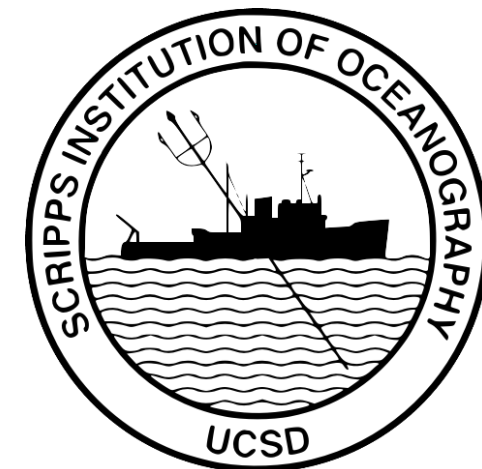




Ocean turbulence: Importance, techniques and case studies

Matthew Alford
Les Houches 2019

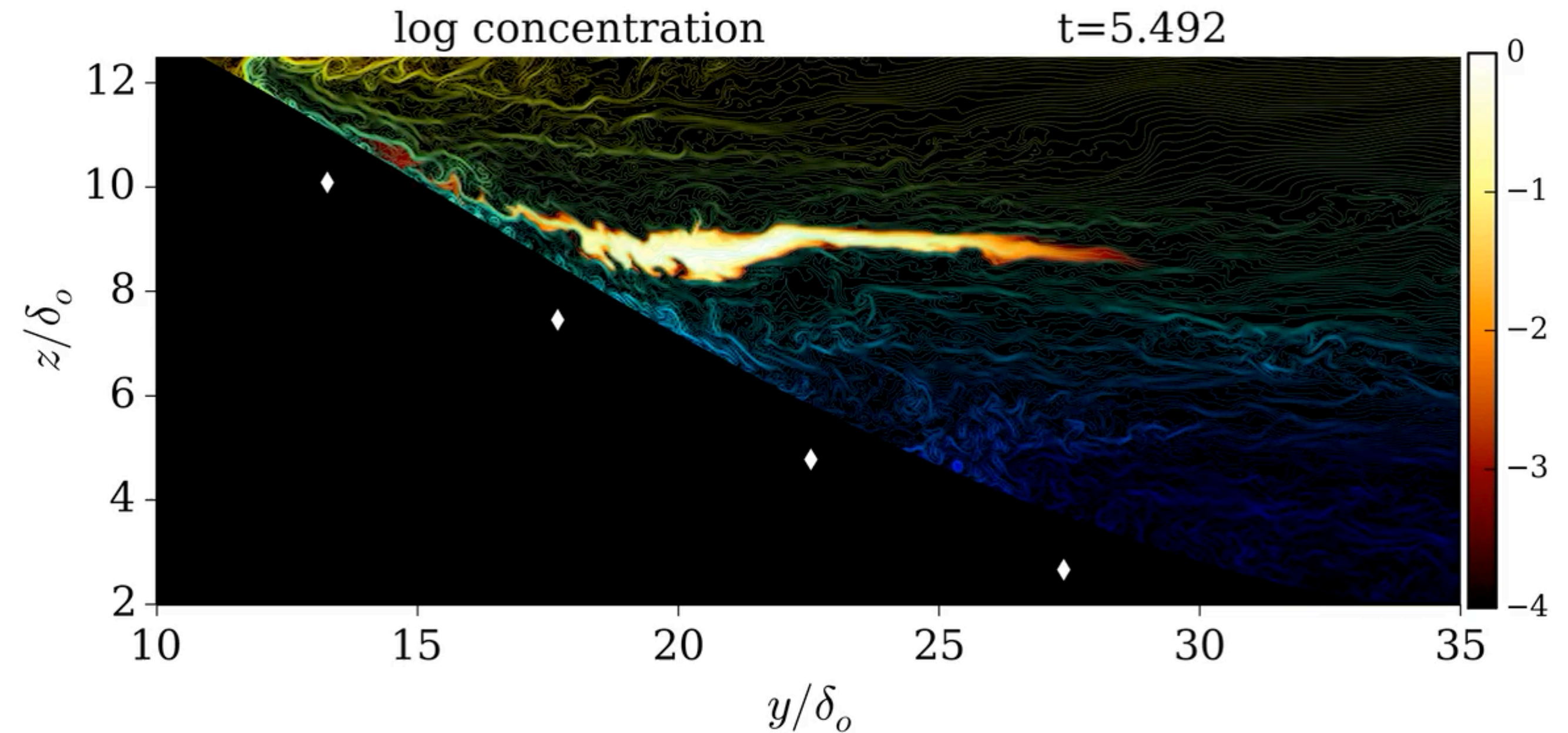


Special thanks to Arnaud Le Boyer, Mike Goldin, Sean Lastuka, San Nguyen, Jonathan Ladner, Sara Goheen, Anna Savage, and Nicole Couto

And THANK YOU TOM AND THIERRY!!



What is turbulence and why is it important?

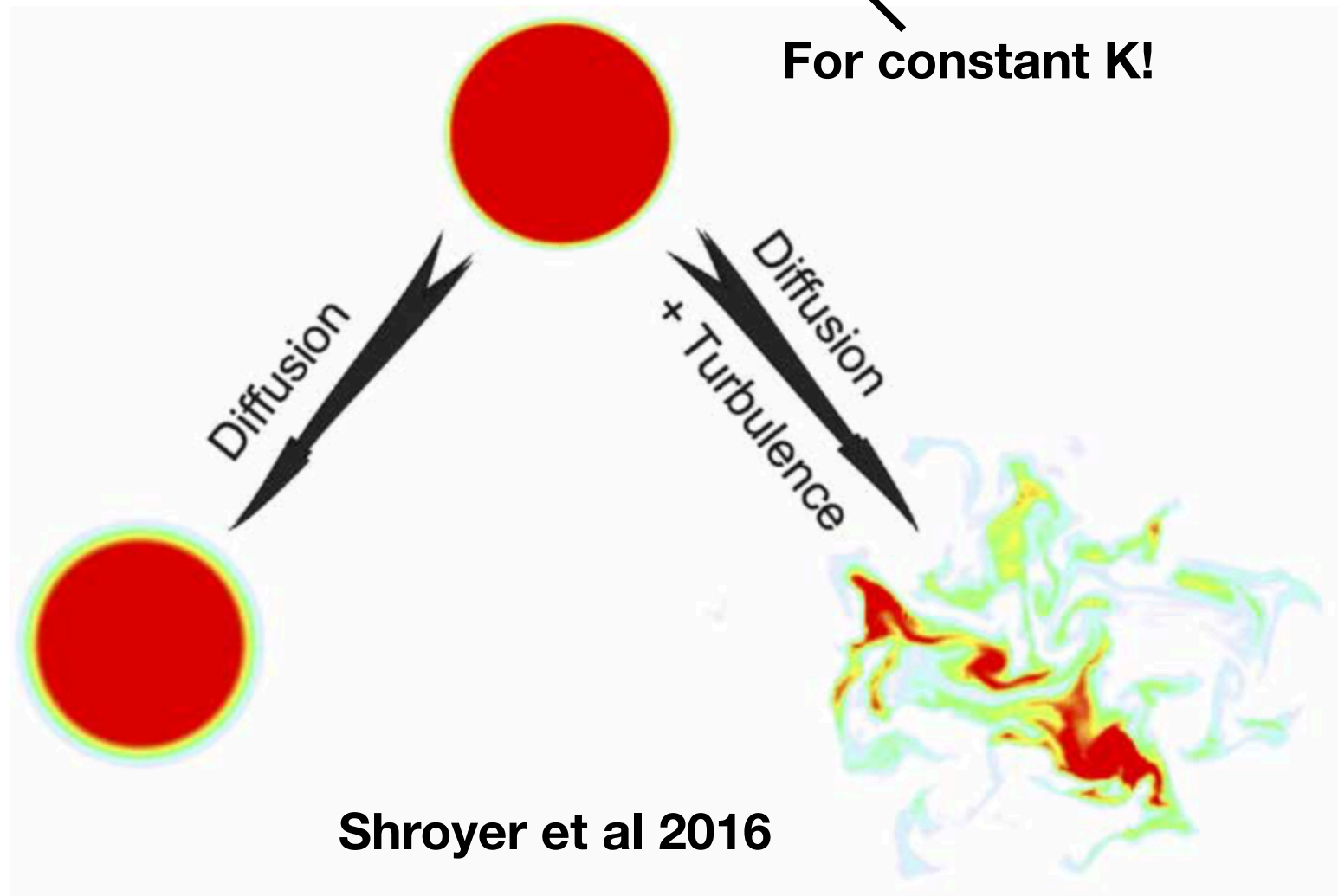


Diffusion, buoyancy flux and diapycnal velocity

Mixing irreversibly affects ocean variables via the buoyancy flux divergence.

$$\frac{Db}{Dt} = -\nabla \cdot (J_b) = K \nabla^2 b$$

For constant K!

