Deep flow and mixing in the Indian Ocean

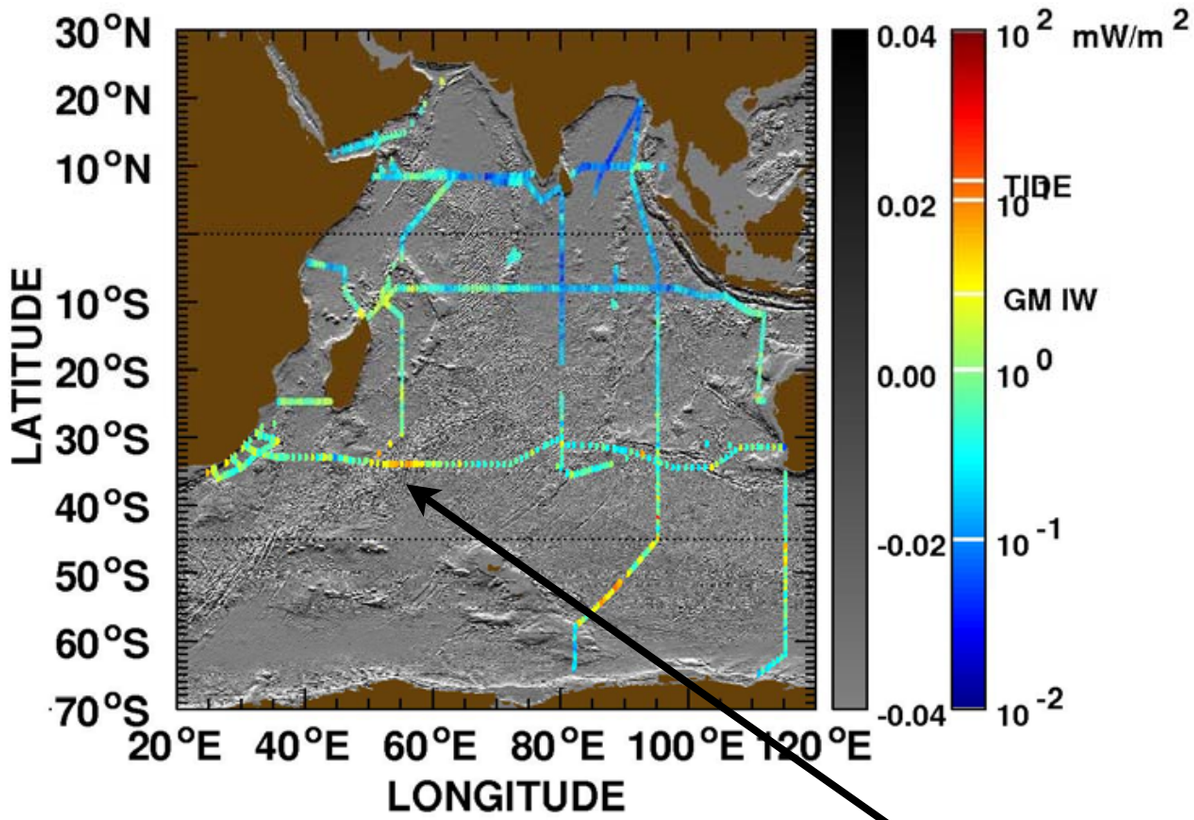
MacKinnon Pinkel Johnston

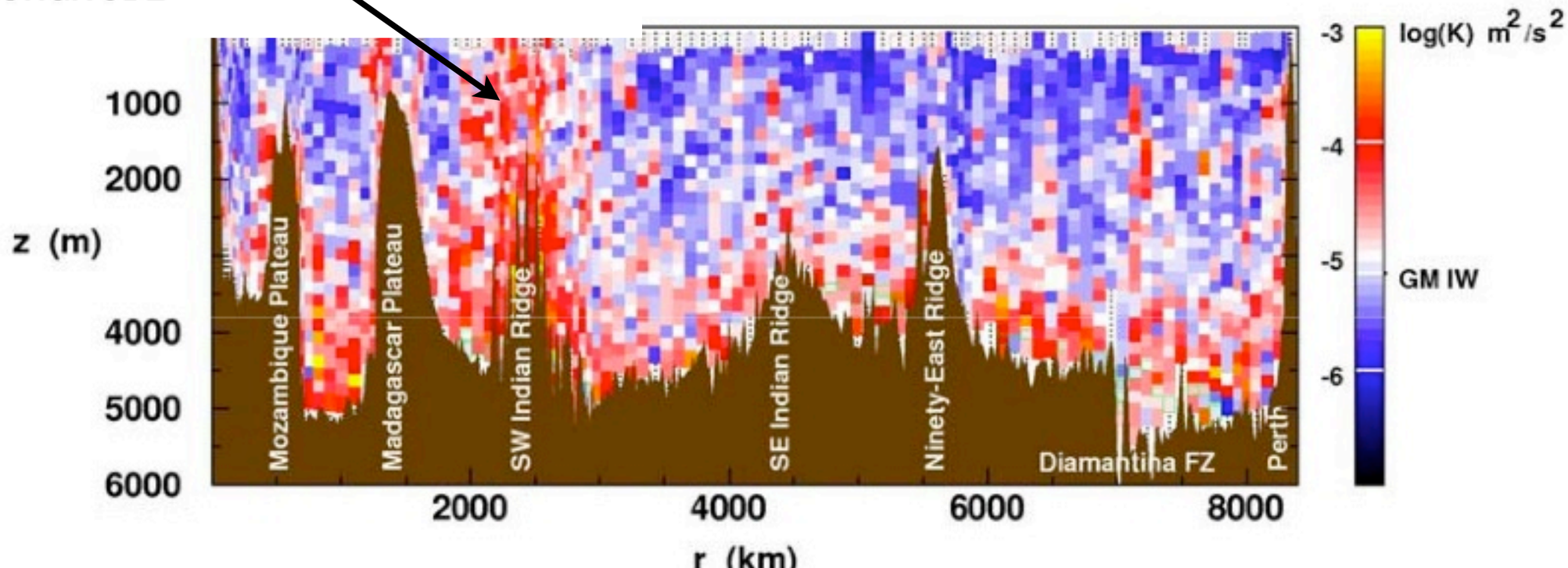
Deep Mixing: Southwest Indian Ocean

Evidence of elevated turbulence above the Southwest Indian Ridge

Kunze et al 06
(+ correction Dec 06)

Estimates from Lowered ADCP measurements during WOCE

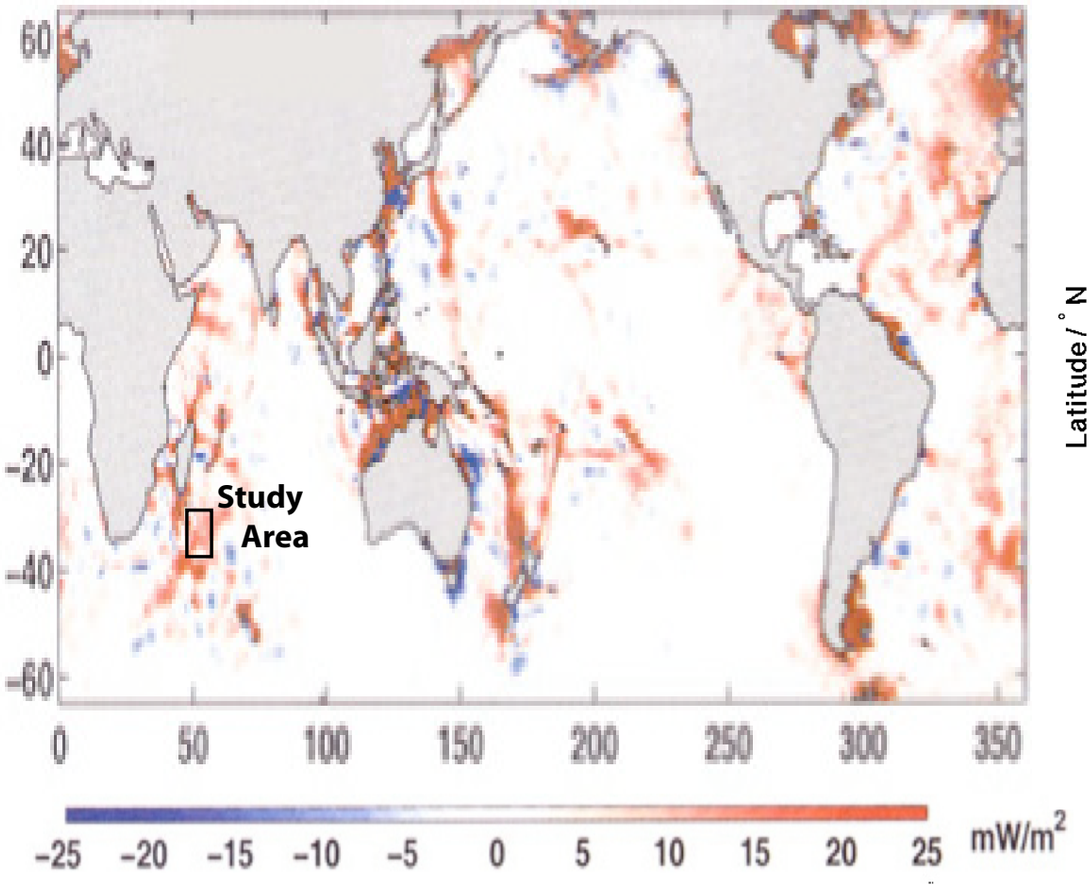




Possible sources of mixing above the SW Indian Ridge

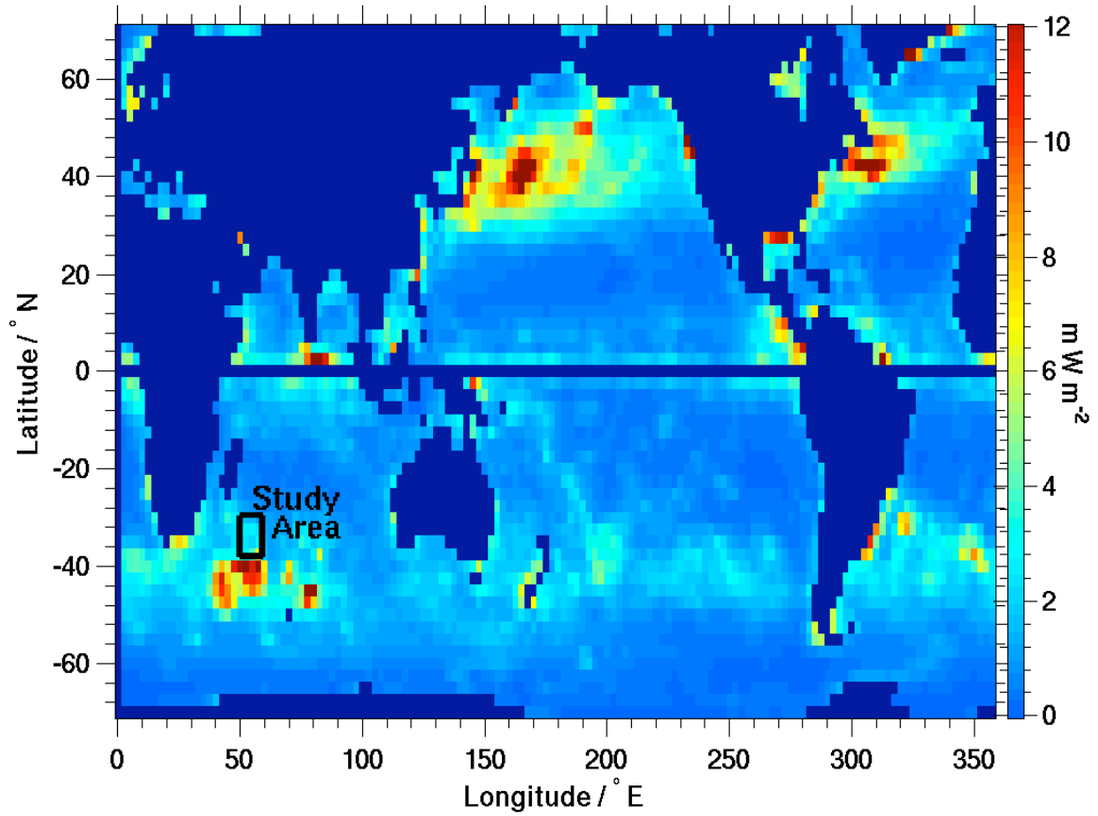
Tidal Generation

Egbert and Ray



Near-inertial Geneartion

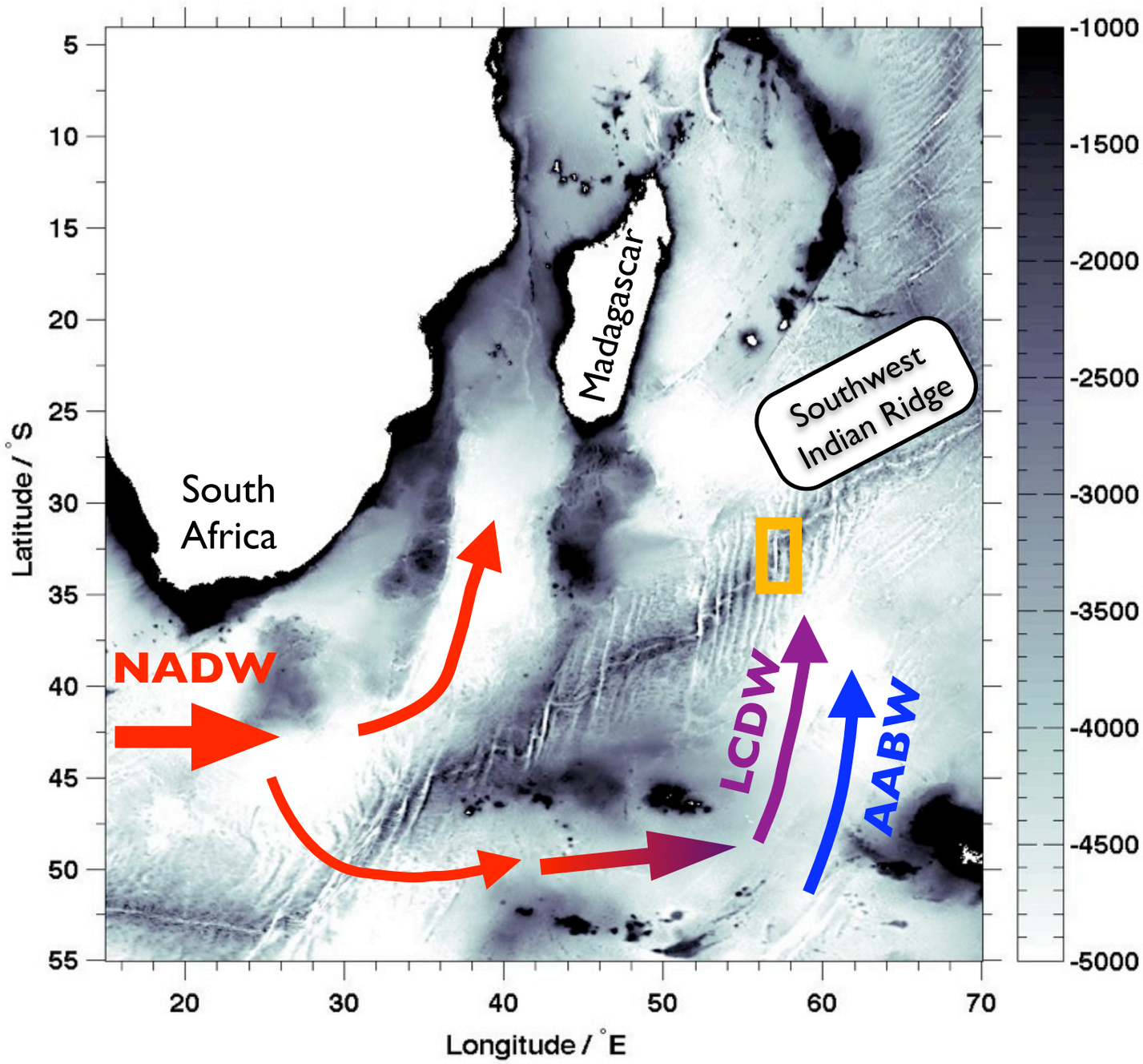
M. Alford



Internal waves with 12.4 hour period

Internal waves with 15 hour period (inertial period in souther ocean)

Deep Mixing: Southwest Indian Ocean



Net overturning rate poorly constrained (3-30 Sv)

Donohue et al 03, van Aken et al 03, Toole and Warren 93, Reid 93, Bryden and Beal 01

