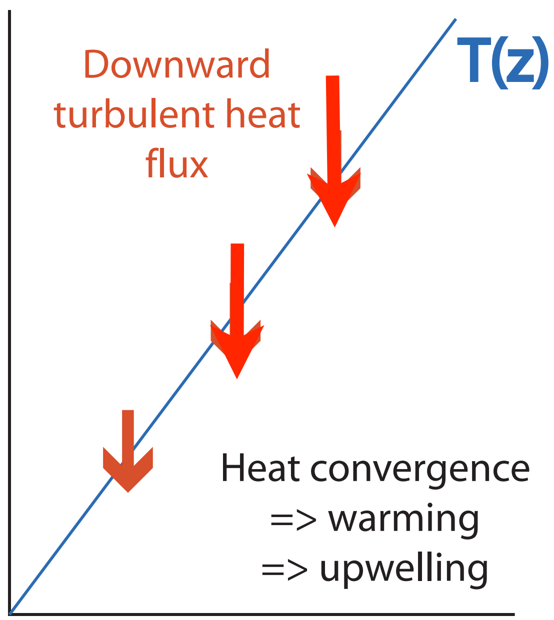


- mixing is patchy in space and time
- not the uniform diffusivity assumed in most large-scale models
- does this matter?

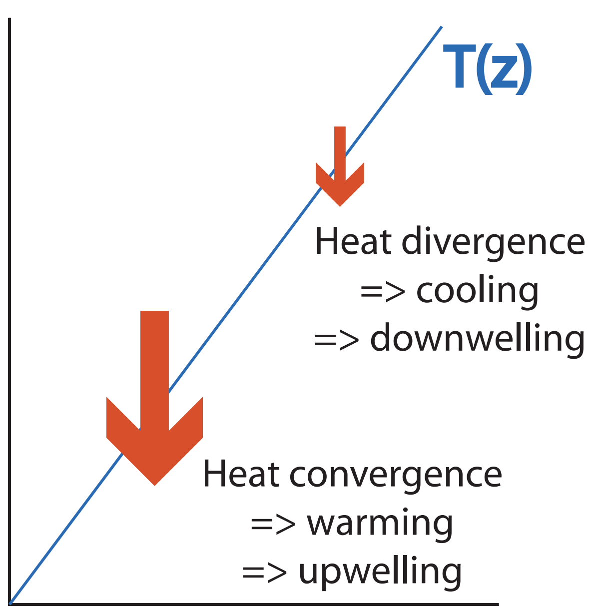
Kunze et al. (2006):

Patchy mixing matters

Vertical structure: key to water mass convergence

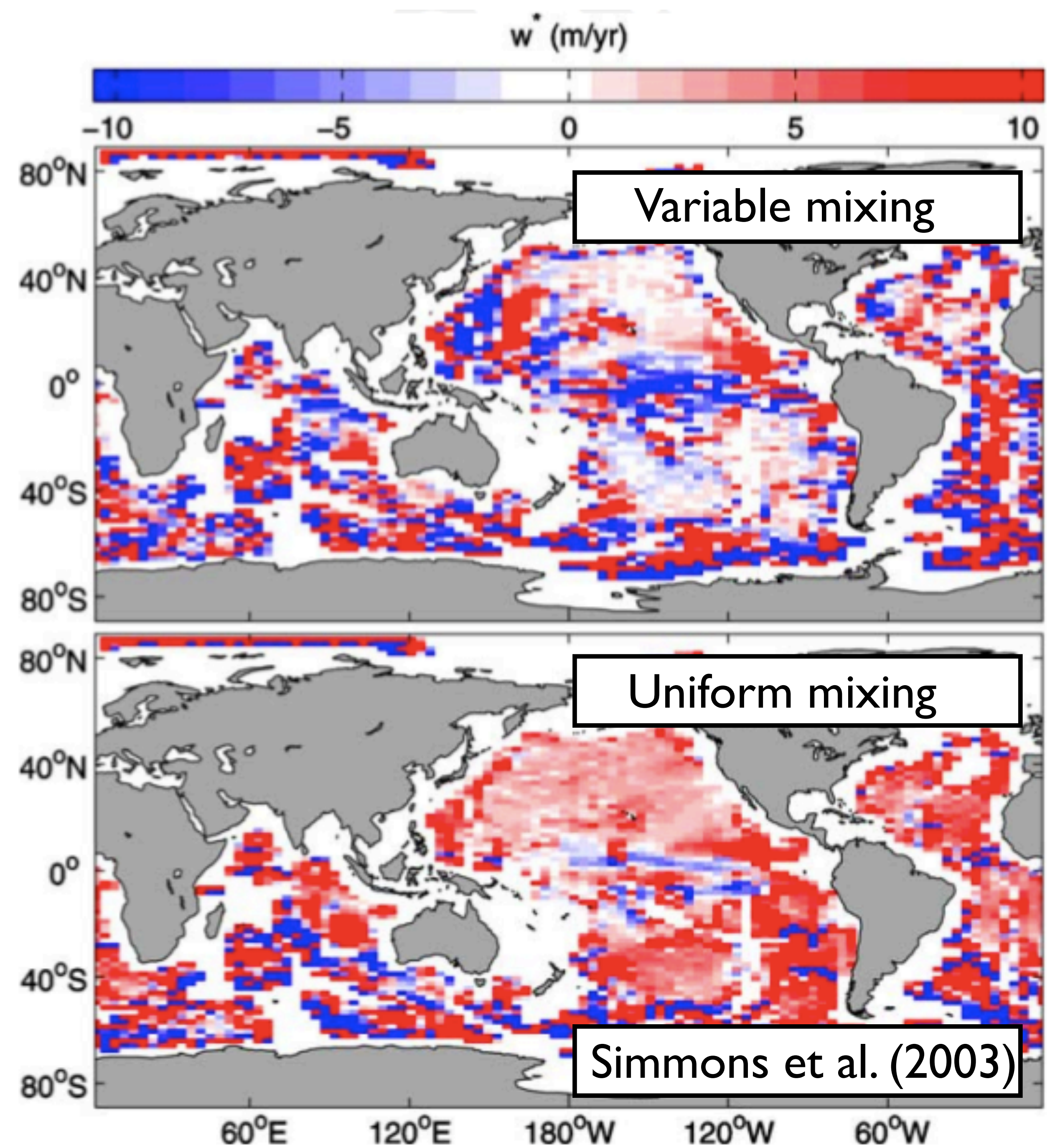


Constant diffusivity



Bottom-enhanced diffusivity

$$w^* \approx \frac{1}{N^2}\frac{d}{dz}[\kappa N^2]$$



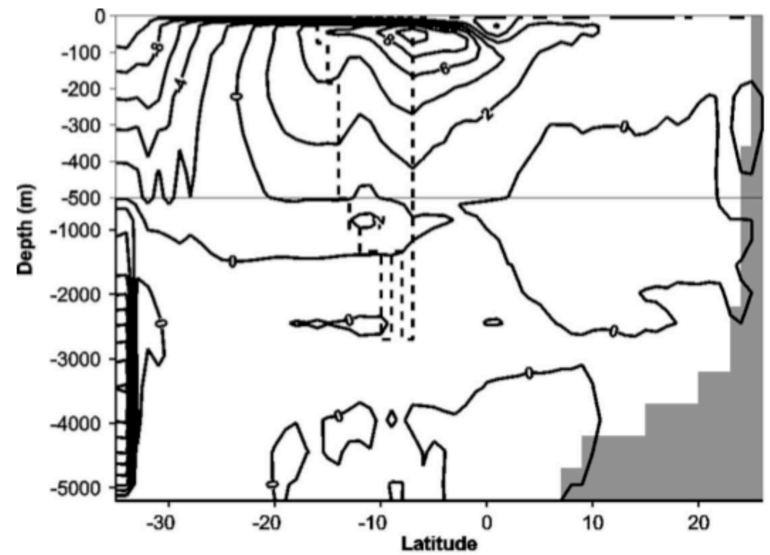
Patchy mixing matters

Palmer et al. (2007):

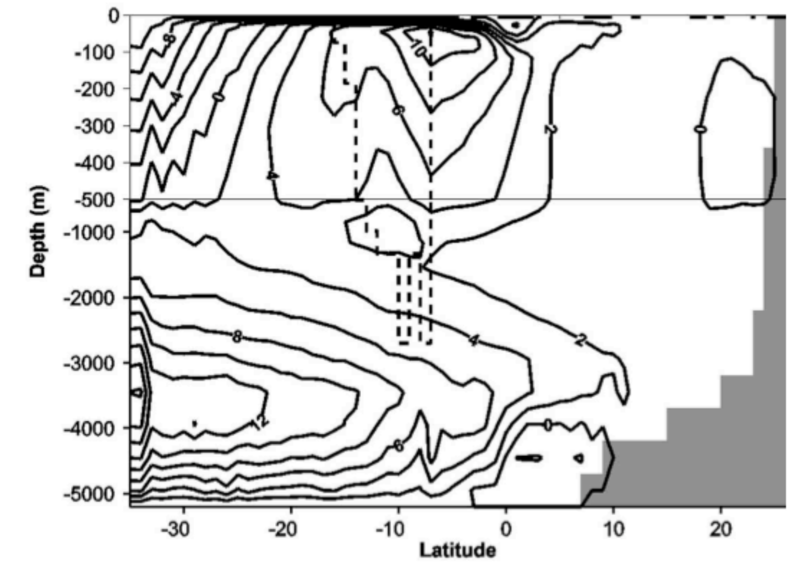
bottom-enhanced diffusivity

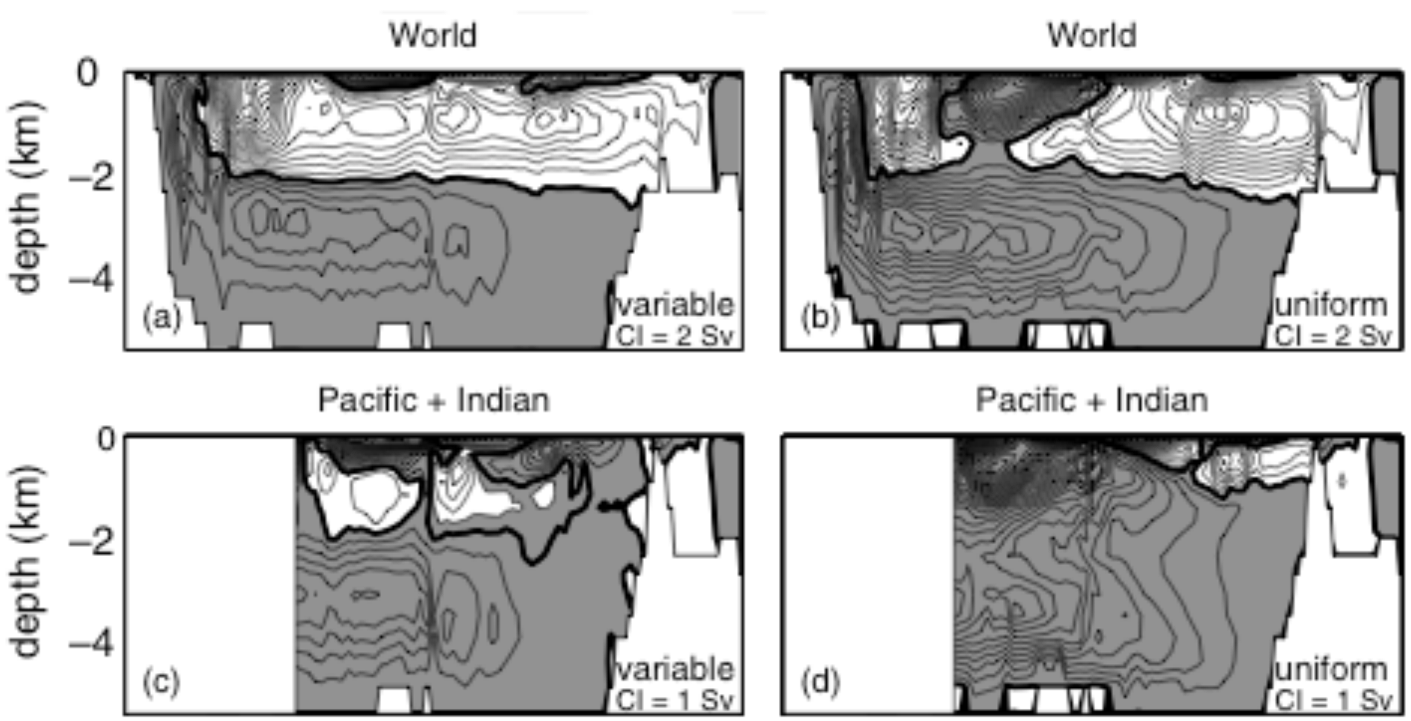
=> deep overturning

Constant $\kappa = 1.2\ 10^{-4}$



Bottom-enhanced diffusivity





bottom-enhanced, spatially-variable mixing

uniform mixing

Simmons et al. (2003):

enhanced mixing over rough topography

=> change in global MOC

also: Hasumi & Suginohara (1999), Huang (1999), Katsman (2006), Saenko (2006), Jochum (2009)

Patchy mixing matters

"A number of lines of evidence, none complete, suggest that the oceanic general circulation, far from being a heat engine, is almost wholly governed by the forcing of the wind field and secondarily by deep water tides... The now inescapable conclusion that over most of the ocean significant 'vertical' mixing is confined to topographically complex boundary areas implies a potentially radically different interior circulation than is possible with uniform mixing. Whether ocean circulation models... neither explicitly accounting for the energy input into the system nor providing for spatial variability in the mixing, have any physical relevance under changed climate conditions is at issue."

- Wunsch and Ferrari, 2004

Outline

Measuring turbulent mixing

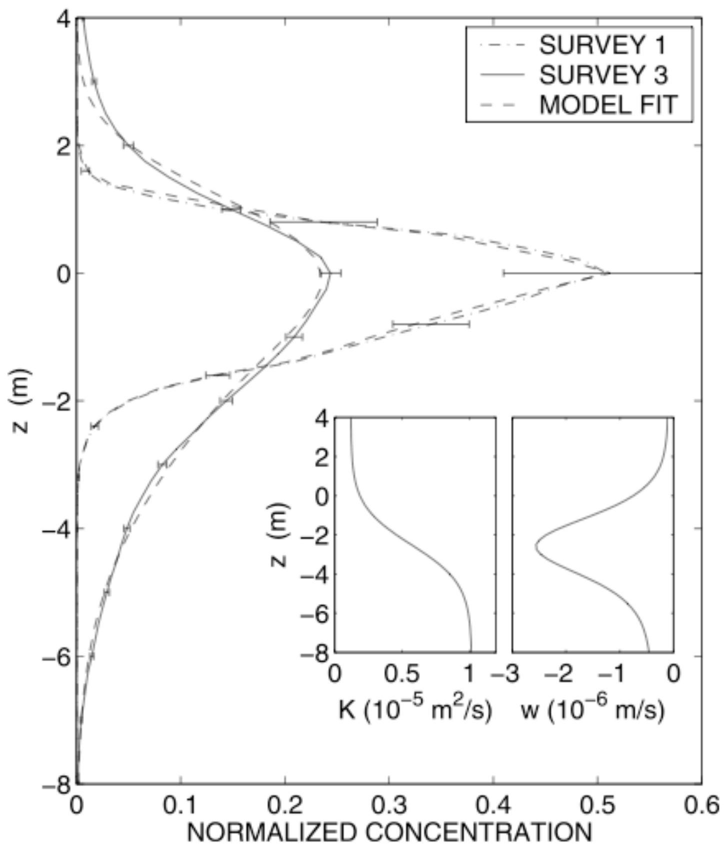
1. Microstructure
2. Thorpe scales
3. Shear-strain spectral estimates
4. Pros/cons/applicability of each method

Modeling turbulent mixing

How can we create a dynamic parameterization that represents internal wave-driven mixing in global models?

Measuring turbulent mixing

"Direct" method: dye dispersal (Ledwell et al., 2004)



Assume $K_\rho \sim K_{dye}$

Indirect method 1: measure turbulence, assume mixing follows

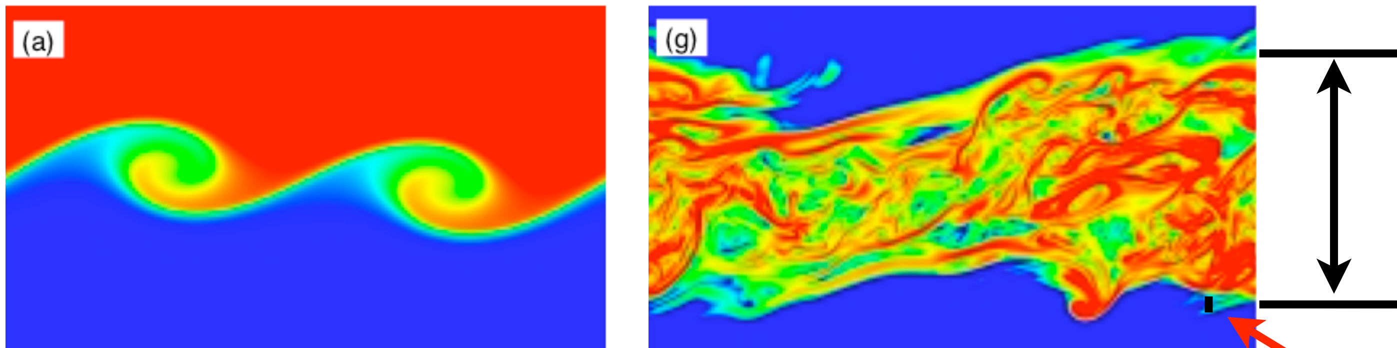
$$K_\rho \approx 0.2 \frac{\epsilon}{N^2}$$

turbulent dissipation rate

(Osborn, 1980)

Measuring turbulence: inertial subrange

Simulations of stratified turbulence (Smyth)

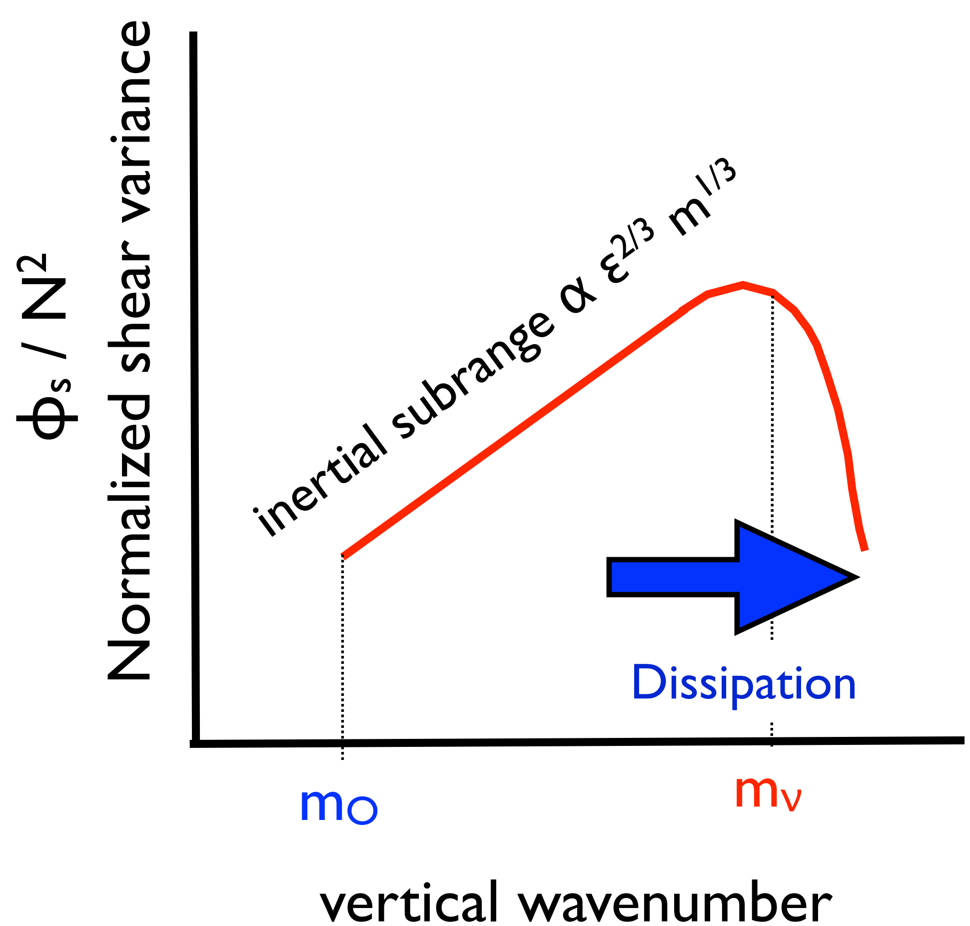


Ozmidov scale:

$2\pi/m_O = (\varepsilon/N^3)^{1/2} \sim 0.1\text{-}10$ m

Kolmogorov scale:

$2\pi/m_\nu = (\nu^3 / \varepsilon)^{1/4} \sim 1\text{-}10$ mm

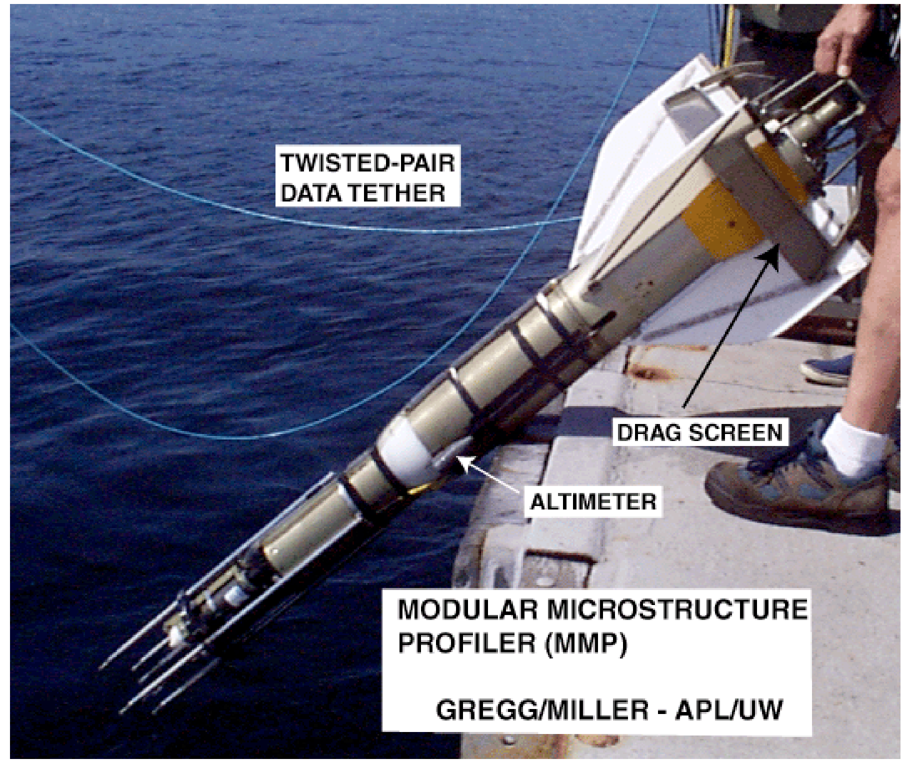


Method 1:
measure shear in inertial subrange
=> ϵ

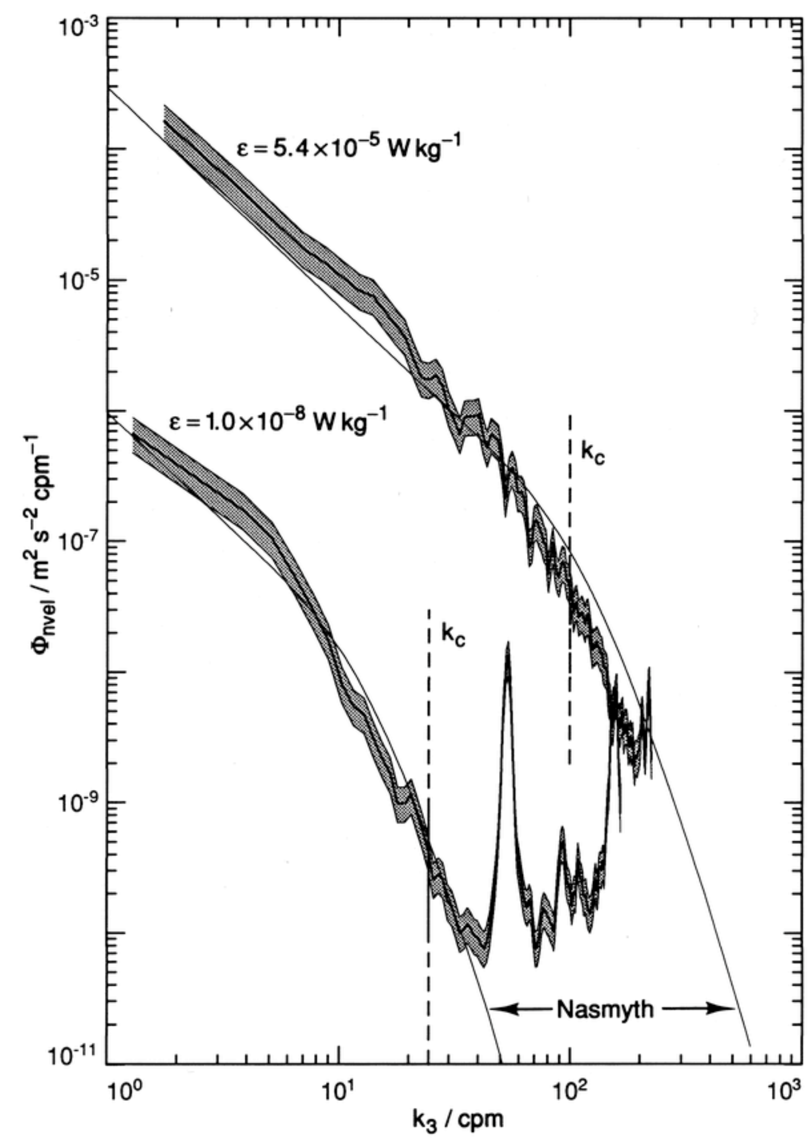
Measuring turbulence: microstructure

VMP (Rockland)

MMP (APL/UW)