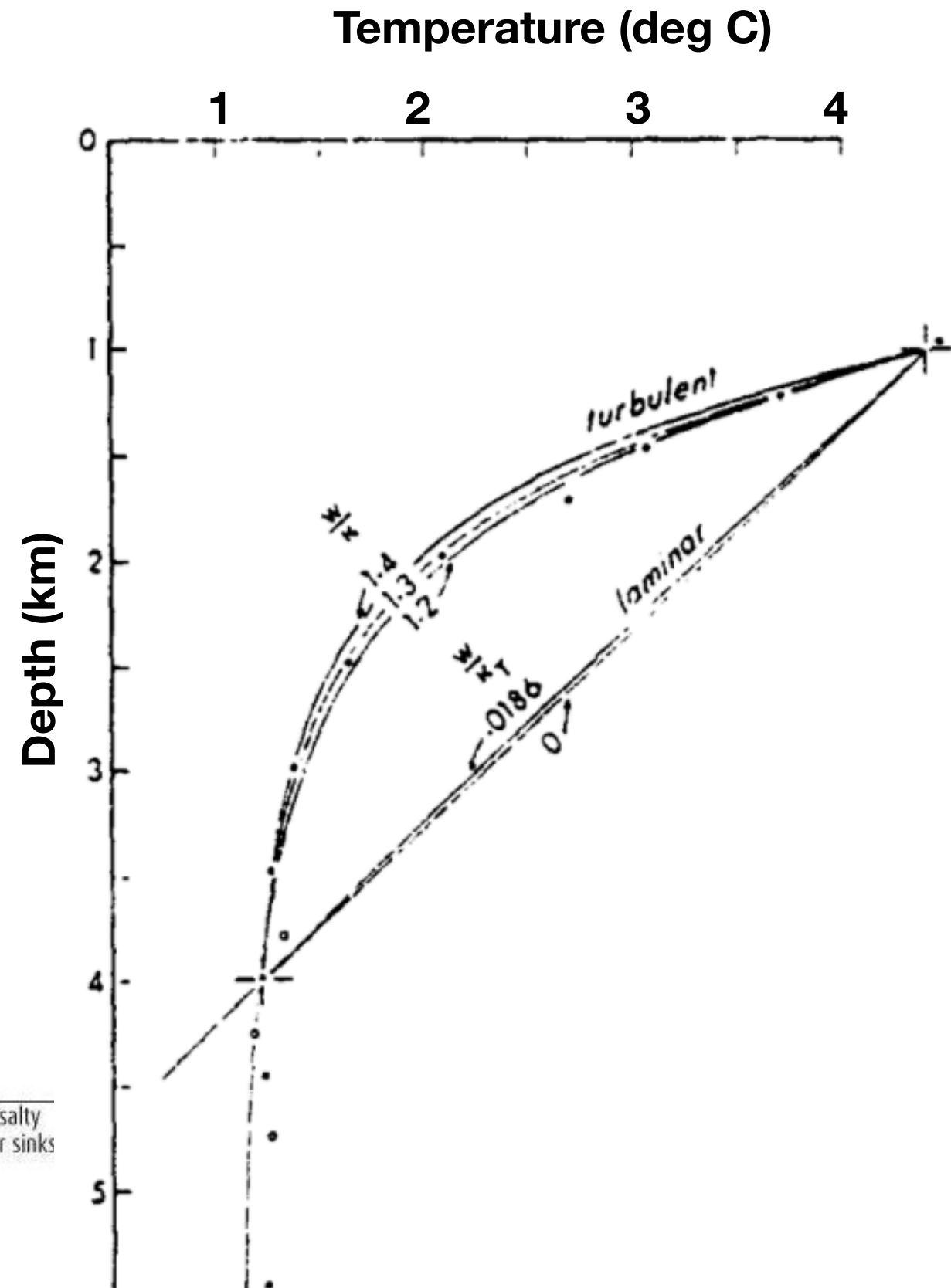
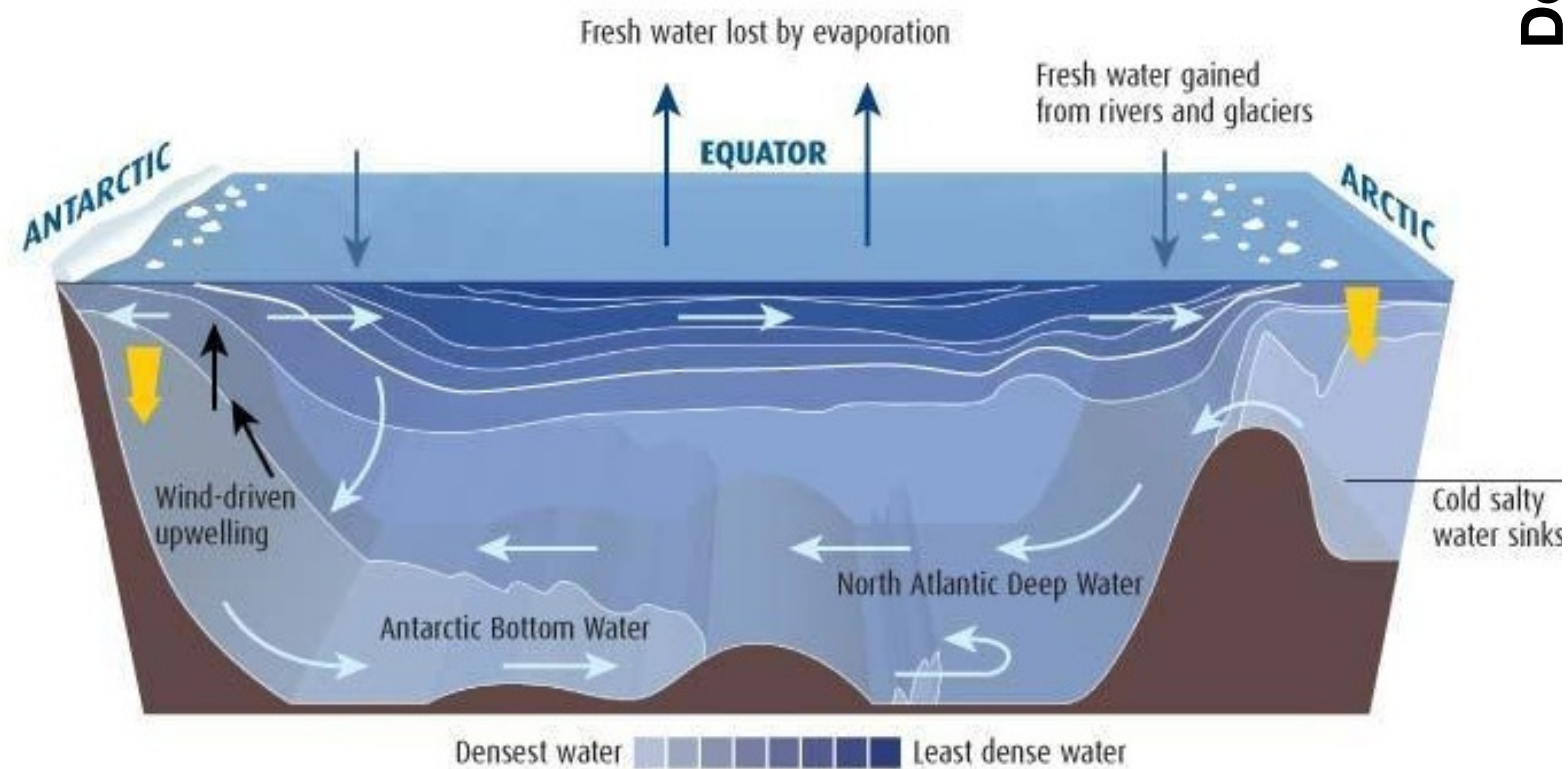


The Munk Balance

$$\frac{Db}{Dt} = -\nabla \cdot (J_b) = K \nabla^2 b$$

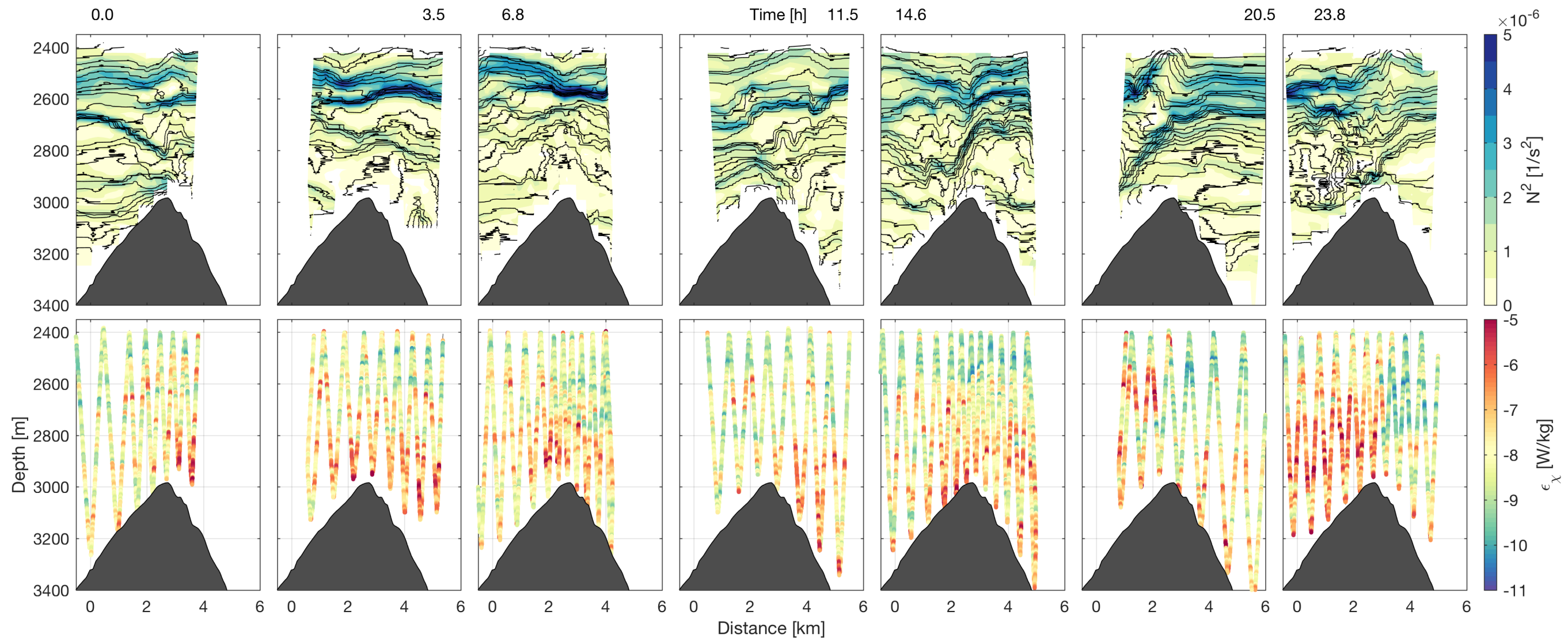
$$w \frac{\partial b}{\partial z} = K \frac{\partial^2 b}{\partial z^2}$$