J.A. MacKinnon (SIO)
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G. Carter (UH)
O. Sun (SIO)
S. Nguyen (SIO)
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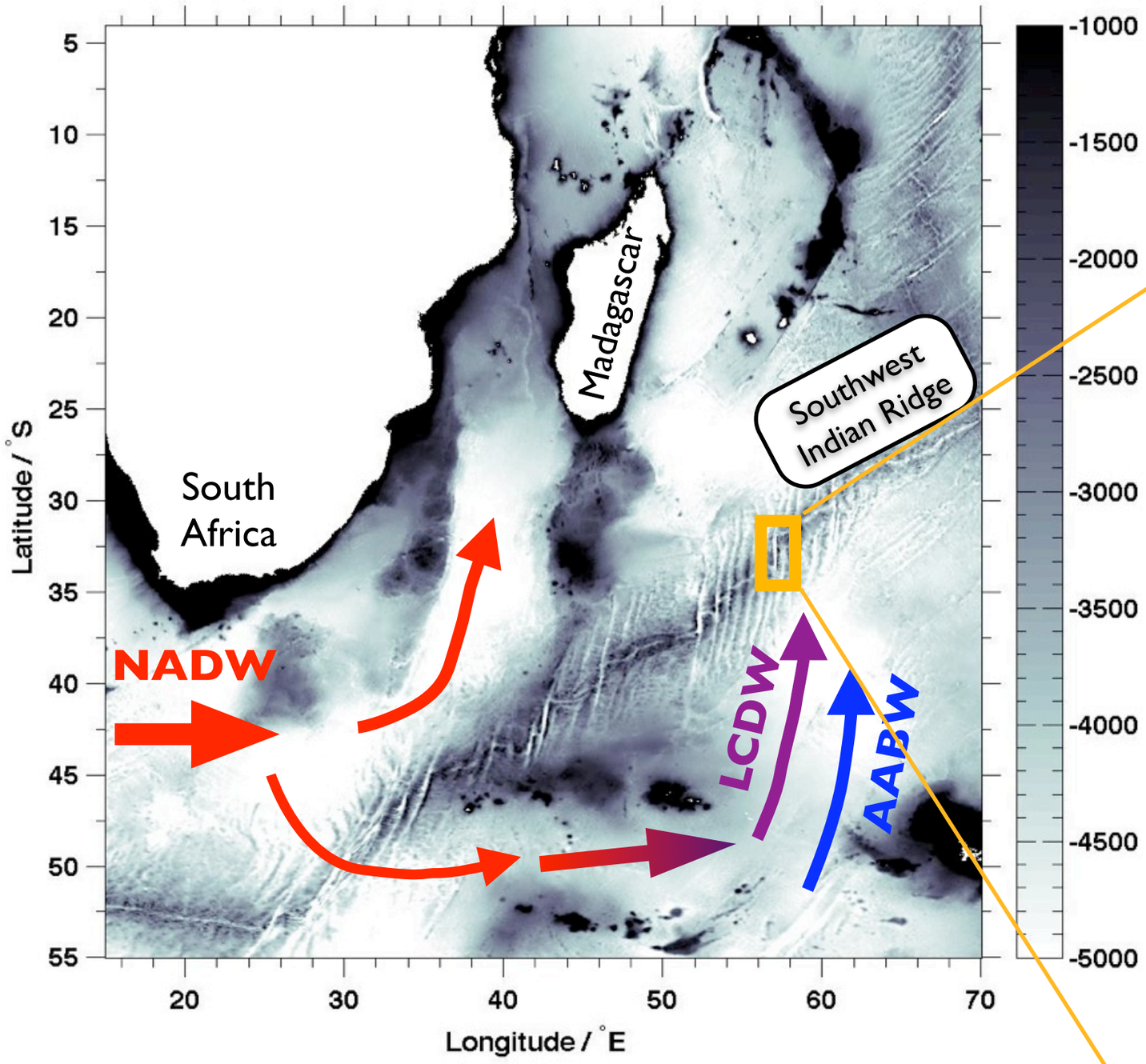
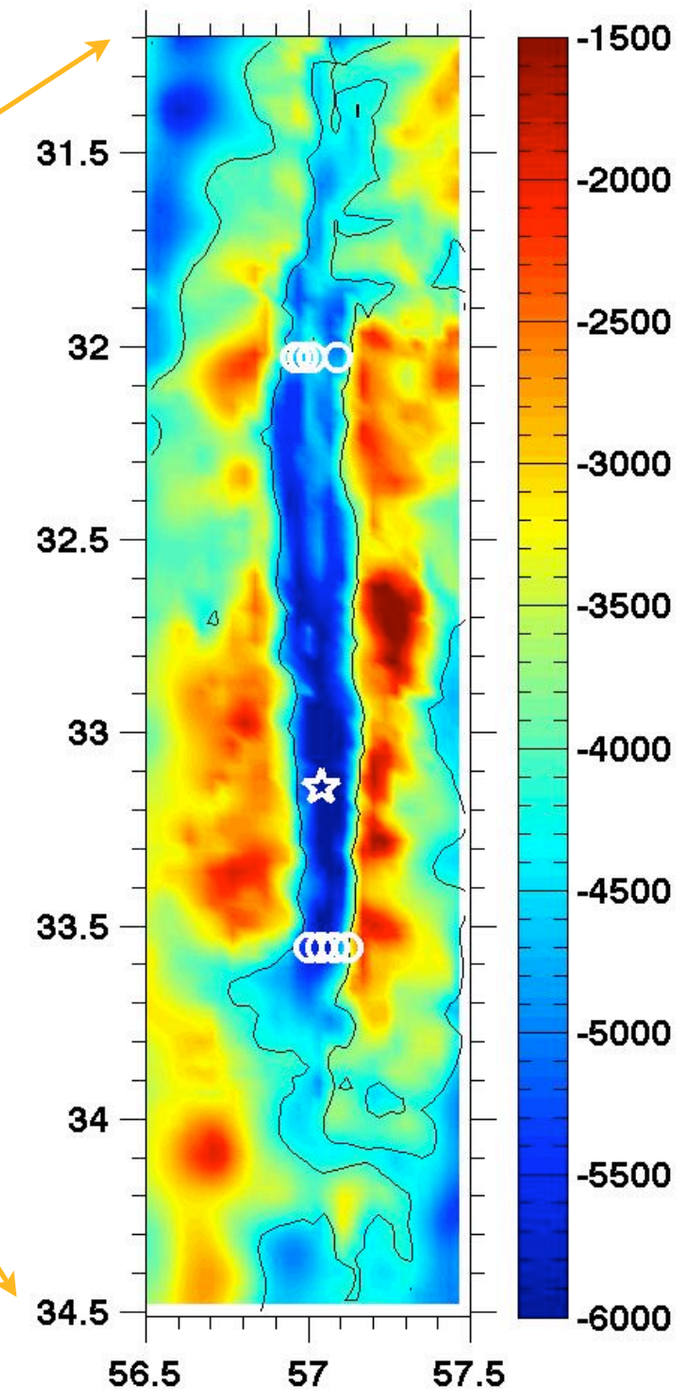
T. Huussen (NOC)

- Dec 07 - Jan 08
- R/V Revelle
- NSF / UC Ship Funds

Deep Mixing: Southwest Indian Ocean



Atlantis II Fracture Zone



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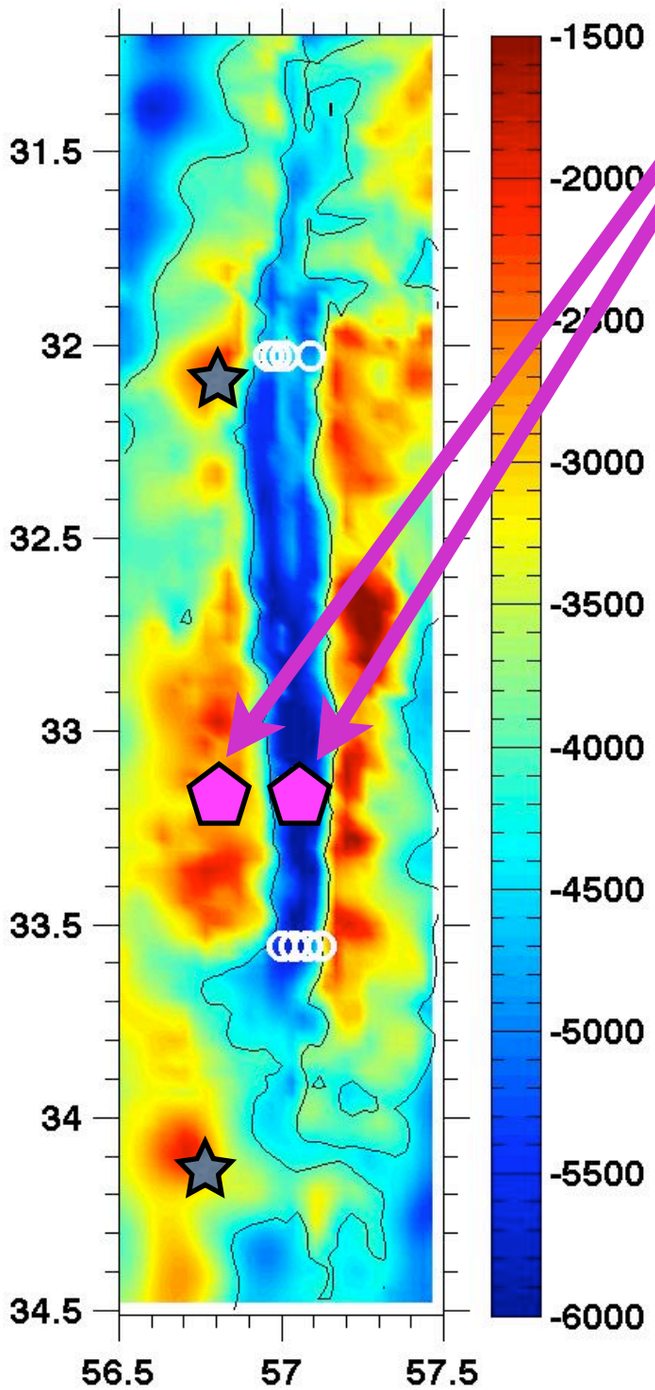
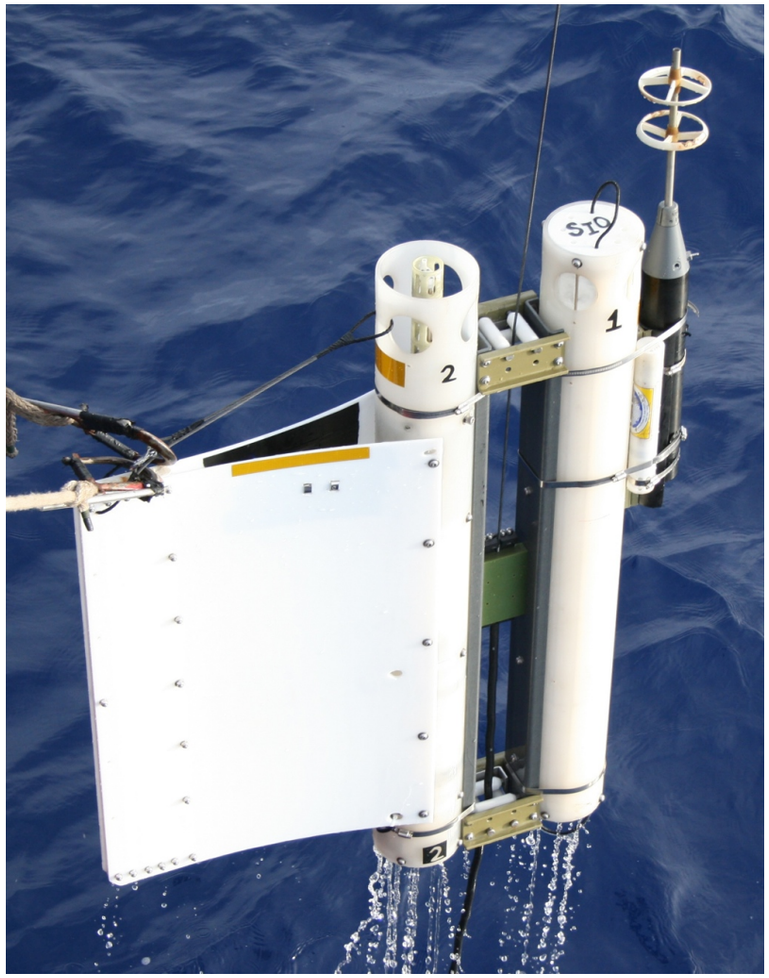
Southwest Indian Ocean: Instruments



4-day time series

Wave-powered wire-walker

- Freely drifting
- Profile to 500 meters
- C, T, P, U, V, Flourescence

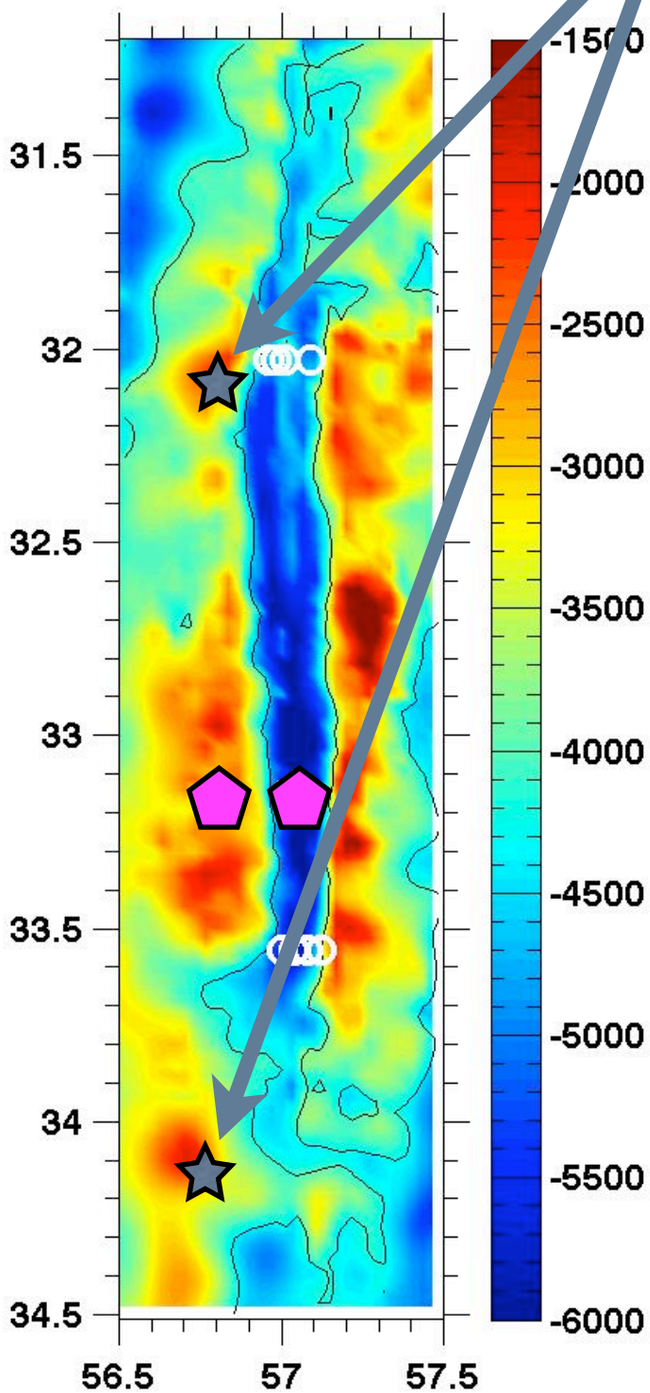


Pinkel "Fast CTD"

- 1000 meters in 5 minutes
- C, T, P, microconductivity

Southwest Indian Ocean: Instruments

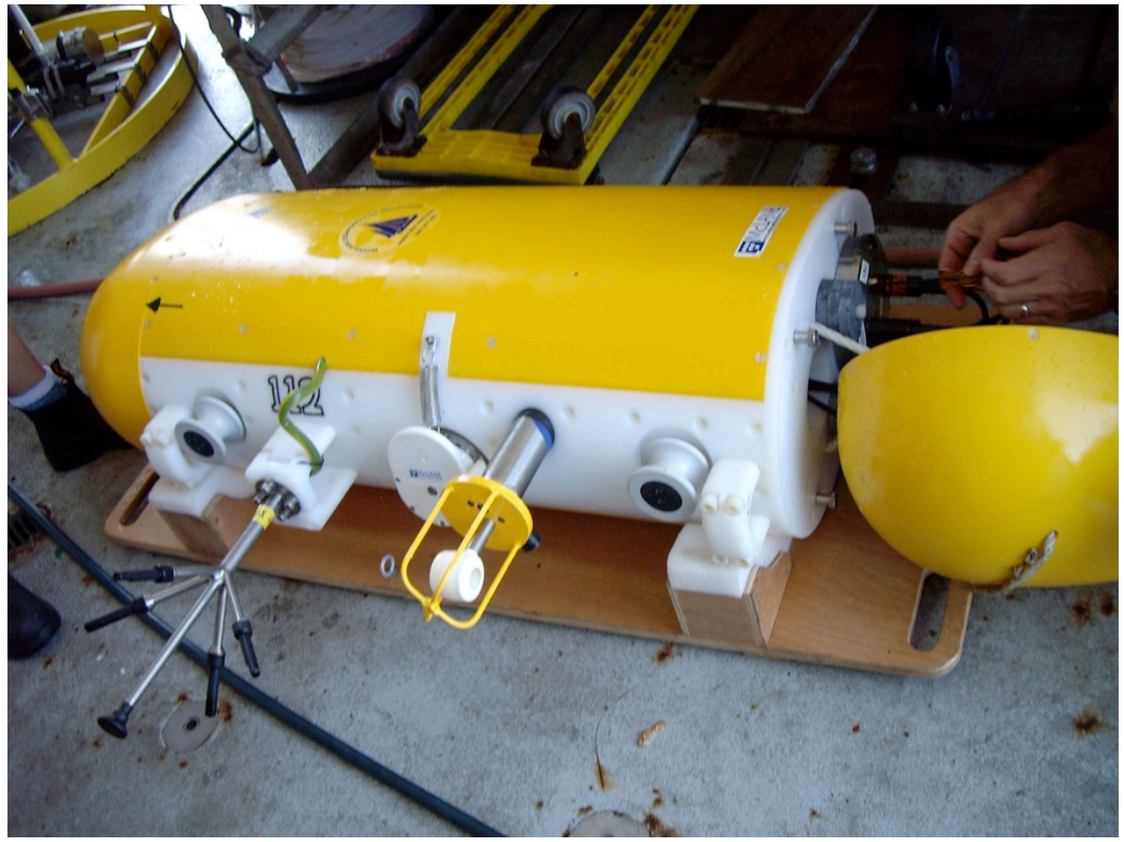
50-day mooring deployments



McLane Moored Profilers

(WHOI mooring pool)

Full depth (2 profilers each) C,T,P, U,V



Southwest Indian Ocean: Instruments

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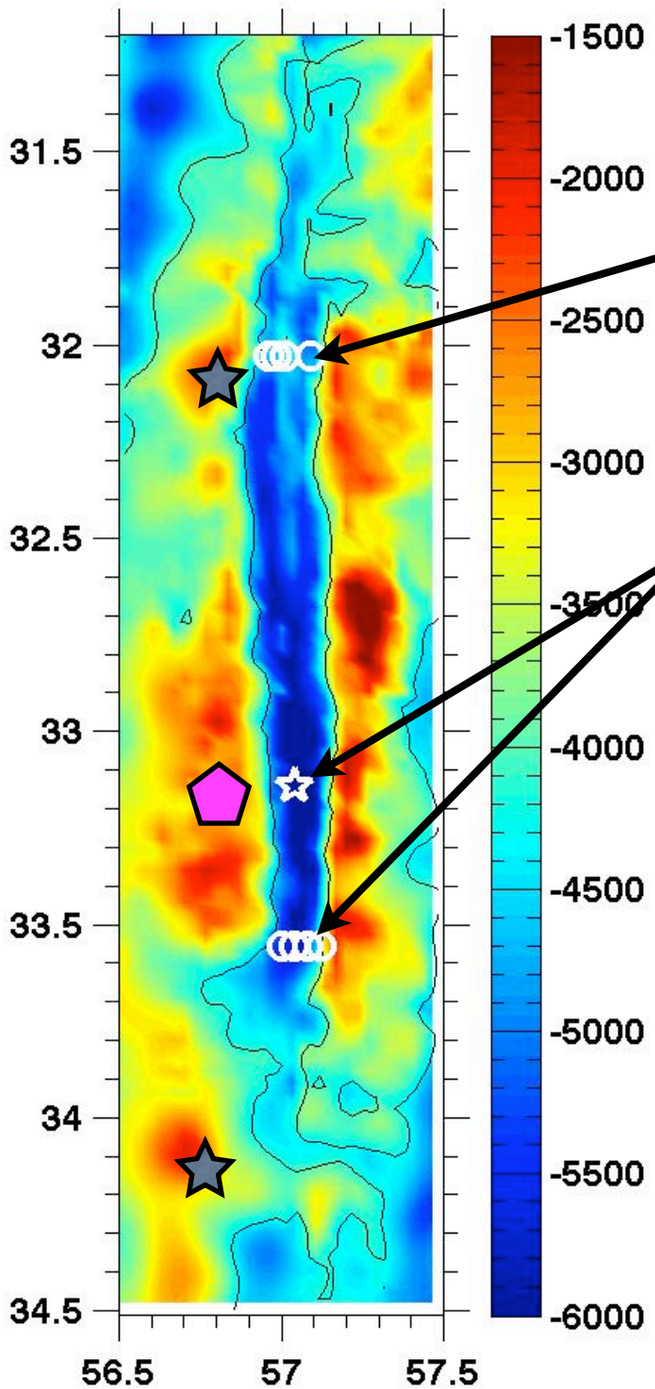