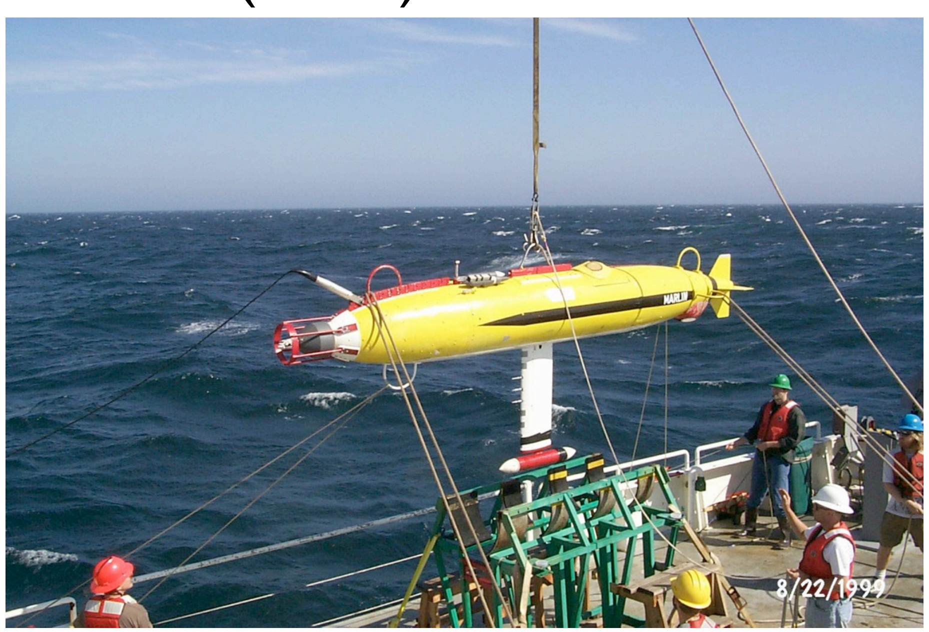


Energy spectrum ~ $m^{-5/3}$



Wesson & Gregg (1994)

Marlin (OSU)

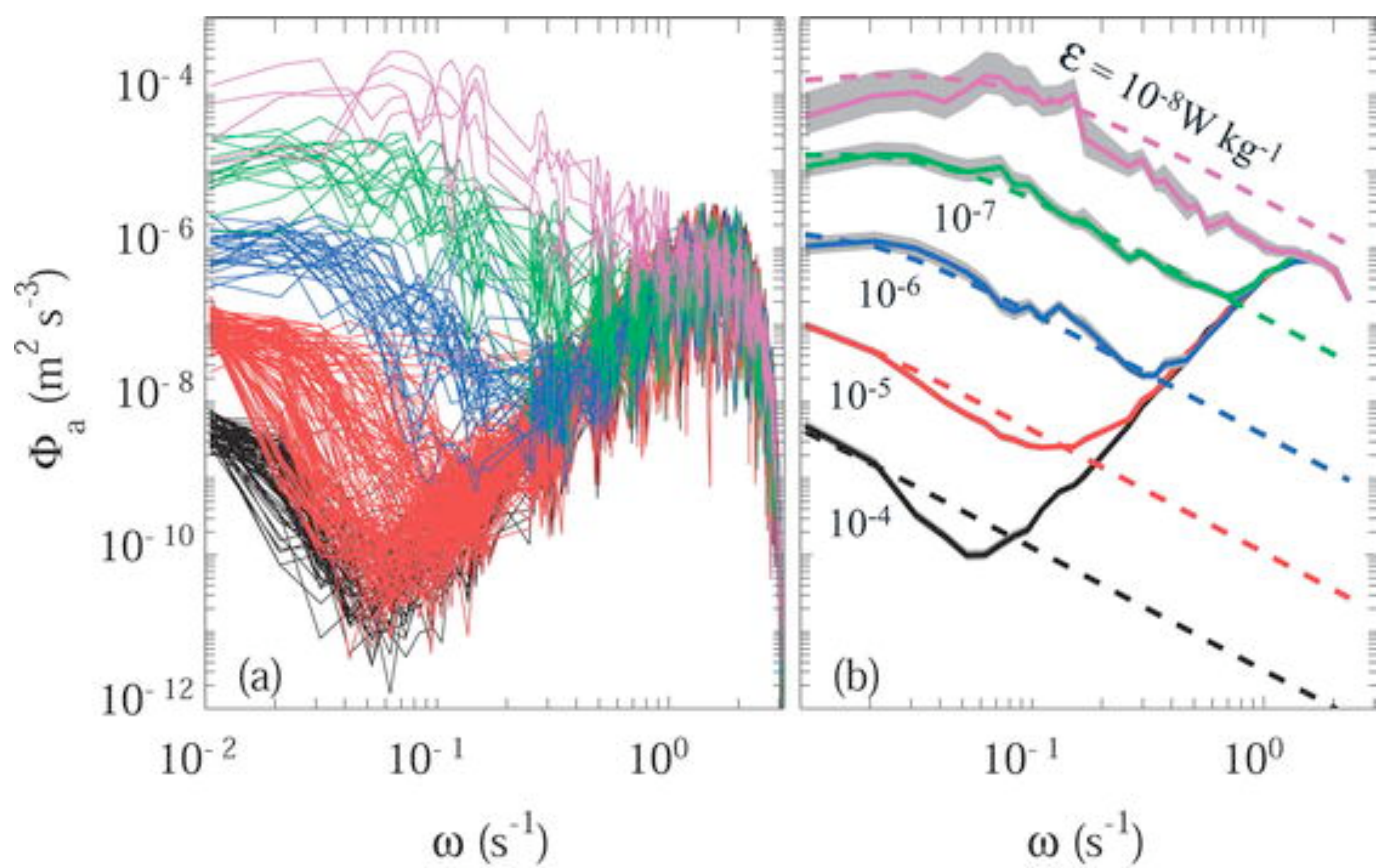


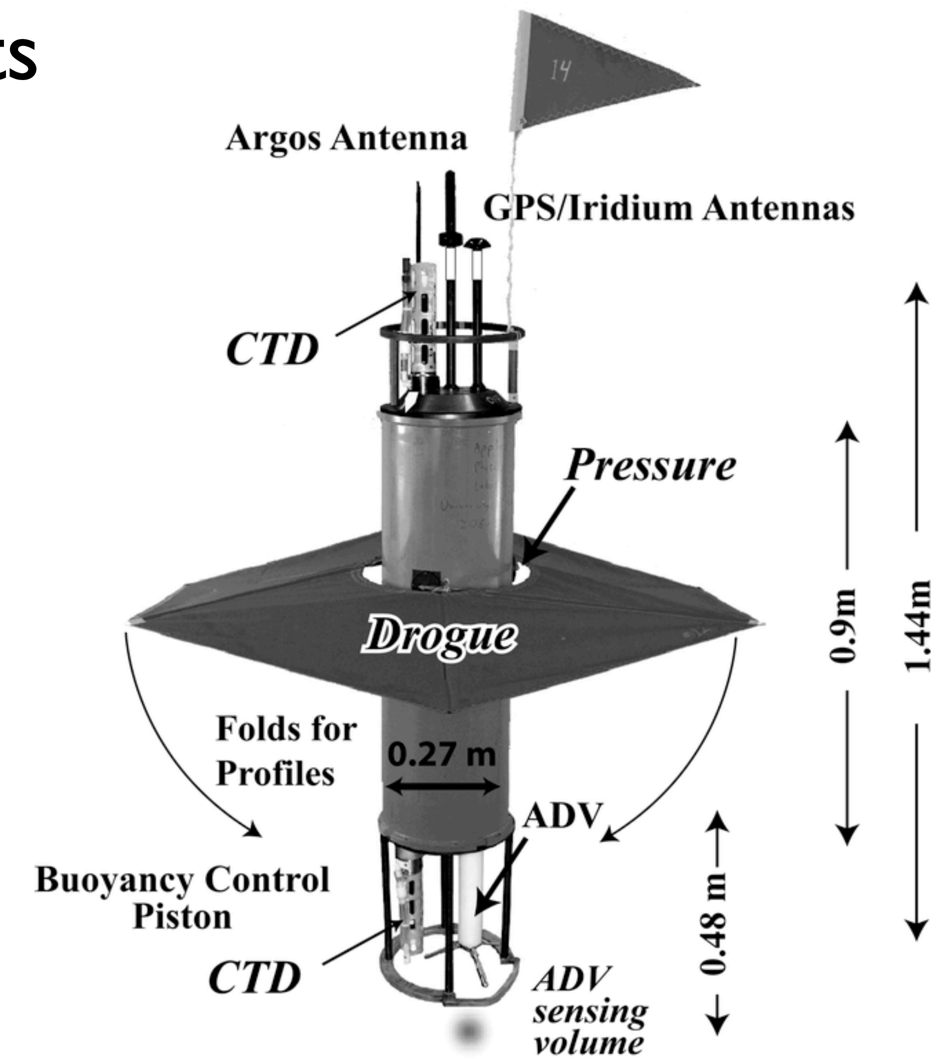
HRP (WHOI)

Measuring turbulence: other platforms

Vertical acceleration spectrum from Lagrangian float

=> inertial subrange in energetic environments





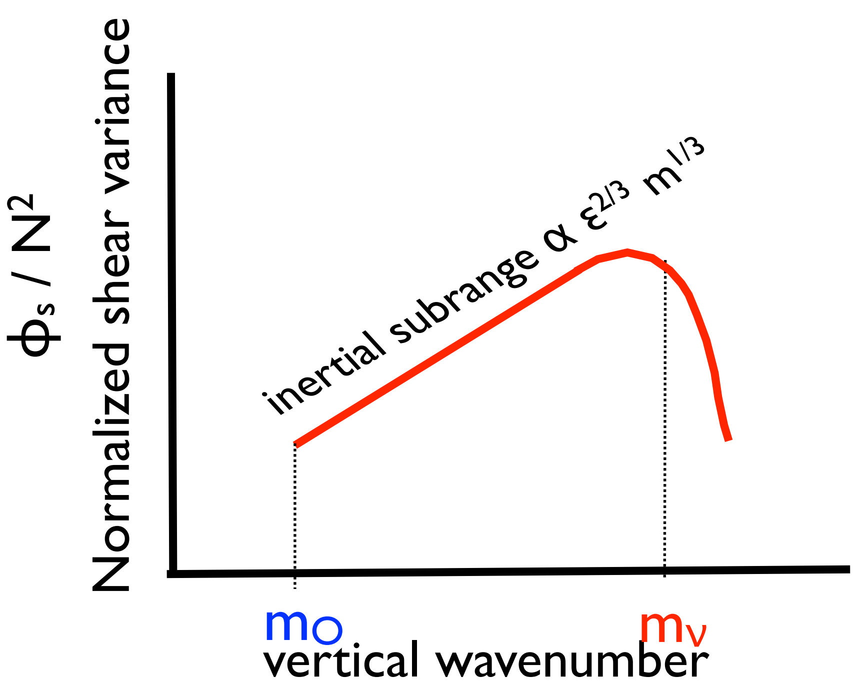
Lien and D'Asaro

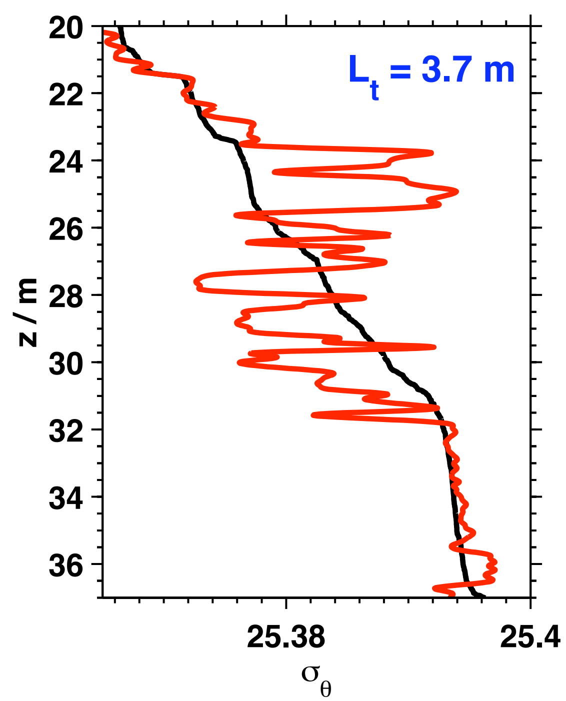
Measuring turbulence: Thorpe scales

Method 2:
measure outer scale of turbulent subrange
density inversions ~ 0.1-10 m

Thorpe scale = rms displacement of density from its sorted depth

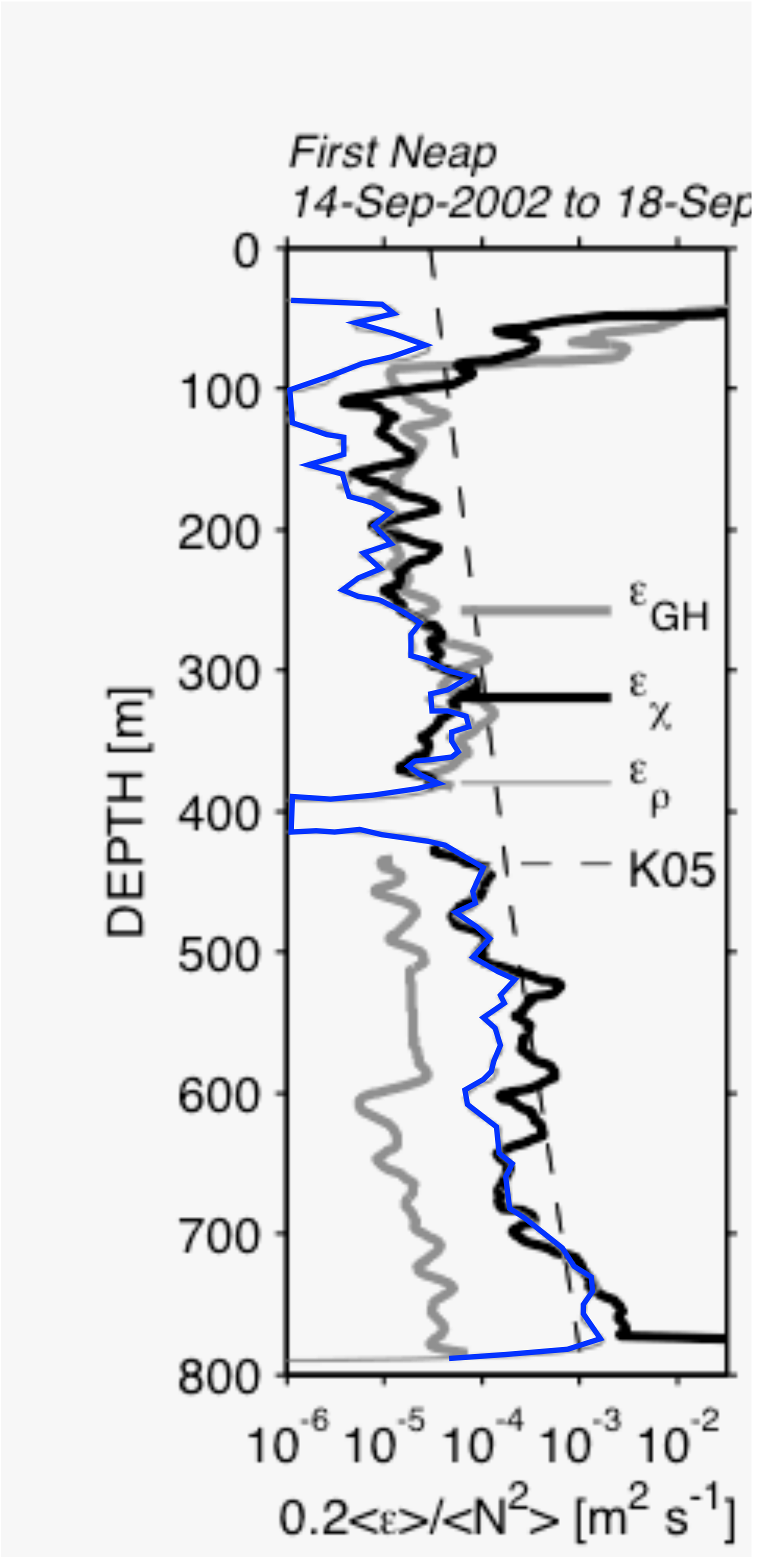
$$L_t \sim L_O = 2\pi/m_O = (\varepsilon/N^3)^{1/2}$$





also: Thorpe (1977), Dillon (1982), Ferron et al. (1998)

Hawaii Ocean Mixing Experiment (Klymak et al., 2008)



ε_t

ε_{micro}

Thorpe scales: advantages

1) fairly direct measure of actual turbulence

2) easy to measure with various instruments:

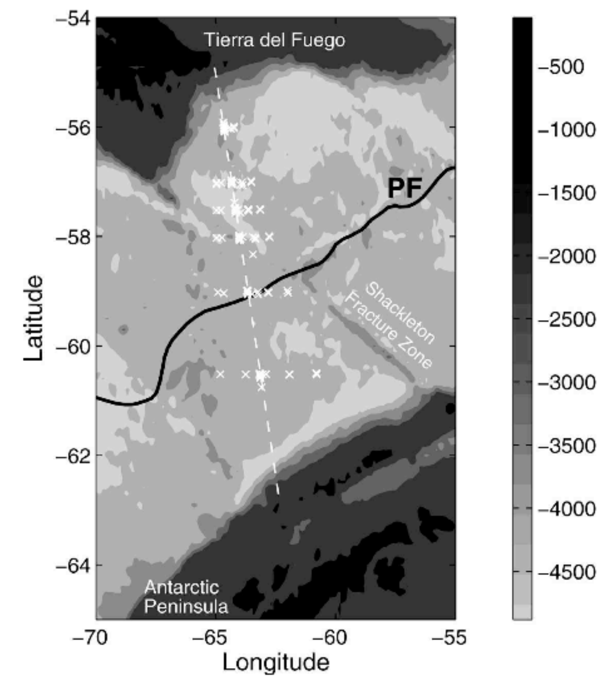
- Standard shipboard CTD:
  Johnson and Garrett (2004), Gargett and Garner (2008)

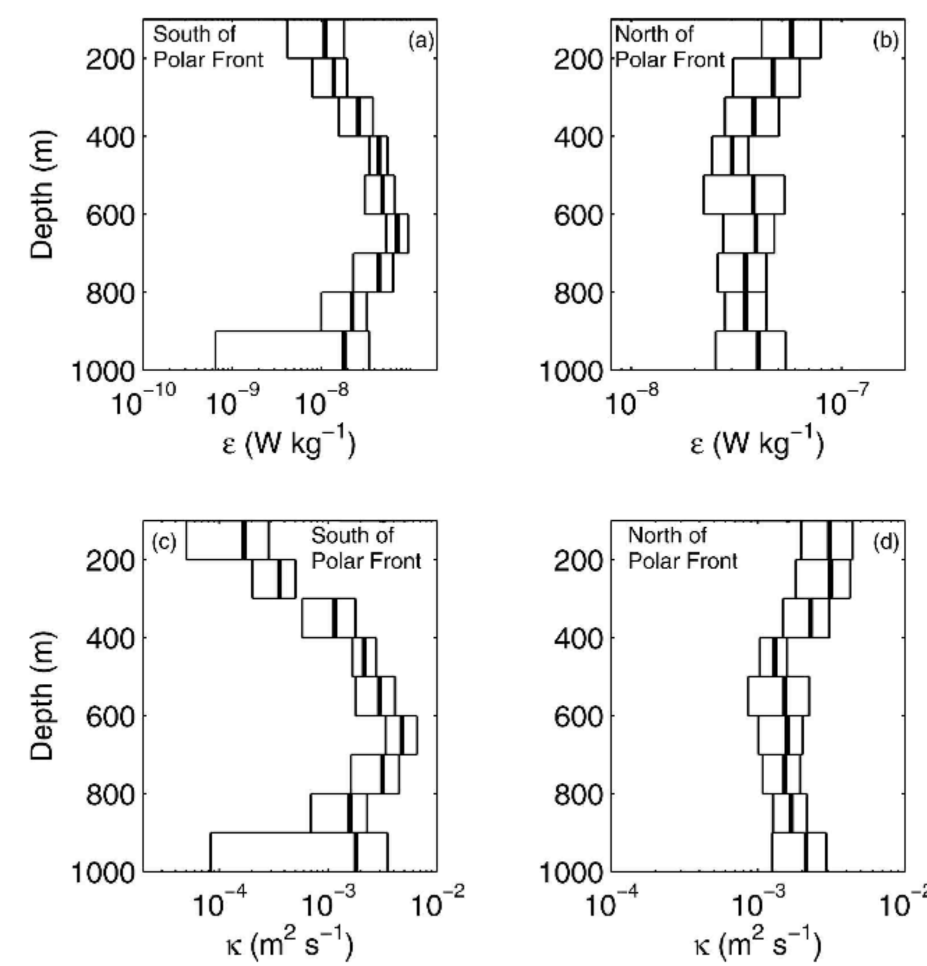
- XCTD
  Thompson, Gille, MacKinnon, & Sprintall (2007)
  Frants, Gille, and Zhao (in prep.)

- Moored profilers

- SeaSoar
  Martin and Rudnick (2007)

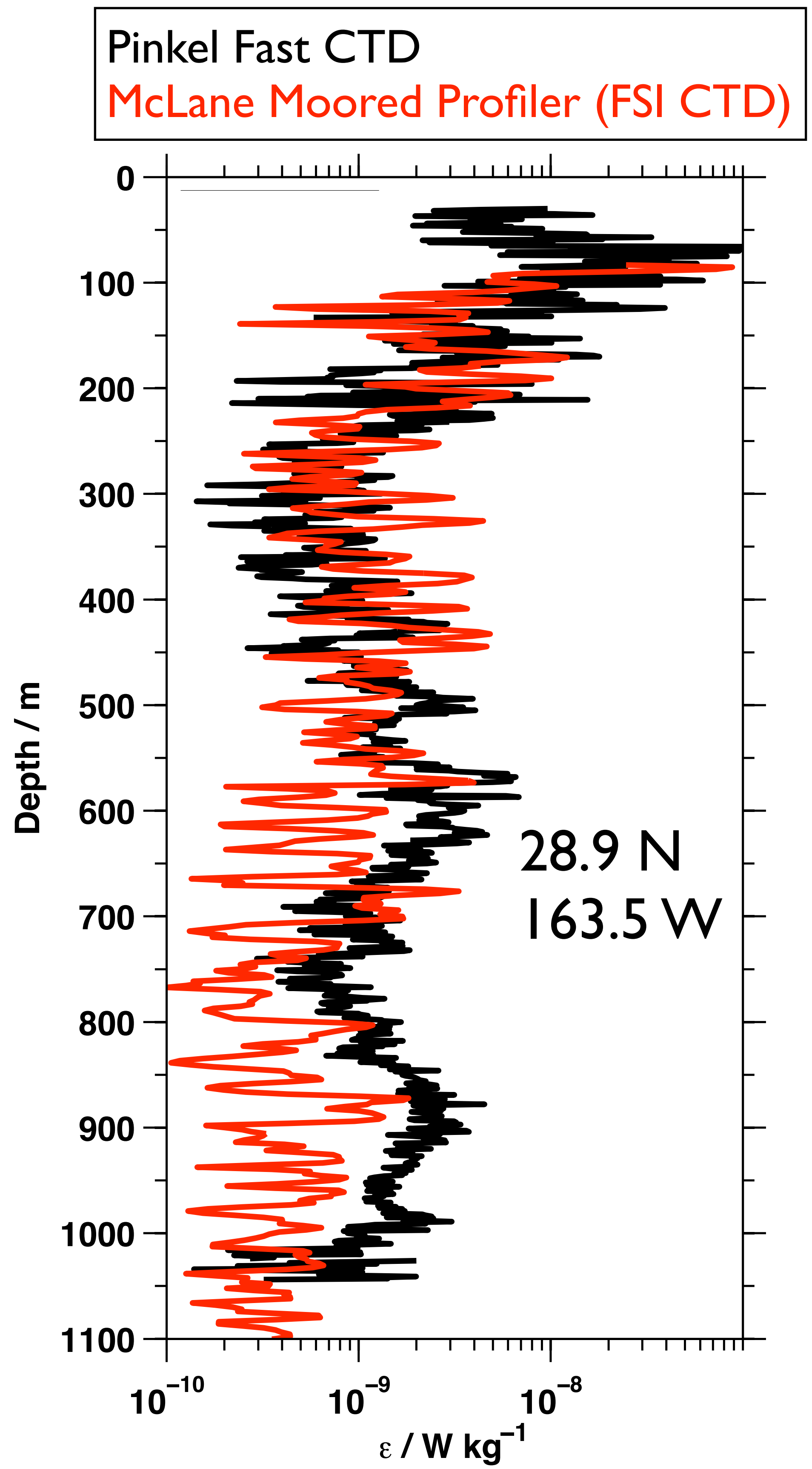
- Other (Argo? Gliders?)