$$K = 10^{-4} m^2 s^{-1}$$

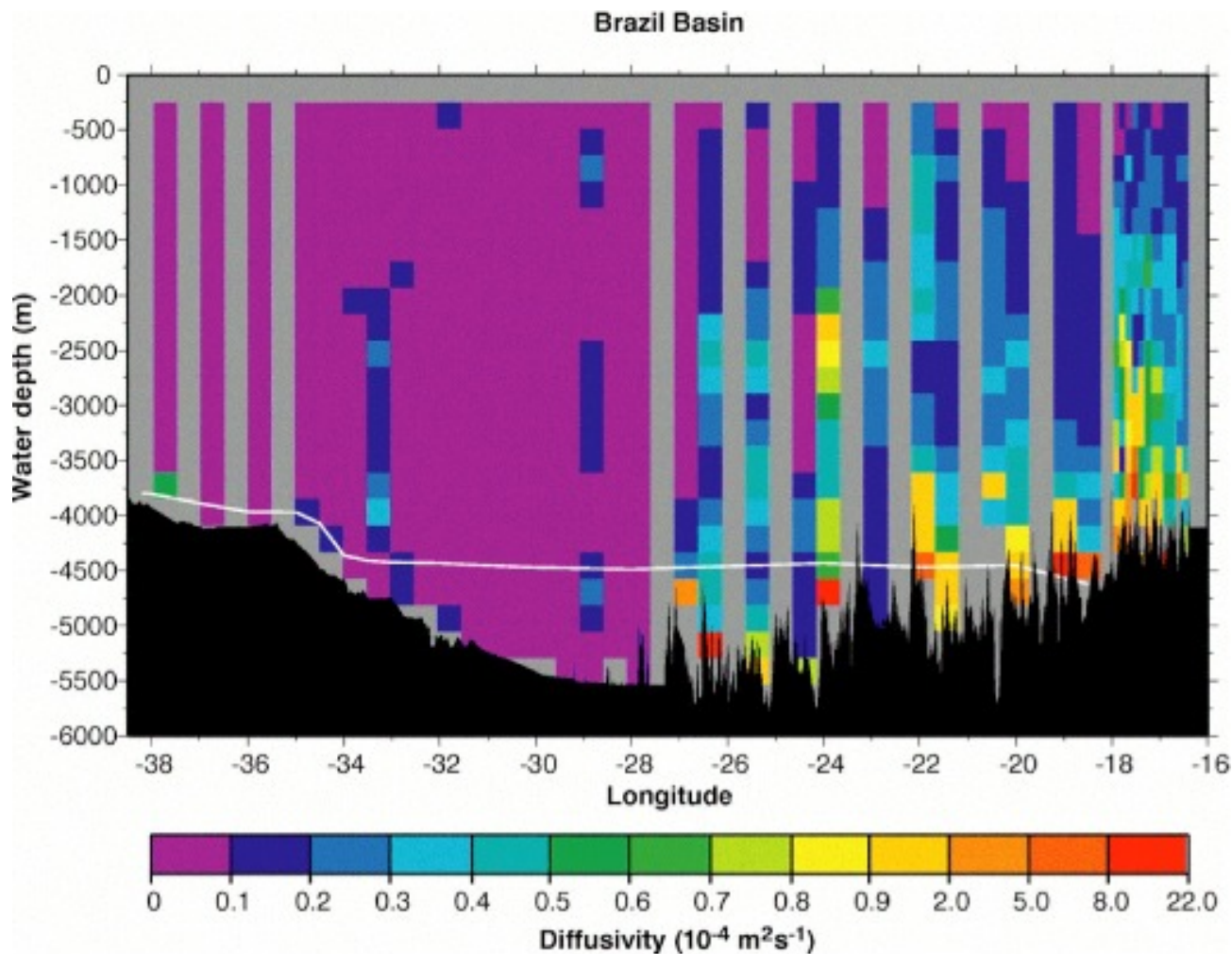


Munk (1961)

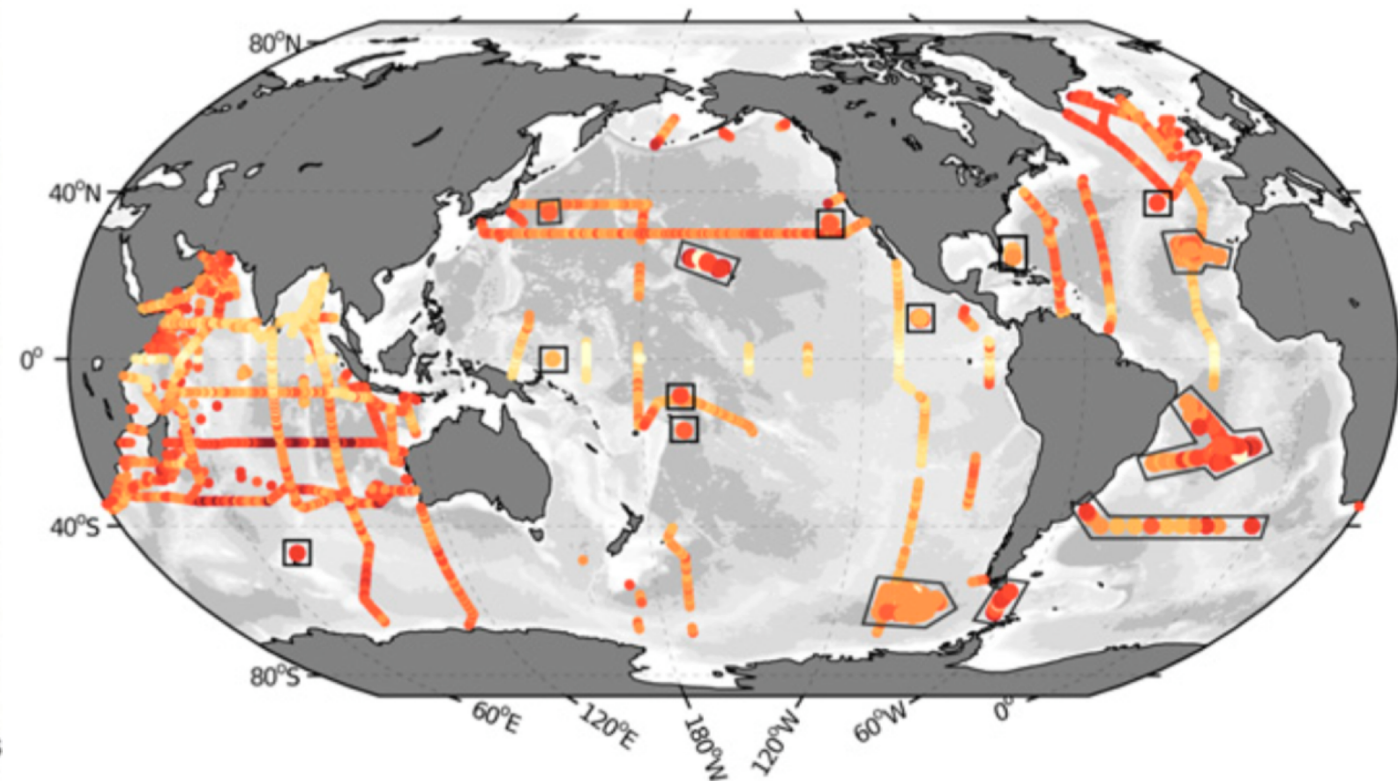
Turbulence in the deep ocean is strong and bottom intensified.



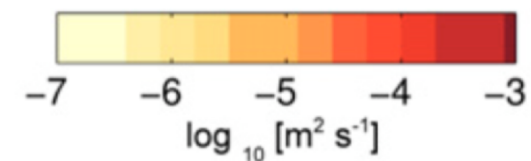
Mixing is highly variable and sparsely measured.