Lowered ADCP

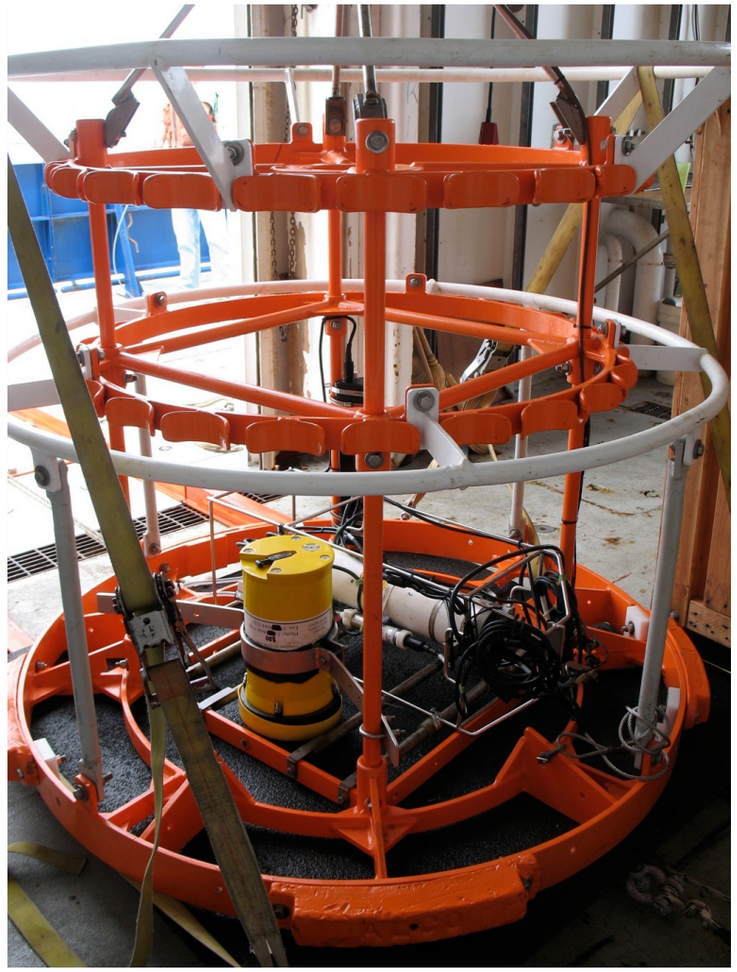
(Kunze et al 06, Polzin)

2 cross-trench sections

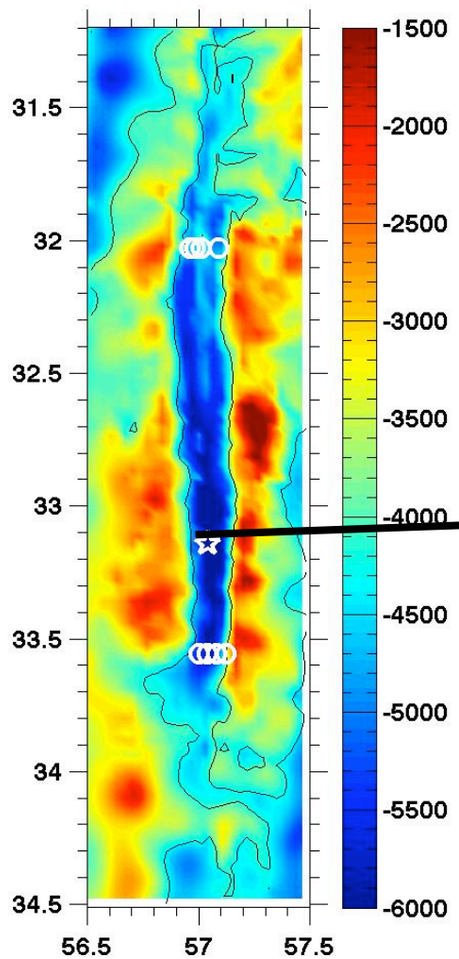
36 hour time series

- 300 kHz RDI broadband
- Full depth (6000 meters)
- Velocity, density => shear, strain
- 8-m nominal resolution
- ~40 meter actual resolution

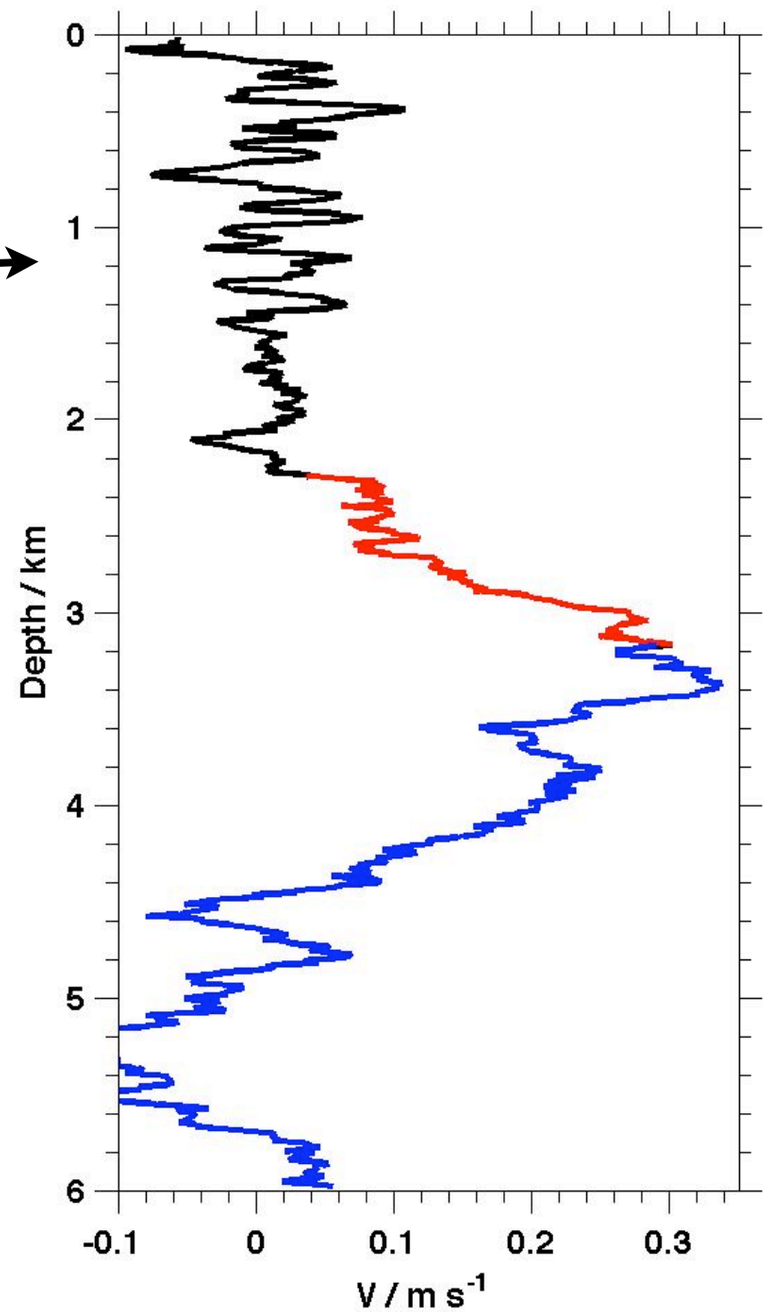
Generous loan by Kevin Speer (FSU)



Strong northward transport of deep+bottom water



Typical V(z)



Water mass transport

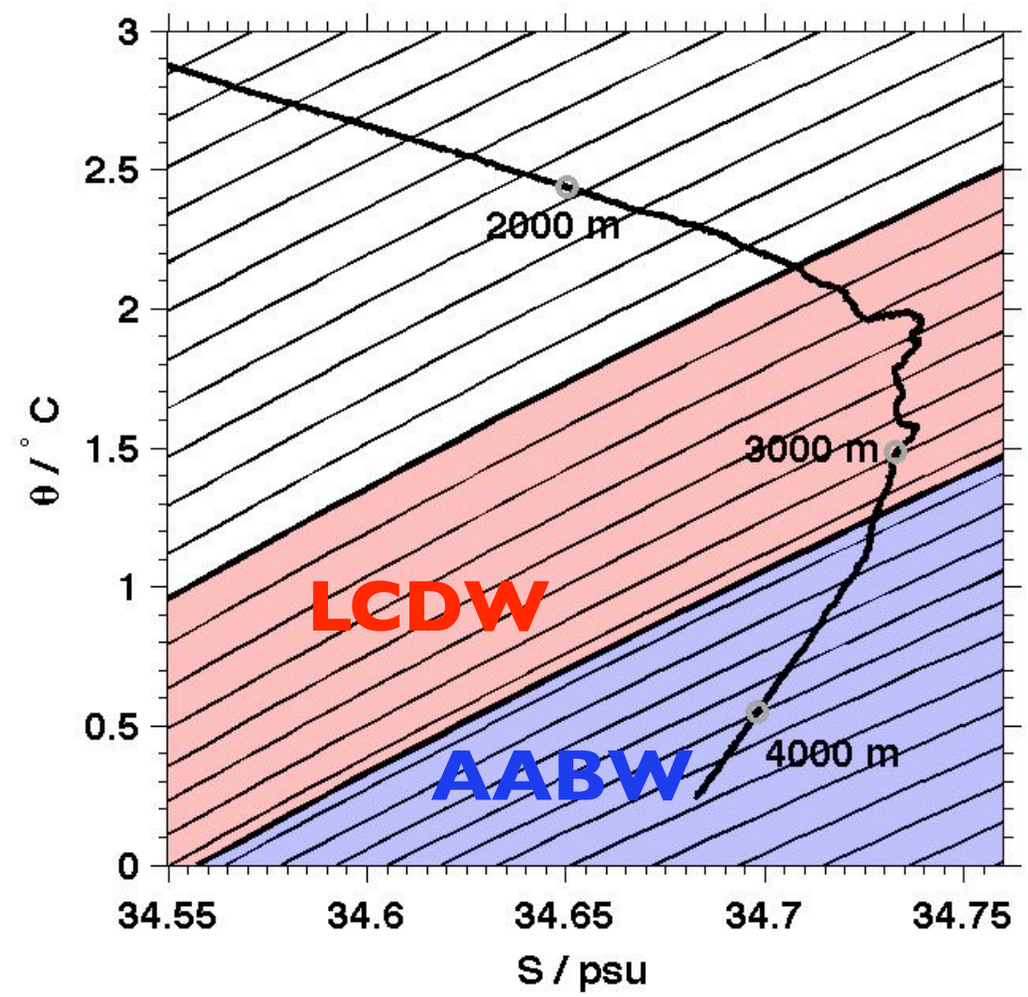
[Jackett & McDougall 97, Donohue & Toole 03]

- deep water

$$\gamma \geq 27.96 \text{ kg m}^{-3}$$

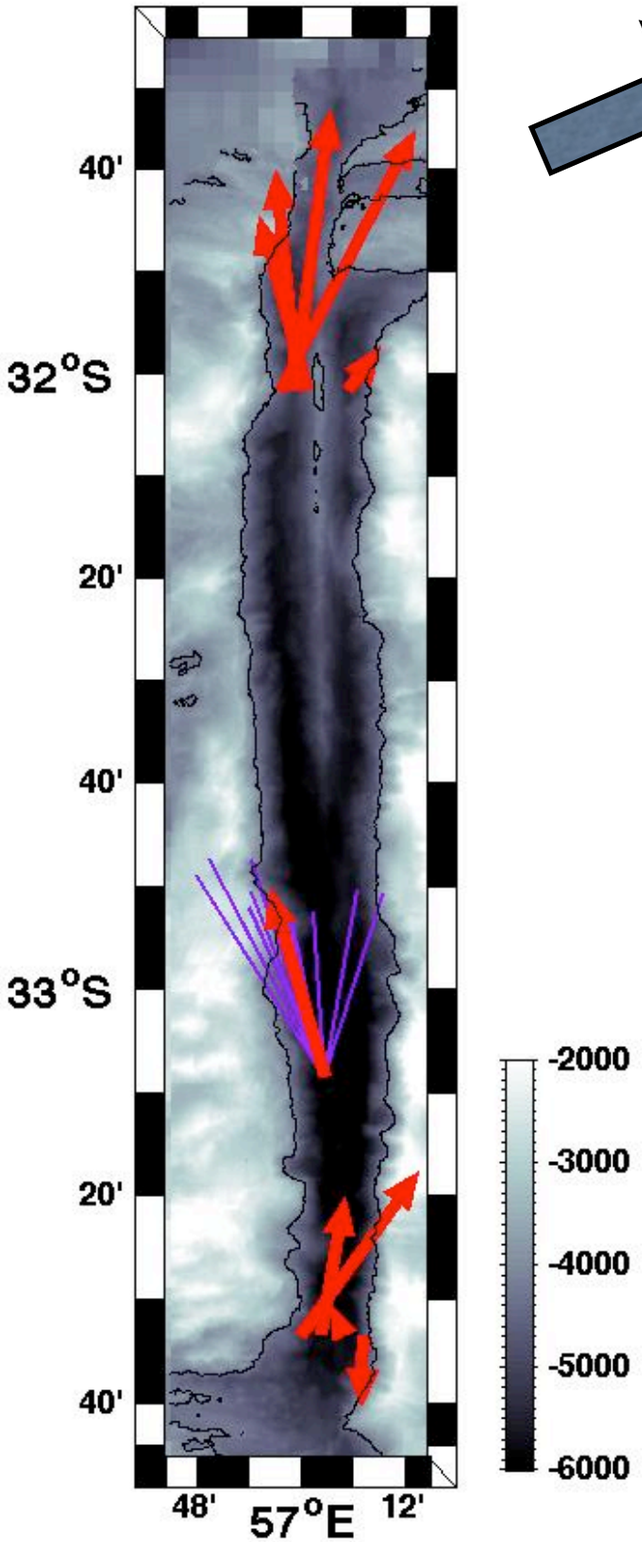
- bottom water

$$\gamma \geq 28.11 \text{ kg m}^{-3}$$



Strong northward transport of deep+bottom water

Depth-integrated transport ($\Upsilon > 27.96$)



Net deep and bottom transport of 3 ± 2 Sv

Compare to 10-15 Sv basin-wide MOC

(consistent with Johnson et al 98
Drijfhout and Naveira Garabato 08,)

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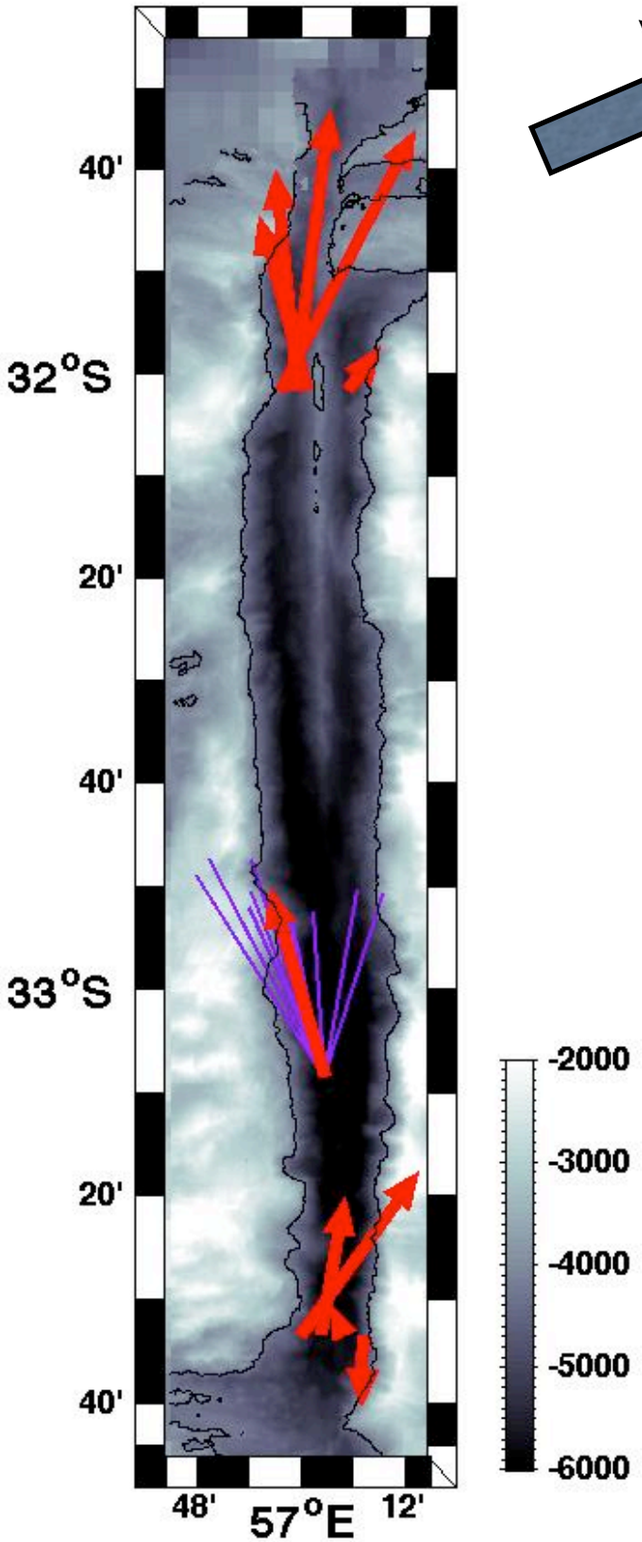