Thompson et al. (2007)

Thorpe scales: difficulties



1. Noise in density profile

minimum size of resolvable overturns

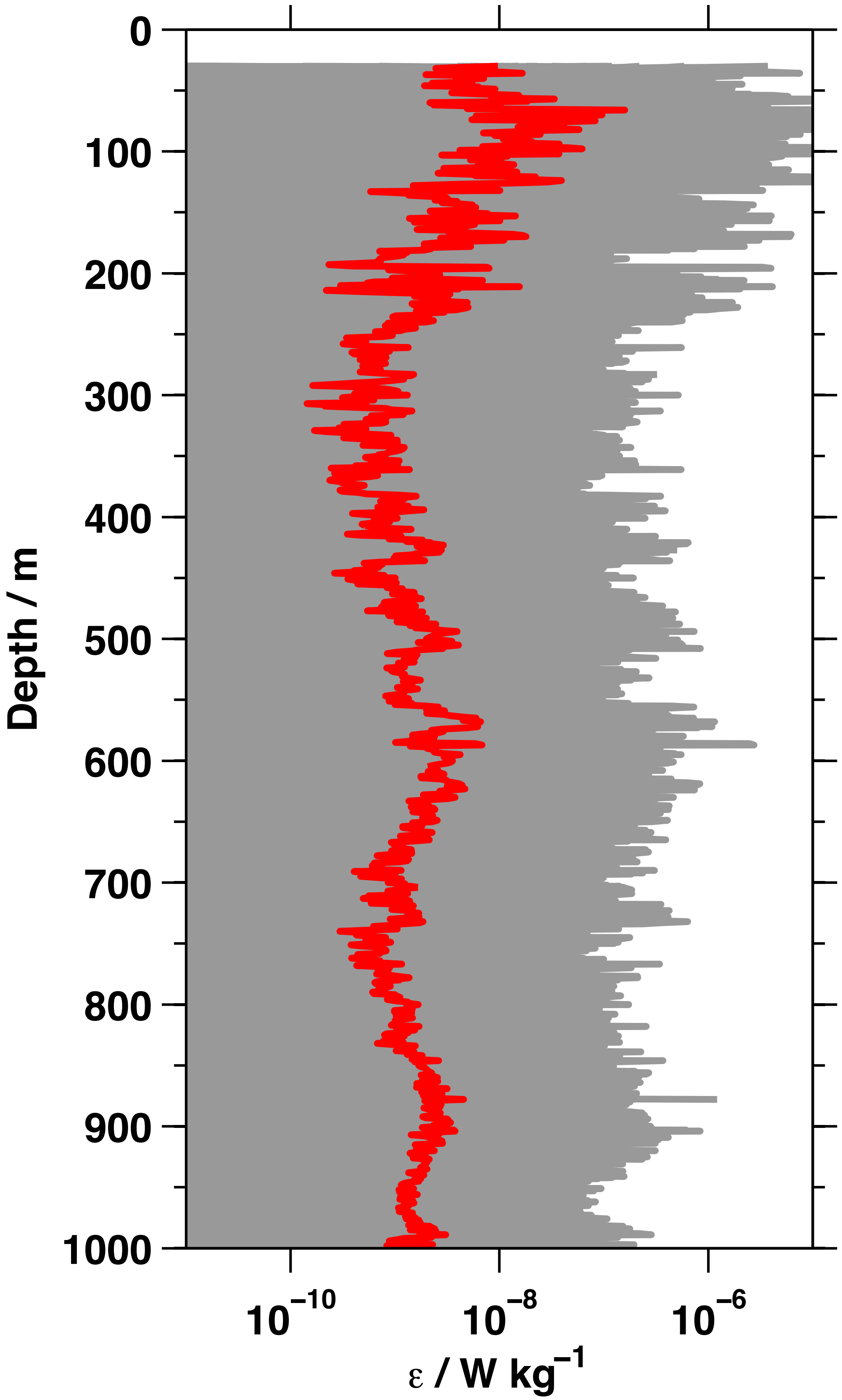
$$L_{\rho min} = \frac{2g}{N^2}\frac{\delta\rho}{\rho_0}$$

(Galbraith and Kelley, 1996)

$$L_O = (\varepsilon/N^3)^{1/2}$$

With weaker N, harder to detect 'real' overturns with noisy data

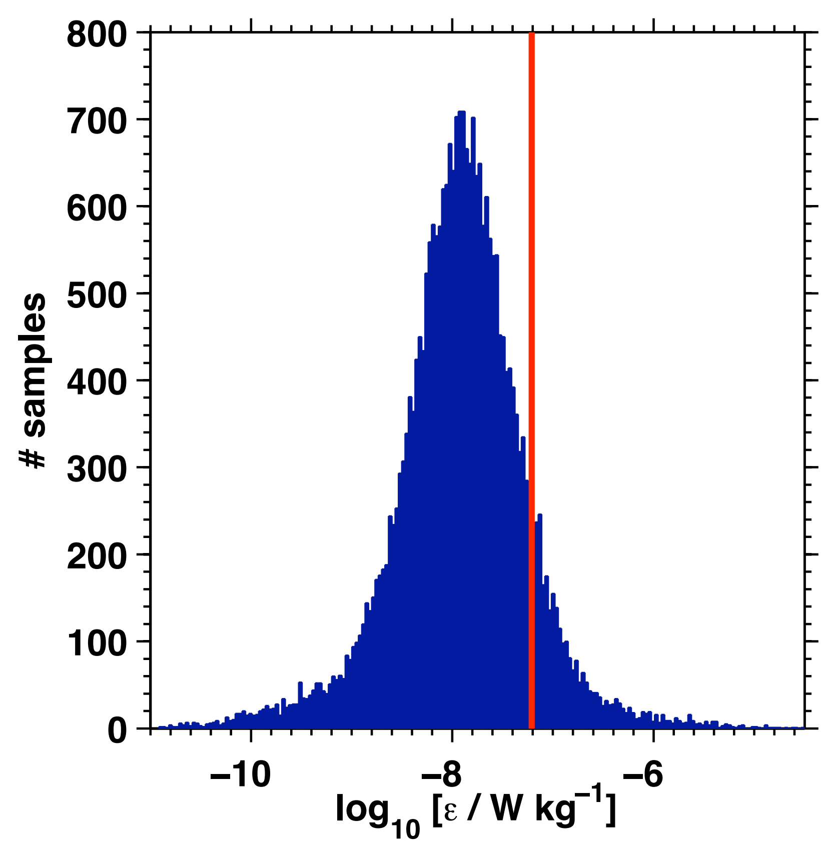
Thorpe scales: difficulties



1. Noise in density profile

2. Statistics converge slowly

Dissipation ~ lognormally distributed, need $\mathcal{O}$(10-100) samples to converge

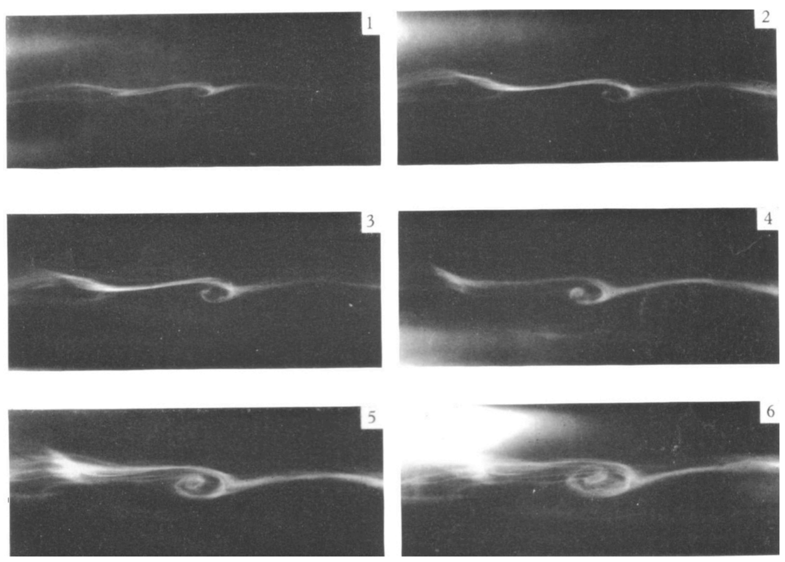


Gregg et al. 93
Baker and Gibson
Davis 96

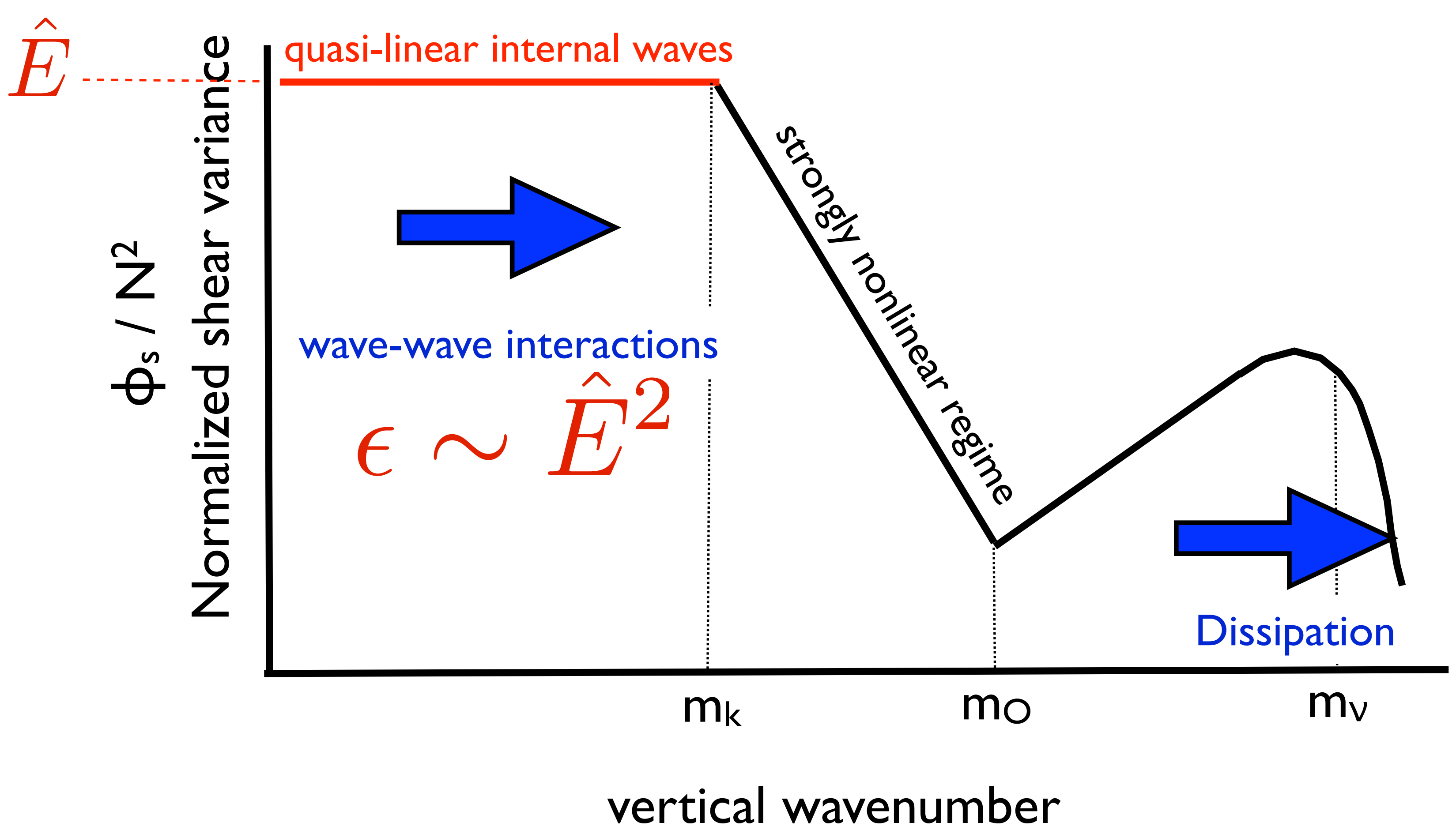
Measuring turbulence: internal waves

Turbulence driven by breaking internal waves

Dissipation rate set by rate at which energy is transfered down-scale through the internal-wave field



Woods 68



Garrett-Munk (GM) spectrum

Cutoff wavenumber at $\mathcal{O}(1)$ Richardson number

$$\Phi_s \times m_k \sim N^2$$

$2\pi/m_k \sim 10$ m

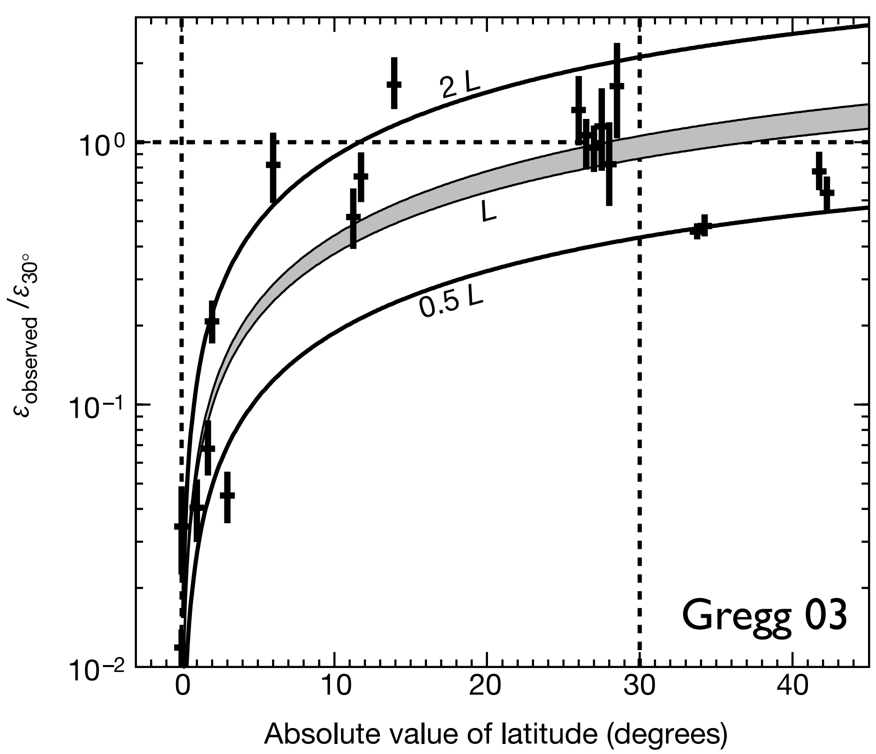
McComas & Muller (1981), Broutman & Young (1986), Henyey et al. (1986), Polzin et al. (1995), Gregg et al. (2003)

Measuring turbulence: internal waves

Verify: $\epsilon \sim \hat{E}^2$

Observed dissipation rates agree with predictions (Gregg, 1989; Polzin et al., 1995; Gregg et al., 2003)

$$\varepsilon = \varepsilon_{30^\circ}\big(N, \Phi_{\text{shear}}(m), \Phi_{\text{strain}}(m)\big) \times L(\theta, N)$$



Numerical simulations of internal wave interactions confirm:
- GM spectrum as steady state
- predicted rates of down-scale energy flow

(Hibiya et al, Winters and D'Asaro, etc)

Measuring turbulence: internal waves

"...If [predicting the dissipation rate based on internal wave dynamics] is even approximately true, the significant oceanographic problem of estimating vertical viscosities and diffusivities for large-scale modeling applications shifts from adequately sampling the processes responsible for mixing to defining the global internal wave climate"

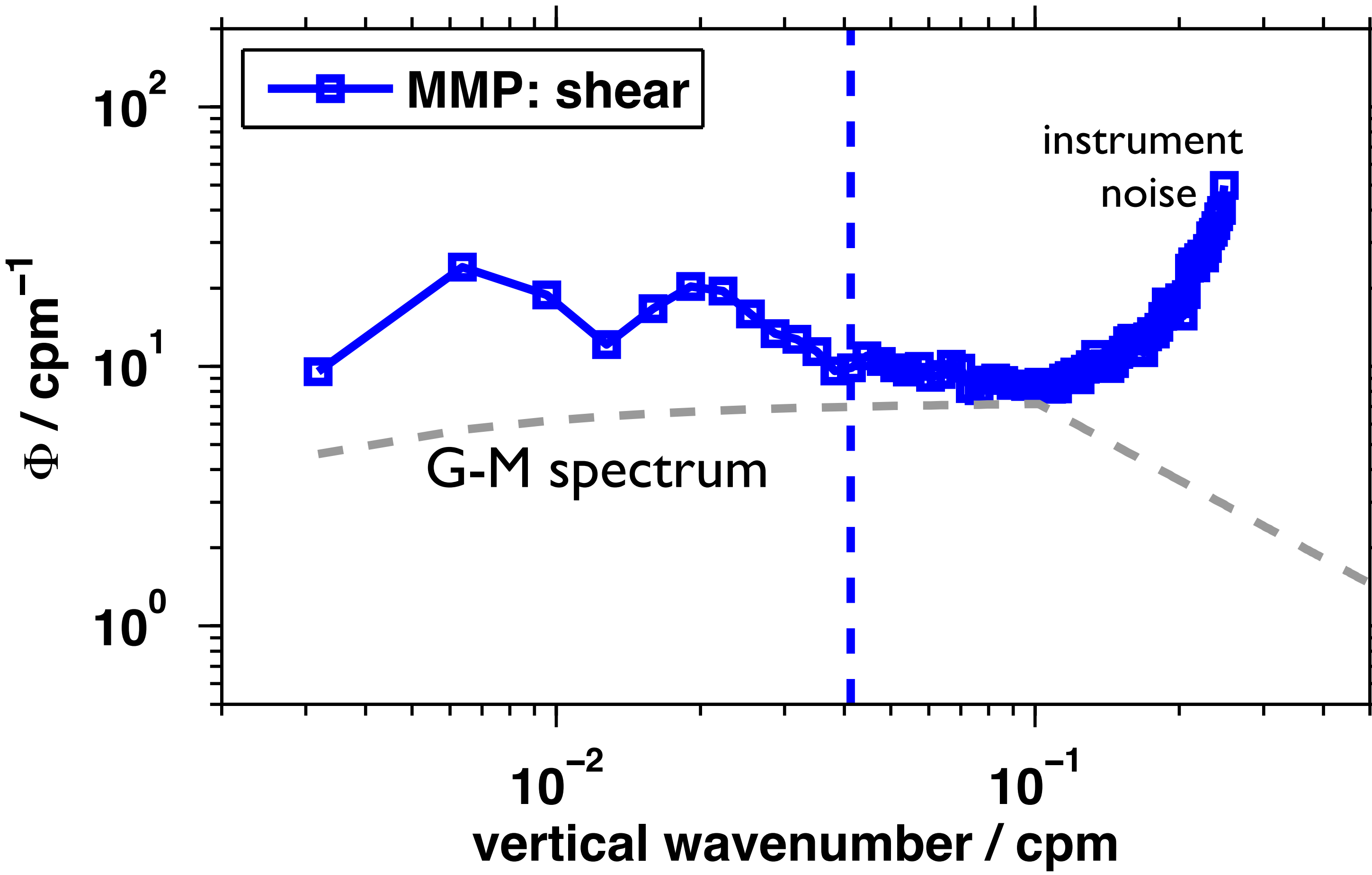
- Wijesekera et al. (1993)

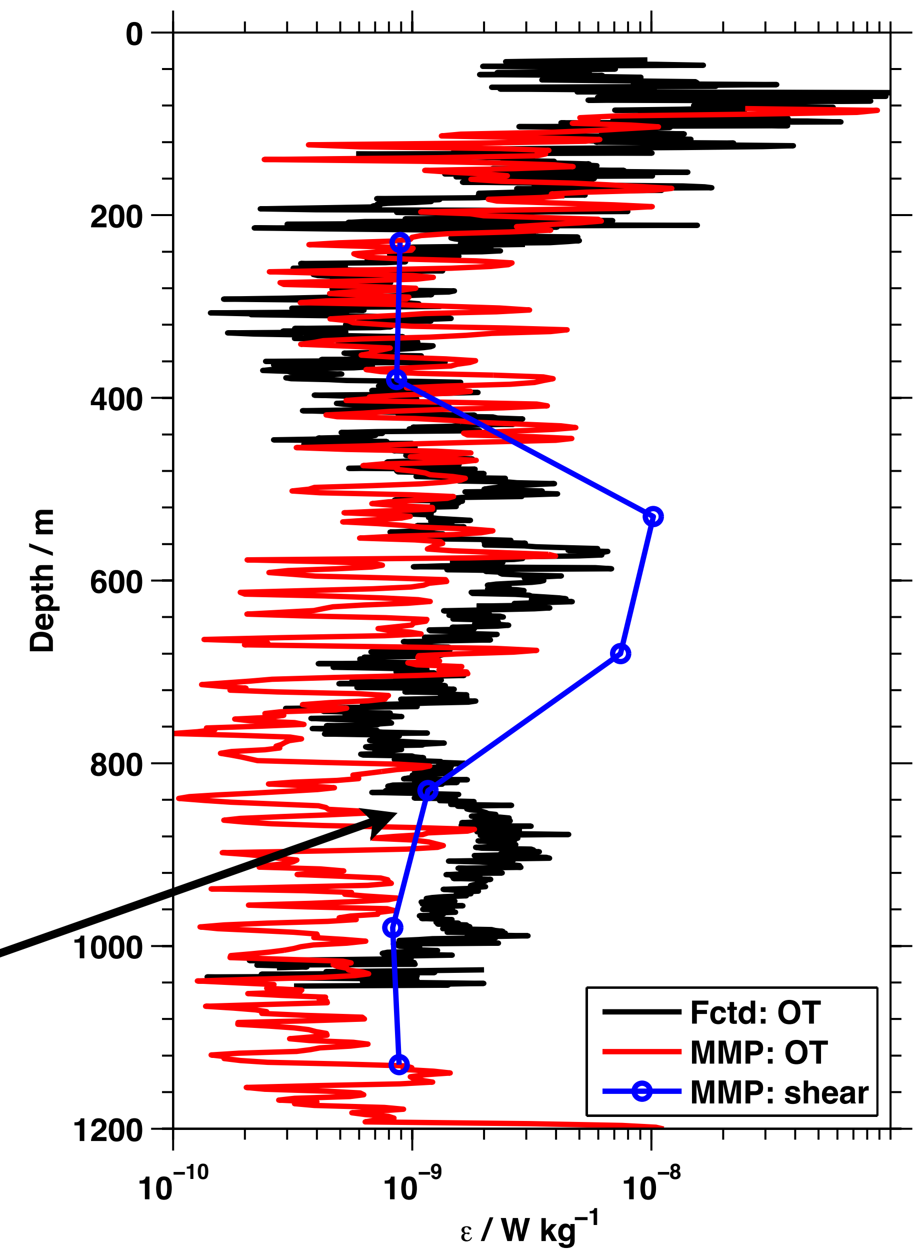
Next: techniques, then some examples

Estimating turbulence: internal wave shear spectra

Estimate Ê by integrating spectra out to cutoff wavelength where

$$\Phi_s \times m_k = 0.7N^2$$



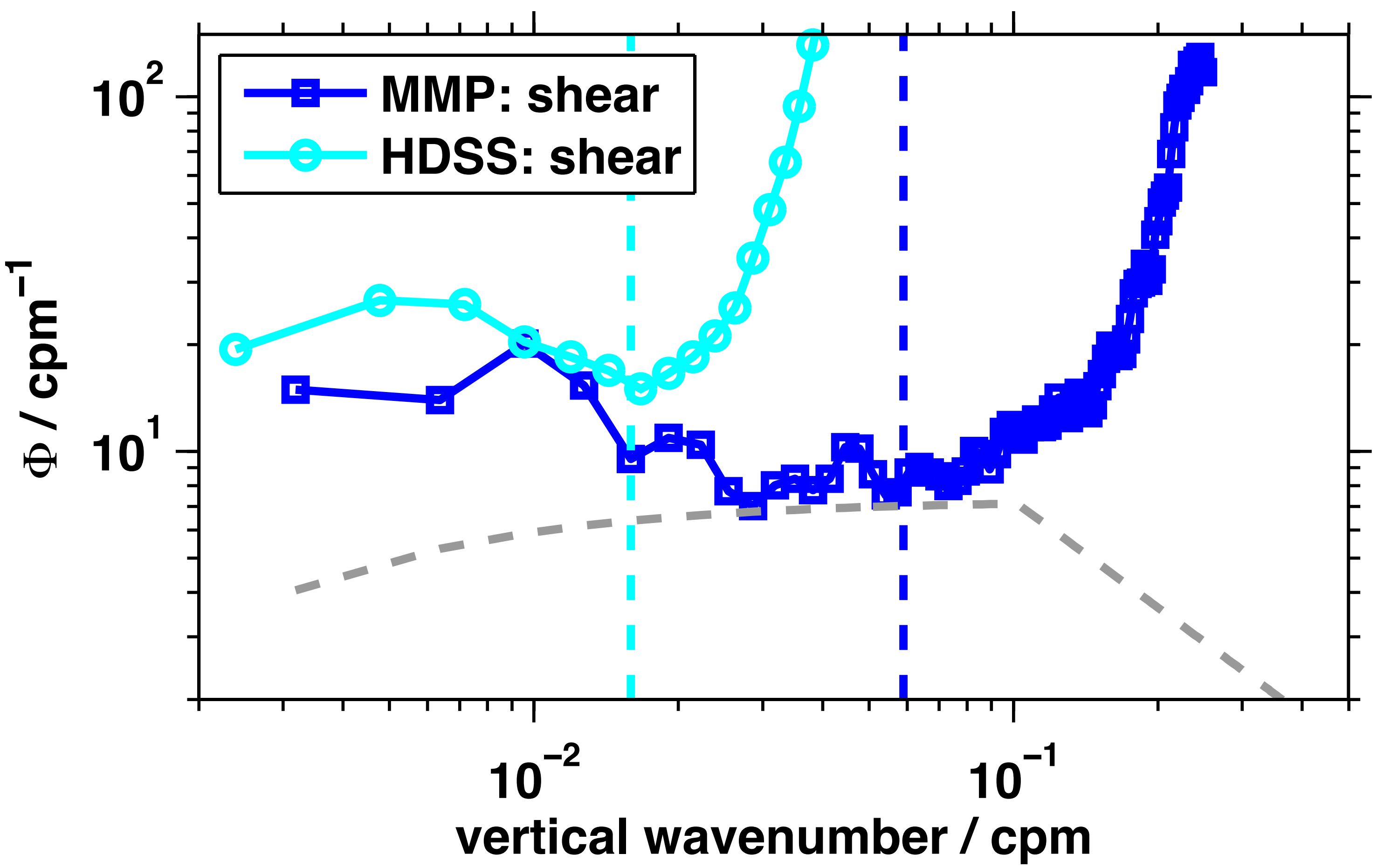


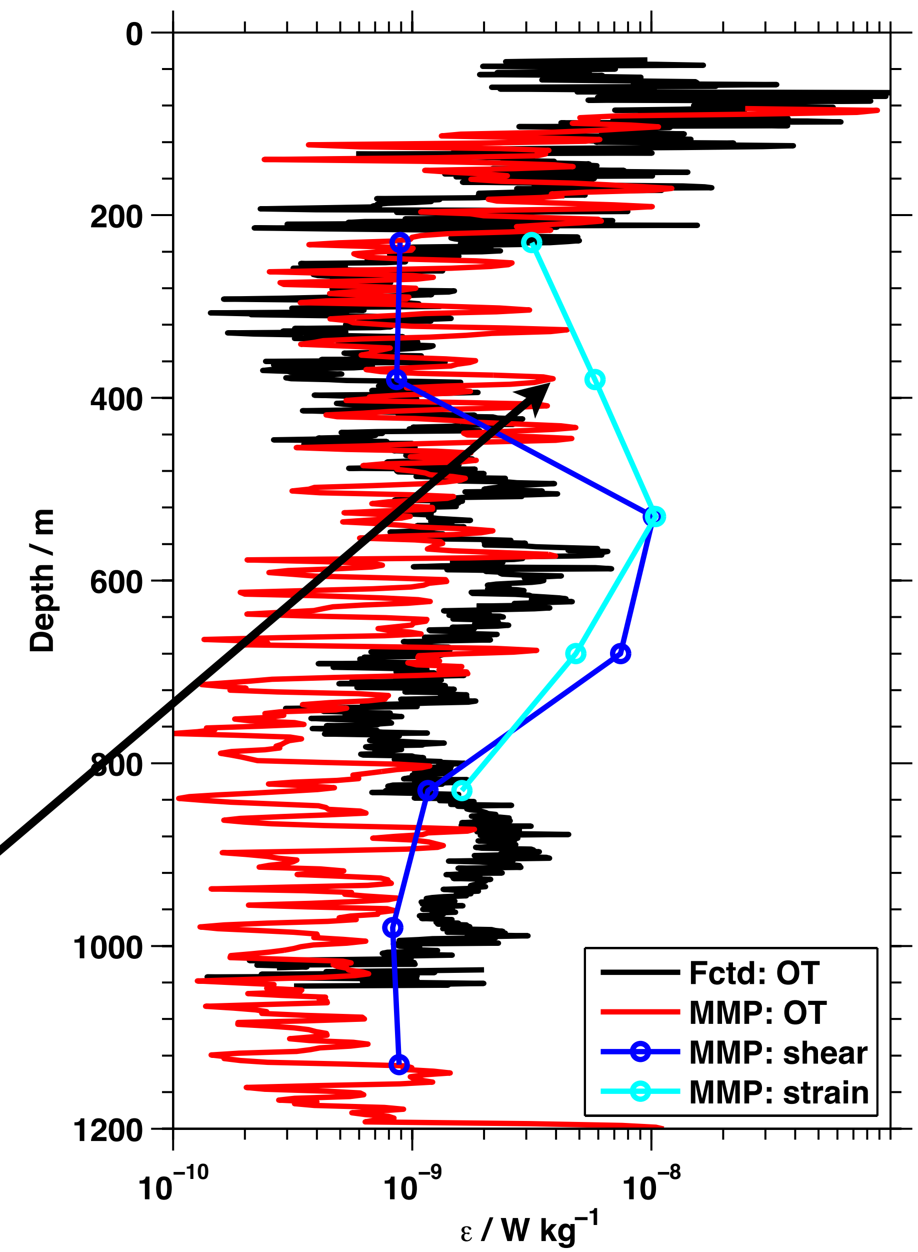
$$\epsilon \sim \hat{E}^2$$

Estimating turbulence: internal wave shear spectra

Issue #1:

with lower resolution measurements, integrate over "good" wavenumbers => can get a biased view IF spectrum is not white