Polzin et al. 97

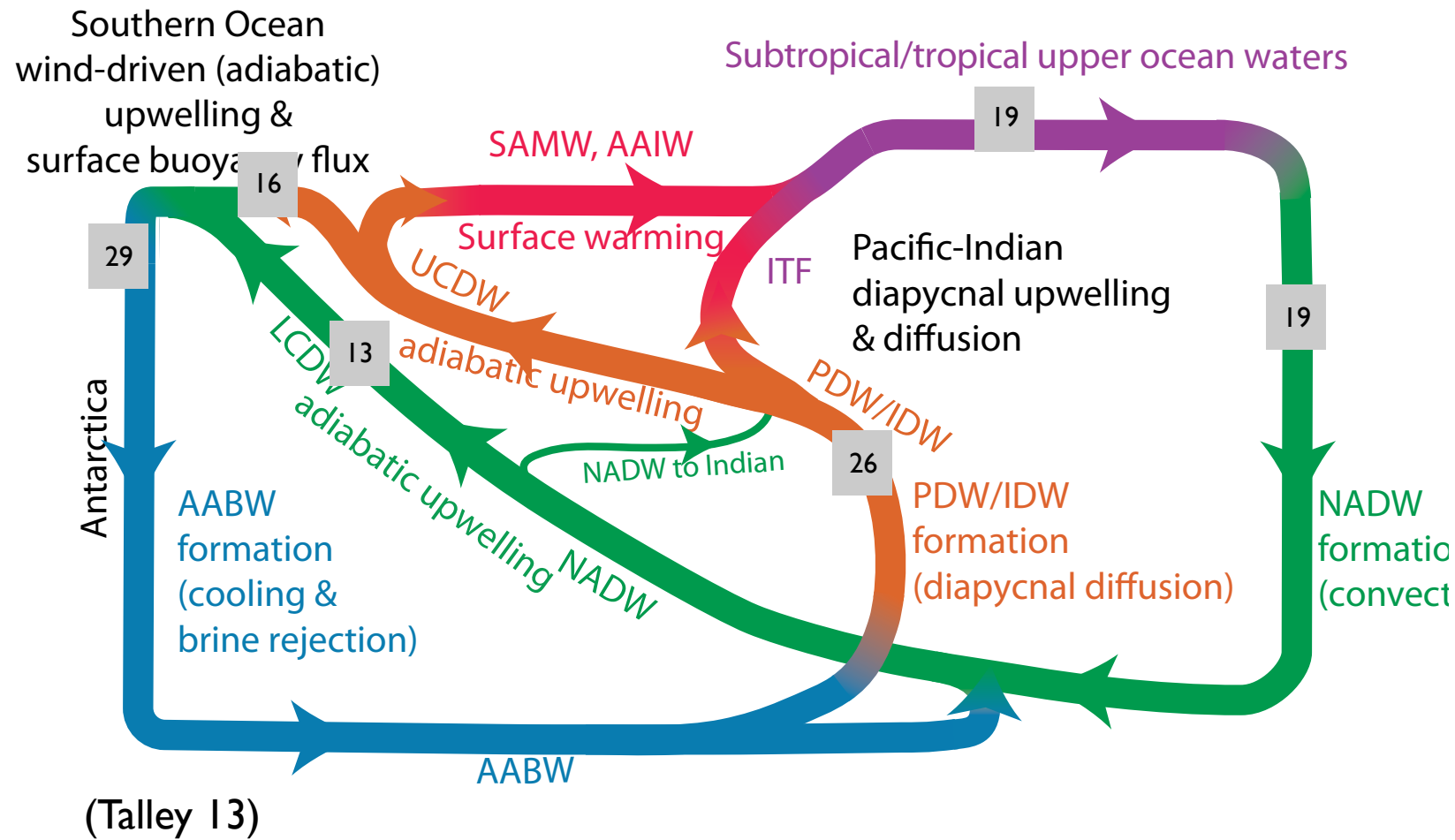


(b) Full depth $\log_{10} K$

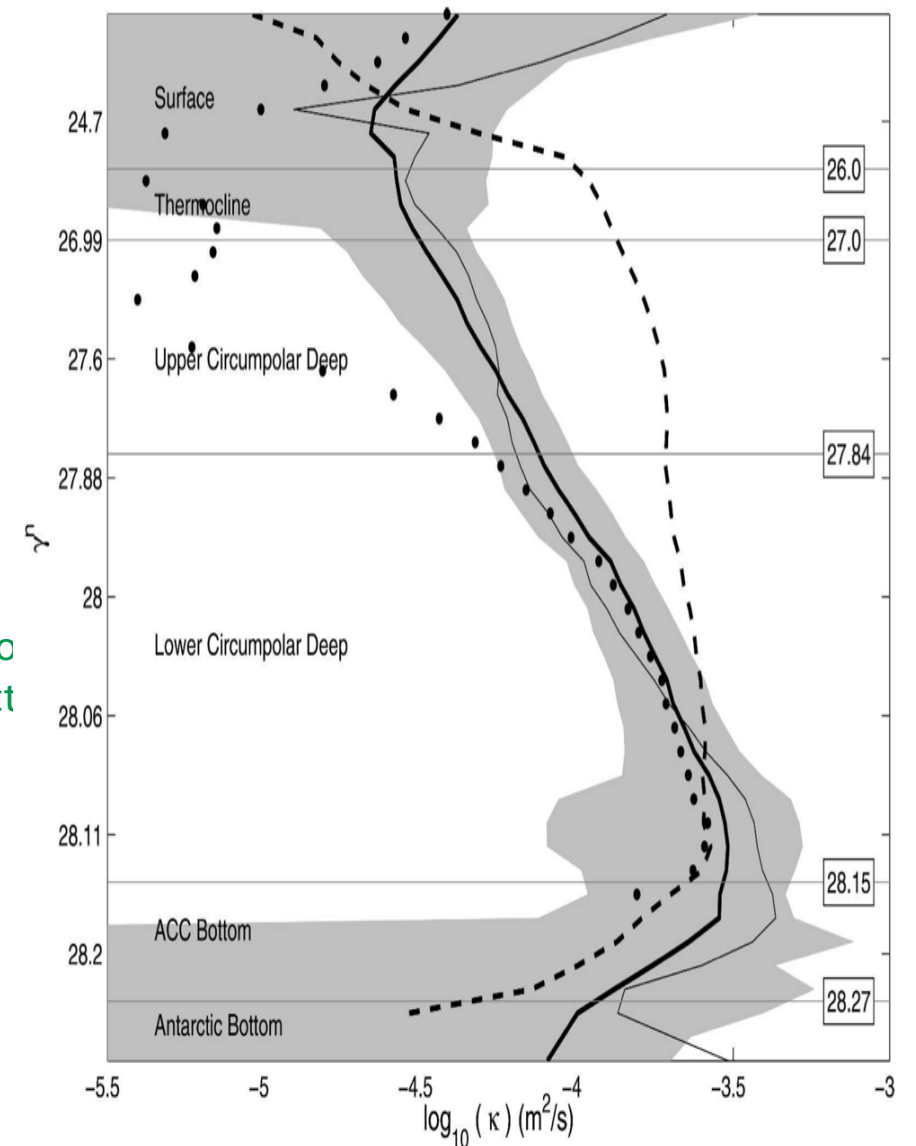


Waterhouse et al 2014

Mixing makes the oceans go 'round



Talley 2013



Lumpkin and Speer 2007

... but which direction?

Munk 1961

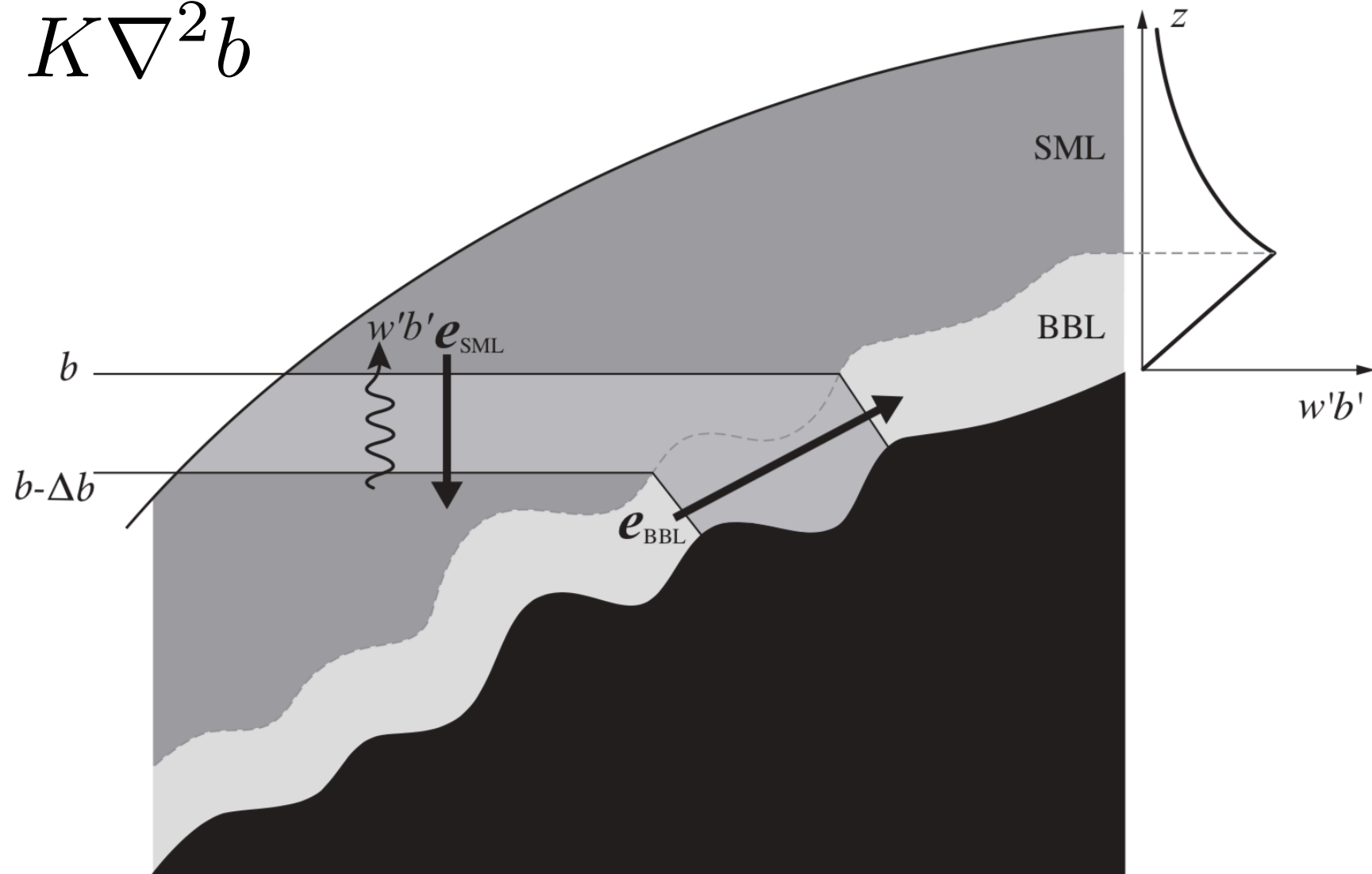
Water upward in interior

Ferrari et al 2017

Water downward in interior,
upward along boundaries

$$\frac{Db}{Dt} = -\nabla \cdot (J_b) = K \nabla^2 b$$

$$w^* = N^{-2} \frac{\partial J_b}{\partial z}$$

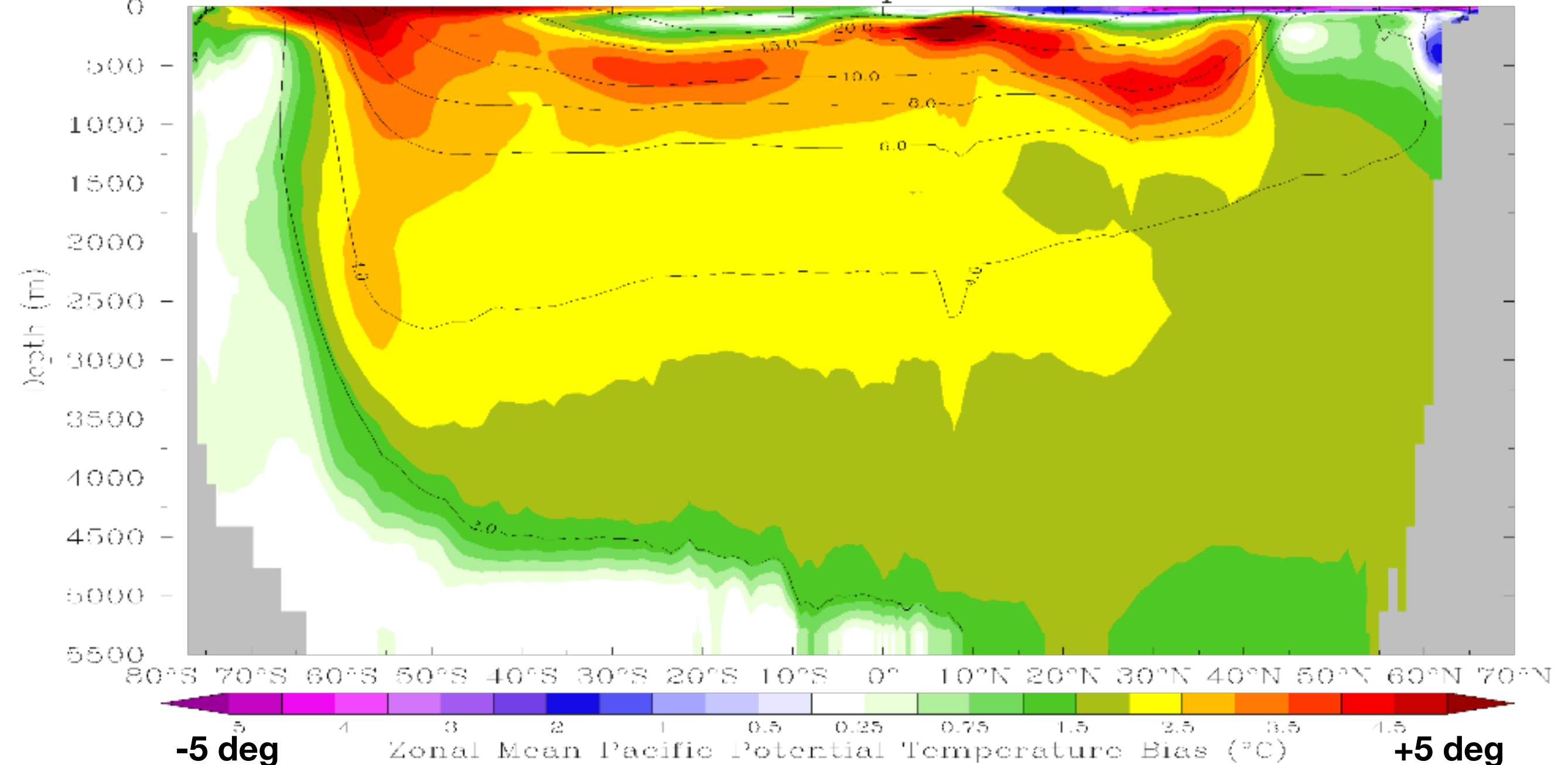


Bottom-enhanced turbulence profiles move water downward not upward!