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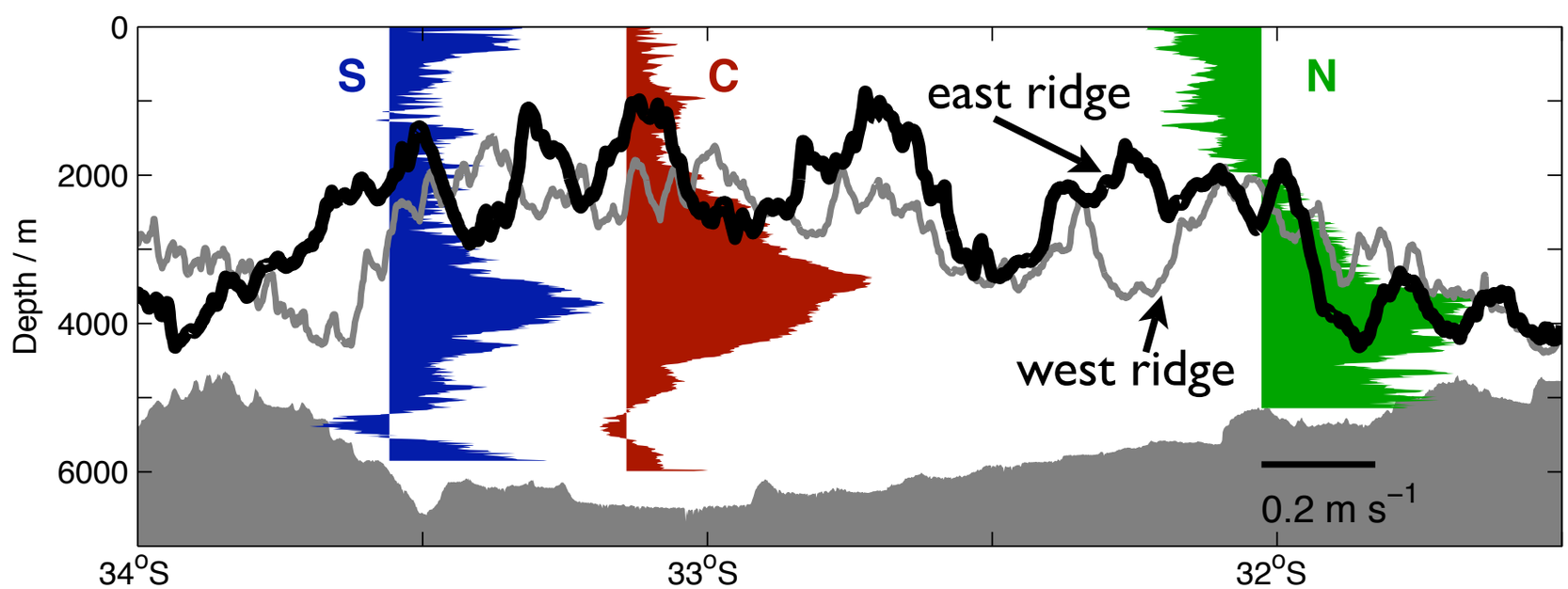
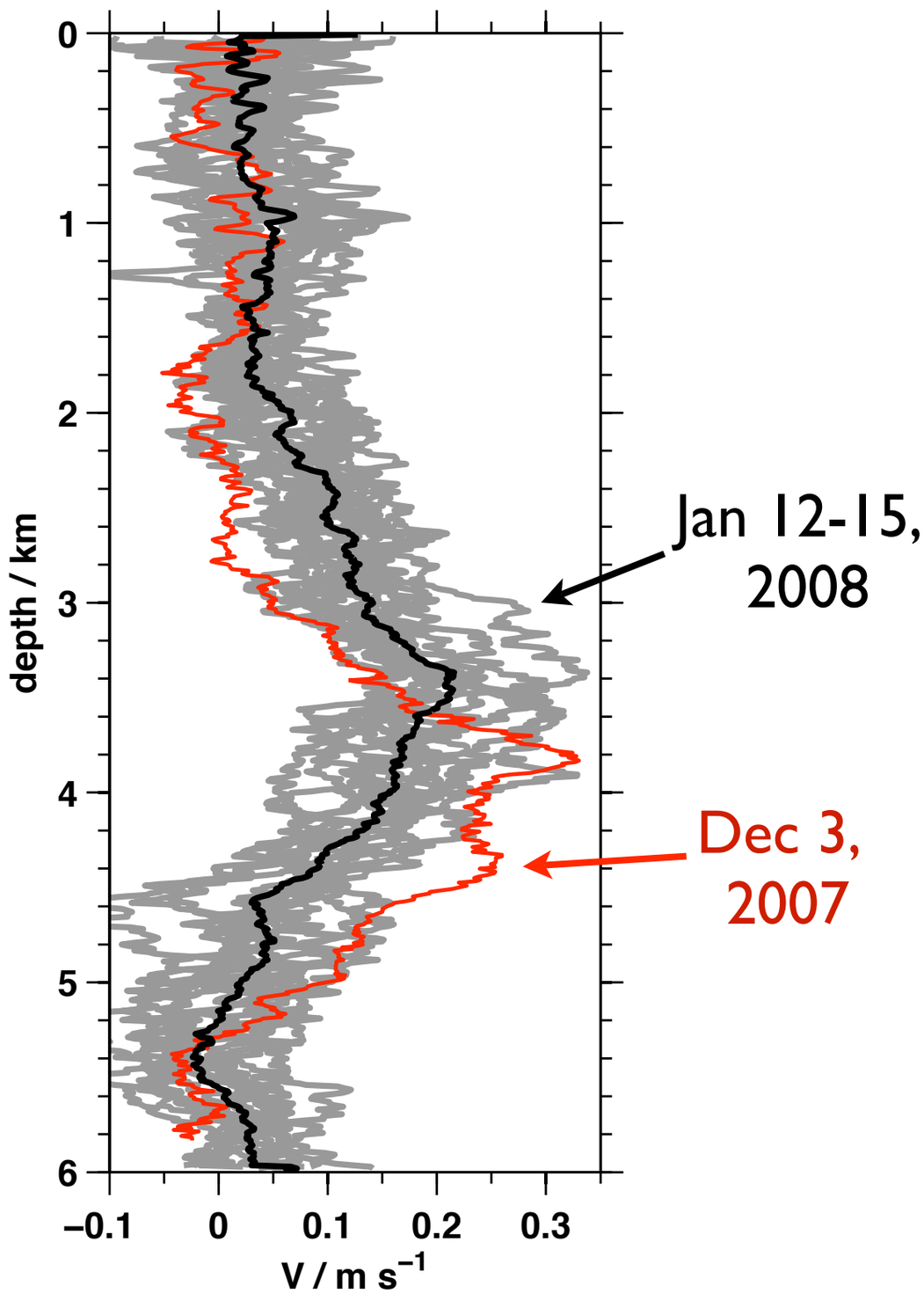
Flow is below bounding topography

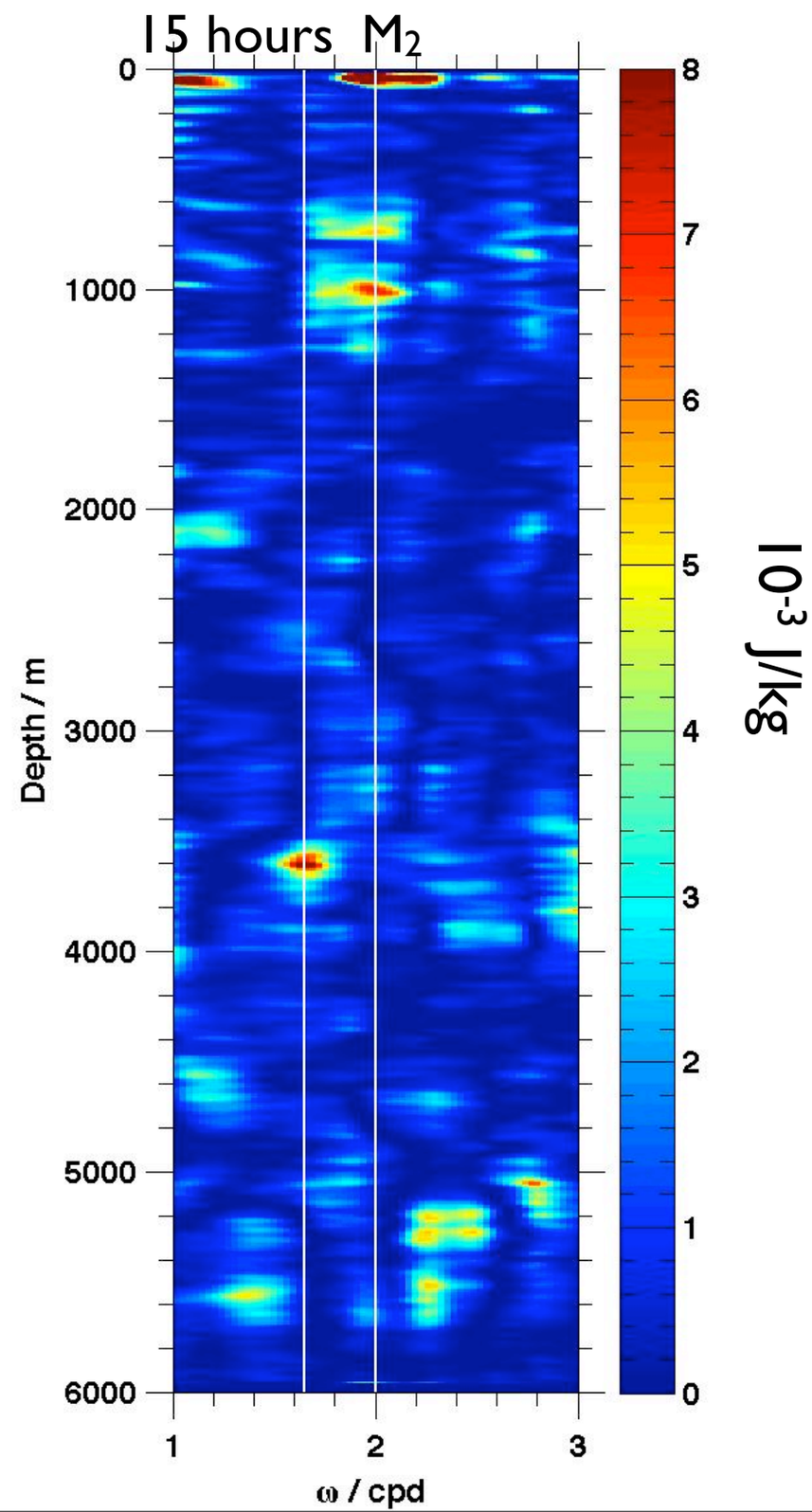


Time variability of Deep Jet

Variability of northward velocity



Harmonic fits of V(z)



Internal tide beams in upper water column

Deep jet oscillates at 15 hours

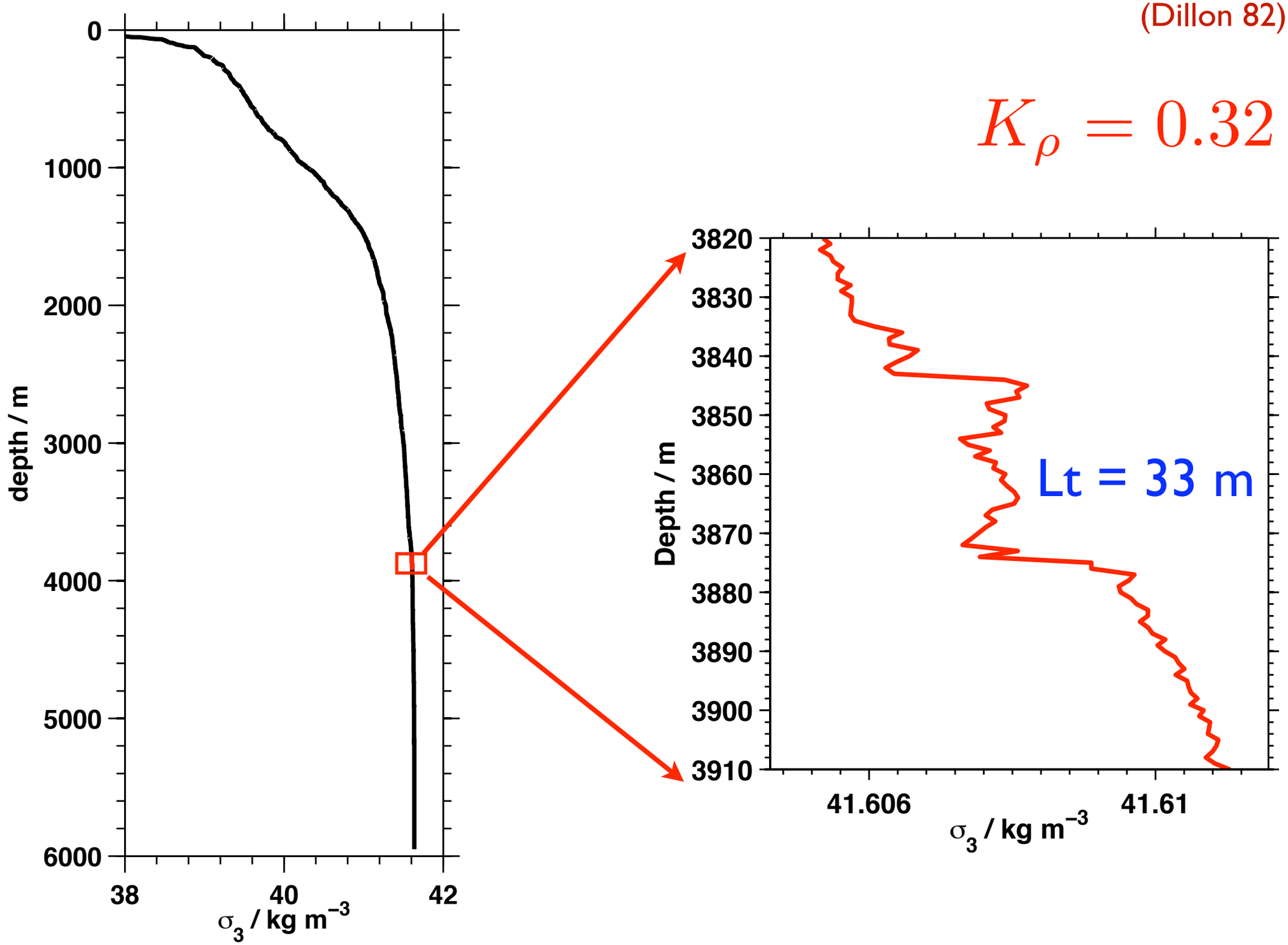
Estimating turbulence - overturns

Static instabilities in density

Thorpe Scale mixing estimate

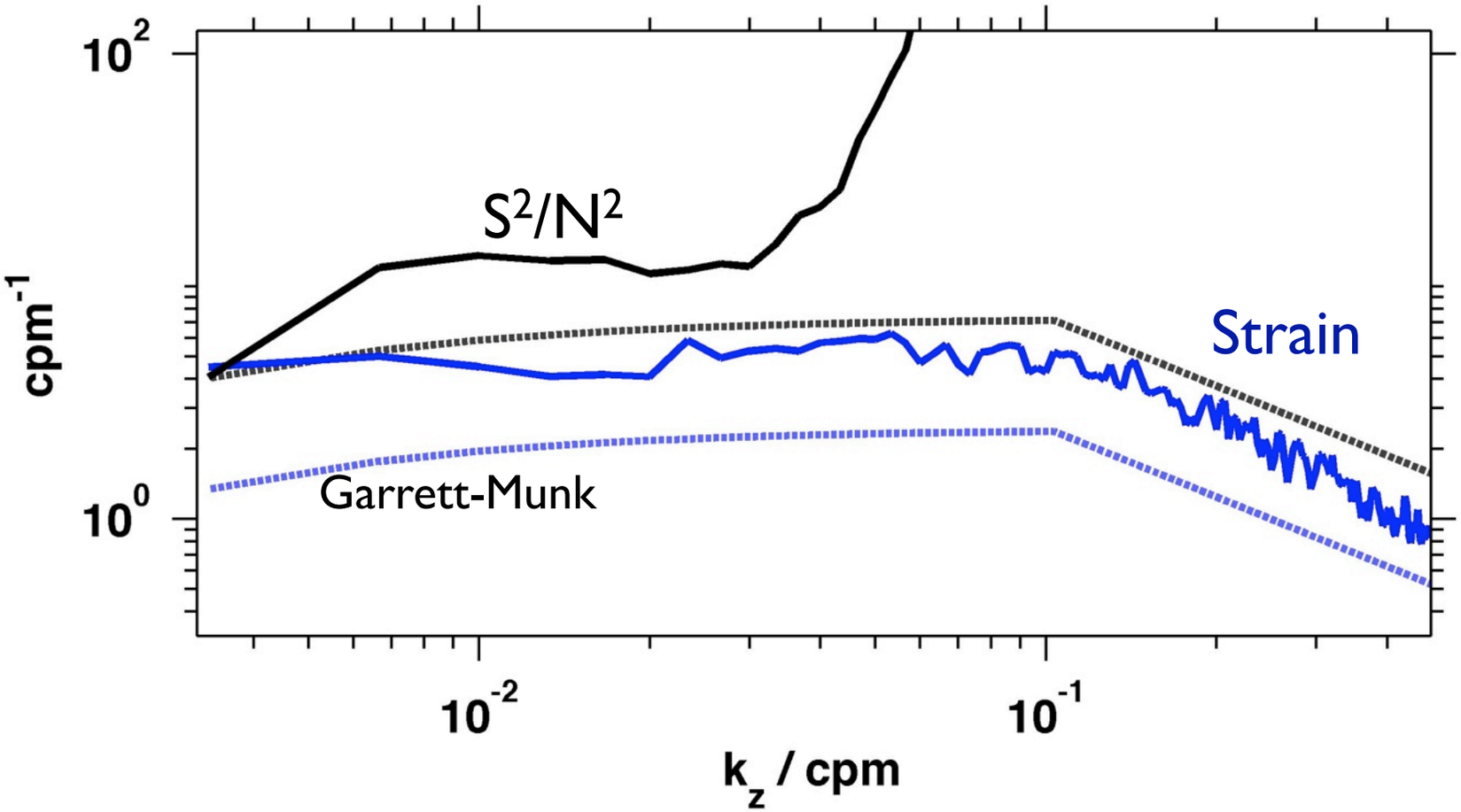
(Dillon 82)

$$K_\rho = 0.32\ N\ L_T^2$$



Estimating turbulence - finestructure

Vertical wavenumber spectra

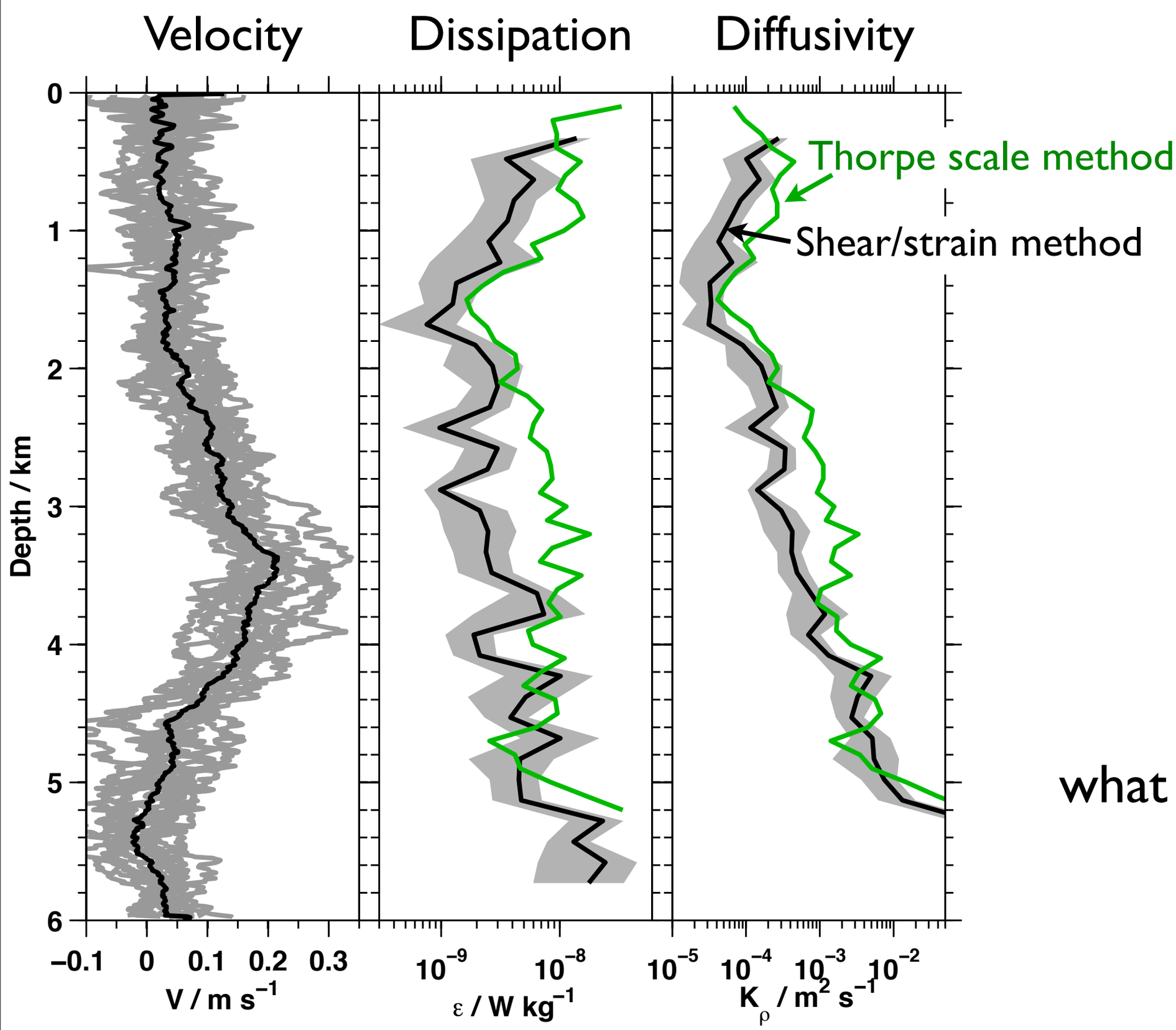


$\kappa = 2 * 10^{-5}\ m^2/s$

Estimate turbulent diffusivity (κ) by comparing shear/strain spectral levels to canonical Garrett-Munk internal-wave spectrum, based on wave-wave interaction theory