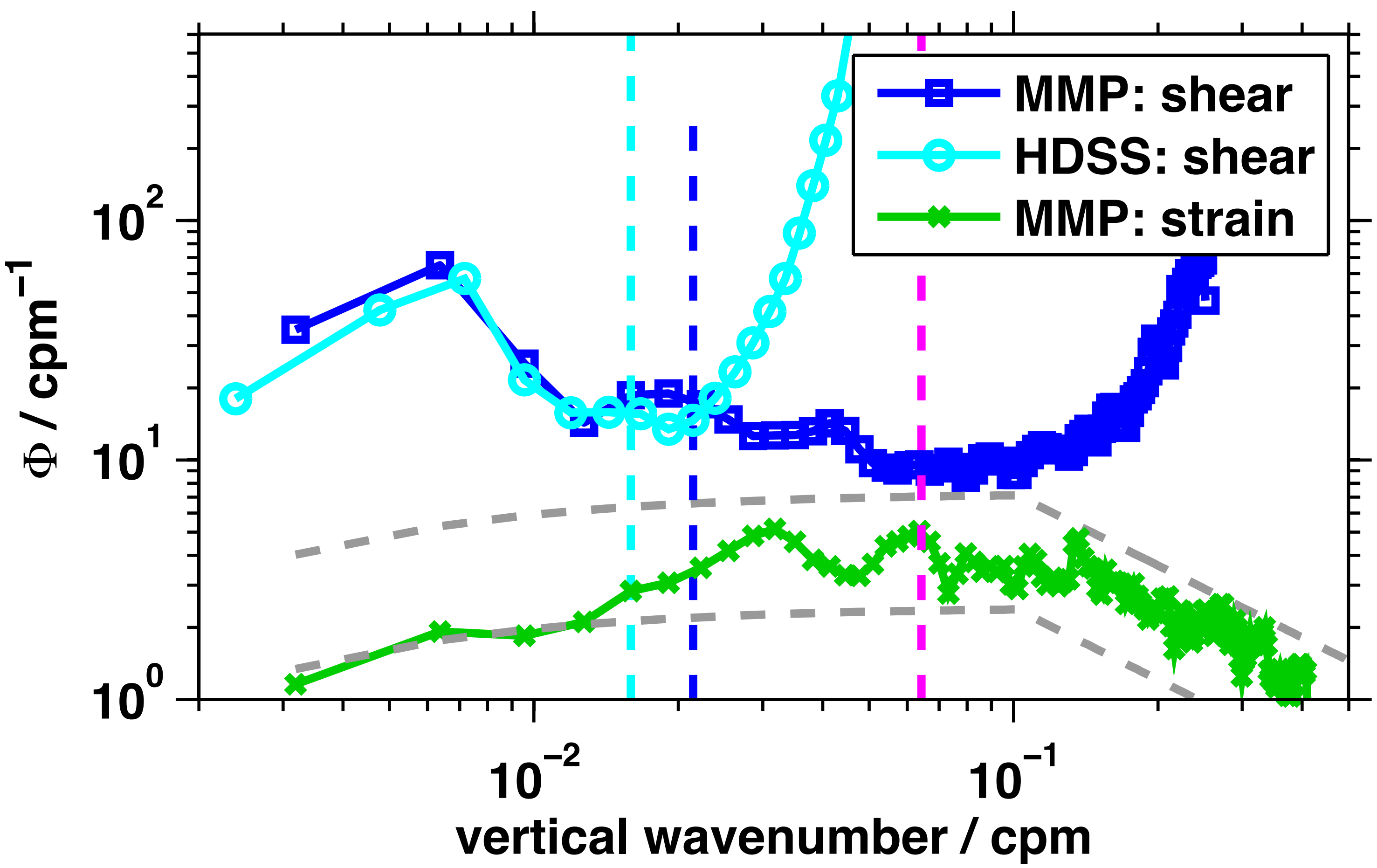


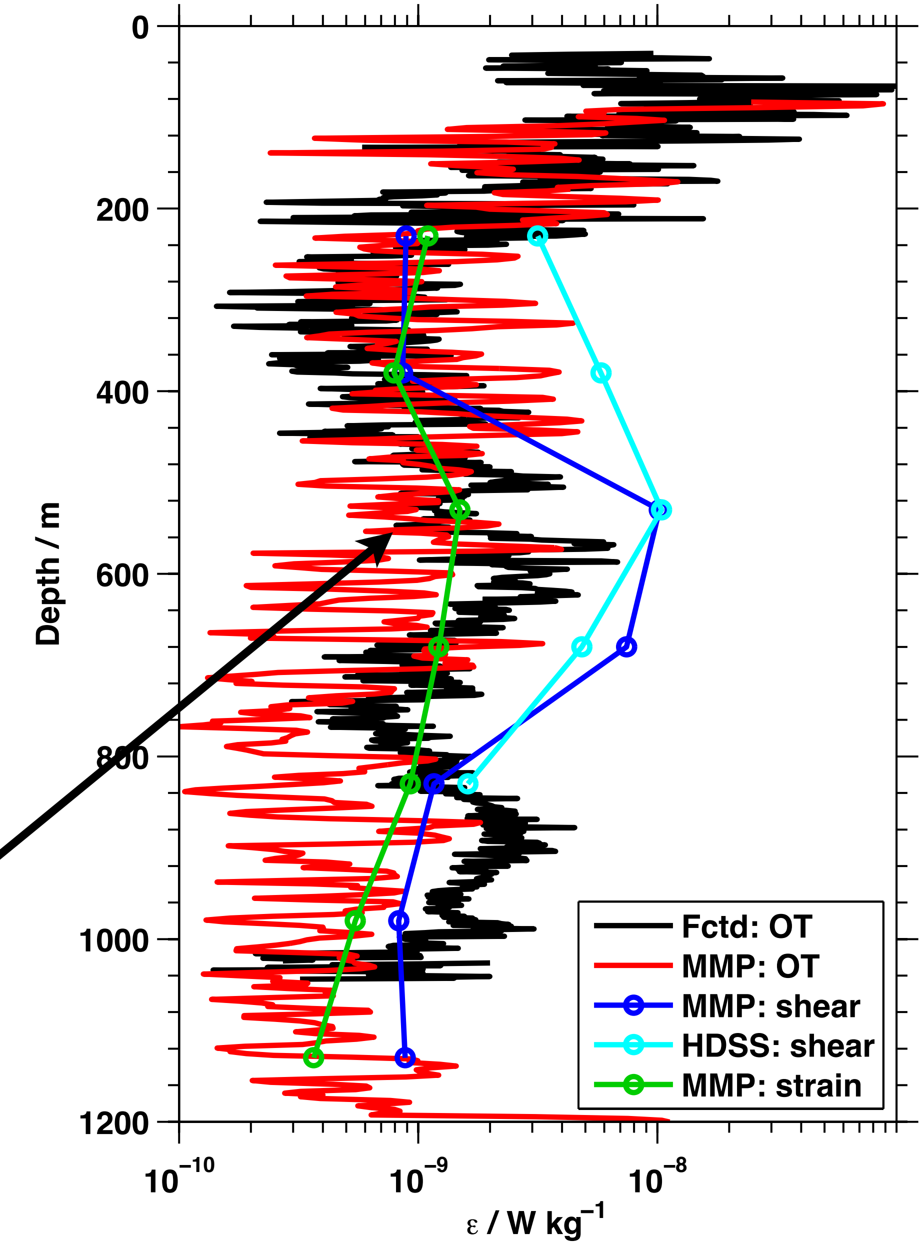


Estimating turbulence: internal wave shear spectra

Issue #2:

- Can use either shear or strain (KE or PE) to estimate total energy
- but shear/strain ratio can vary by a factor of 10

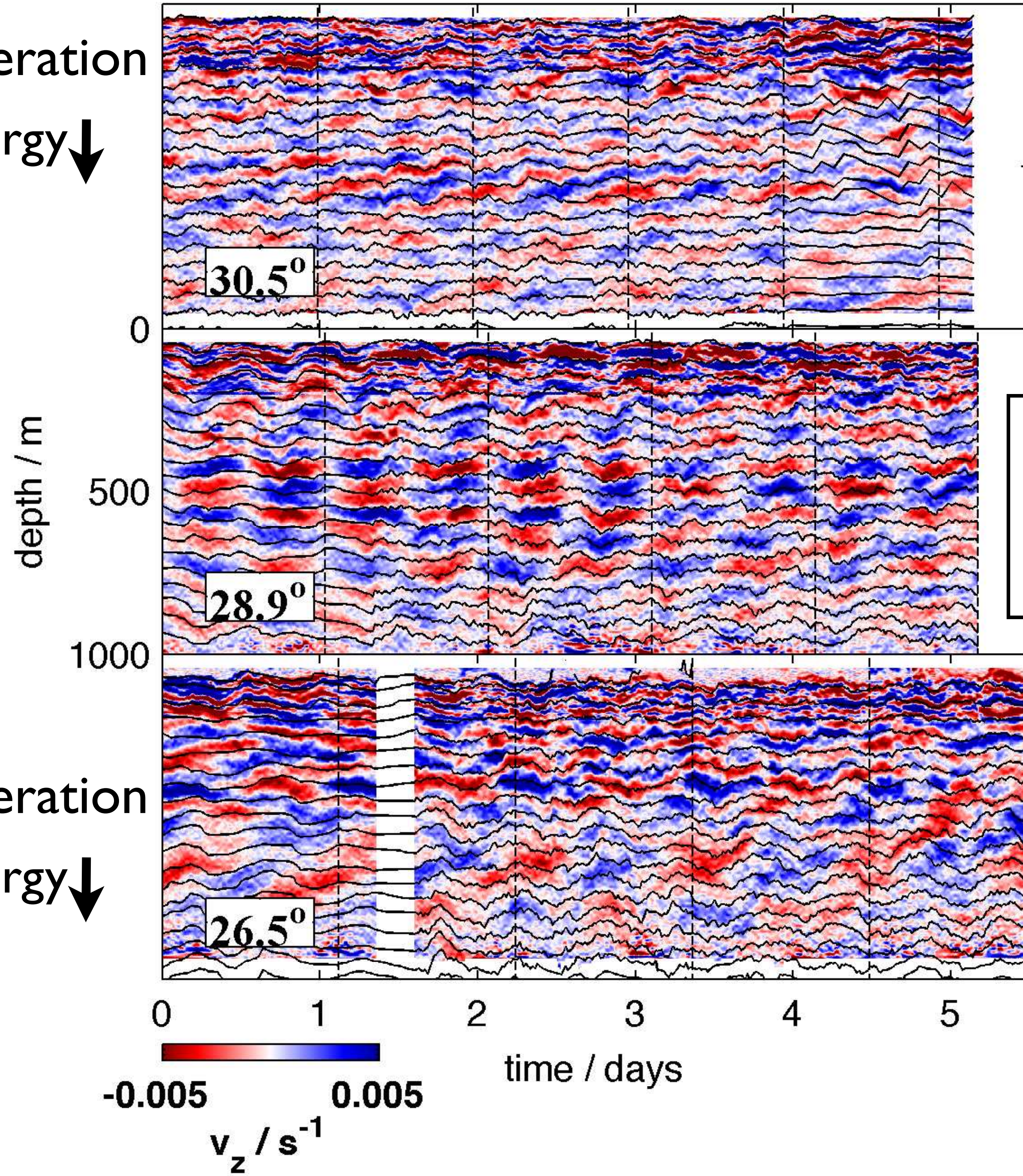




Time series of near-inertial shear at three moorings

Surface generation

Phase↑ Energy↓



Vertically standing
(PSI generation)
Ri = 0.7

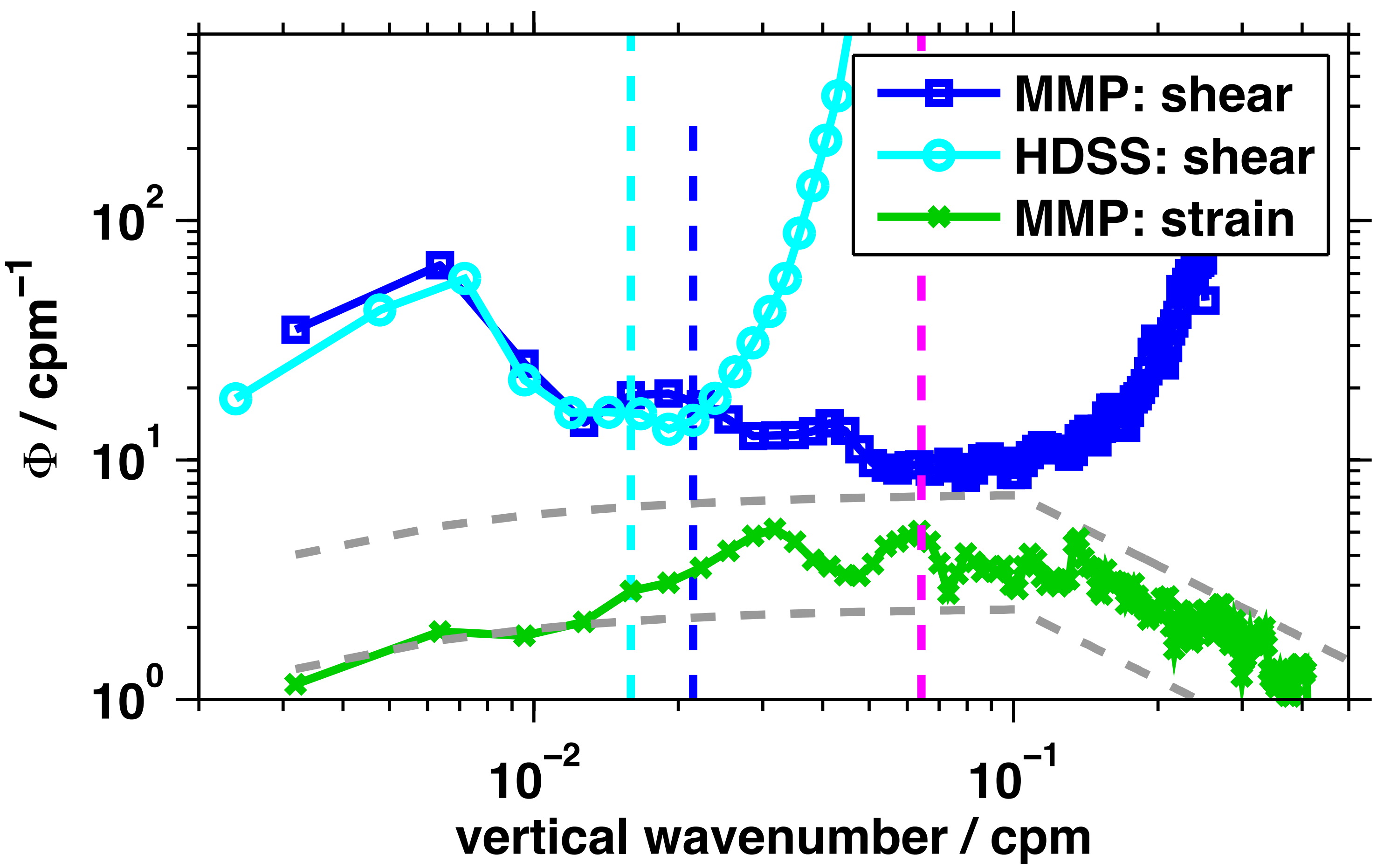
Surface generation

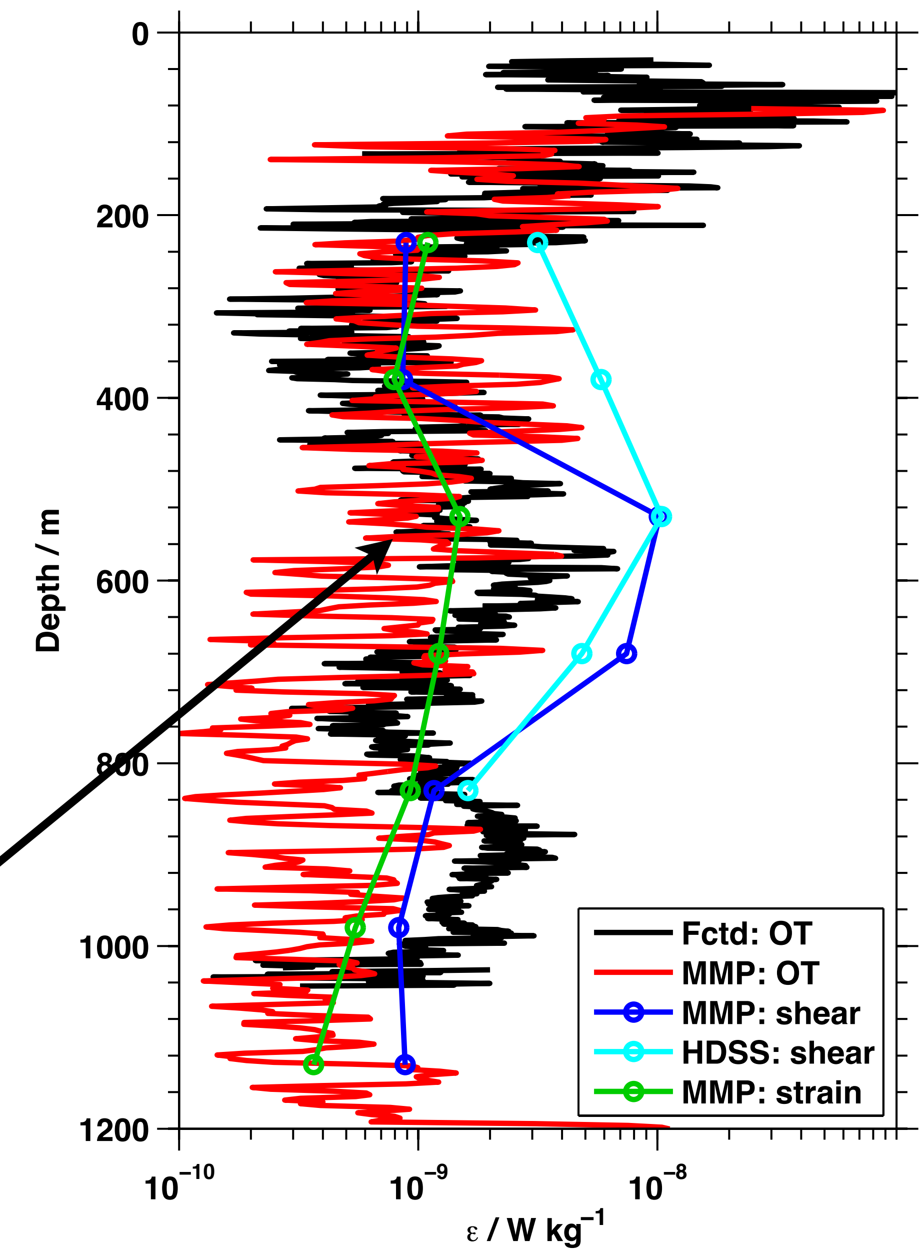
Phase↑ Energy↓

Estimating turbulence: internal wave shear spectra

Issue #2:

- Can use either shear or strain (KE or PE) to estimate total energy
- but shear/strain ratio can vary by a factor of 10