Mixing matters for climate.

Change after 2000 Years with $4 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ Added Diffusivity

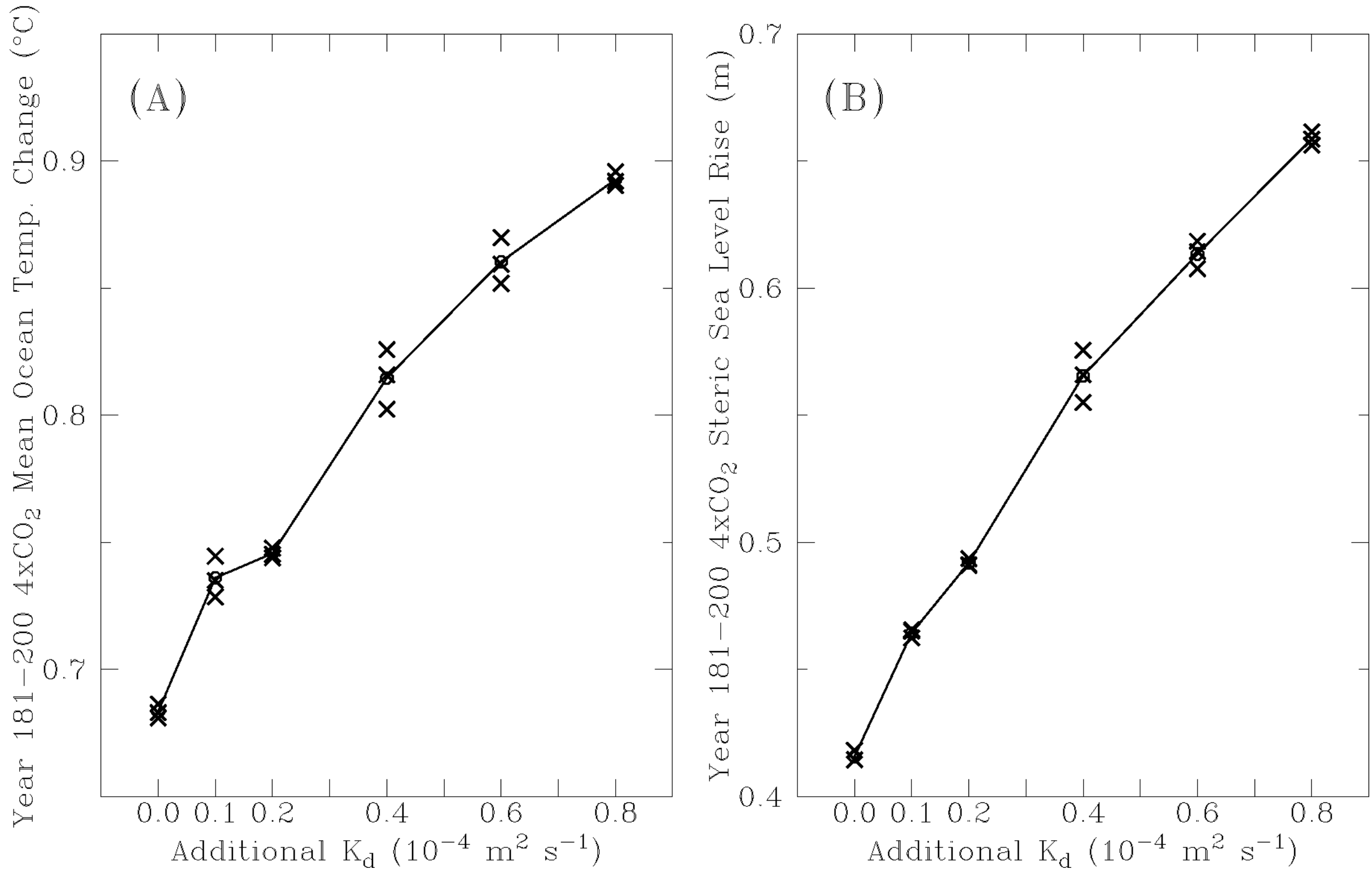
CM2G Kd = 0.4 Pacific Potential Temperature Bias Years 1901 - 2000



Zonal Mean Pacific Temperature Change (°C)

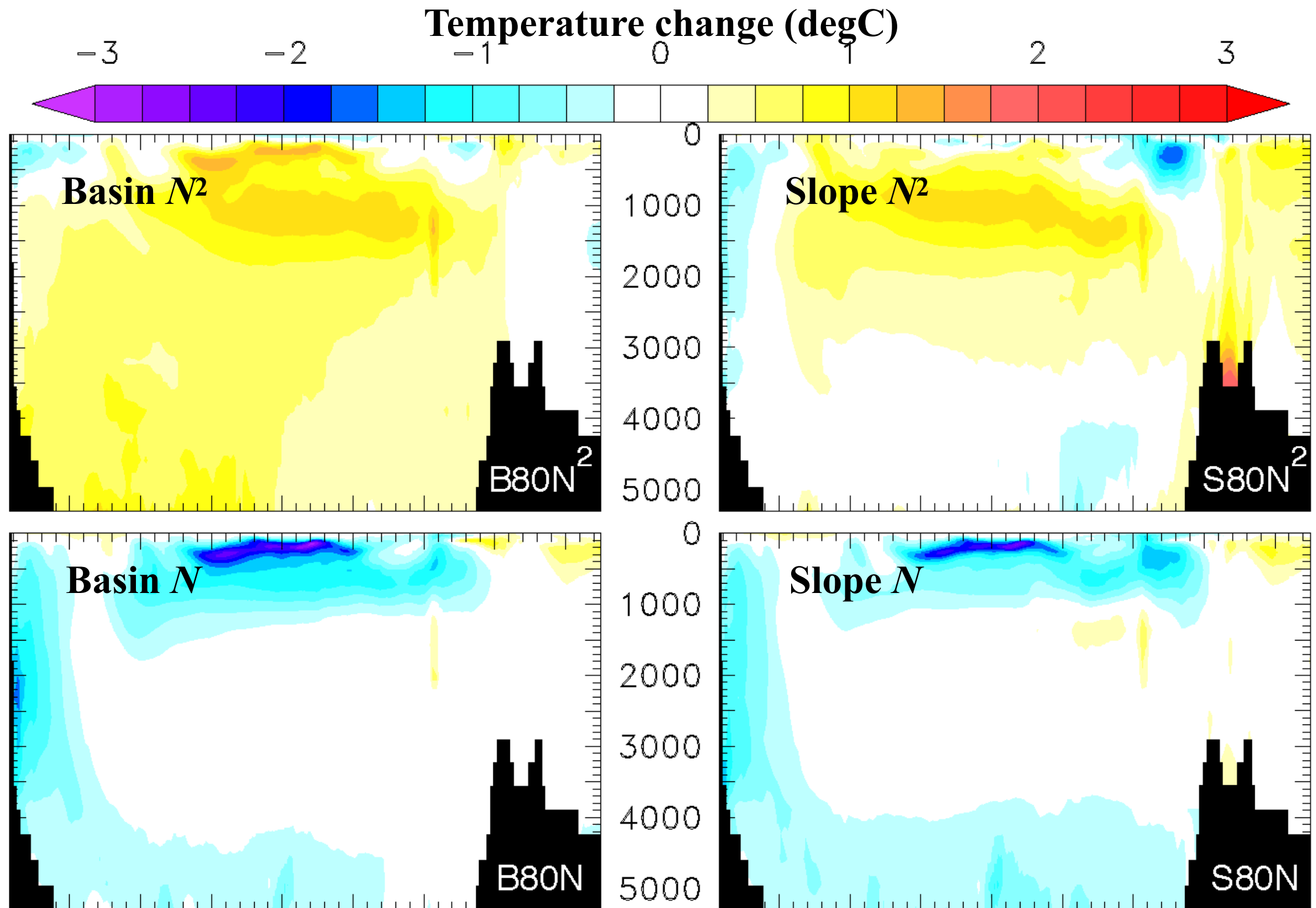
Courtesy Bob Hallberg

Mixing matters for climate.

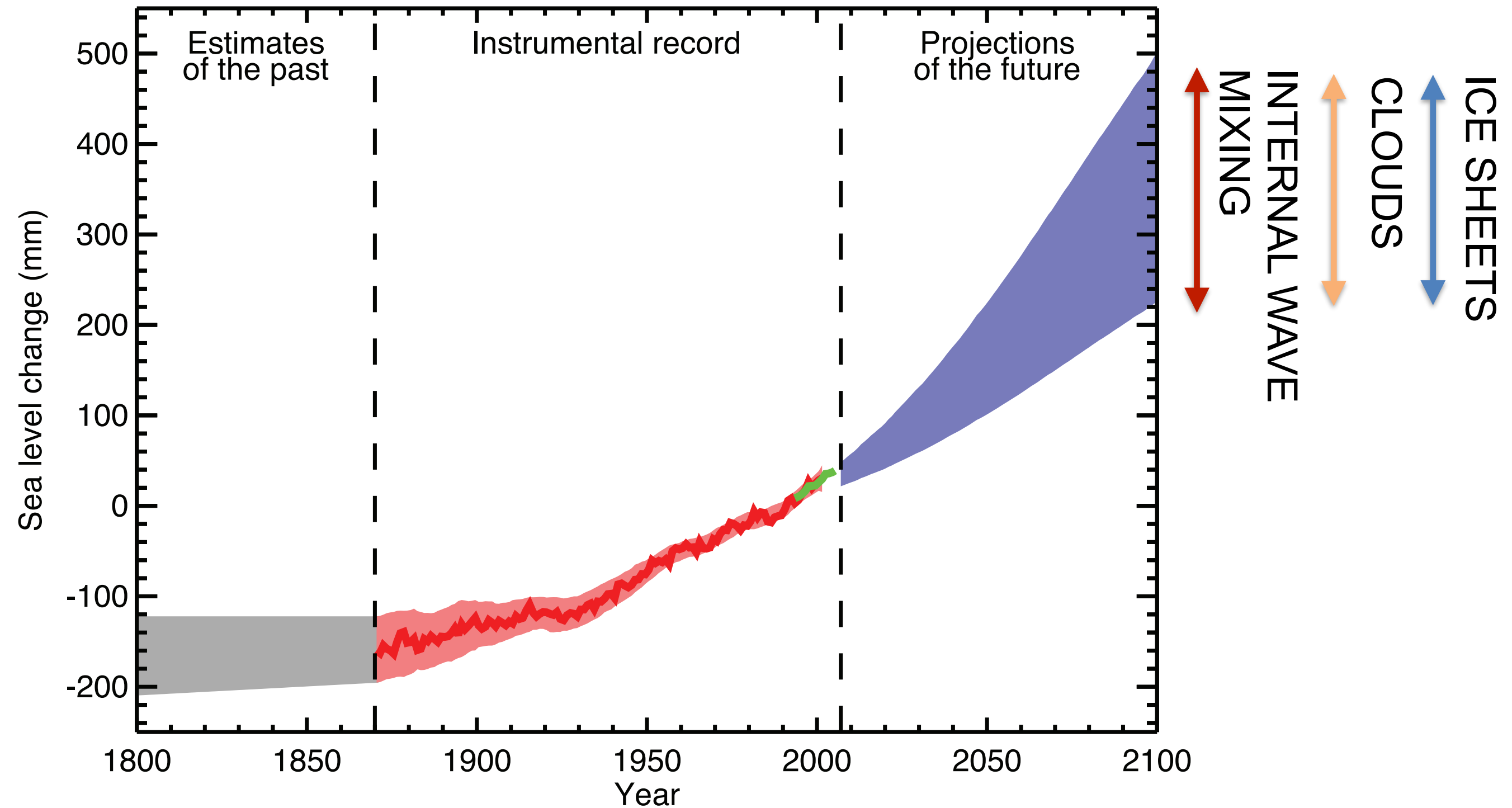


Courtesy Bob Hallberg

Mixing matters for climate.