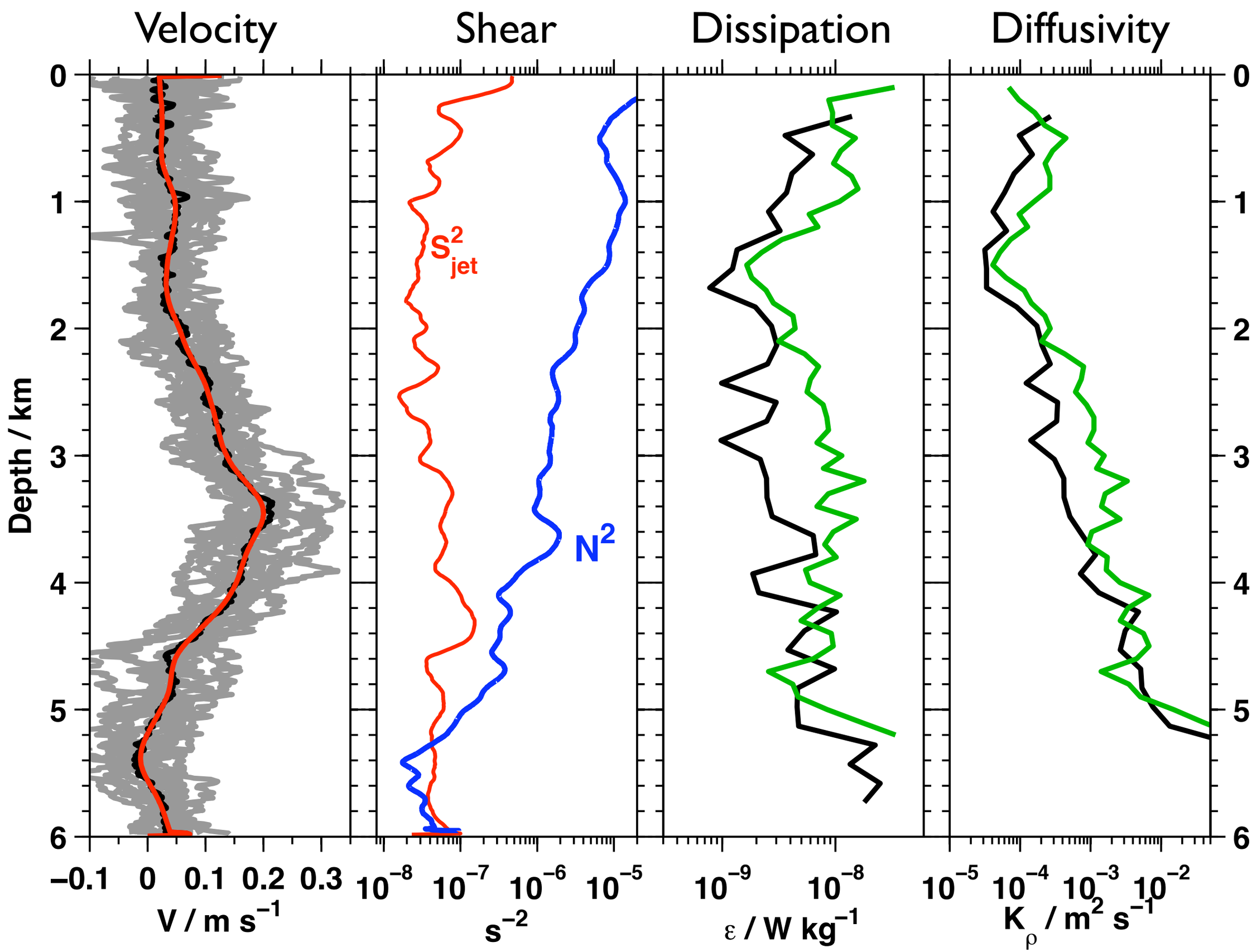
(Gregg et al 03, Polzin, McComas and Muller)

Turbulence profiles

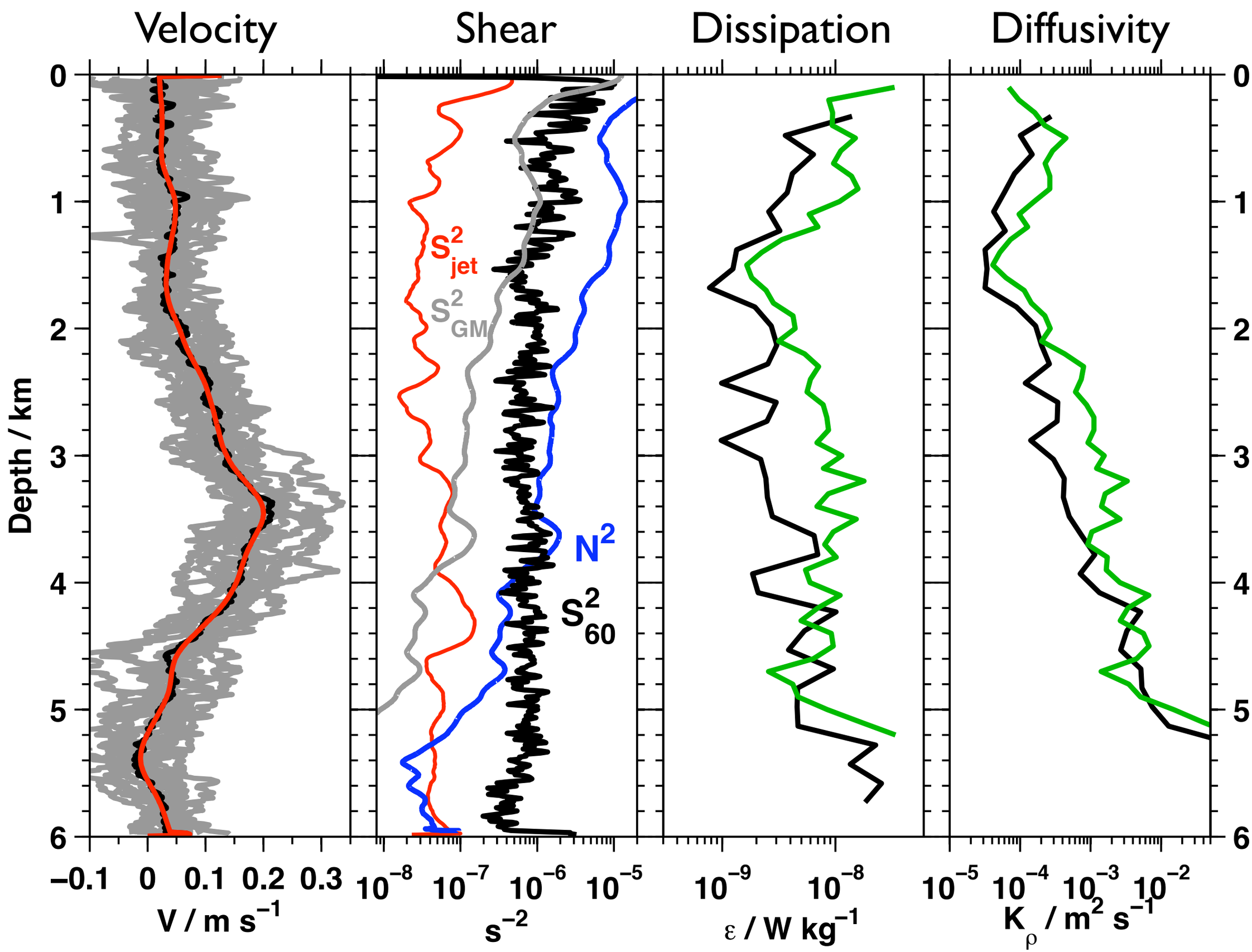


what produces mixing?

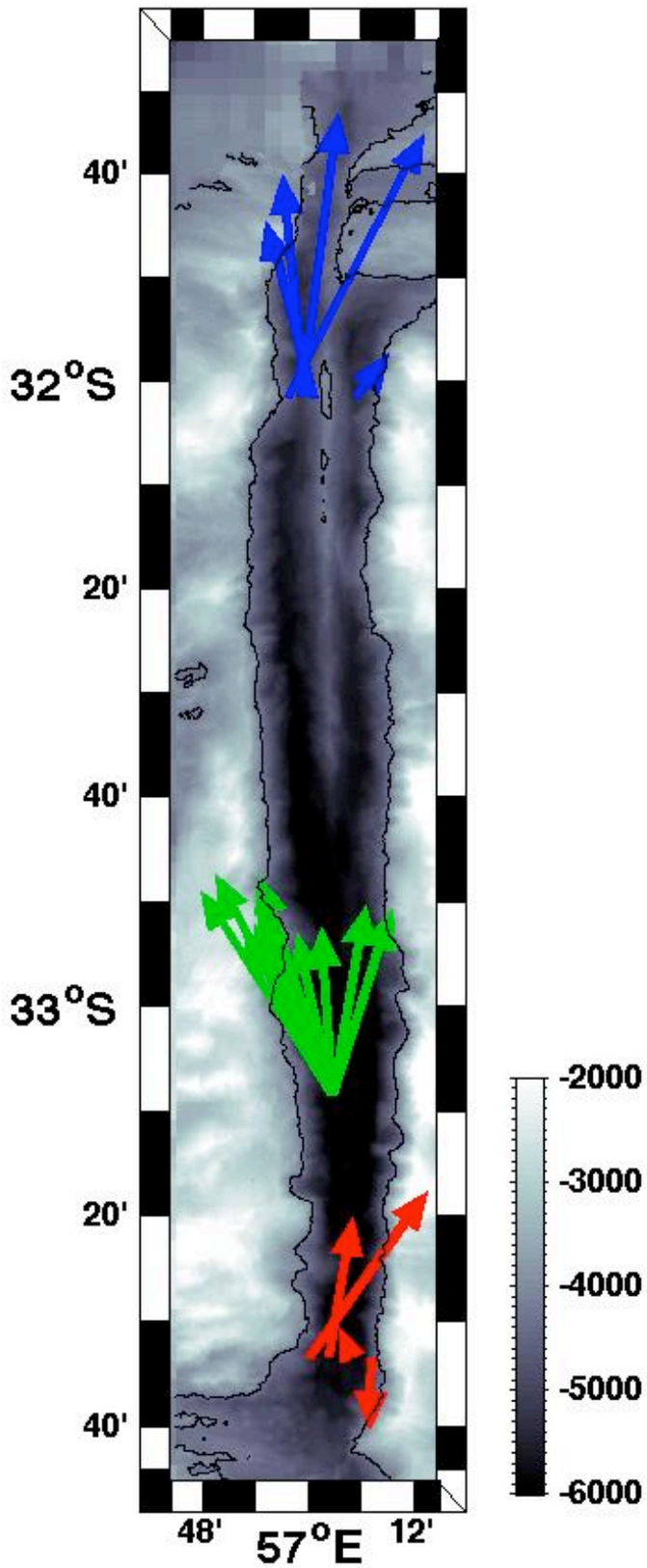
Mean jet shear not unstable



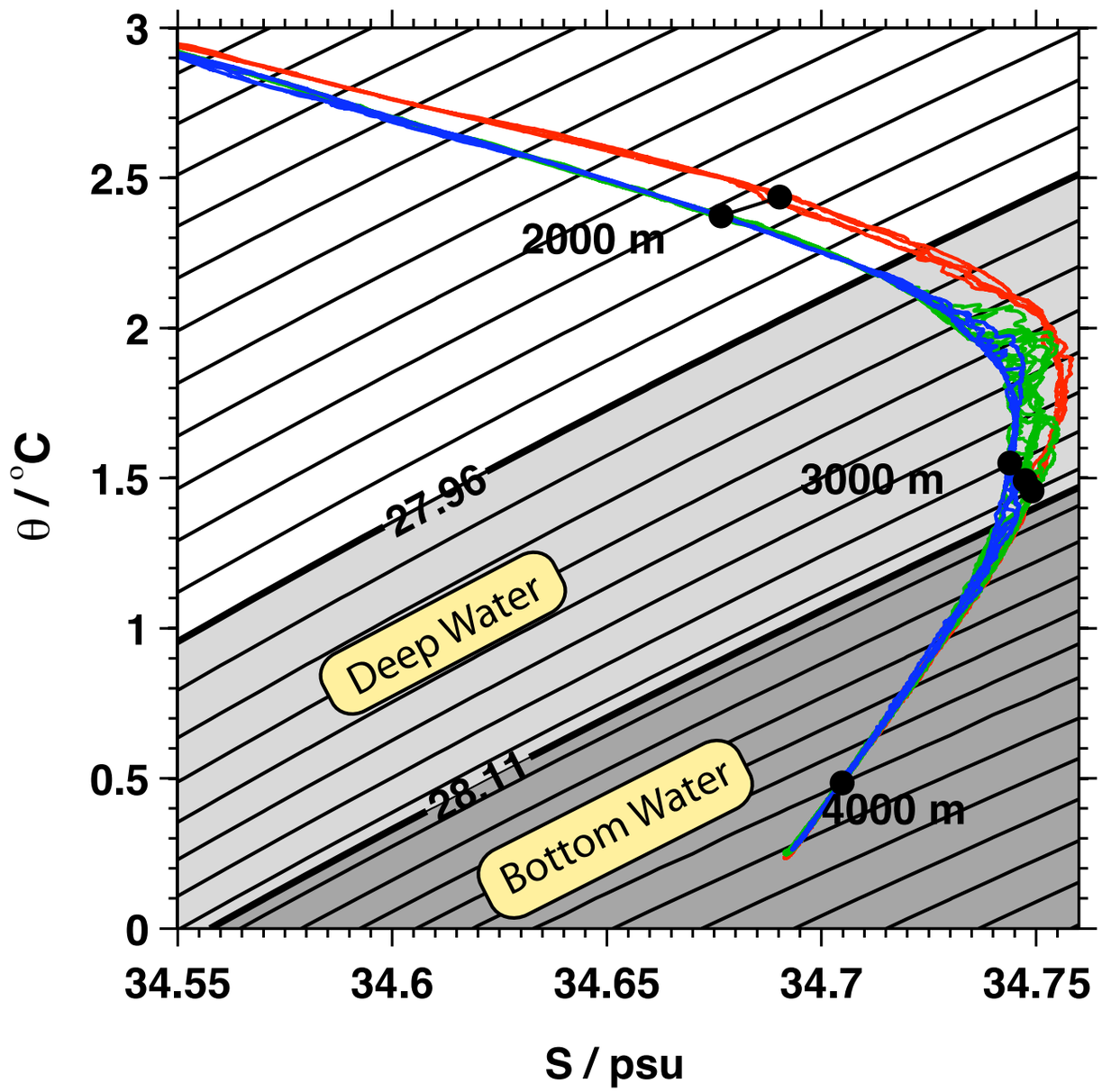
Fine-structure shear elevated



Mixing away the deep salinity maximum



Steady change in water properties as water flows north through fracture zone



What mixes away the salinity maximum?