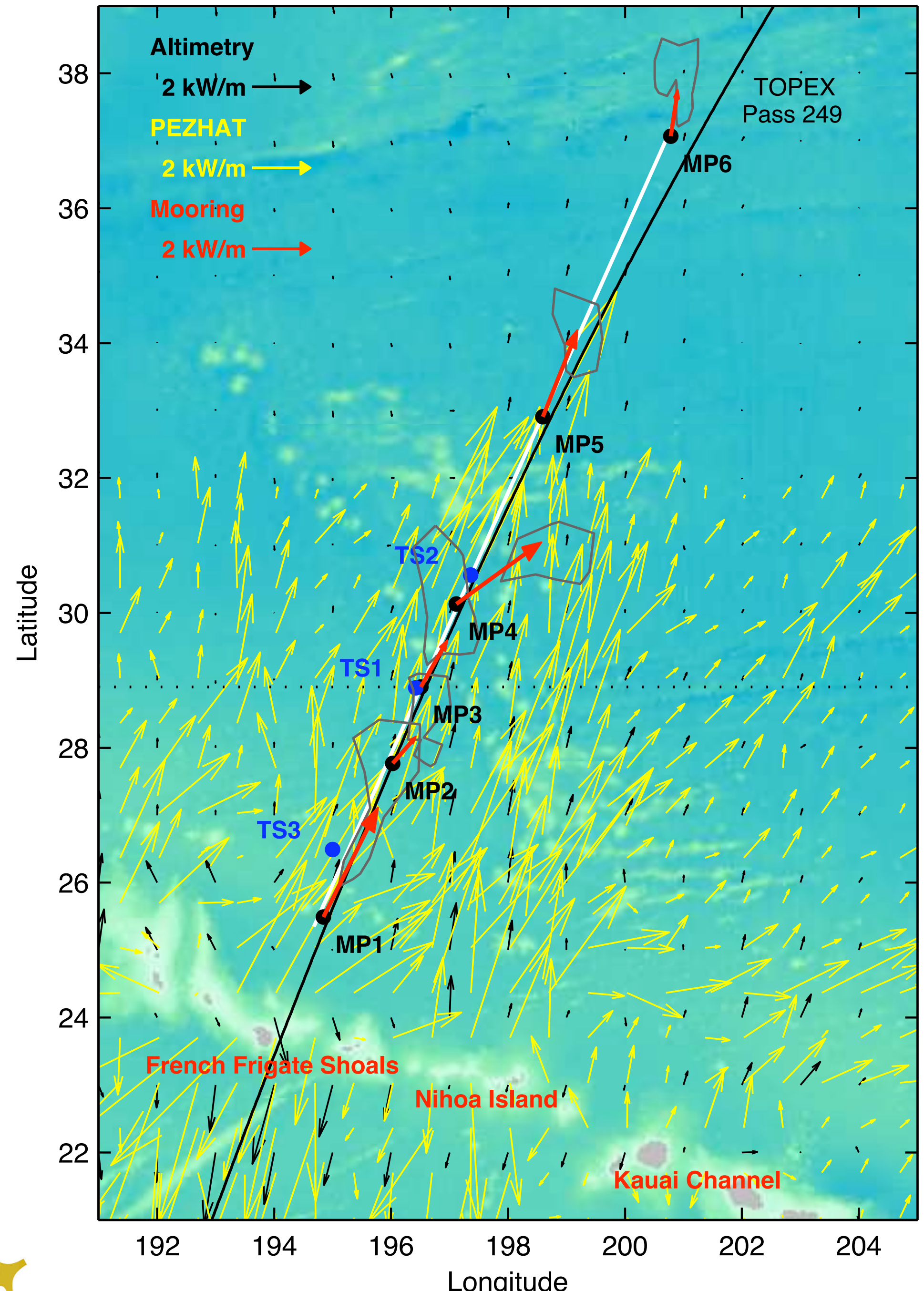


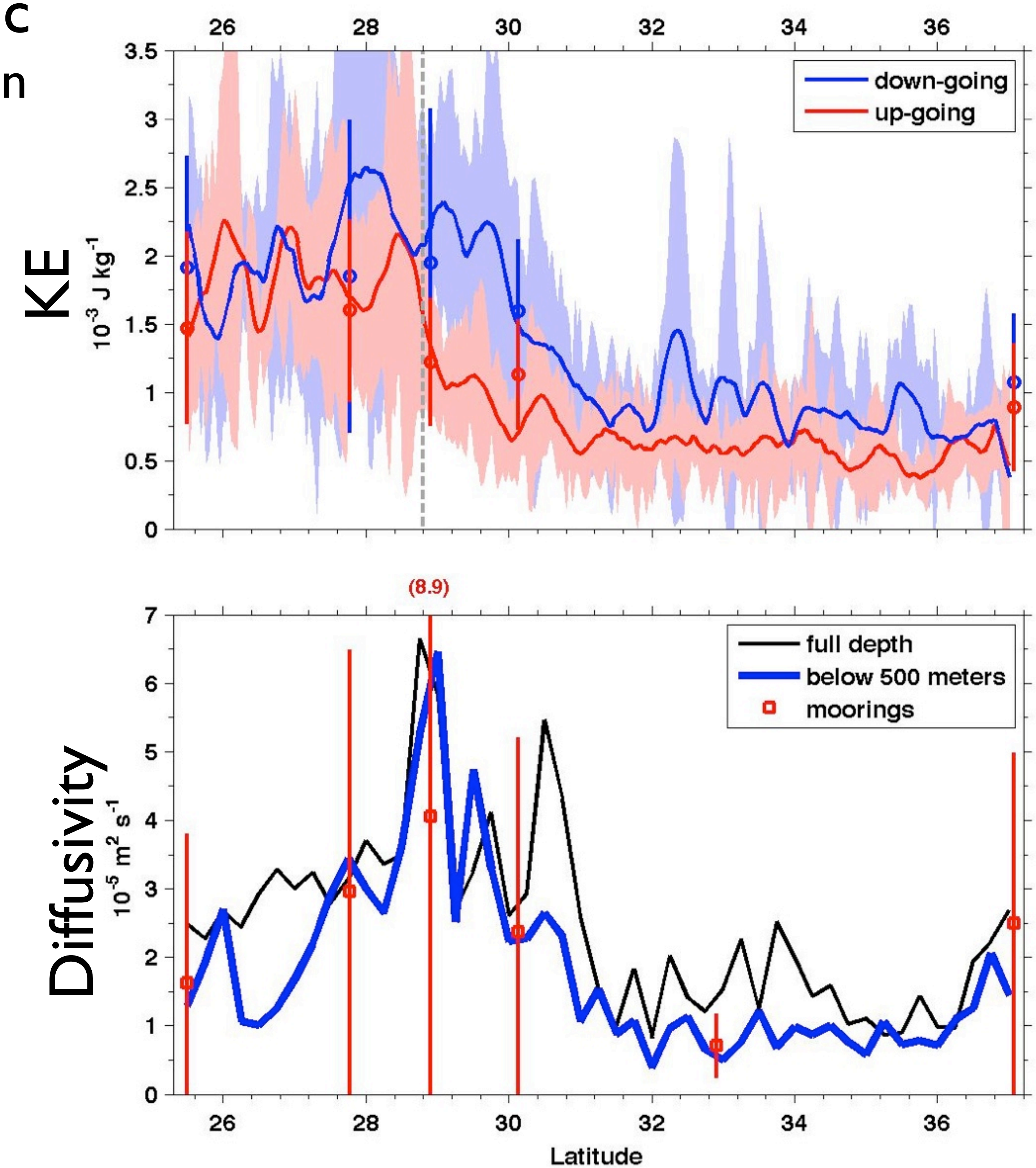


Mixing estimate: example 1

Internal Waves Across the Pacific

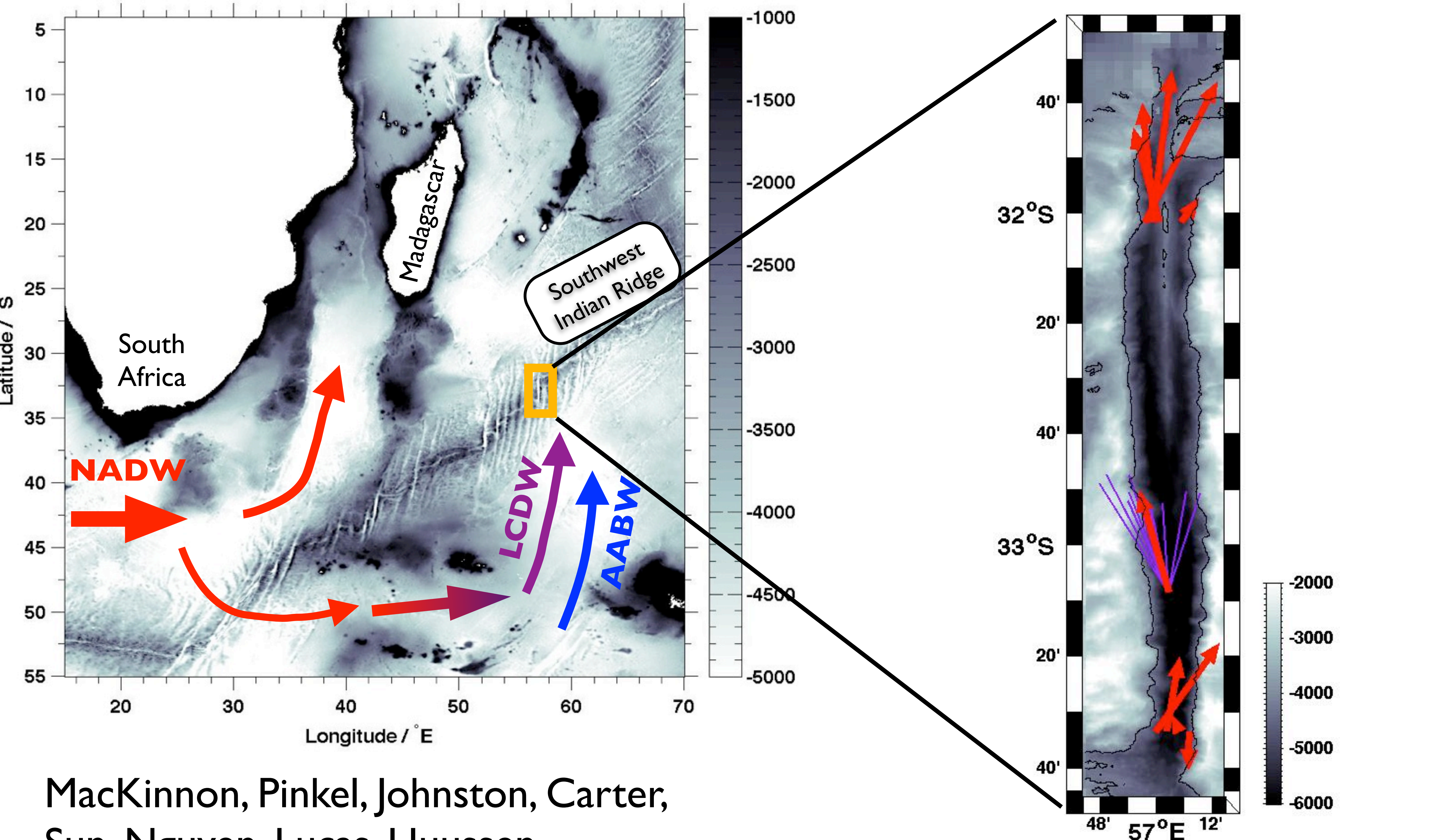
Alford, MacKinnon, Pinkel, Klymak, Sun





(Alford et al 07, MacKinnon and Winters)

Mixing estimate: example 2



MacKinnon, Pinkel, Johnston, Carter, Sun, Nguyen, Lucas, Huussen

Dec 07 - Jan 08

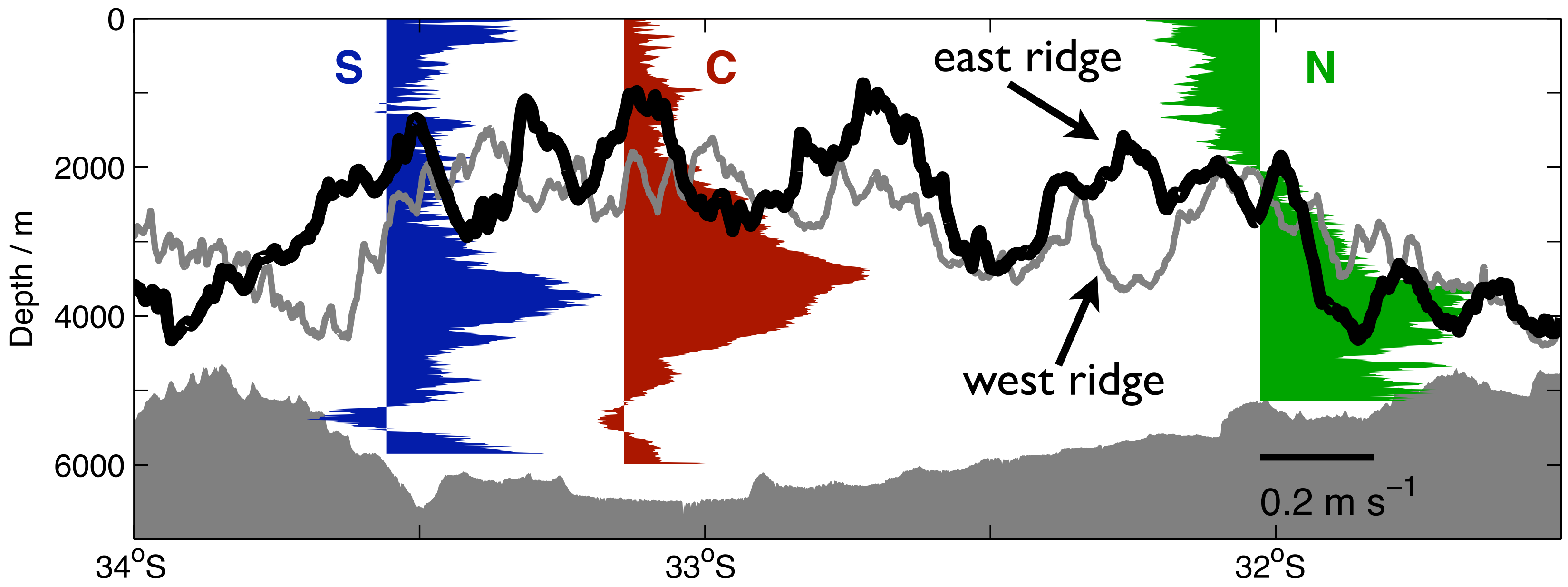
+ UC ship funds

Net deep and bottom transport of 3 ± 2 Sv

Compare to 10-15 Sv basin-wide MOC

Strong northward transport of deep + bottom water

Strong flow below bounding topography



Strong northward transport of deep + bottom water

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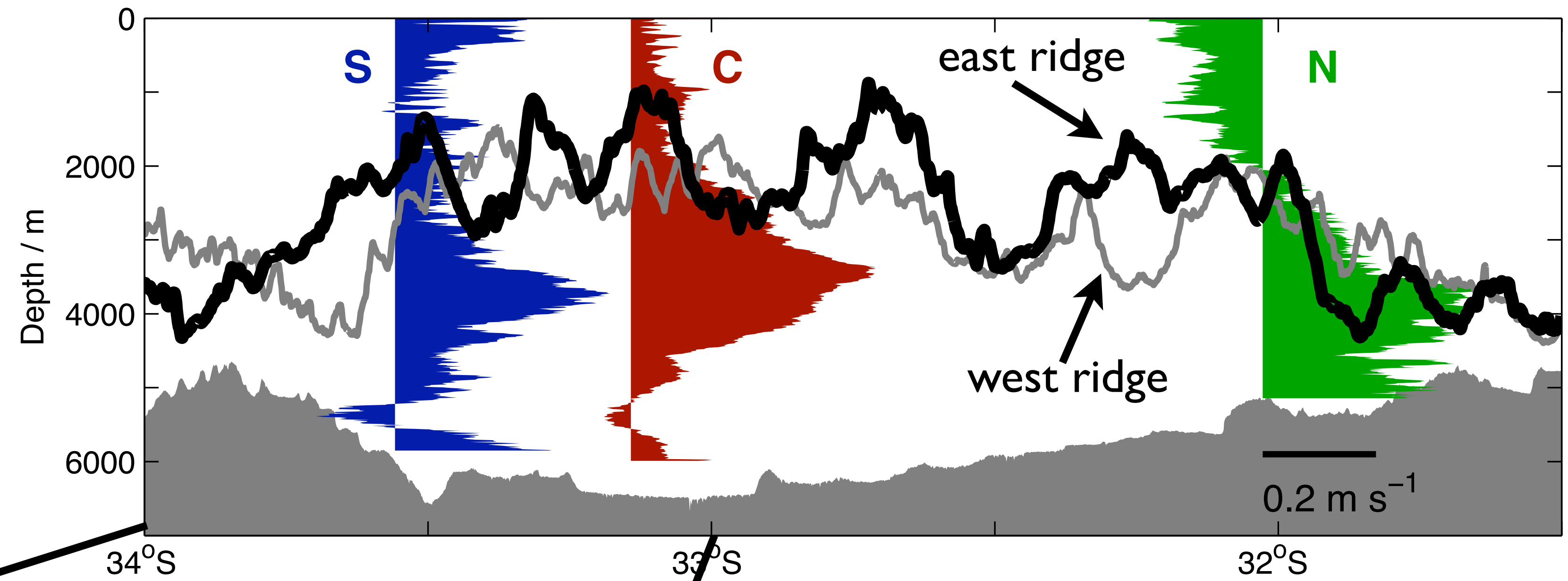
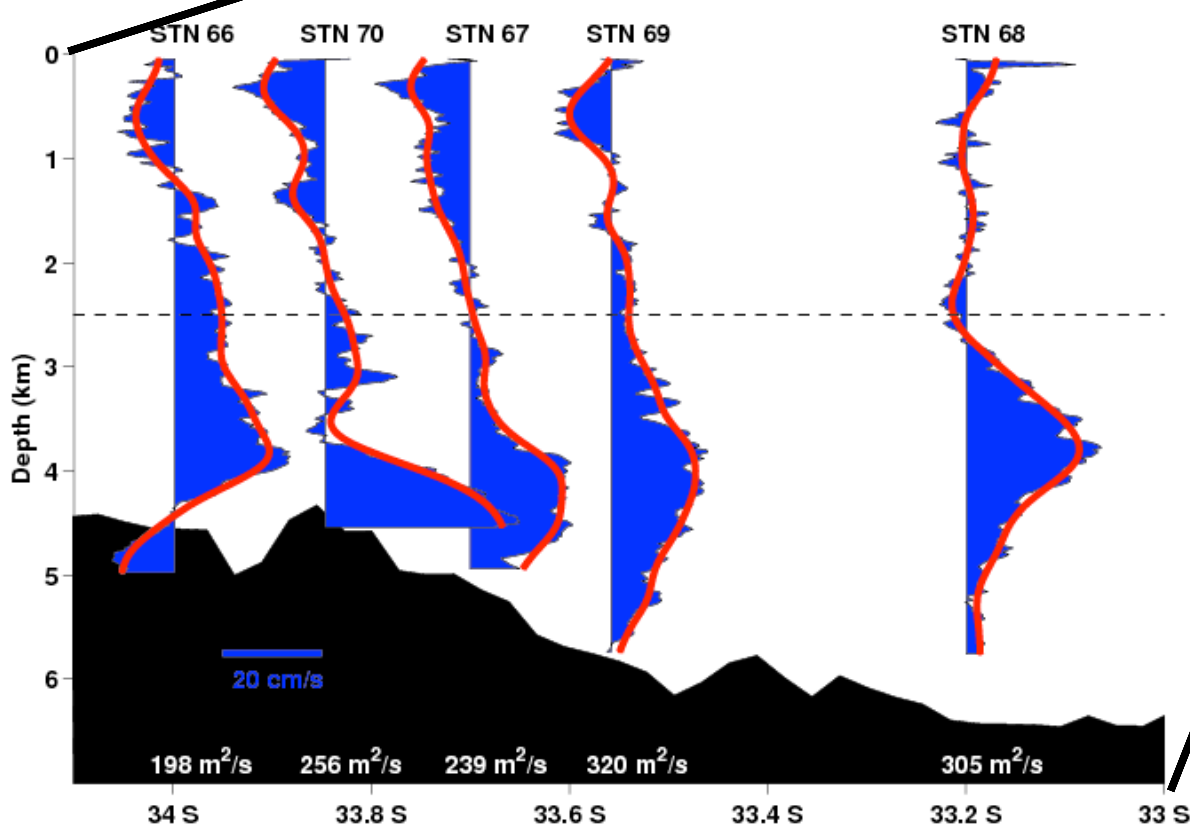
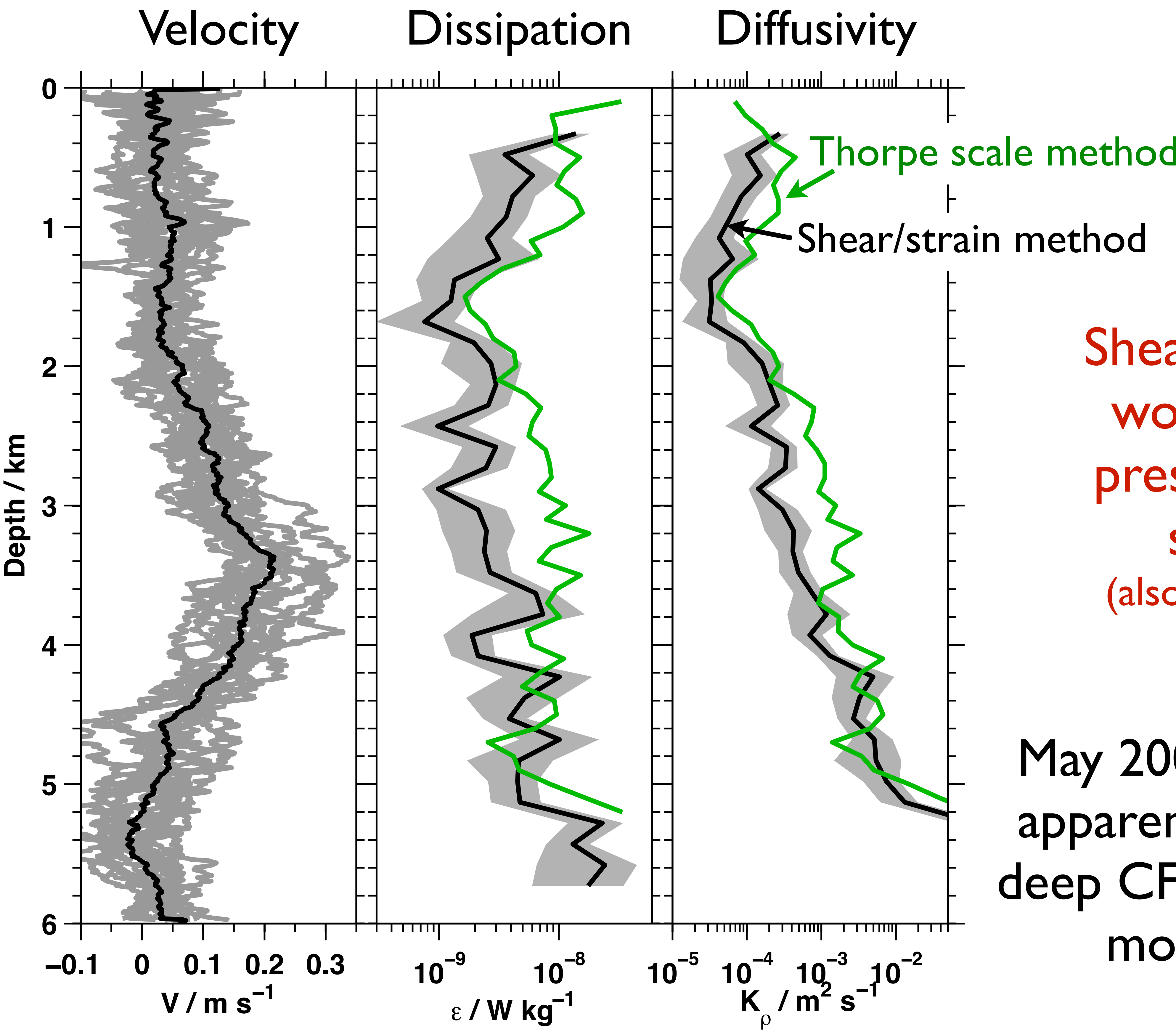




New measurements by Clivar (April 2009)

Swift, Johnson, Ascani, et al.

Mixing from LADCP data

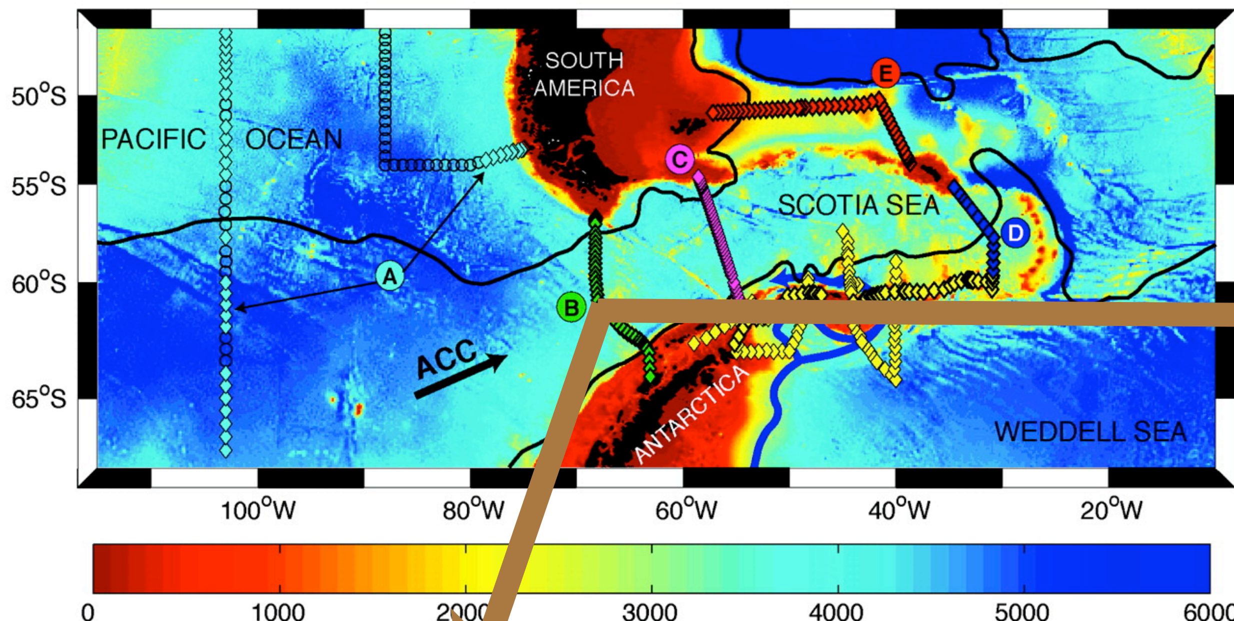


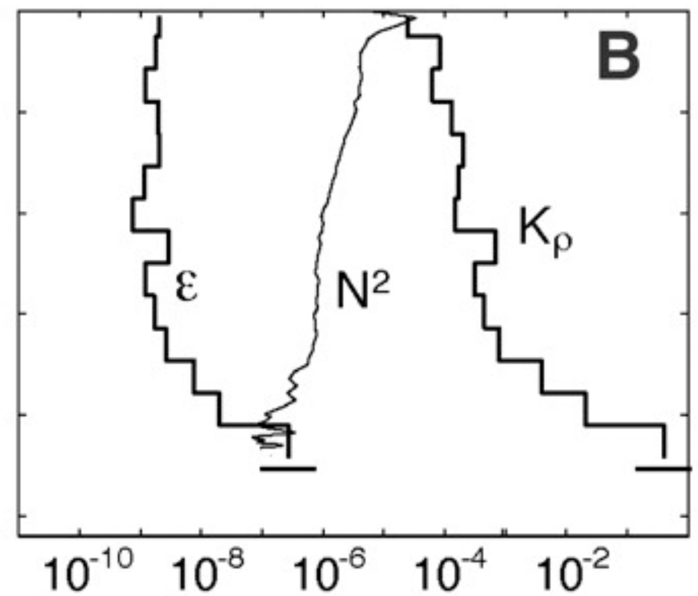
Shear/strain method works even in the presence of a mean sheared flow
(also: Winkel et al., 2002)

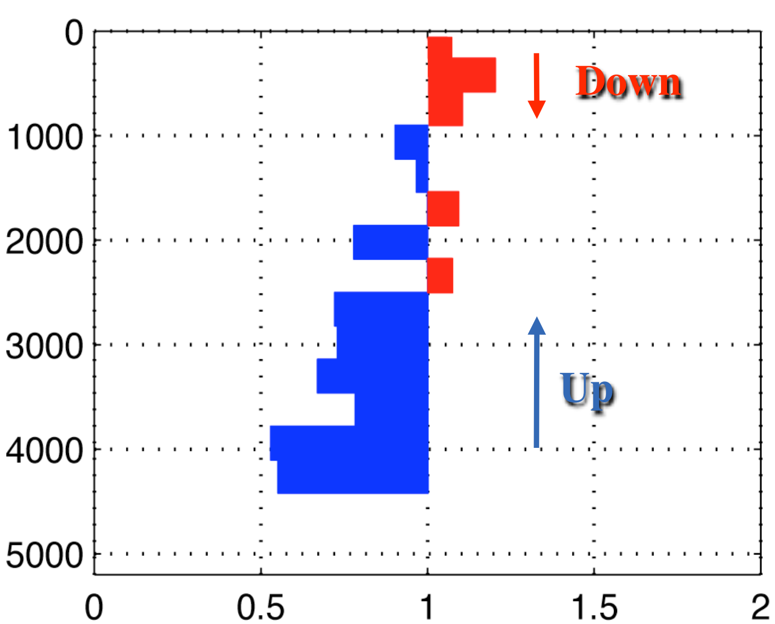
May 2009: Clivar confirms apparent "mixing away" of deep CFC minimum as flow moves northward

Mixing estimate: example 3

LADCP estimates of turbulent diffusivity (Naveira Garabato et al., 2004)







- Substantial bottom-enhanced turbulent mixing in Drake Passage

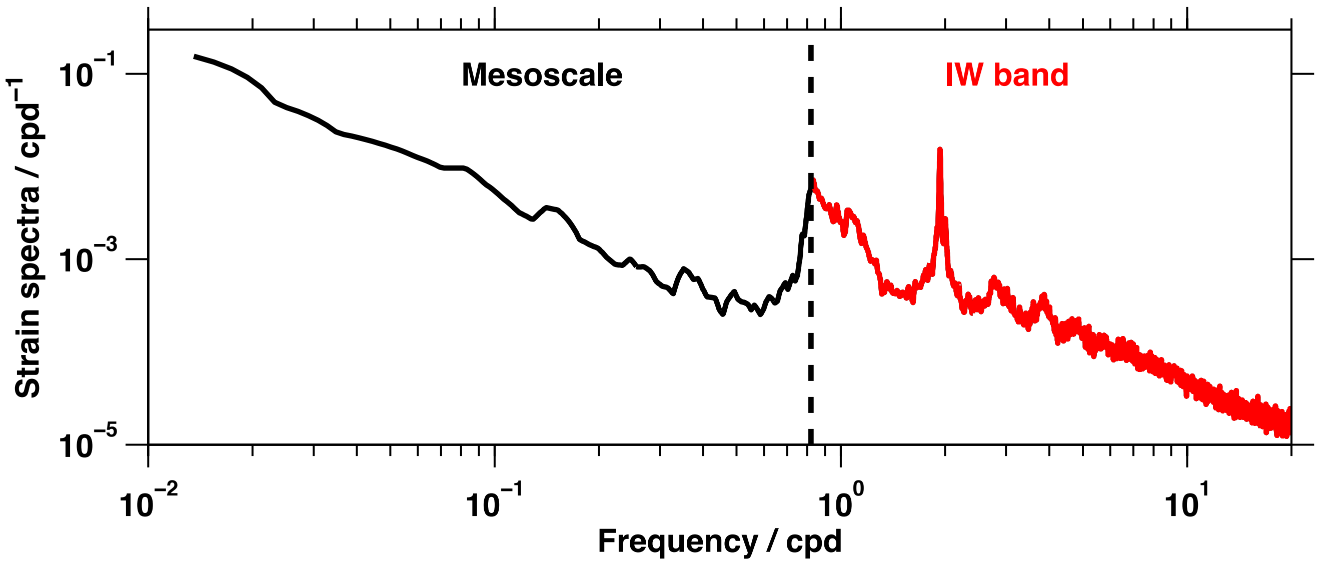
- However, Kunze argues deep values are off by an order of magnitude due to incorrect shear/strain ratio...