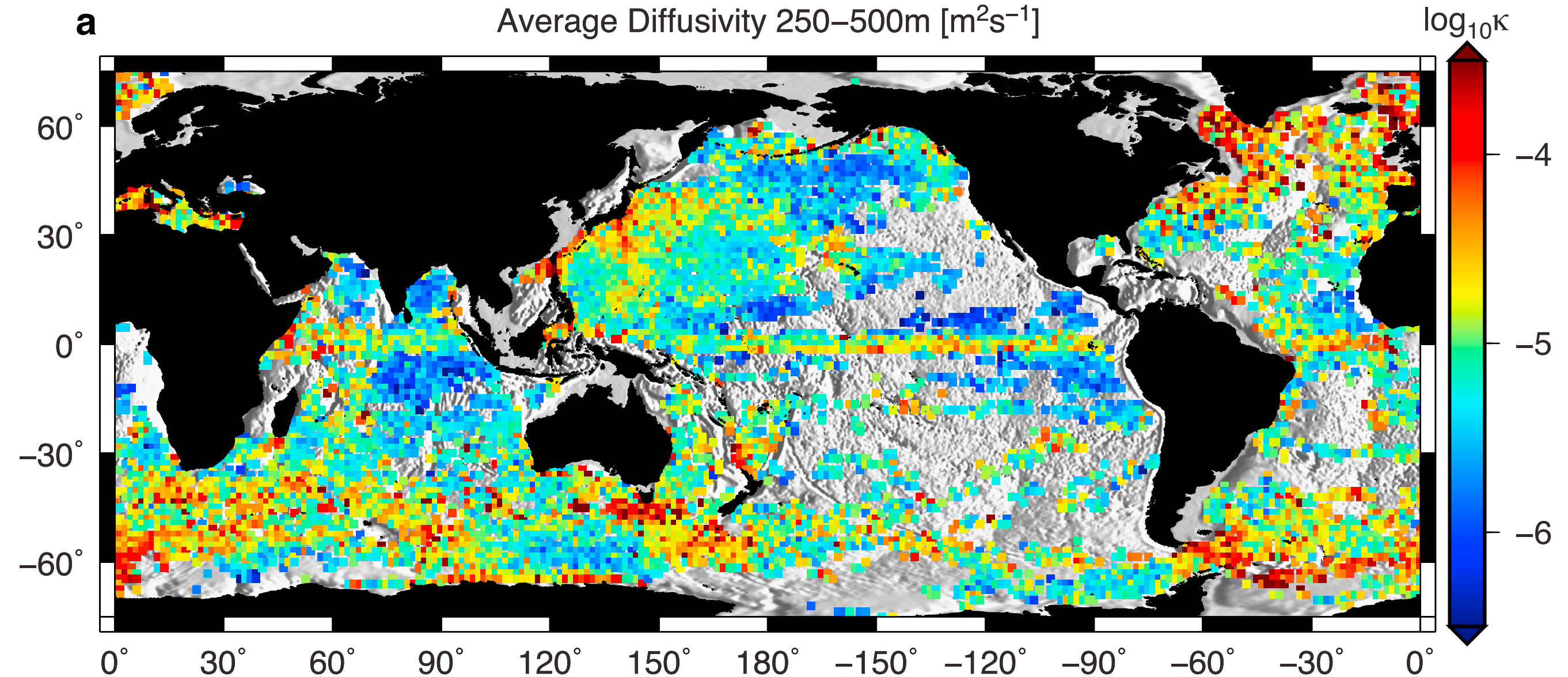


Importance to Climate



Parameterized turbulence from Argo

a Average Diffusivity 250–500m [m^2s^{-1}]

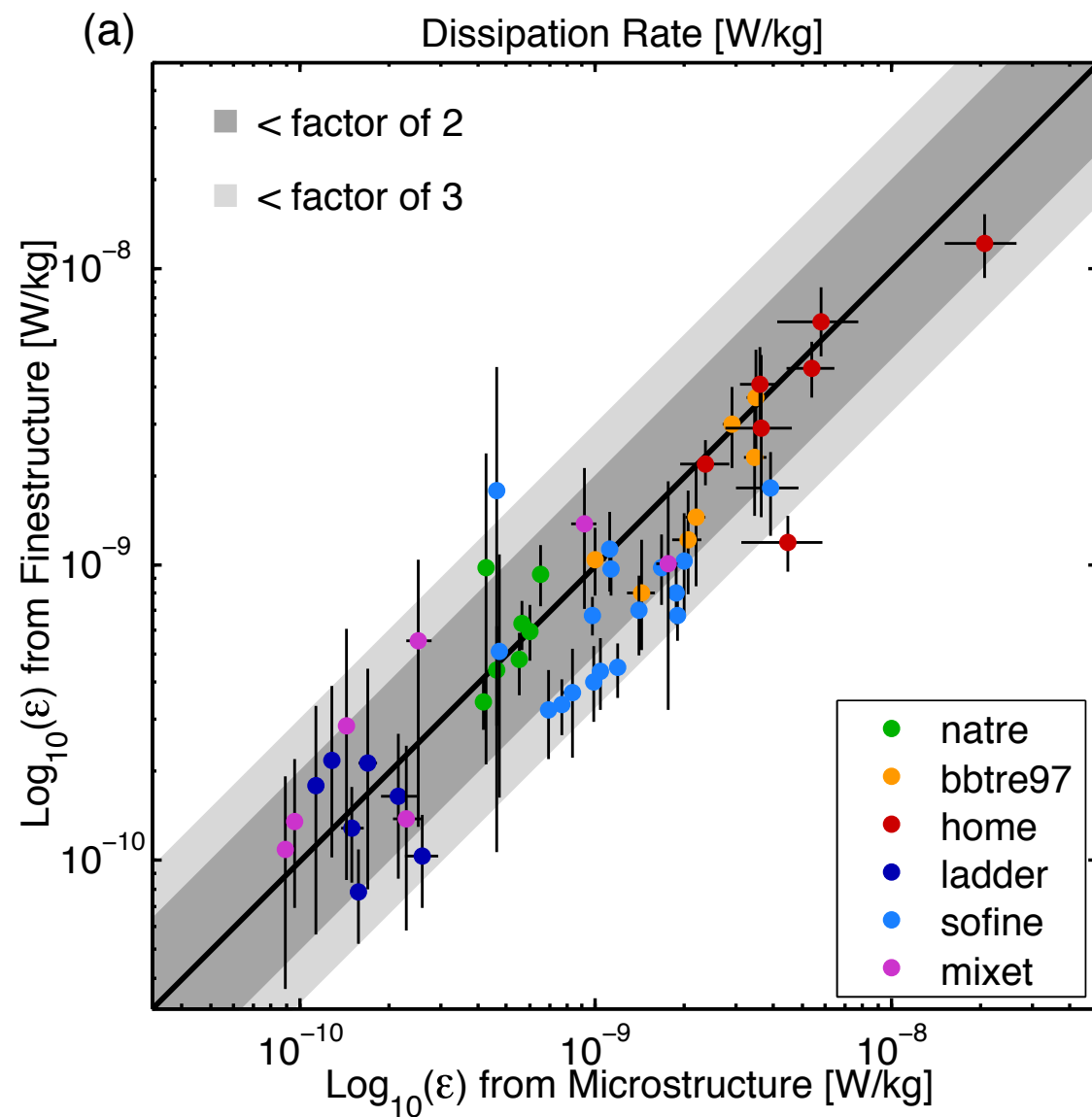


Whalen, Talley and MacKinnon, 2012
Whalen, MacKinnon, Talley, Waterhouse 2015
Whalen et al 2018

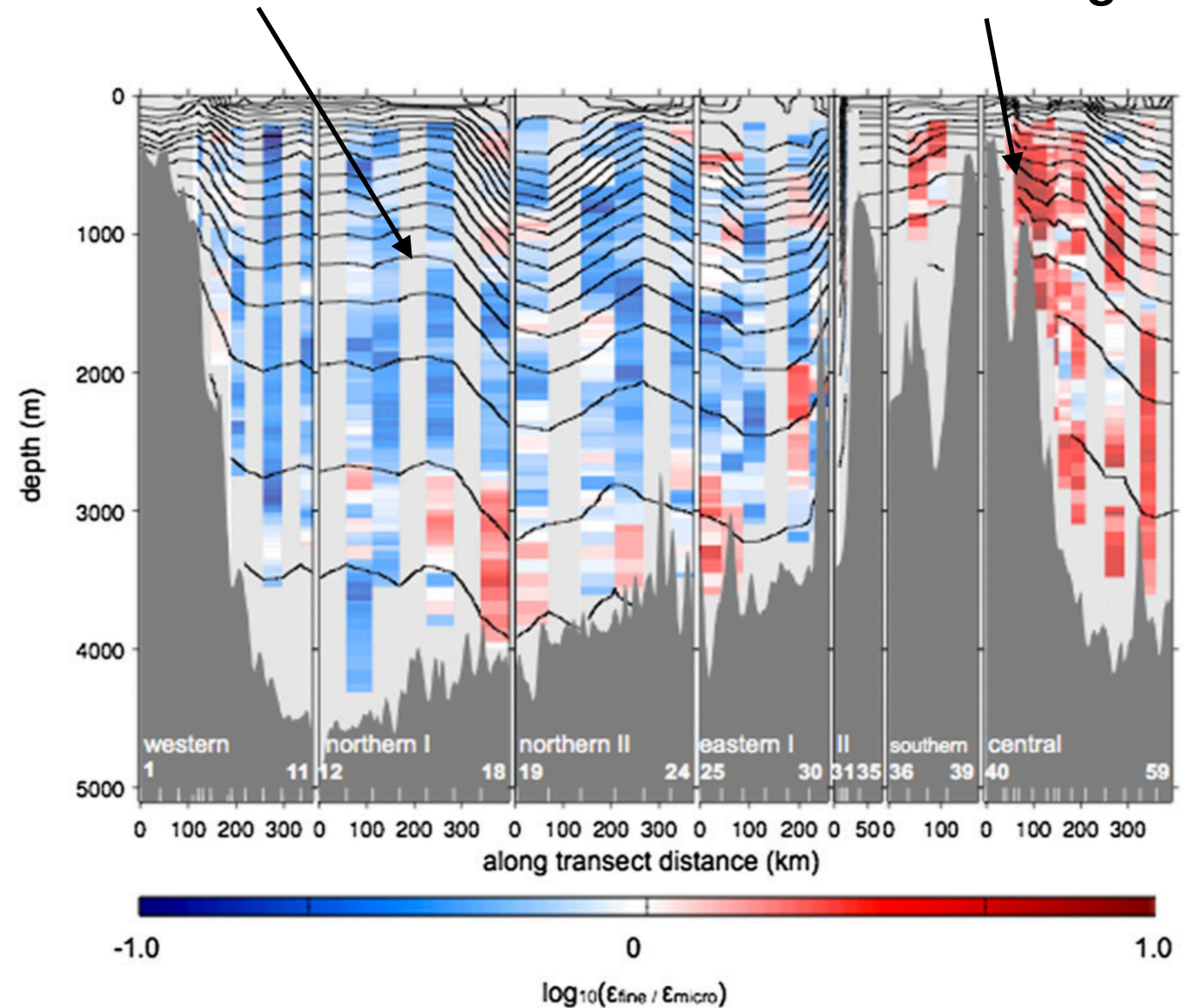
Our parameterizations work, except when they don't.