1) Vertical/diapycnal turbulent mixing

$$\frac{\Delta S(z)}{\Delta t} = \kappa \frac{\partial^2 S}{\partial z^2}$$

$\Delta S(z)$: observed change between southern and northern profiles

Δt: transit time through fracture zone ~ 15-20 days

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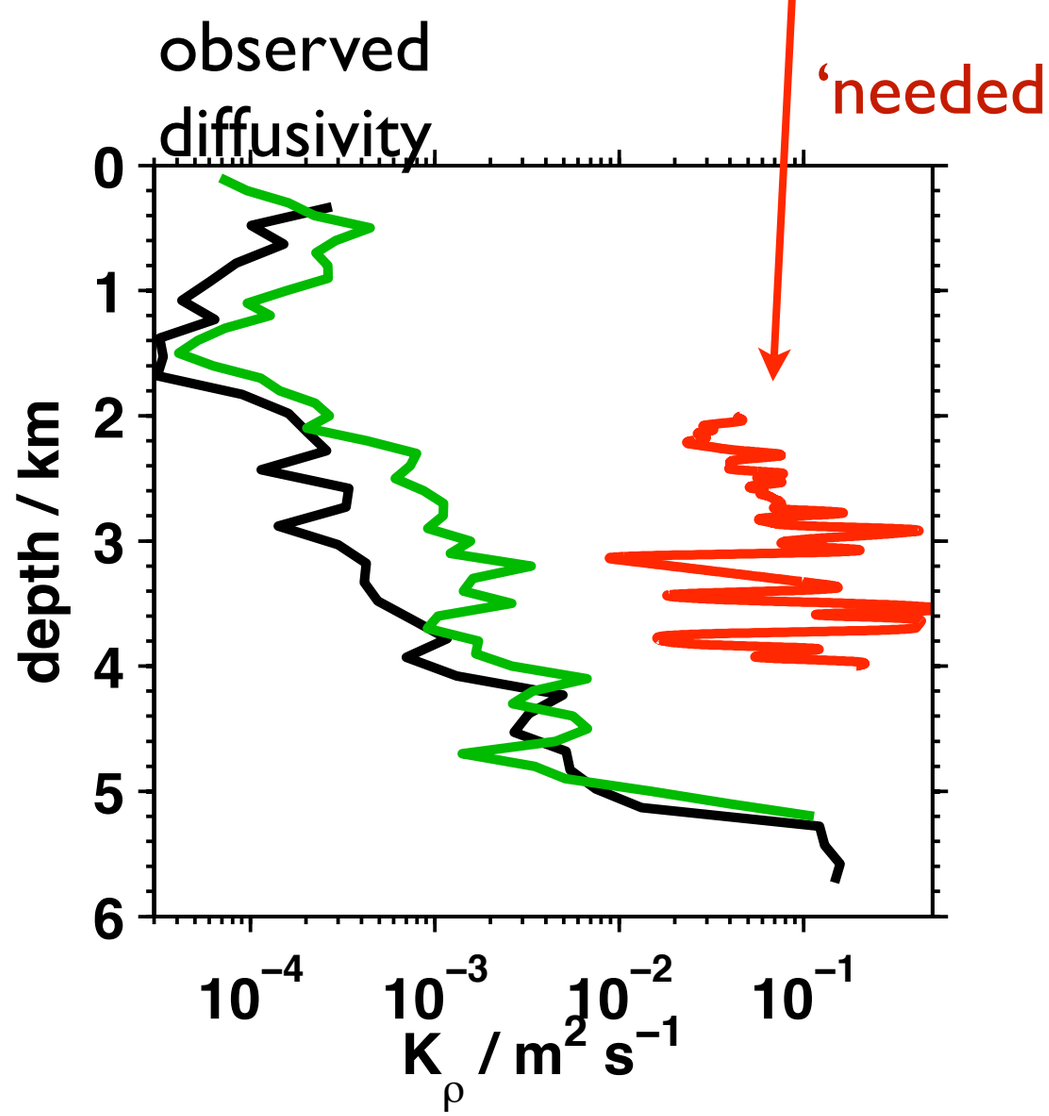


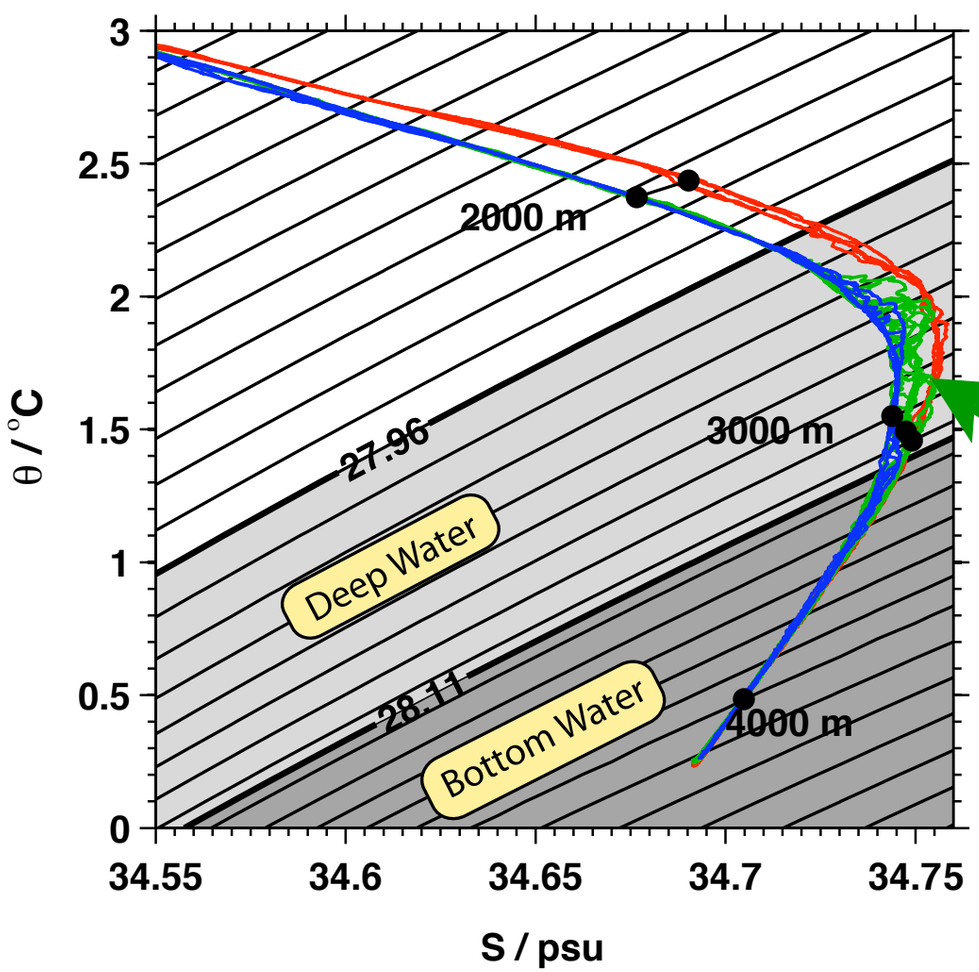
Explanation for discrepancy:

- longer transit time due to recirculation
- stronger mixing elsewhere in FZ than what we observed

What mixes the salinity maximum?

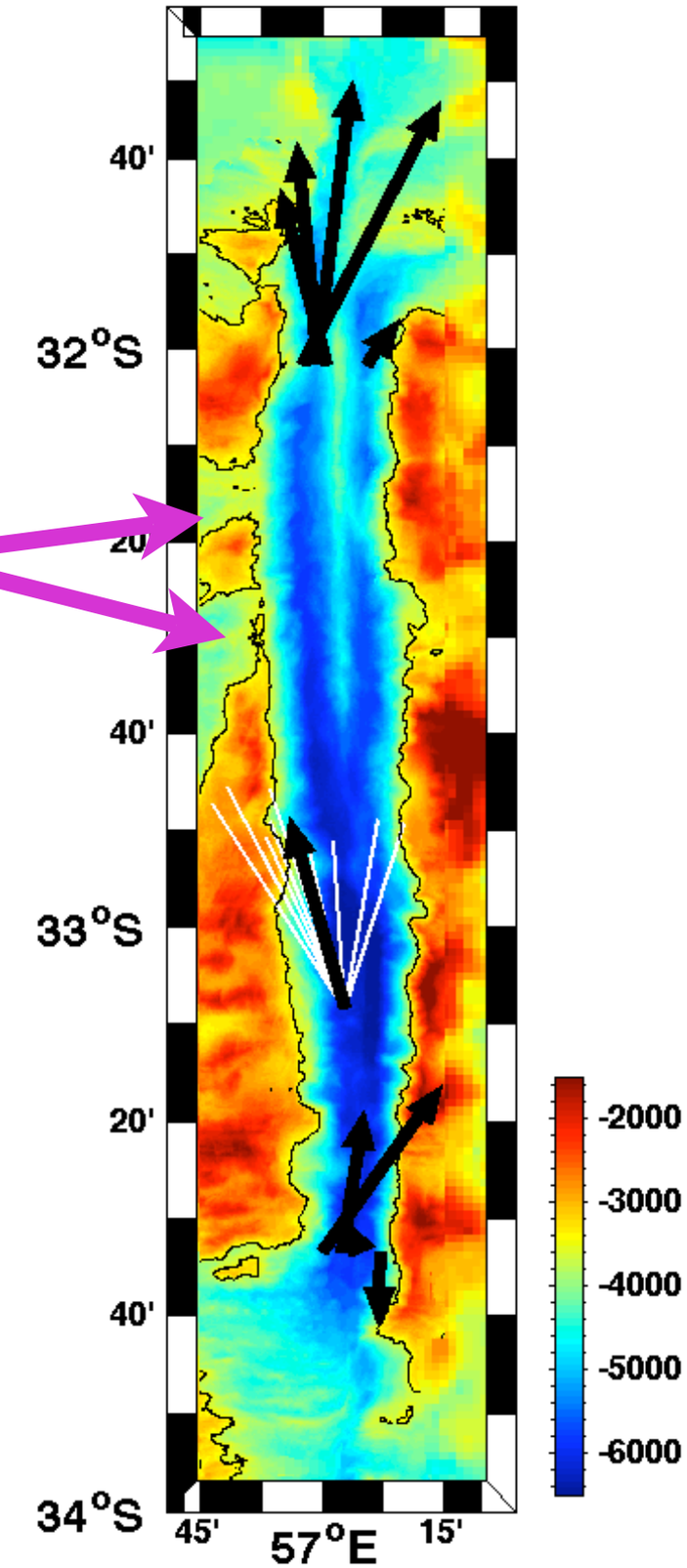
2) Lateral (isopycnal) stirring

$$\frac{\Delta S}{\Delta t} = \kappa_H \frac{\partial^2 S}{\partial y^2}$$

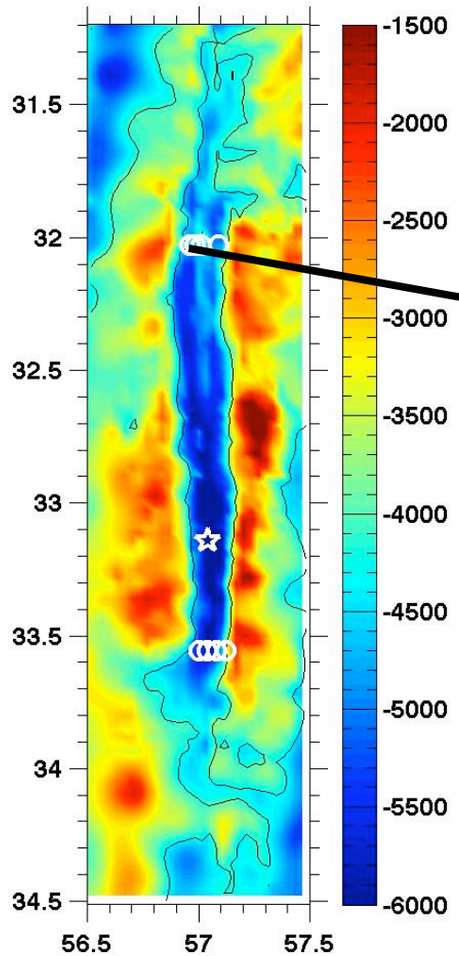


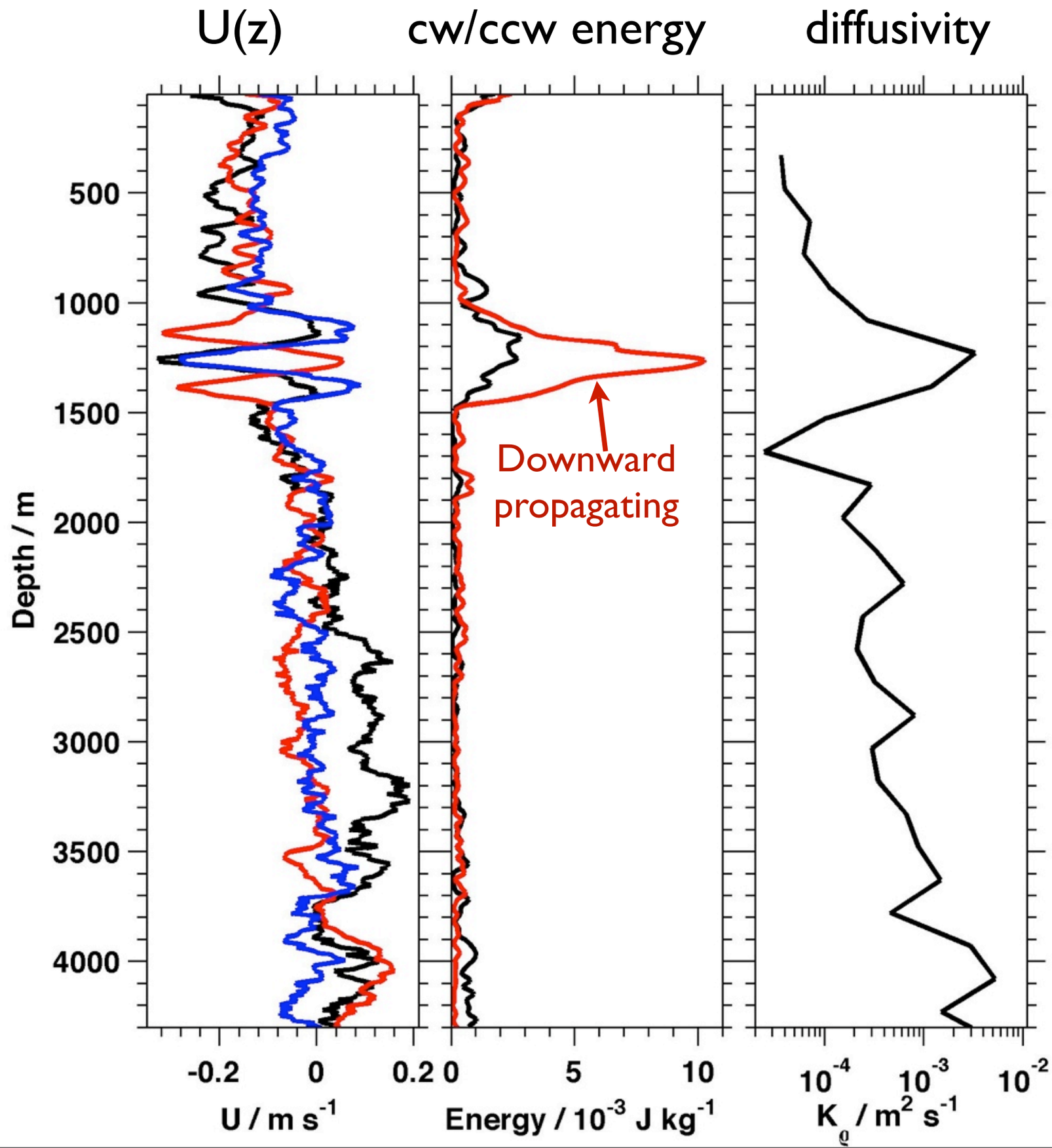
possible leakage of fresher Madagascar Basin water through gaps in the ridge

variability in T-S time series



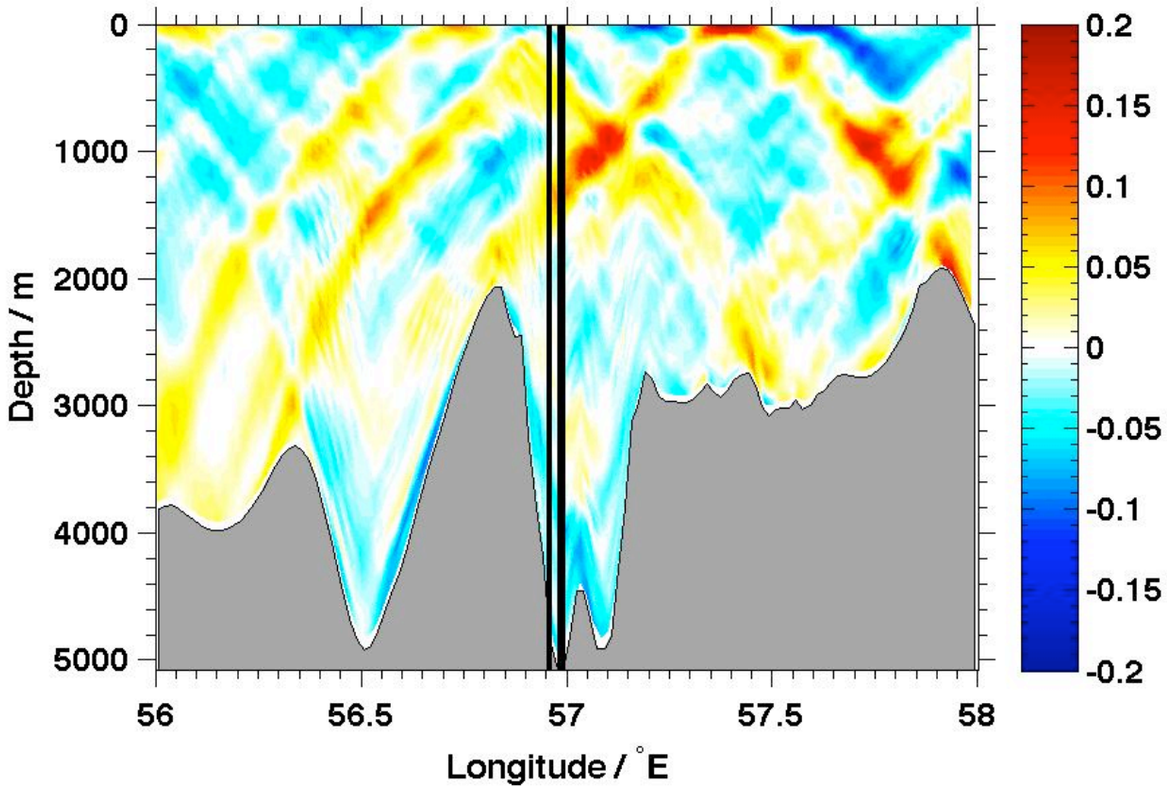
Tidal beams in upper ocean



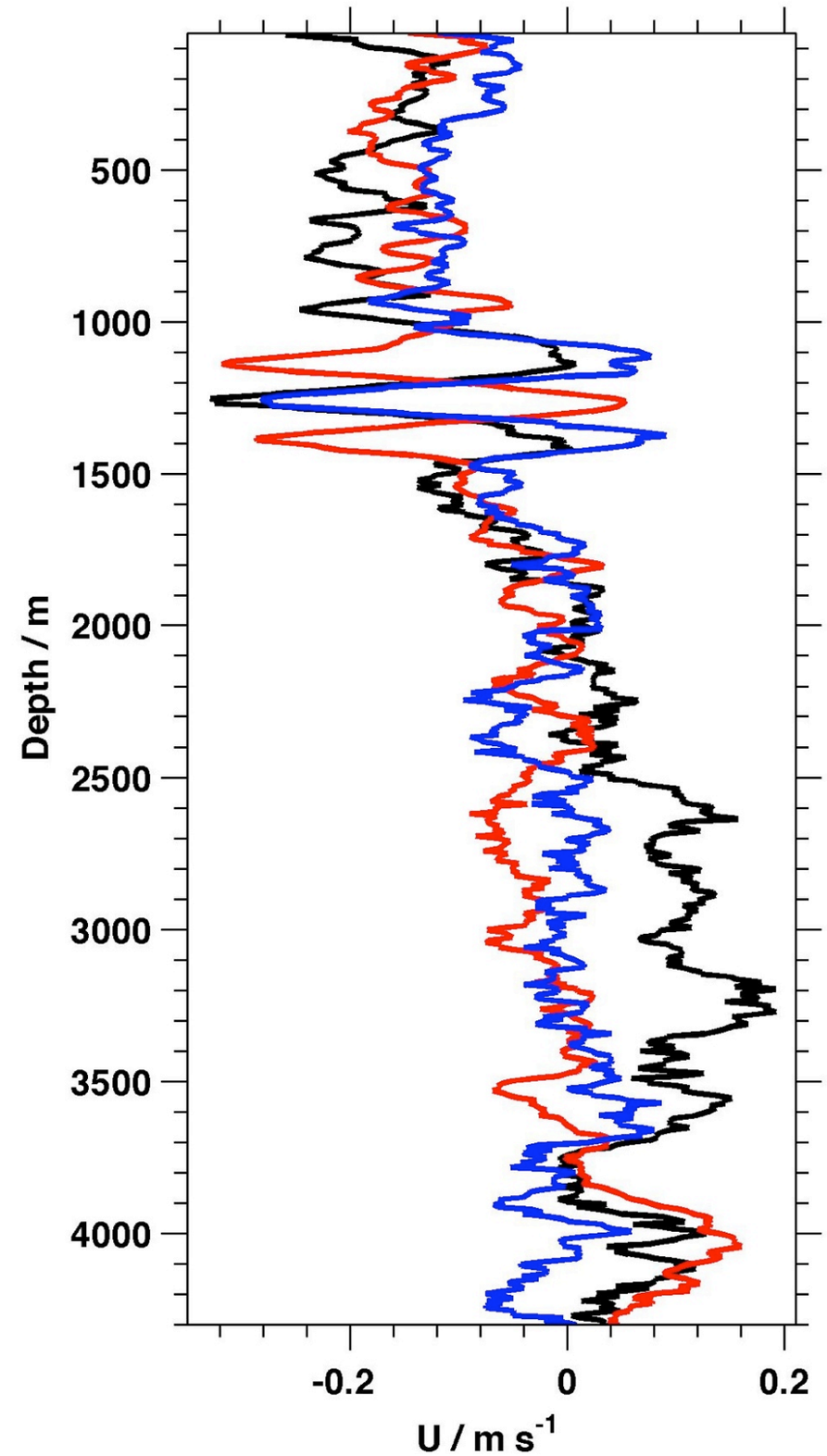


Tidal beams: model results

Princeton Ocean Model (G. Carter)