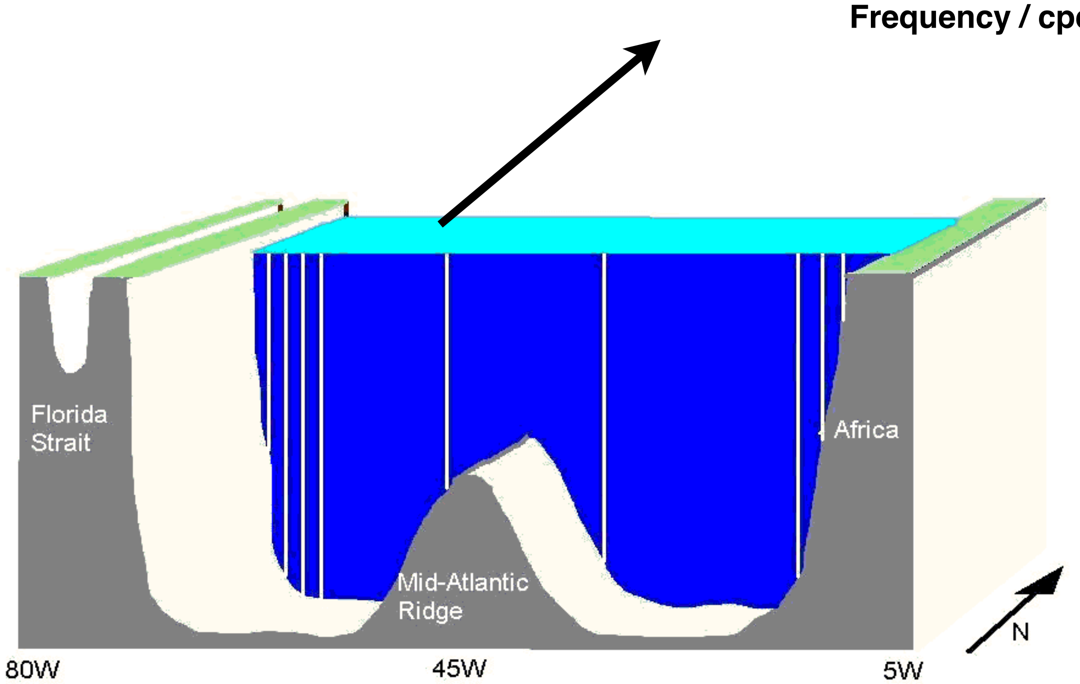
Mixing estimates: more examples

Global patterns: WOCE, ARGO, XCTDs?

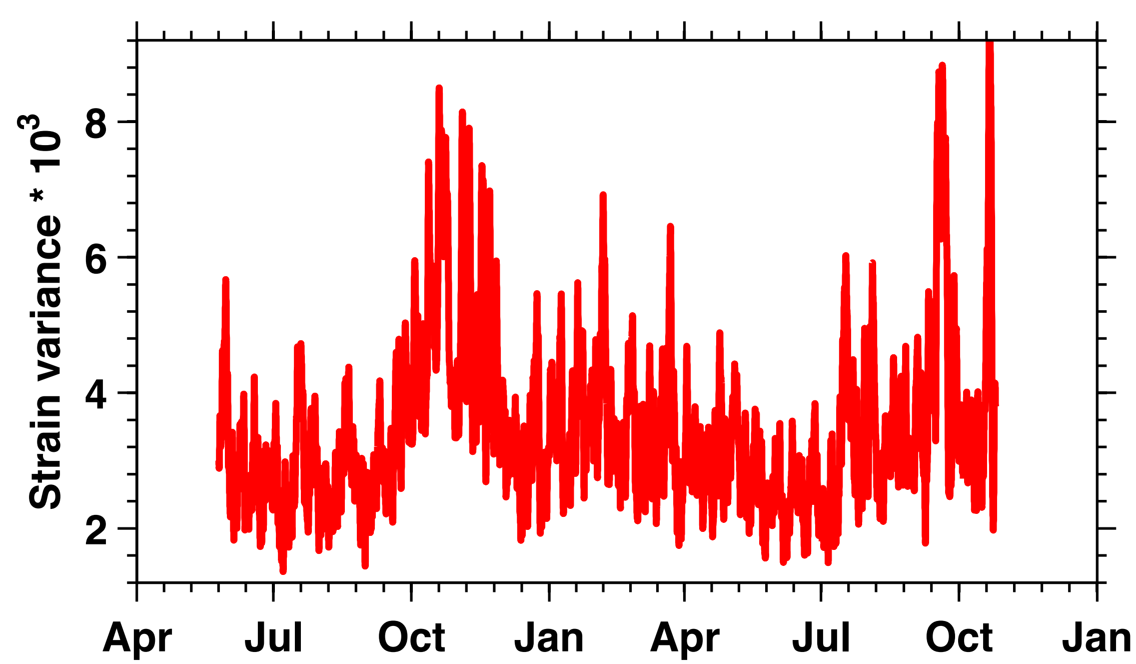
Rapid Mooring array along 24N (public domain data, courtesy of BODC)

Student Projects?





Energy of IW-band

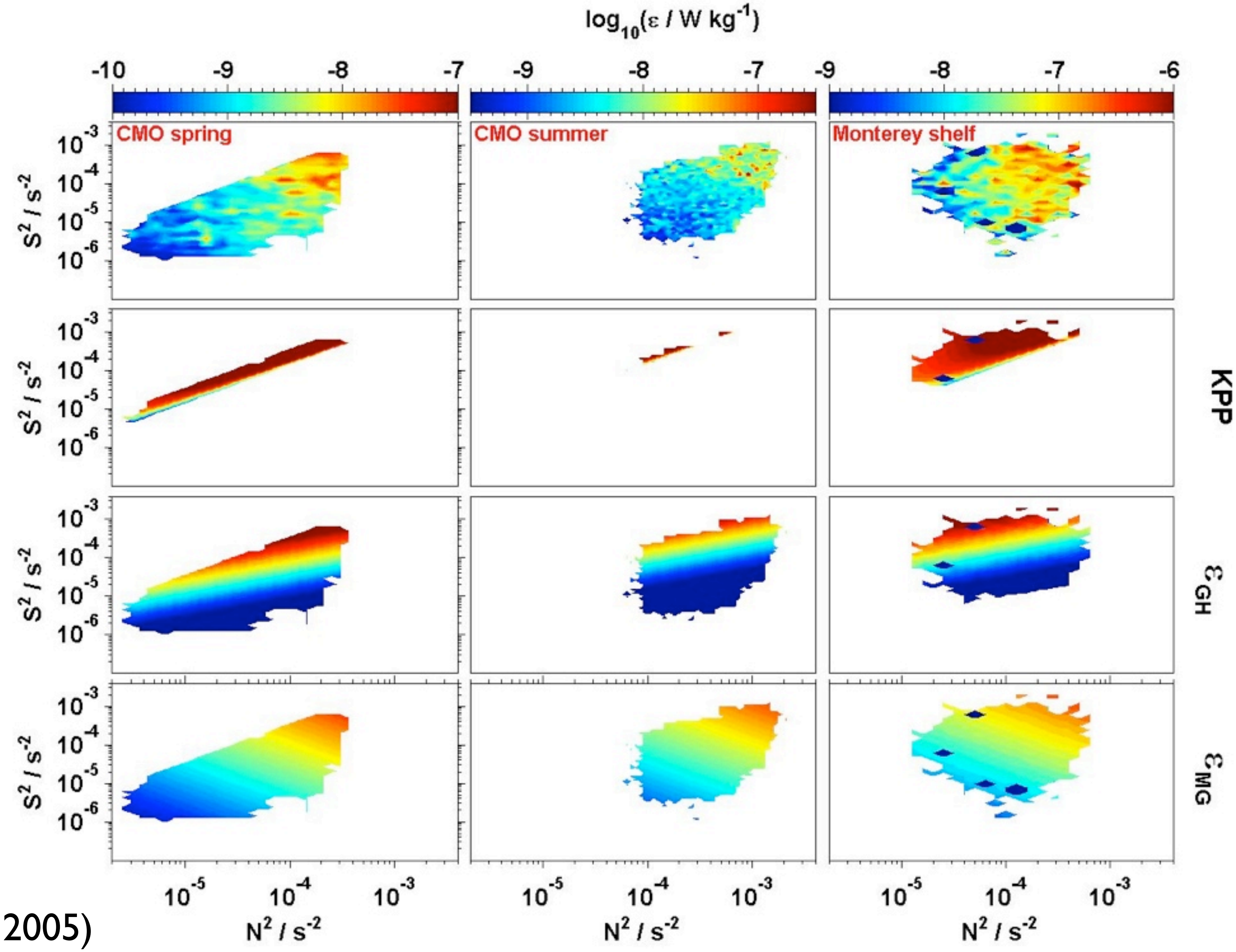


Exceptions: coastal mixing

Coastal internal-wave field doesn't have the same spectral nature:
- much lower vertical bandwidth

=> different rate of down-scale energy transfer

$\varepsilon_{coast} \sim N * S$

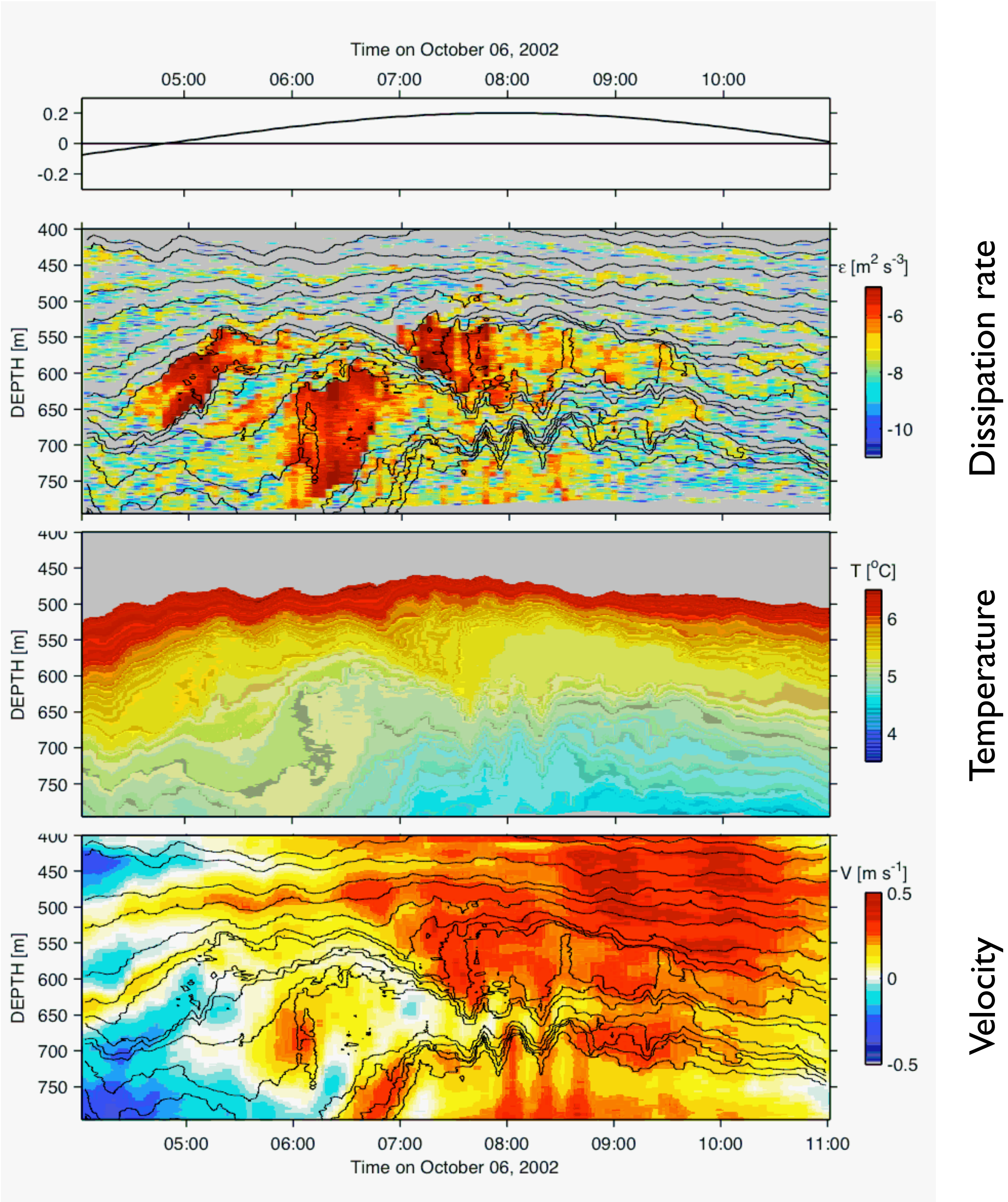


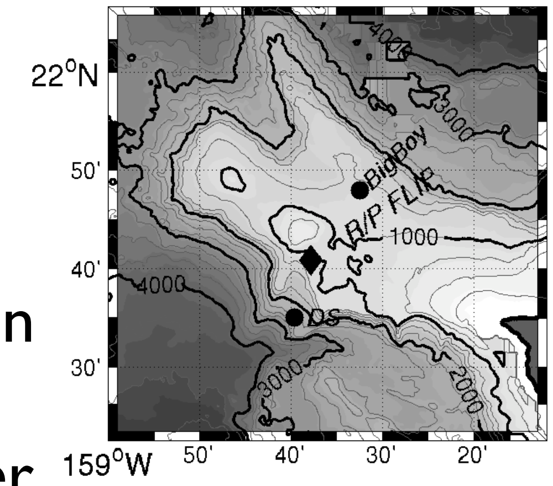
MacKinnon and Gregg (2002, 2005)

Exceptions: directly-breaking internal tide

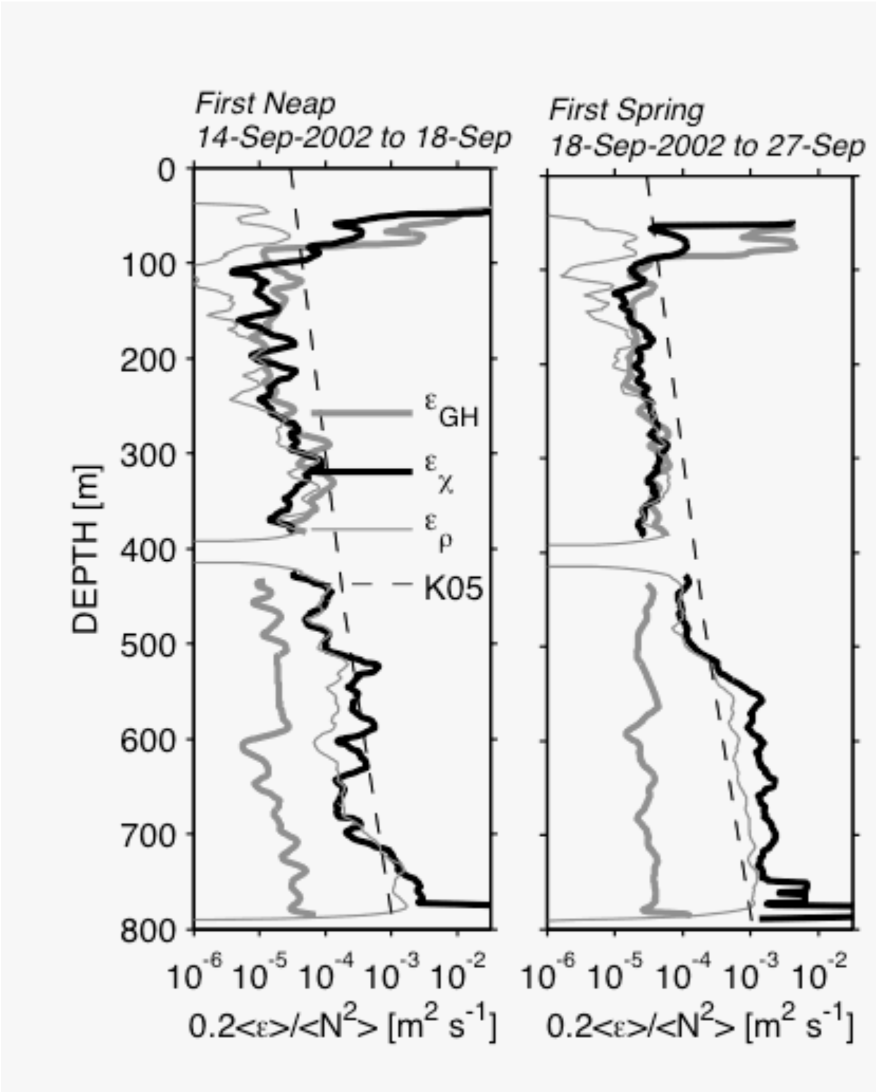
Hawaiian Ocean Mixing Experiment (HOME)

Huge overturns as internal tide sloshes up and down a steep slope



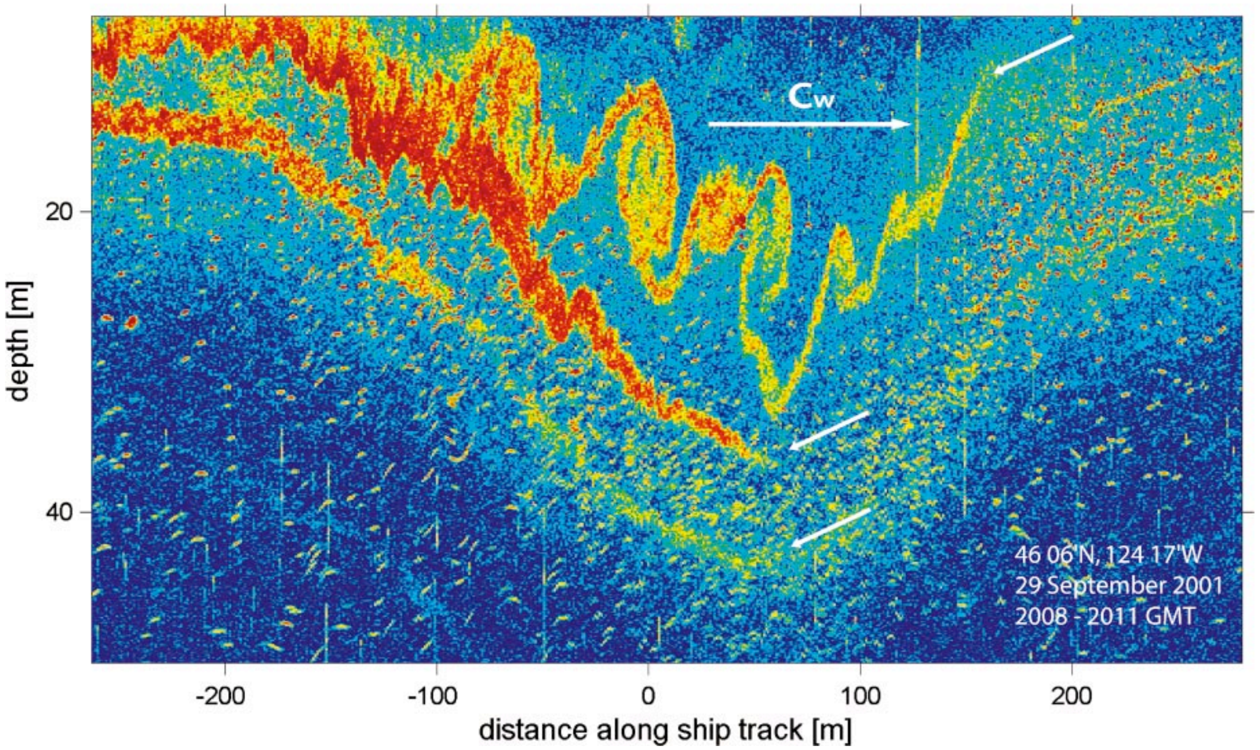


Gregg-Henyey parameterization works in upper water column, but not for the deeper, stronger mixing.

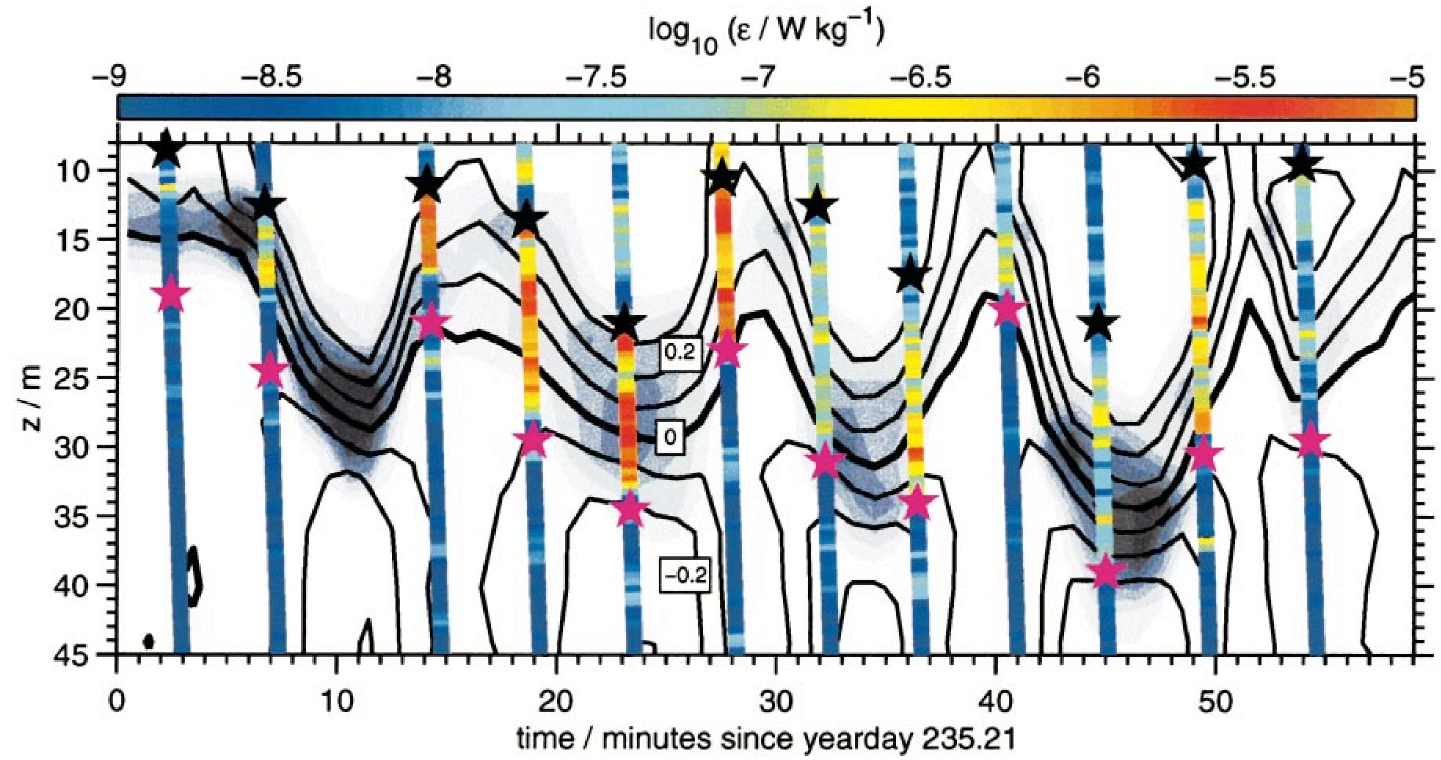


Klymak et al 07

Exceptions: directly-breaking internal tide



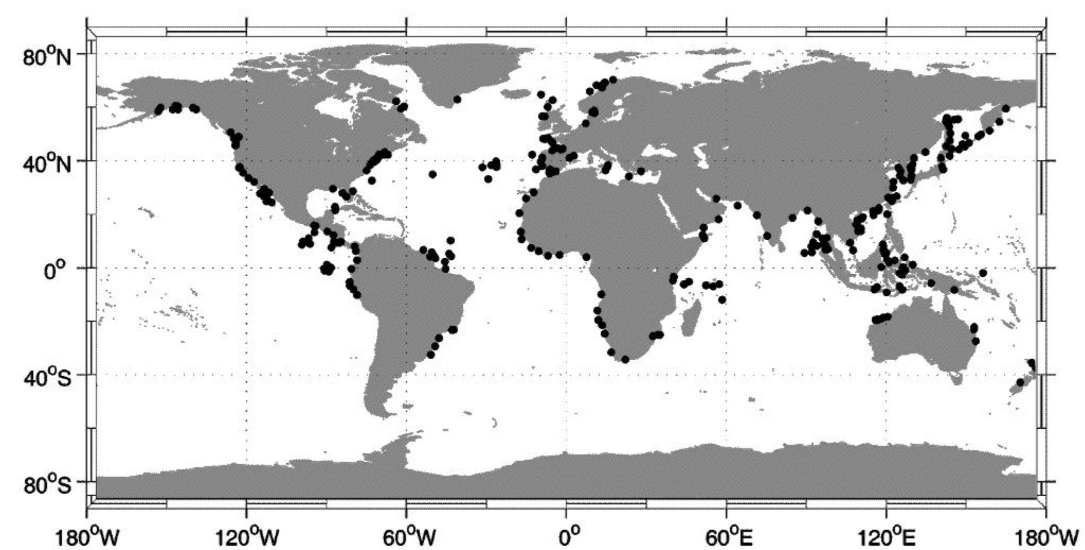
Moum et al. (2003)