Finestructure
estimate 5-10
times too small

Finestructure
estimate 5-10
times too large

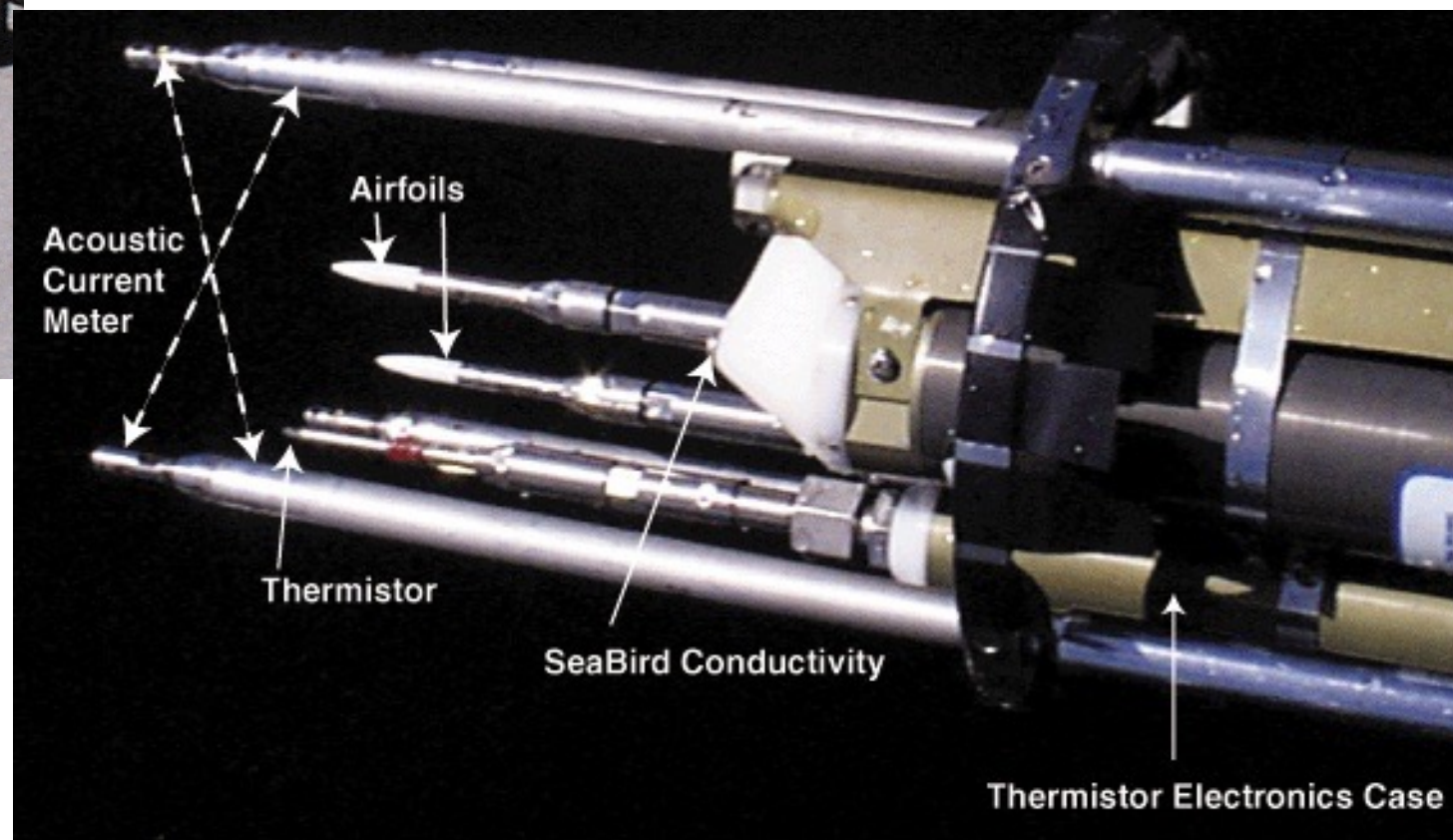
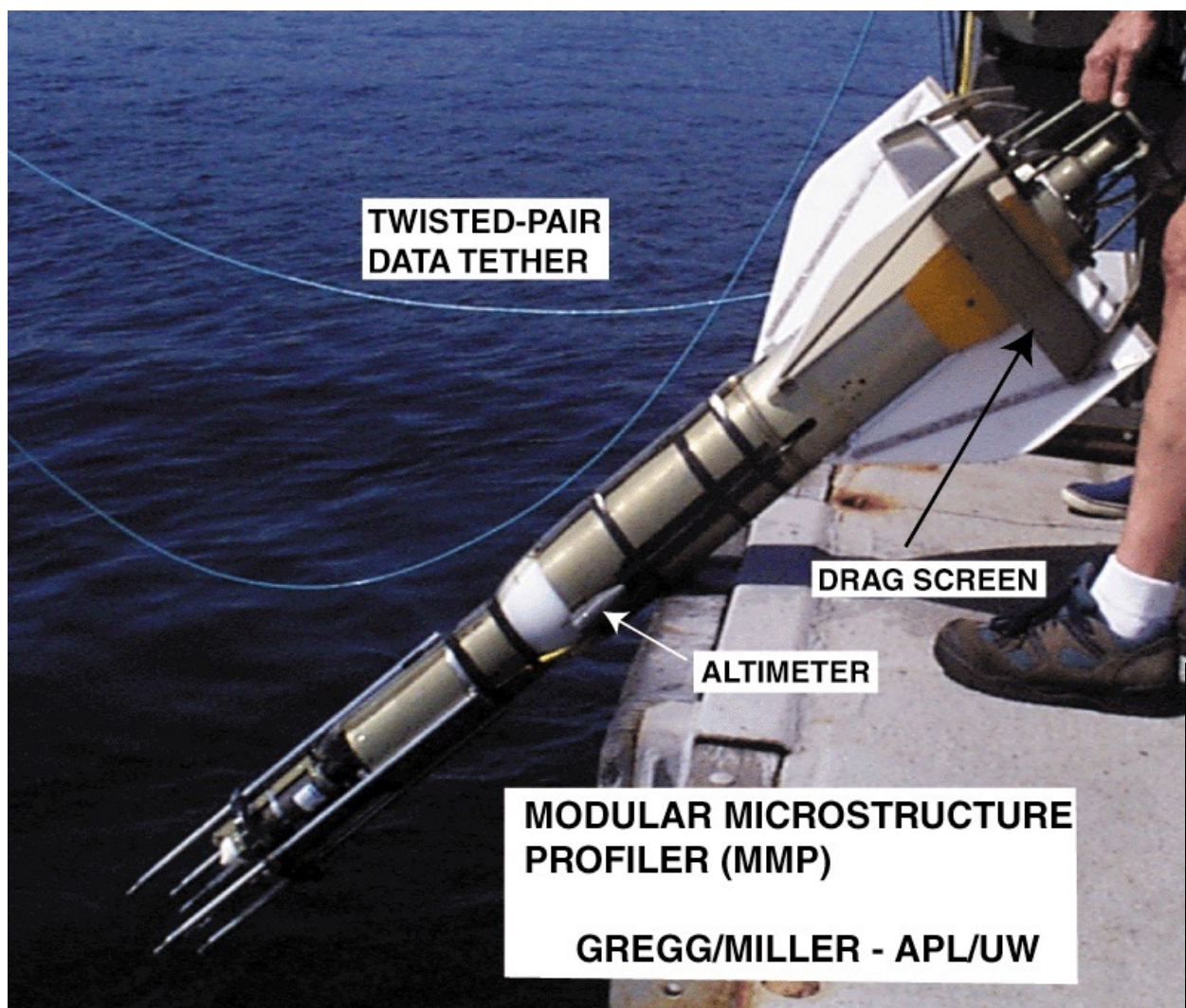


Whalen et al, 2015



Waterman et al, 2014

How do we measure turbulence and why should we believe it?