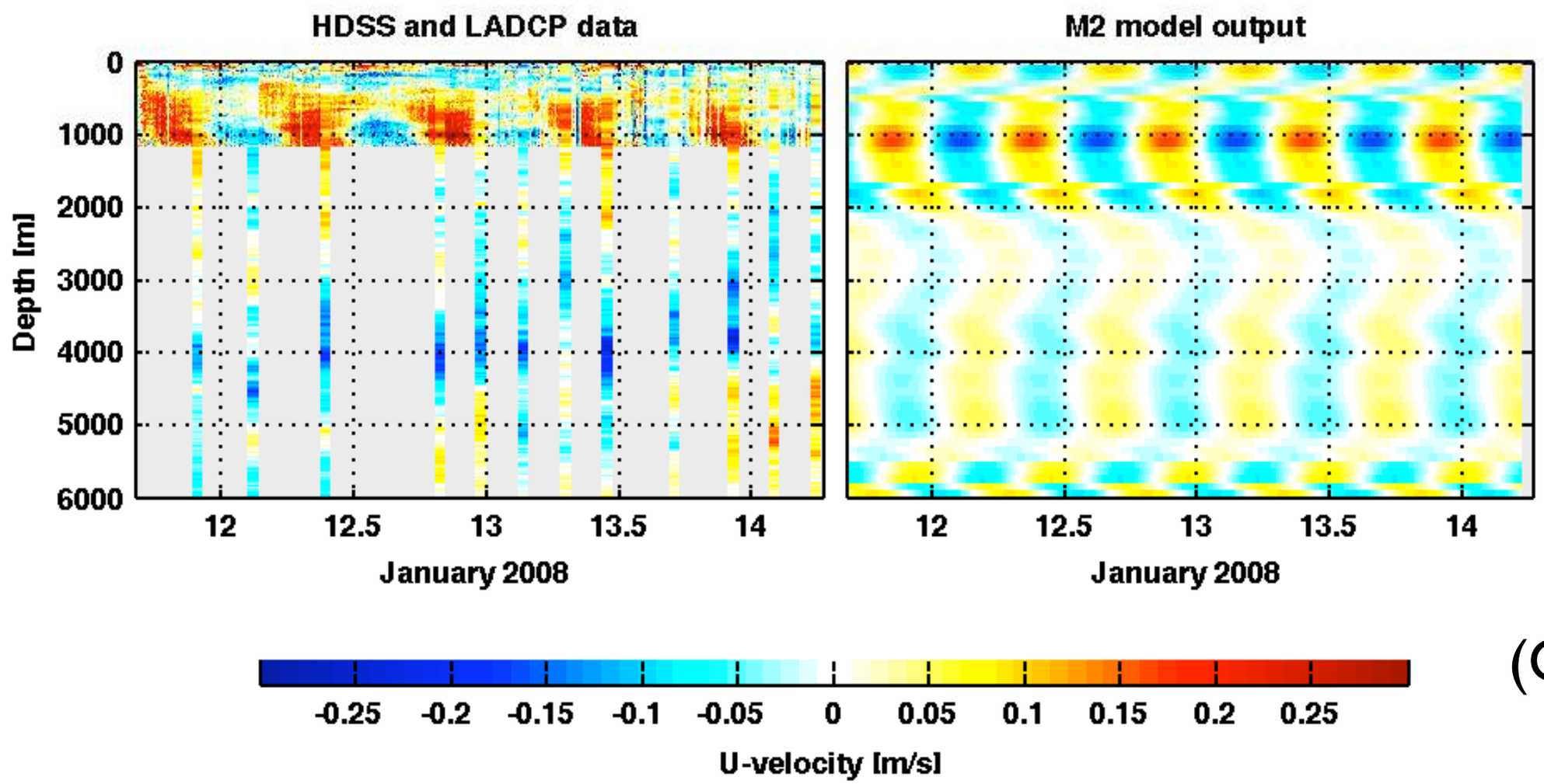


Data



- Modeled tidal beams fill the domain
- Ridge corrugation close to tidal wavelength
- Enhanced upper ocean shear and turbulence along entire length of SW Indian Ridge?

Tidal beams: model data comparison



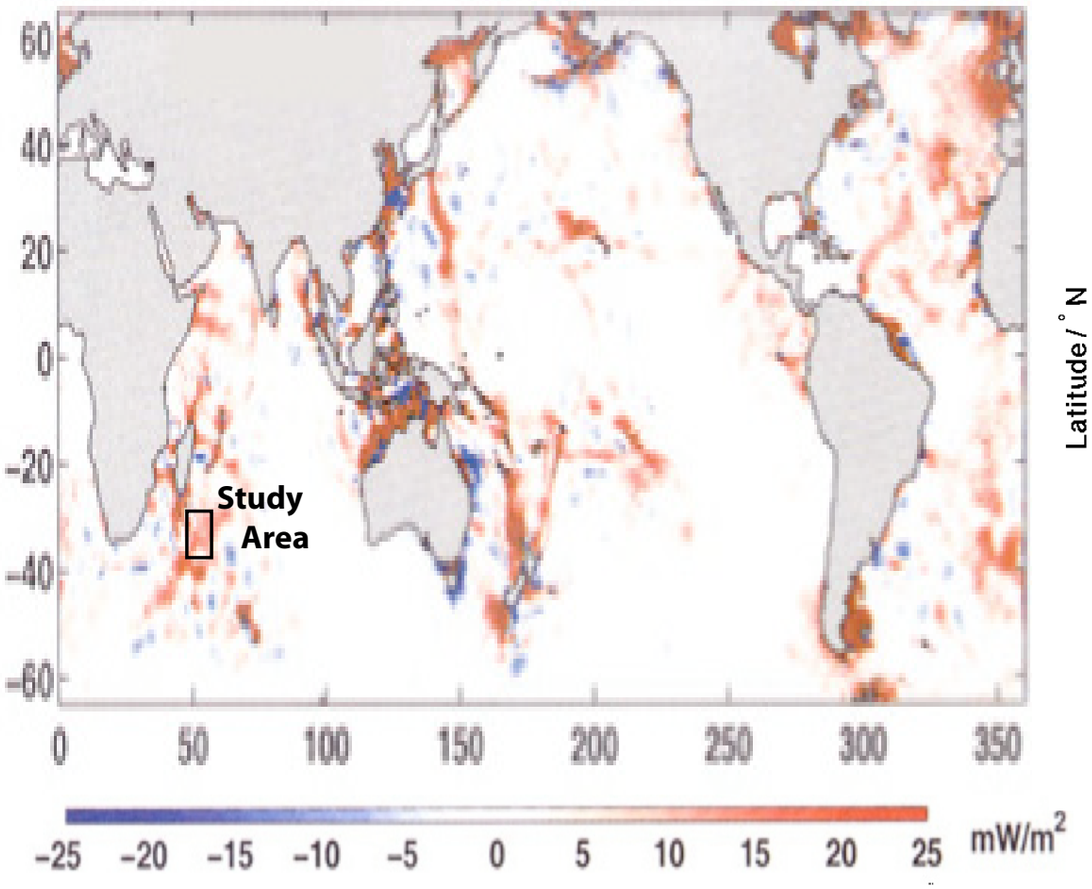
(G. Carter)

Model reproduces vertical structure and phase of tidal beam. Next step is use model to extrapolate observed mixing along the 1000 km long ridge

Aside: what happened to the inertial waves??

Tidal Generation

Egbert and Ray



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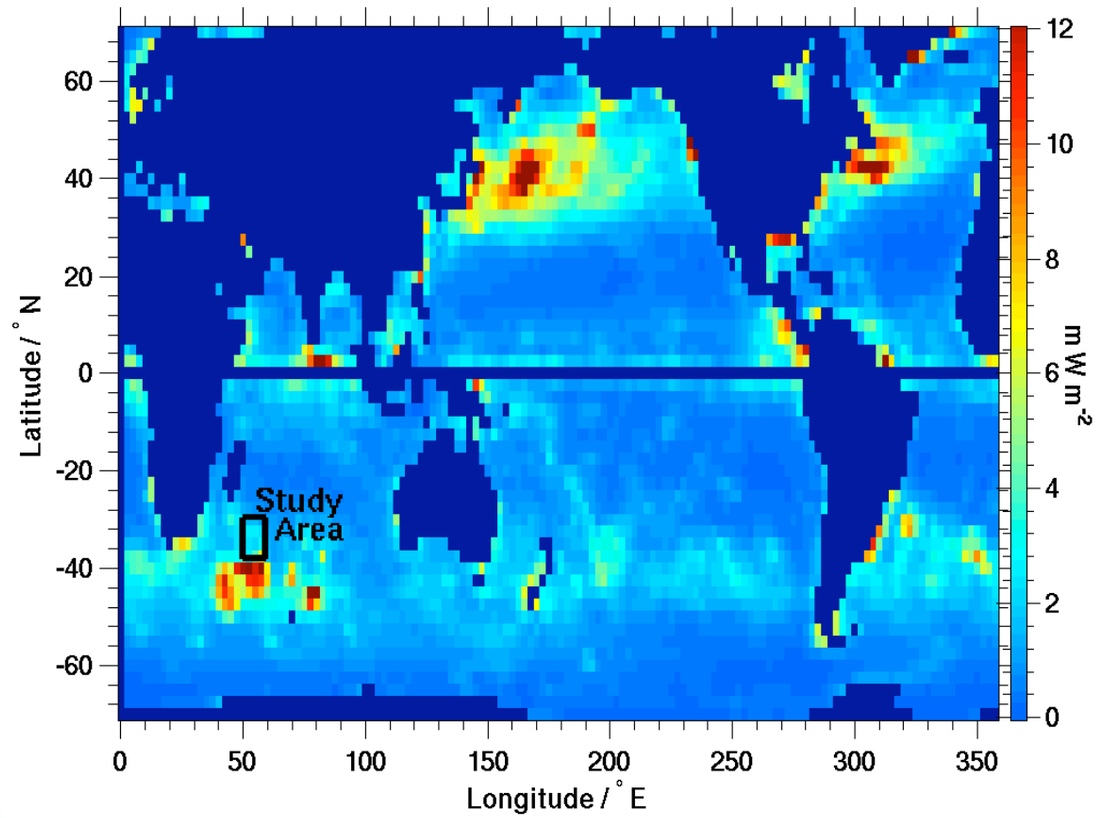

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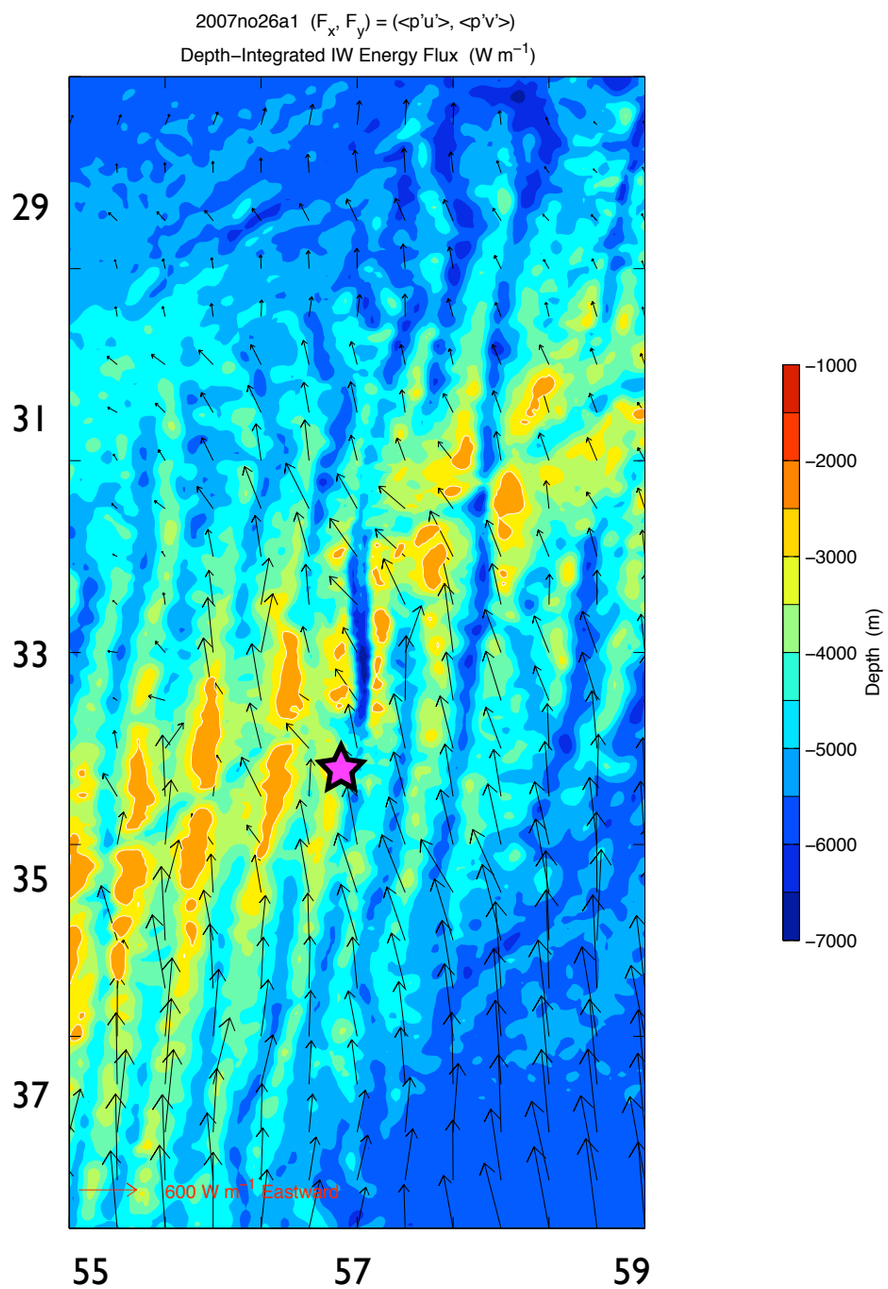

Actual average wind input during cruise period = 6 mW/m^2 (42-52 S) => ~5 kW/m

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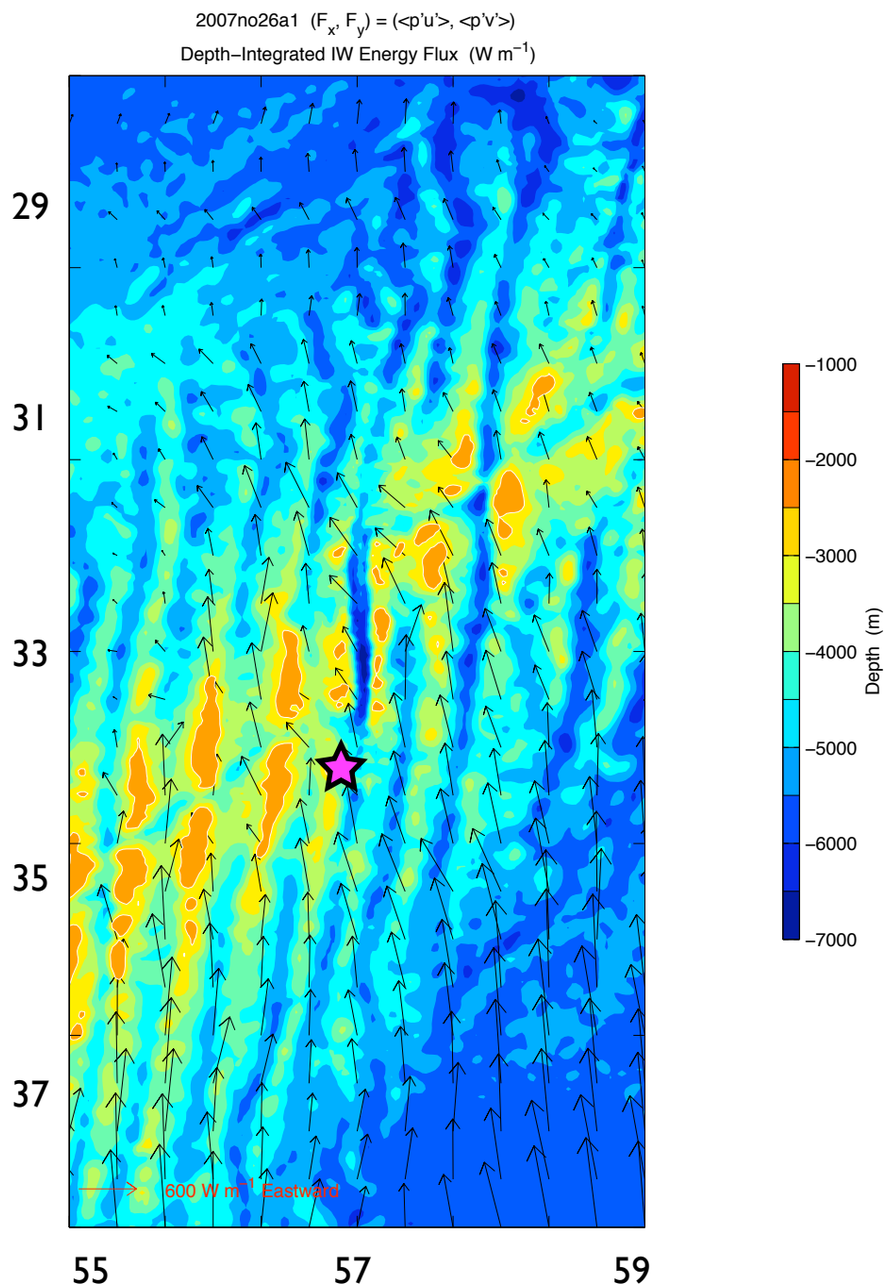