MacKinnon and Gregg (2003)

50-75 % of total average daily mixing occurs in these few minutes

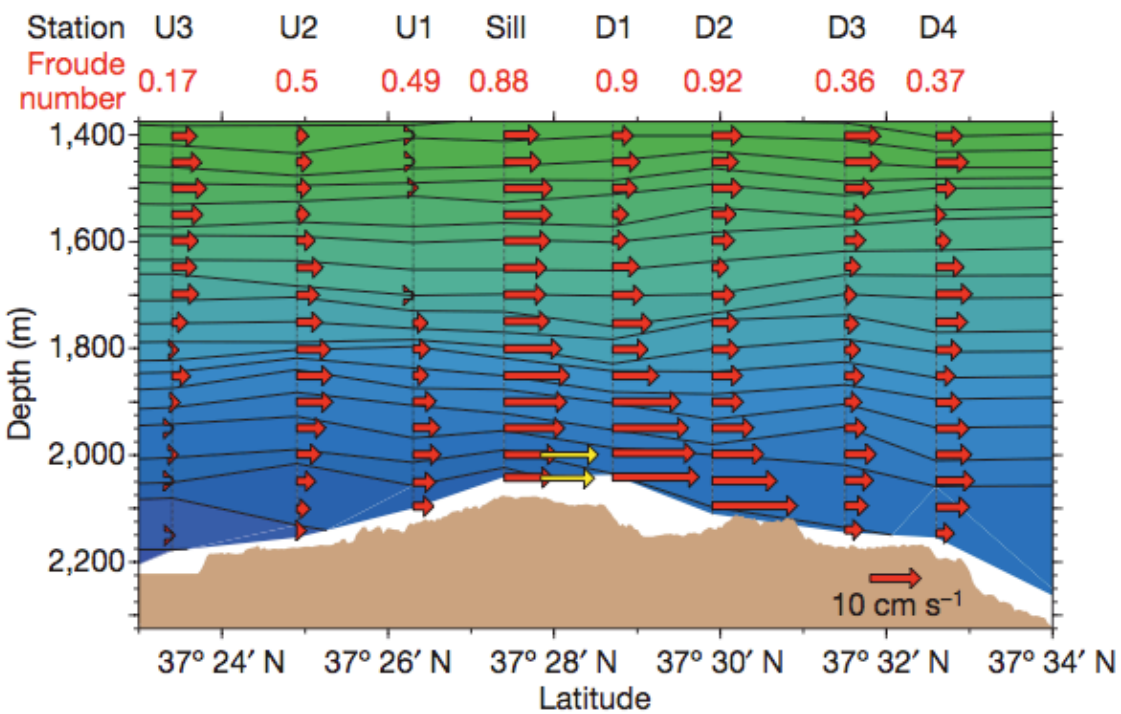
Solitons around the world

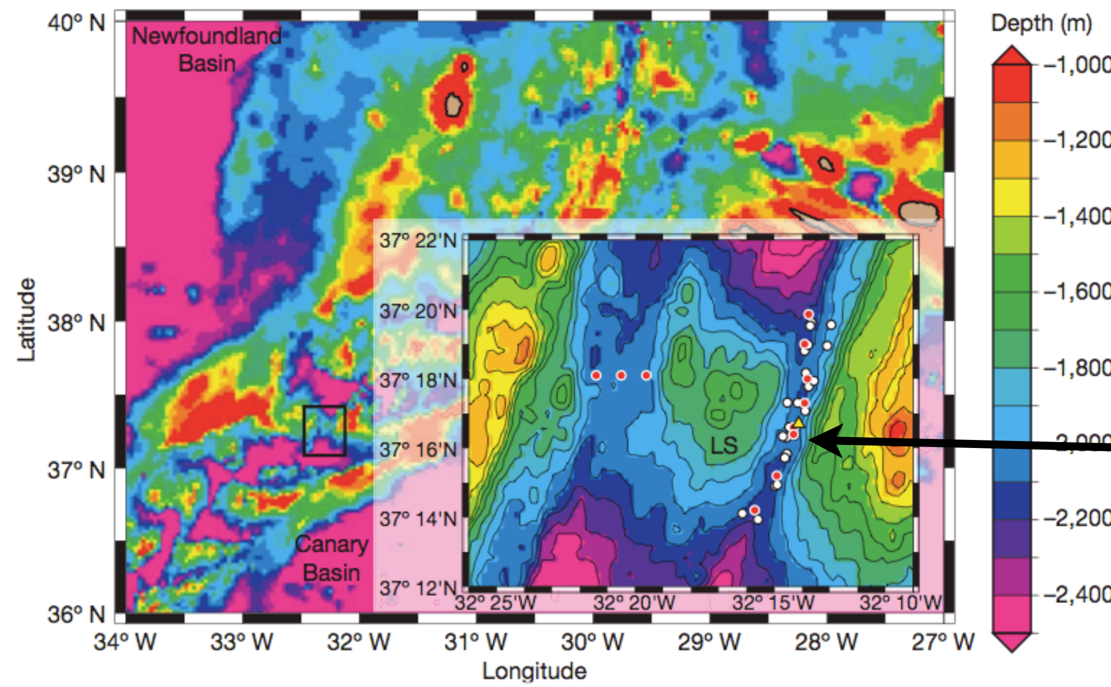


Apel et al. (2006)

Exceptions: hydraulically-controlled flows

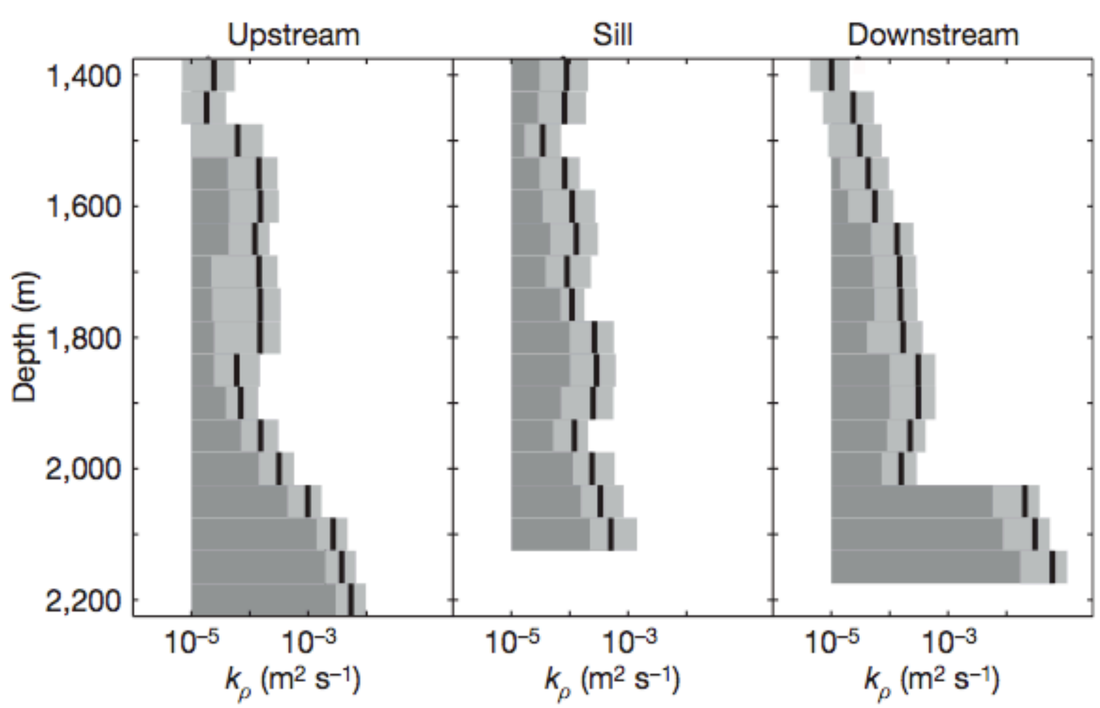
Mixing may be large wherever deep flow accelerates through constrained fracture zones





2 km wide

St. Laurent and Thurnherr (2007)



Diffusivity

- Small fracture zones ubiquitous on mid-ocean ridges at mid-depth

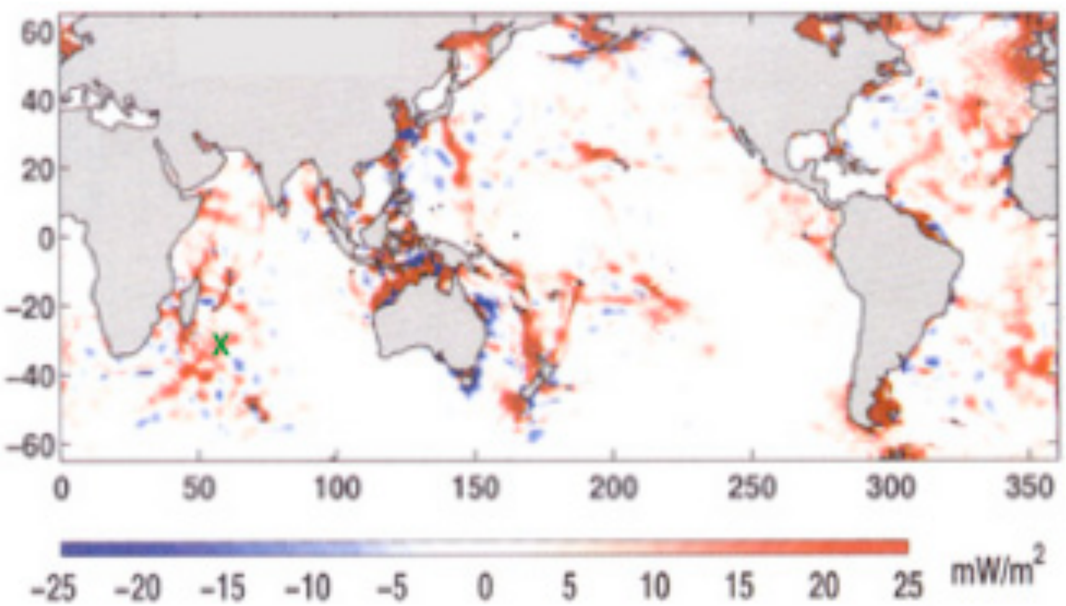
- Similar results found in deepest fracture zone (Romanche FZ, Polzin et al 96)

Modeling turbulent mixing

Can't explicitly resolve internal waves in climate models.
3 steps to parameterize their role:

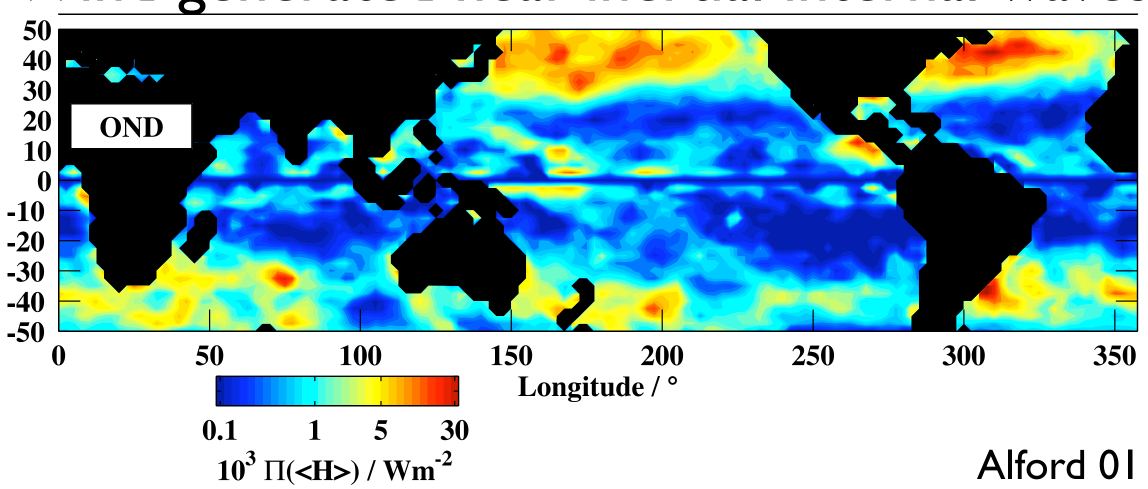
1) Wave generation

Internal-Tide Generation



Egbert and Ray 01

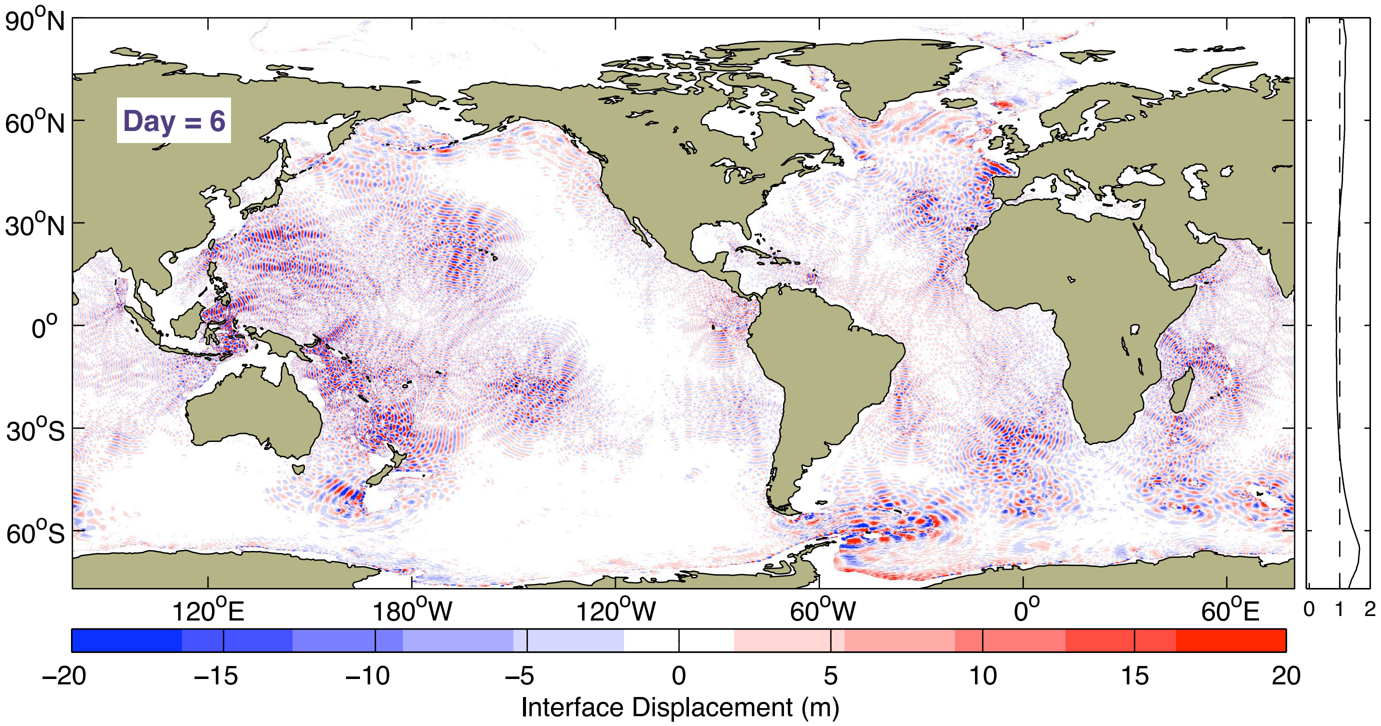
Wind-generated near-inertial internal waves



Alford 01

2) Wave propagation

Internal-Tide Propagation

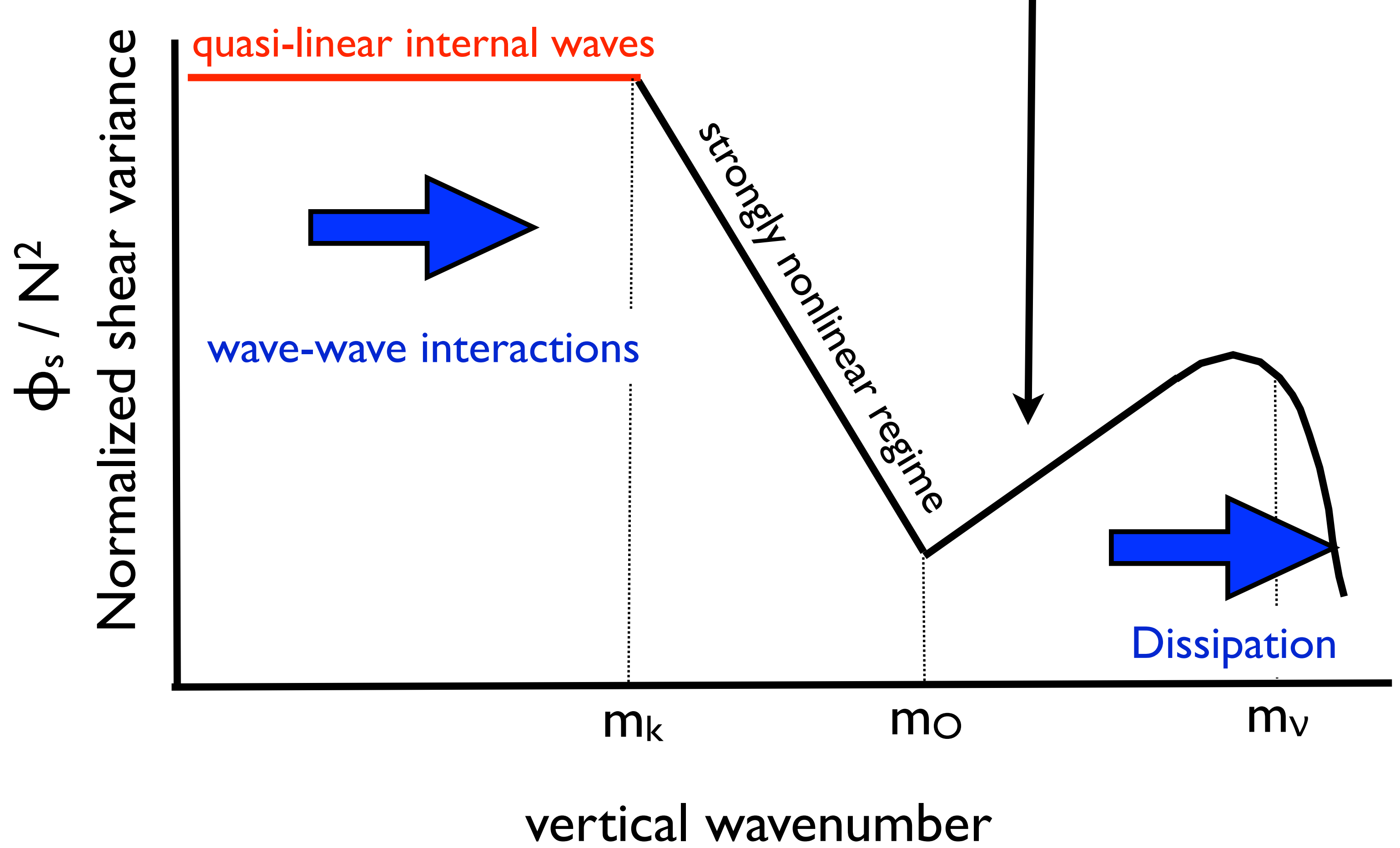


Simmons 07

3) Wave breaking ...

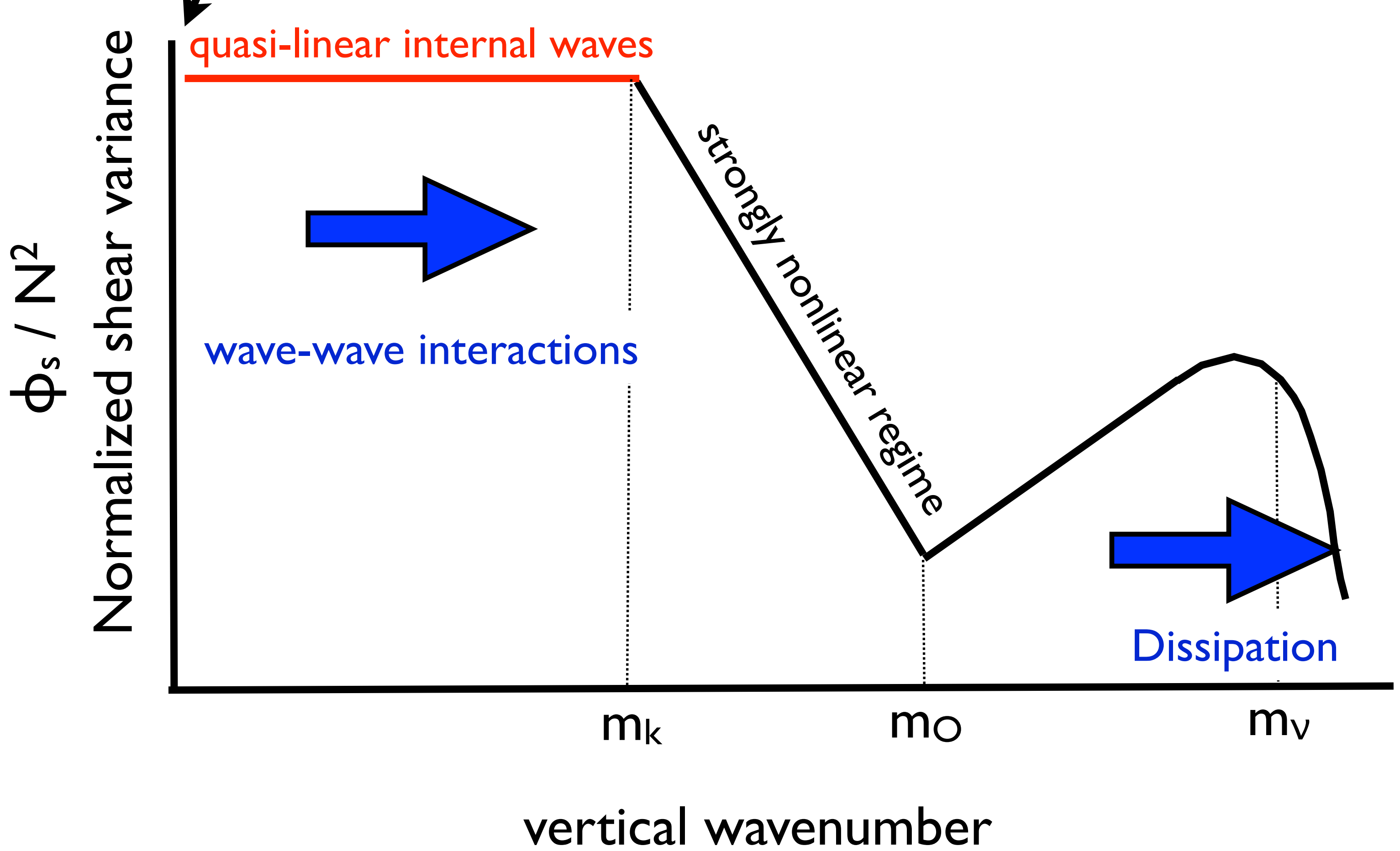
Modeling turbulent mixing

Many mixing parameterizations assume you are able to resolve the scales of motion that produce turbulence (e.g. Mellor-Yamada, KPP, LES...), which is rarely true in global models away from boundaries



Modeling turbulent mixing

Can we create a parameterizaton that uses the RESOLVED large-scale internal waves and our dynamical understanding? (CPT)



Modeling turbulent mixing

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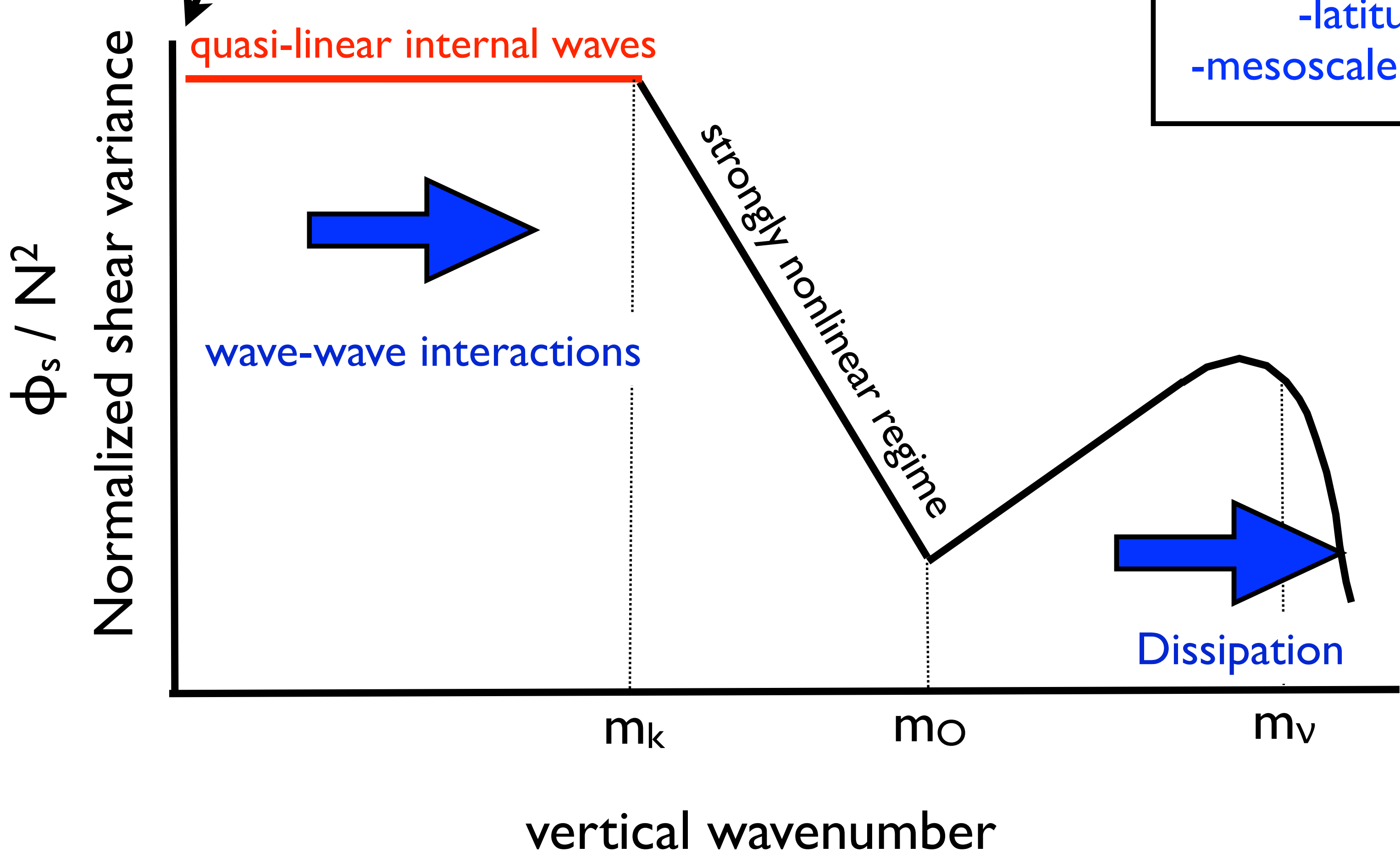
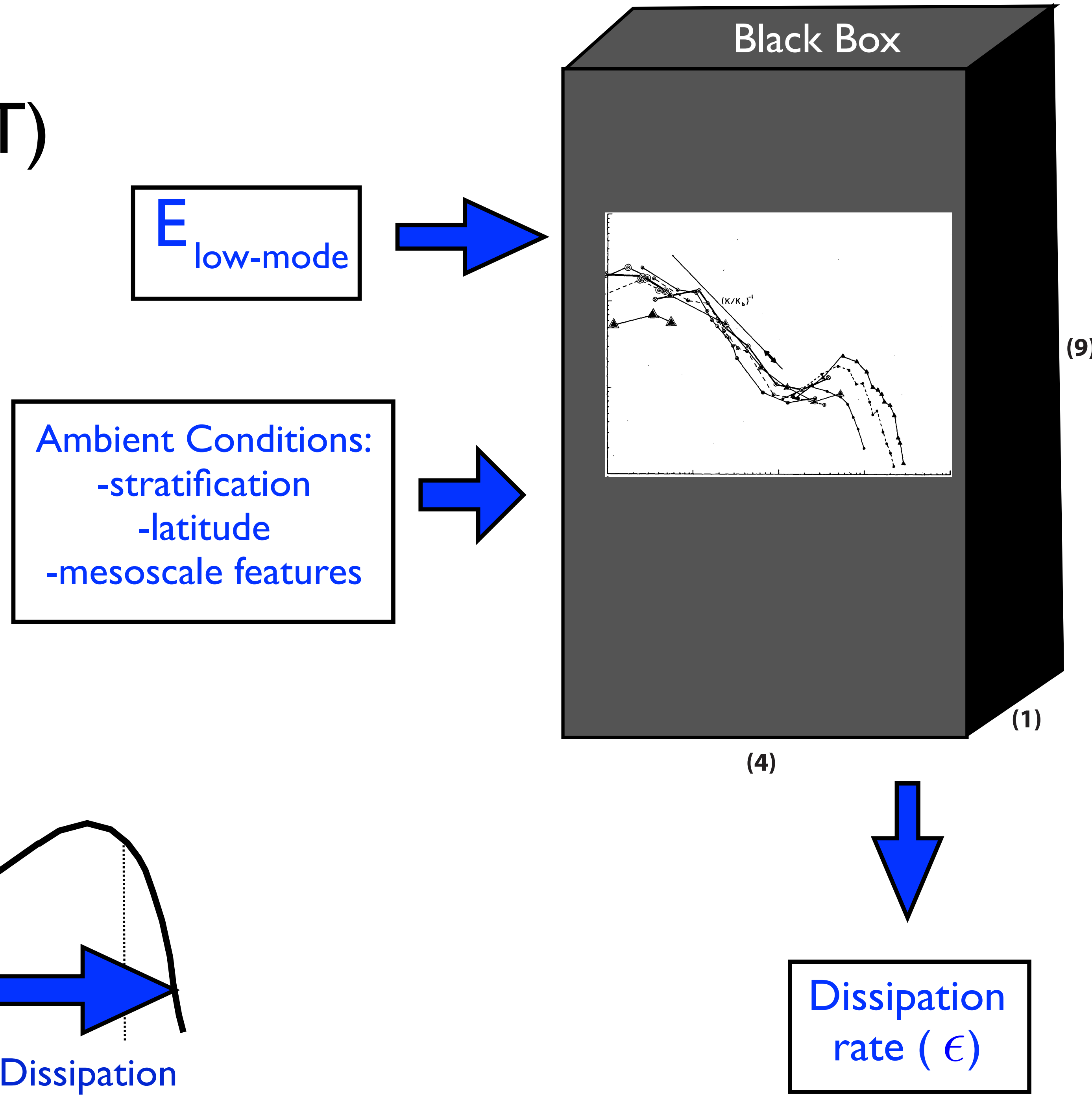
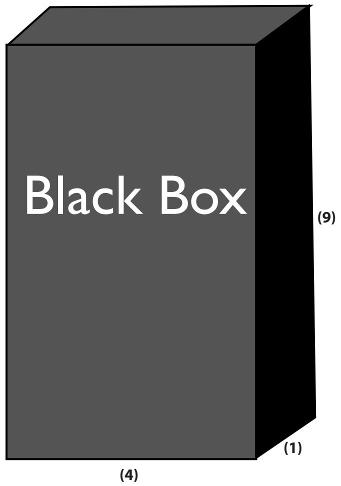
Student Project?





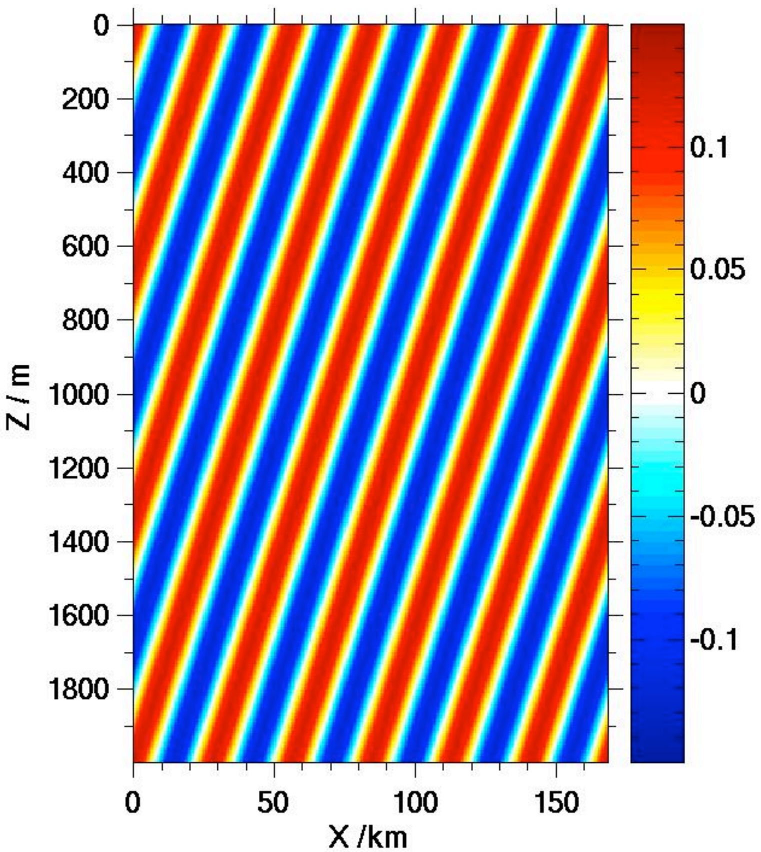
Modeling turbulent mixing: process studies

Using numerical process studies to develop parameterizations of internal-wave energy transfer and dissipation



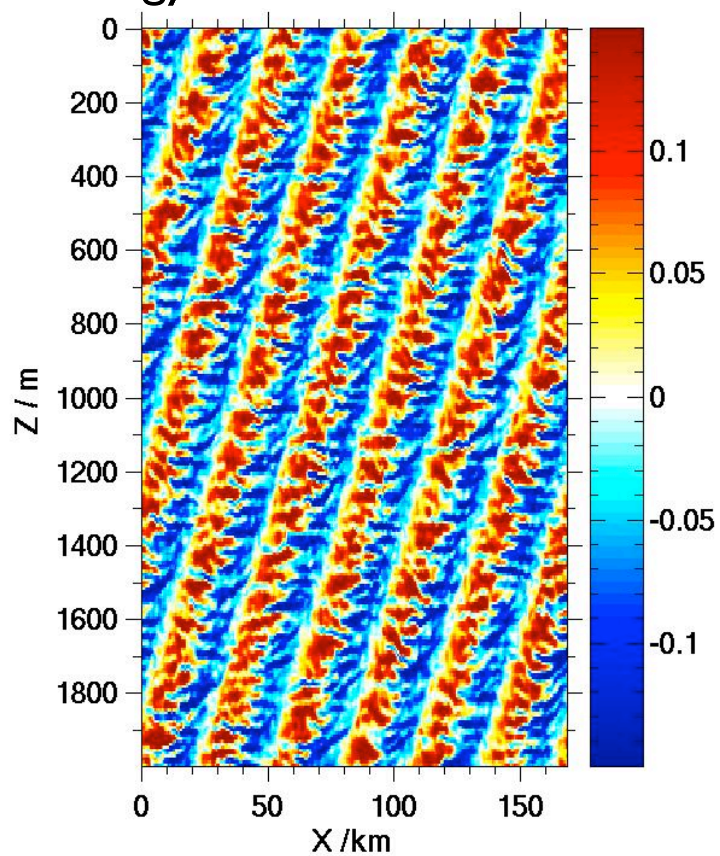
Initialize

One wave + white noise



After a while

Energy transfer to small-scale waves



Result: dissipation rate as a function of low-mode wave energy, based on understanding wave-wave interaction growth rates and bicoherence

Next step: collapse complex results into a form suitable for possible use in large-scale models

Conclusions

- Fine-scale estimates of diapycnal mixing provide "reasonably" accurate values, within a factor of 2-10

- They turn the mixing measurement problem into a problem of measuring the global internal-wave climate, which can be done from a huge range of platforms

- Similar ideas may be useful for developing dynamic parameterizations of internal-wave driven mixing for use in global numerical models

Mixing for the masses

Jennifer MacKinnon

7 May 2009

Teaching Possibilities

Undergraduate:

- Waves (111)
- Dynamical Physical Oceanography? (new)

Graduate:

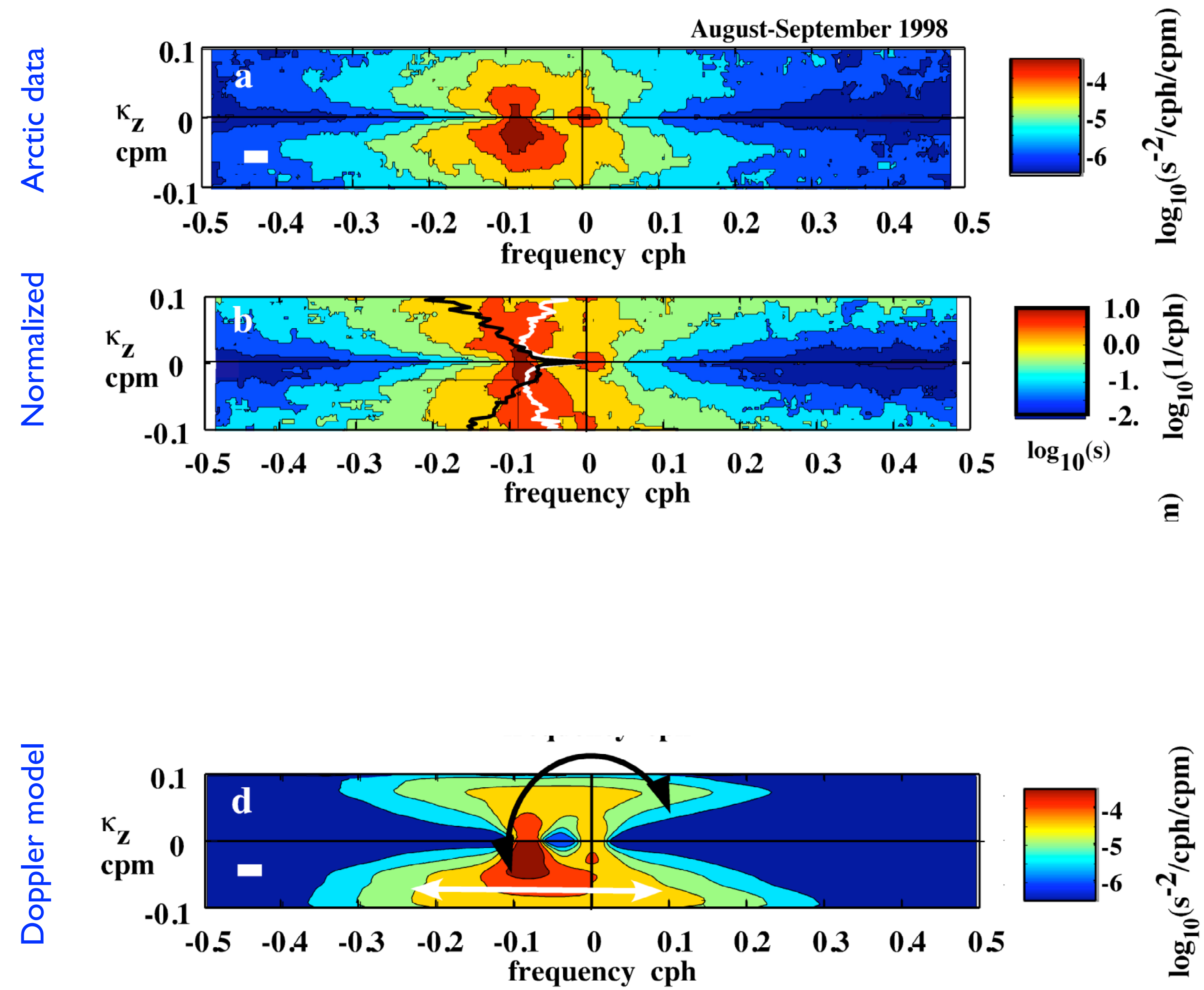
- Wave Fundamentals (202 A,B)
- Ocean Waves (211 A,B)
- Ocean Mixing (213)
- Current topics in PO (219)
- Internal Waves and other small-scale dynamics (new)

Is the spectrum a myth?

Doppler shifting makes for broadened frequency band at higher wavenumbers.

$$s_{Eul} = s_0 \exp(i\, \underline{k}*\underline{x} + \underline{k}*(\underline{V}\, t) - \omega\, t)$$

Intrinsic shear only at inertial and vortical (f=0) frequencies, advected by horizontal currents



Pinkel 07

** get correct reference **

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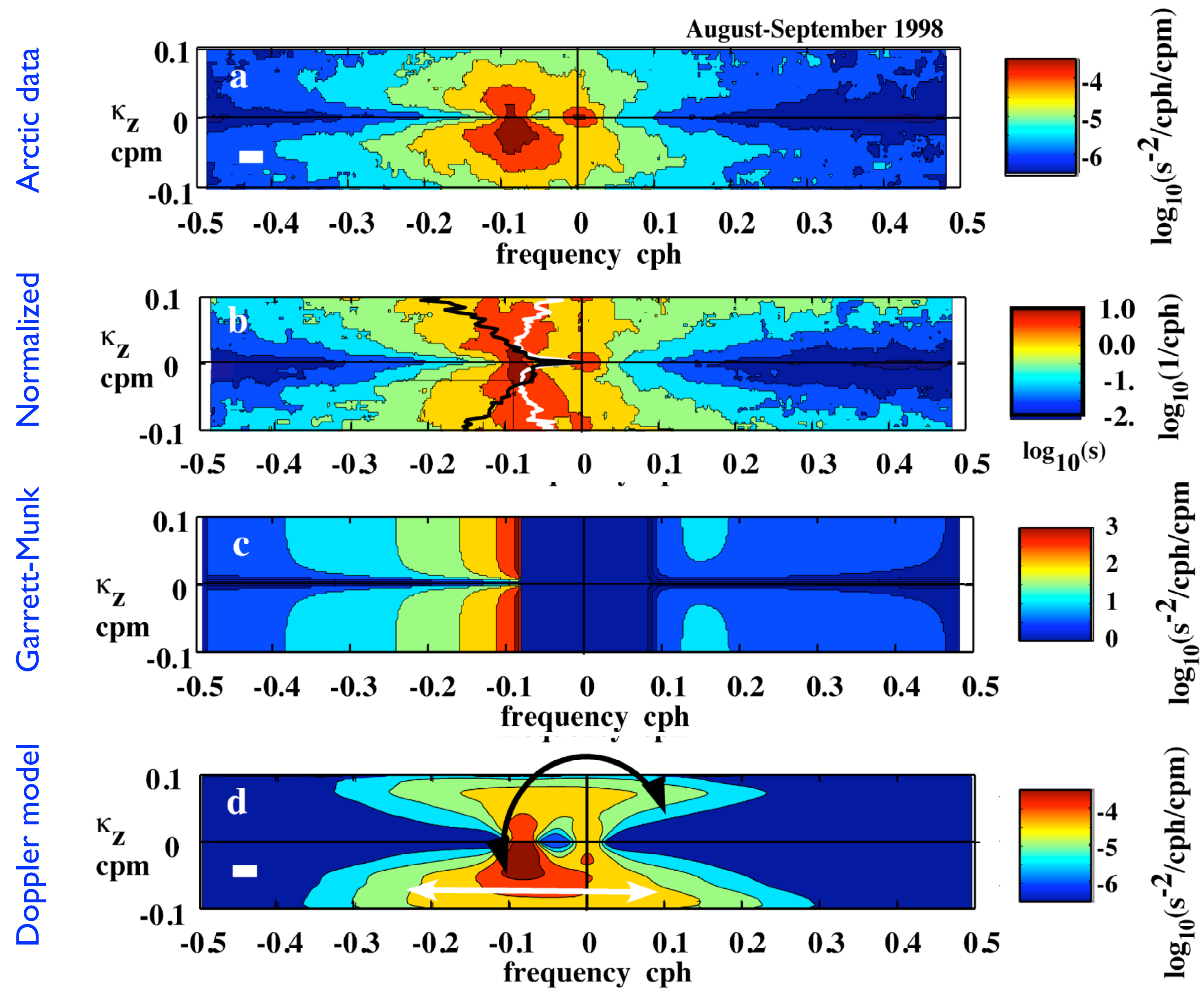
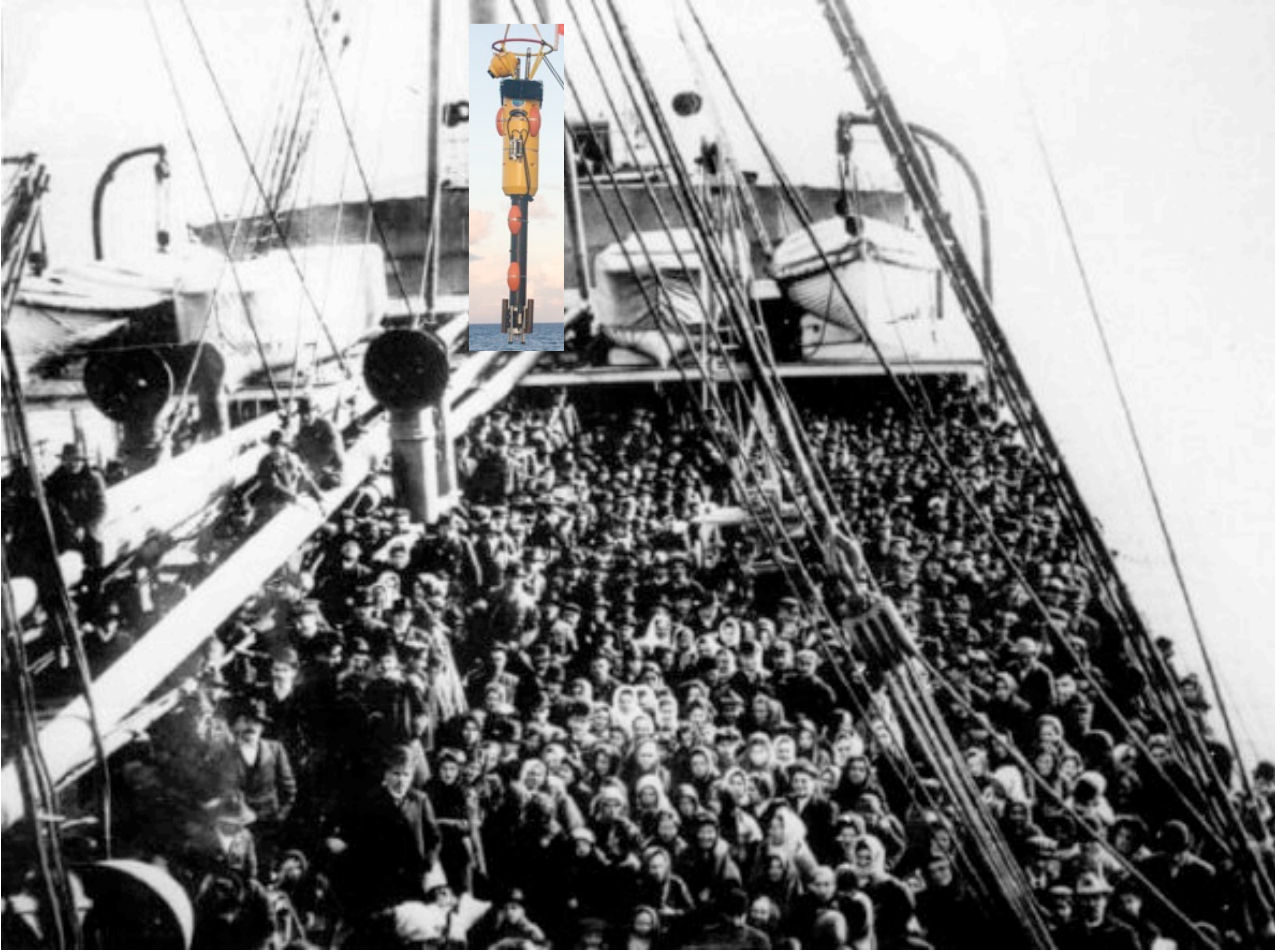


Pinkel 07

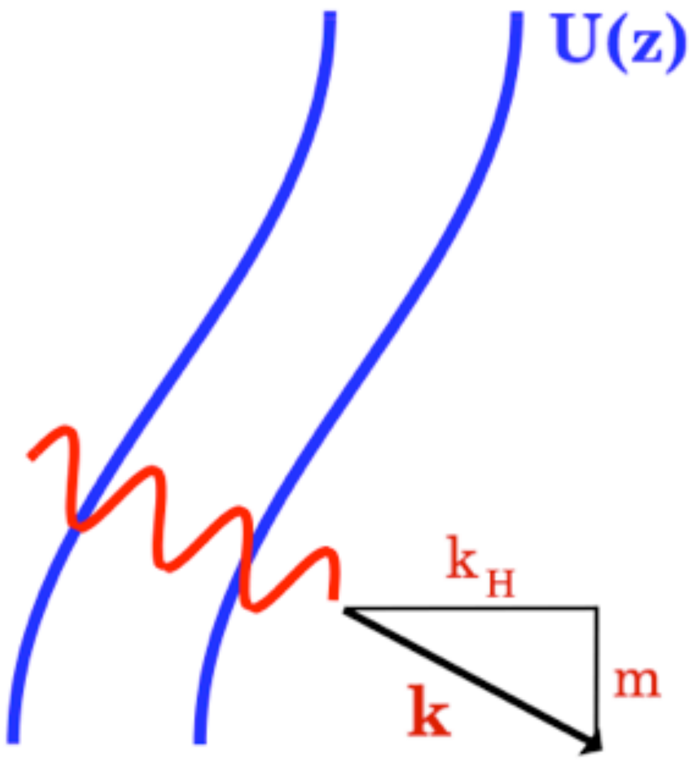
** get correct reference **



** is this resolution ok??*

henyey et al 86, polzin et al 95

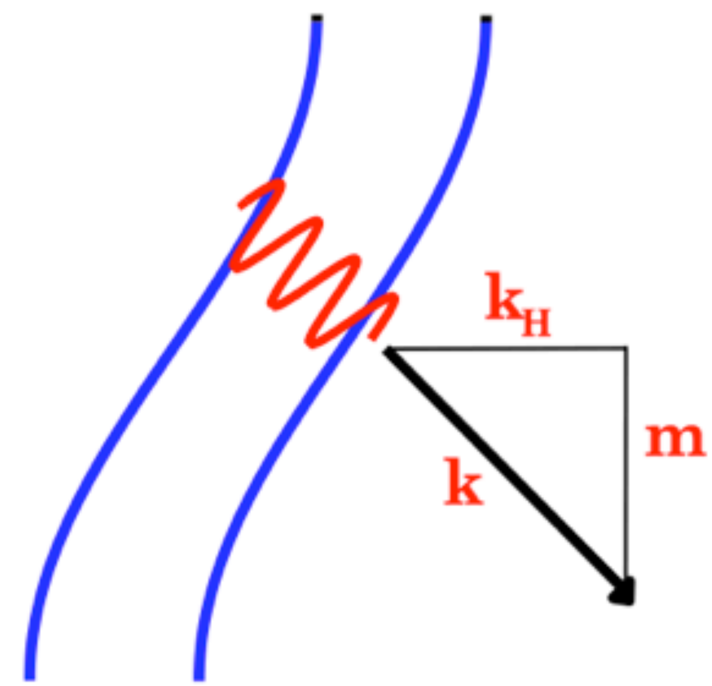
Step 1: Small-scale waves propagating through background shear experience a shrinking vertical scale



$$\frac{\mathrm{dm}}{\mathrm{dt}} = k_H \cdot - \frac{\mathrm{dU}}{\mathrm{dz}}$$

small-scale waves

large-scale waves



Step 2: smaller-scale waves break

$$\epsilon \approx \left\langle \frac{\mathrm{dE}}{\mathrm{dm}} \frac{\mathrm{dm}}{\mathrm{dt}} \right\rangle \quad \Longrightarrow \quad \boxed{\epsilon \approx \frac{\mathrm{dE}}{\mathrm{dm}}\, k_H\, S}$$