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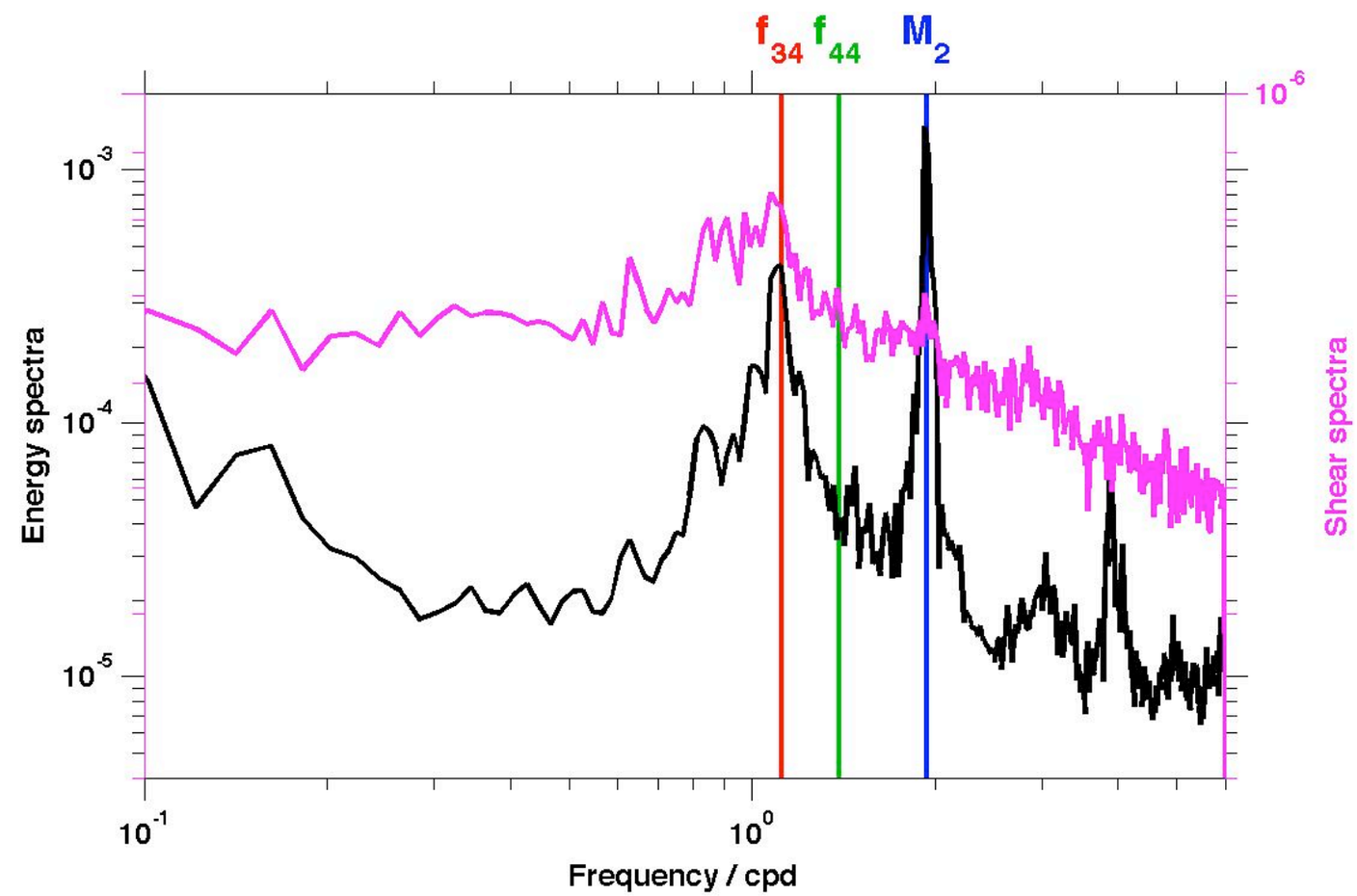
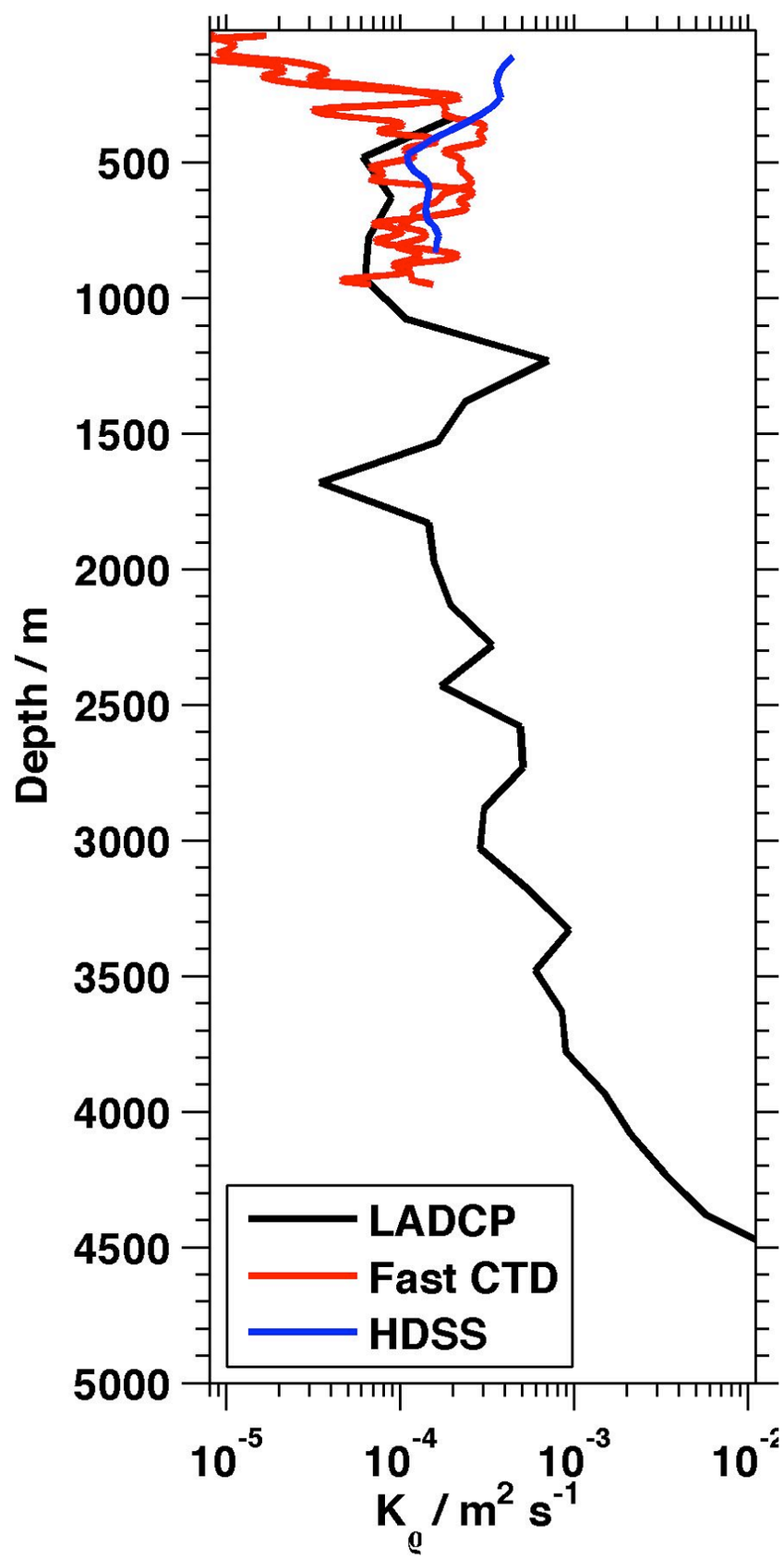
Mooring spectra

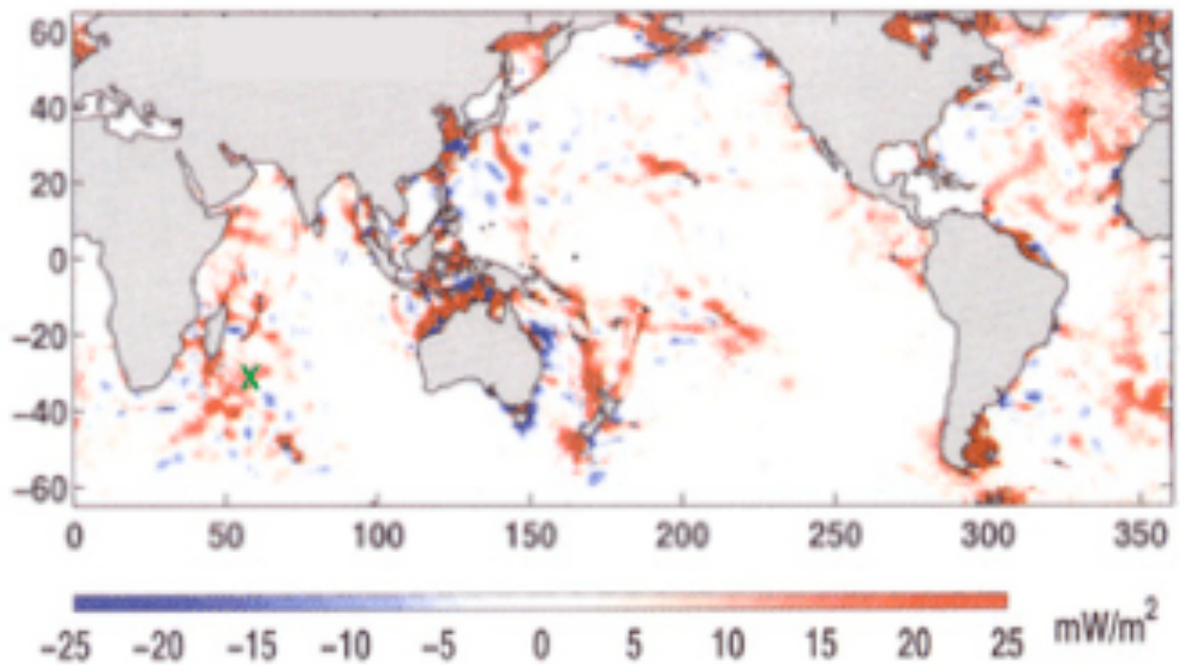


Low modes must dissipate in ~10 deg latitude. Surface/ bottom bounces? ACC fronts?

Conclusions - another example of patchy mixing



- Dissipation in upper 2500 m only (above ridge crests) is about 15 mW/m^2, similar to Egbert and Ray



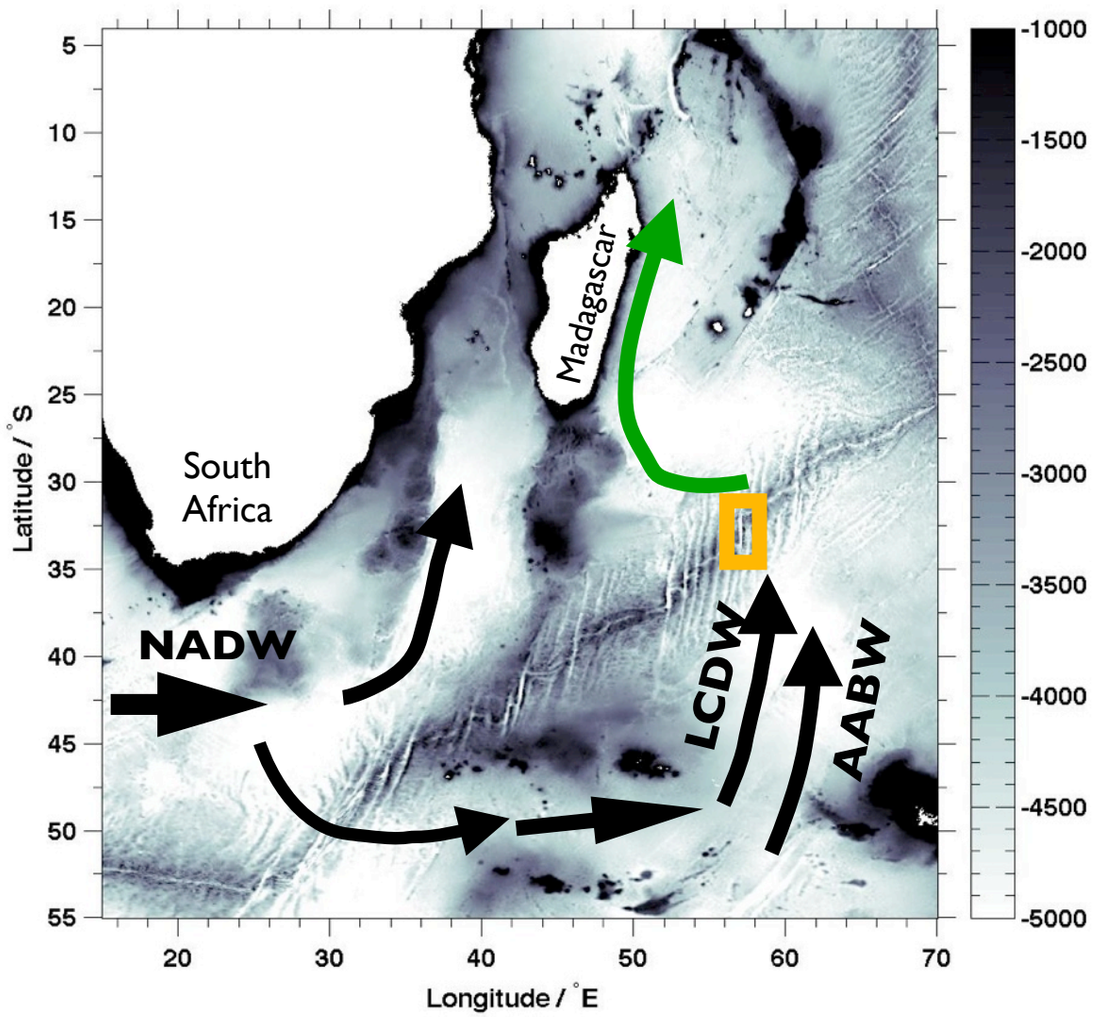
- Extrapolating along entire SW Indian Ridge gives a rough total dissipation rate of 12 GW

- Deep mixing in series of fracture zones much larger

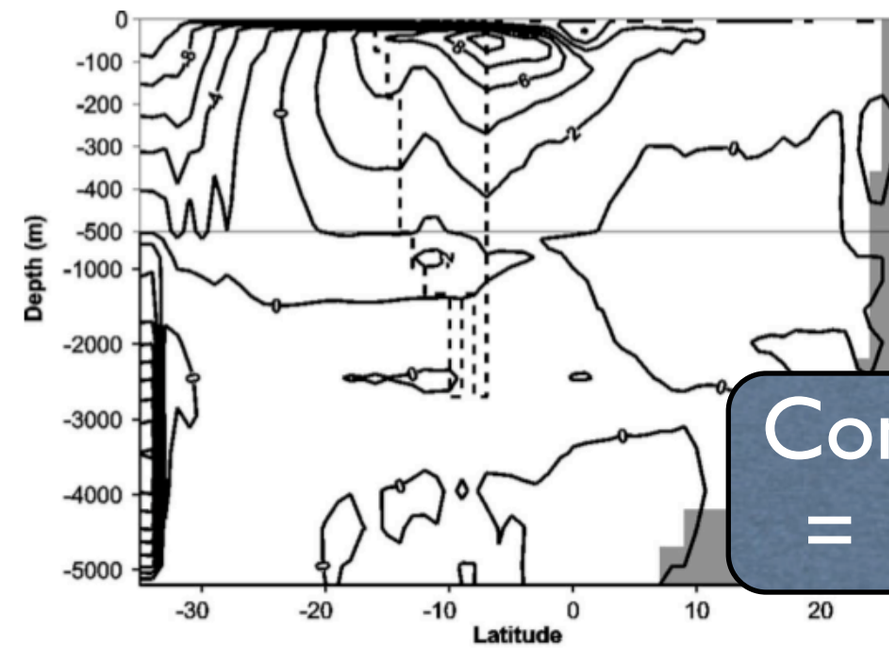
- Indian Ocean mixing concentrated in western half of basin, Drijfhout and Naveira Garabato 07 argue that this zonal mixing asymmetry significantly impacts basin-wide circulation patterns.

Consequences of patchy mixing

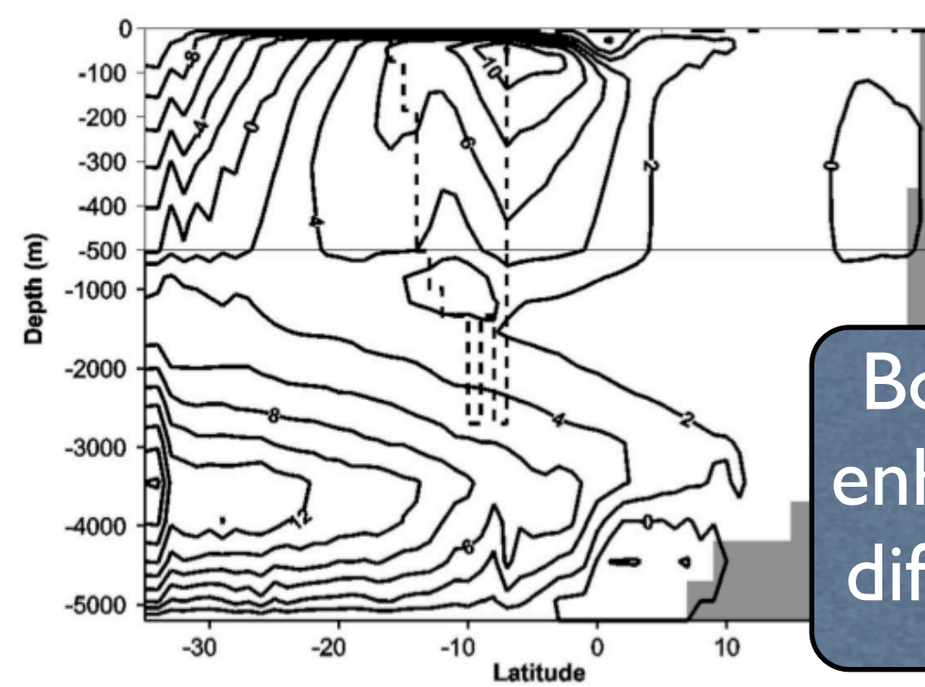
Strong mixing may continue as bottom water flows north in concentrated boundary current (Donohue et al 03)



Palmer et al 07: Modeled Indian Ocean overturning streamfunction



Constant κ = 1.2 10^{-4}



Bottom enhanced diffusivity