Microstructure: the pioneers

- They had to get right:
 - Shear probe and thermistor fabrication - fast and passivated
 - Vehicle with minimal motion
 - Calibration procedures
 - Low-noise analogue circuitry
 - Steady drop speed $\sim 0.5\text{-}0.9$ m/s and easy launch/recovery

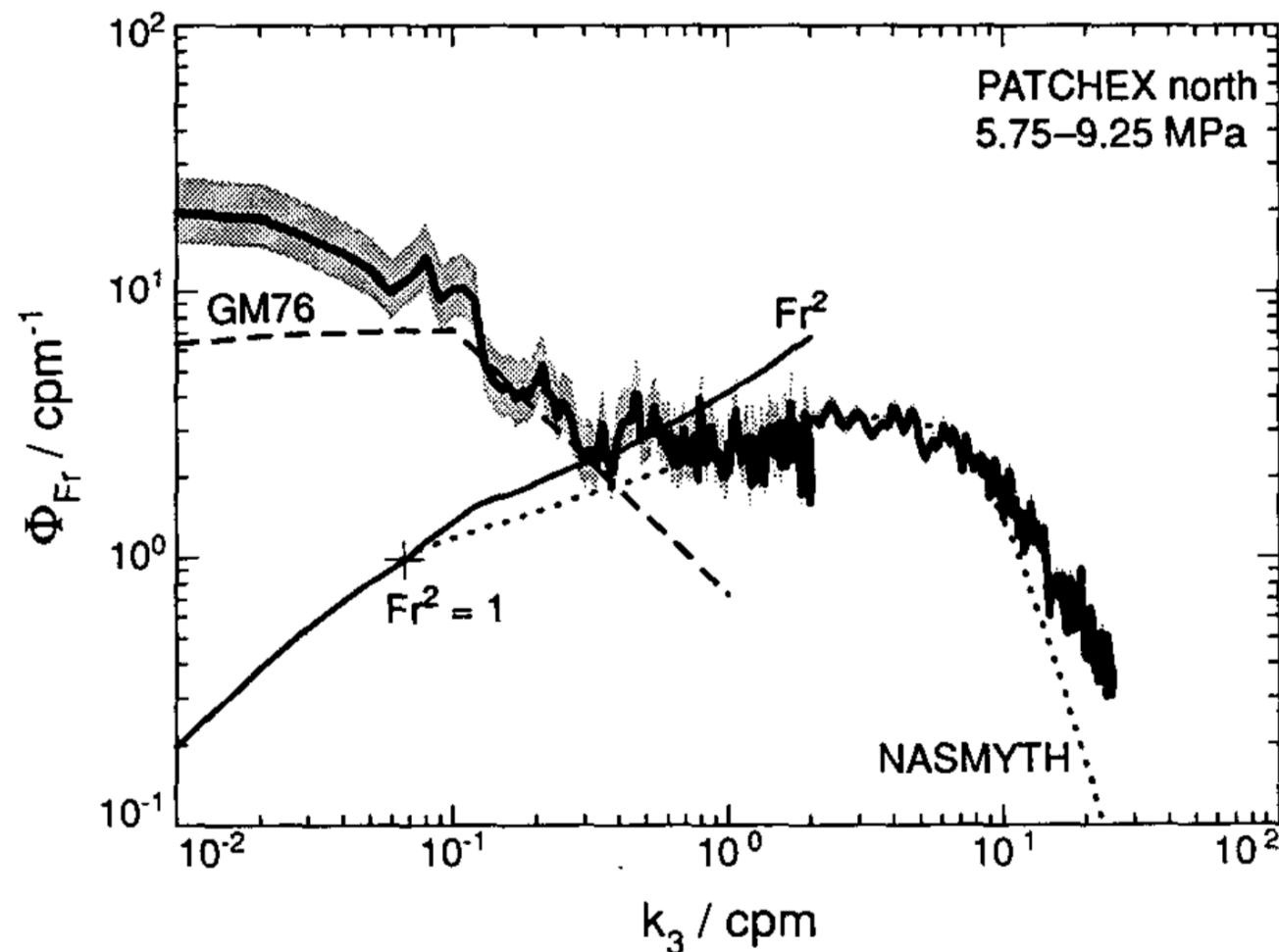


Microstructure 101

Osborn (1980)

$$\overline{u'w'} \frac{\partial \bar{u}}{\partial z} = J_b - \epsilon$$

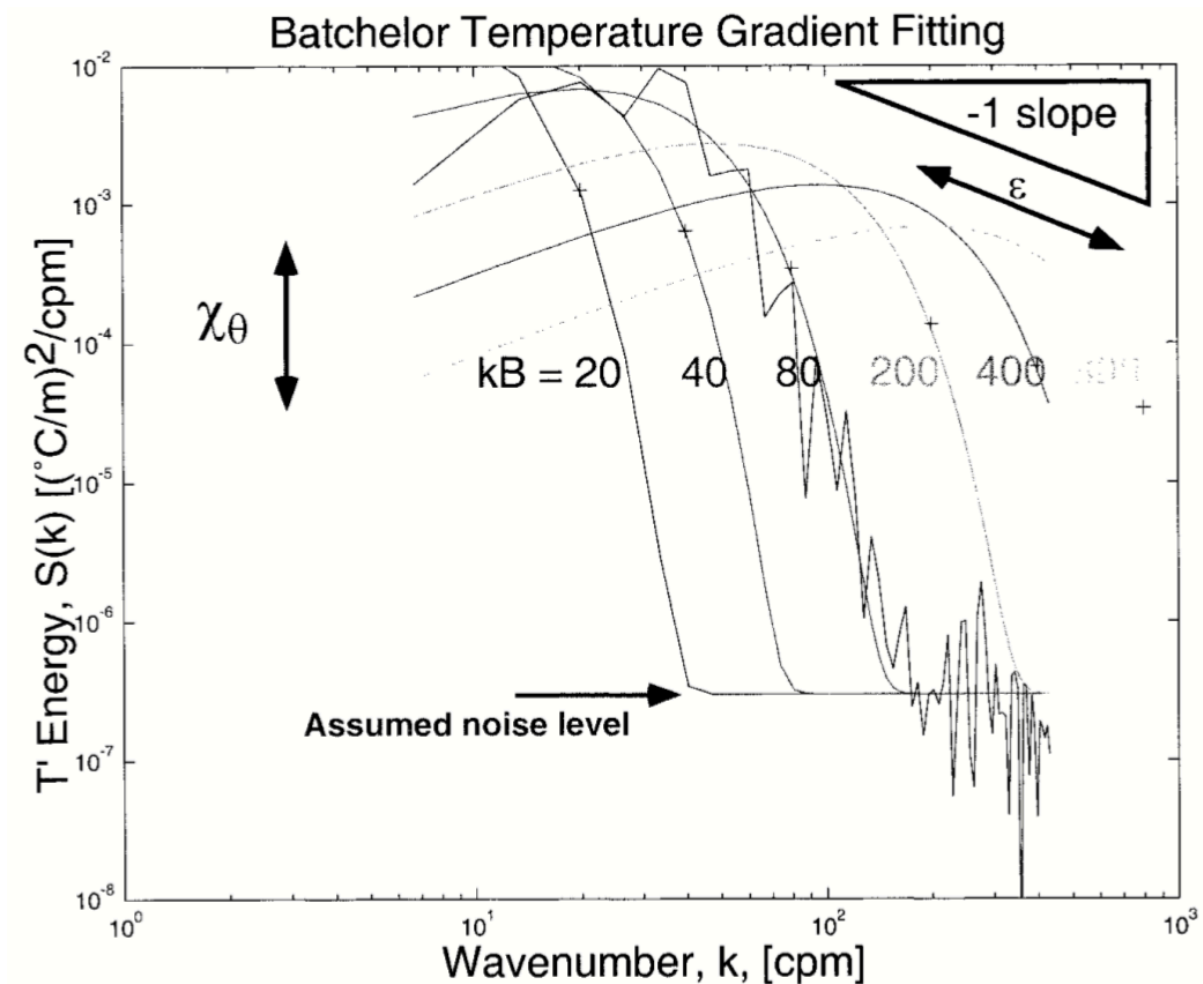
$$K_\rho \equiv -\frac{J_b}{N^2} = \frac{R_f}{1 - R_f} \frac{\epsilon}{N^2}$$



Osborn/Cox (1972)

$$-2\overline{w'\Theta'} \frac{\partial \bar{\Theta}}{\partial z} = \chi_T$$

$$K_T \equiv -\frac{\overline{w'\Theta'}}{(\partial \bar{\Theta} / \partial z)} = \frac{\chi_T}{2(\partial \bar{\Theta} / \partial z)^2} = \kappa_T \frac{\overline{(\nabla \Theta')^2}}{(\partial \bar{\Theta} / \partial z)^2}$$



Turbulence is not hard to measure, nowadays

RSI microrider on slocum



Epsi on wire walker



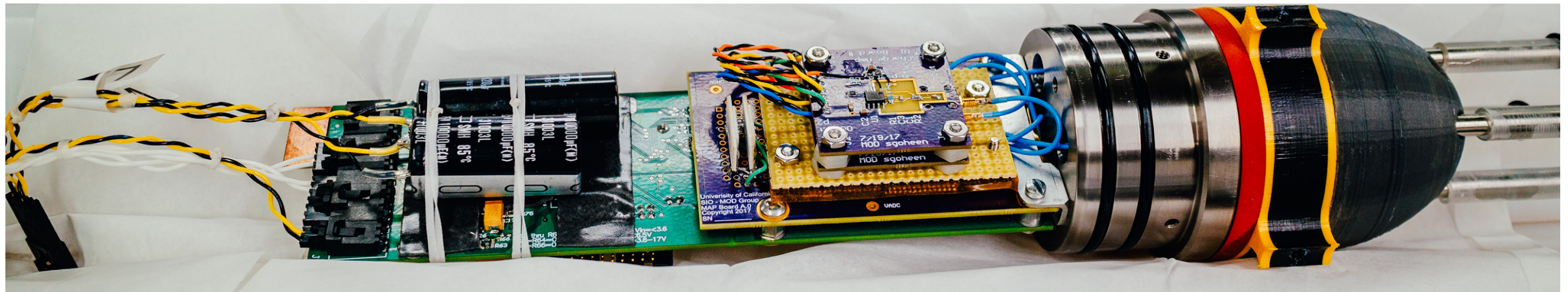
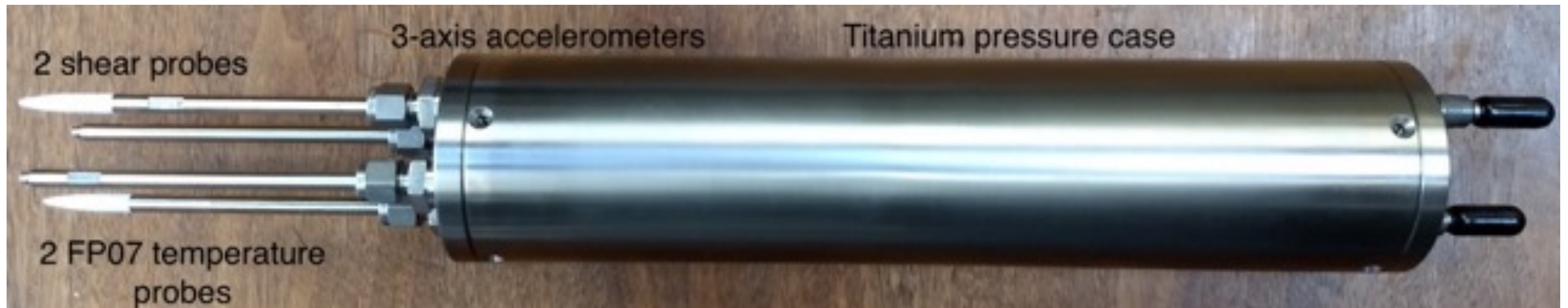
OSU chi-pod on Solo



RSI on ALAMO



Epsi



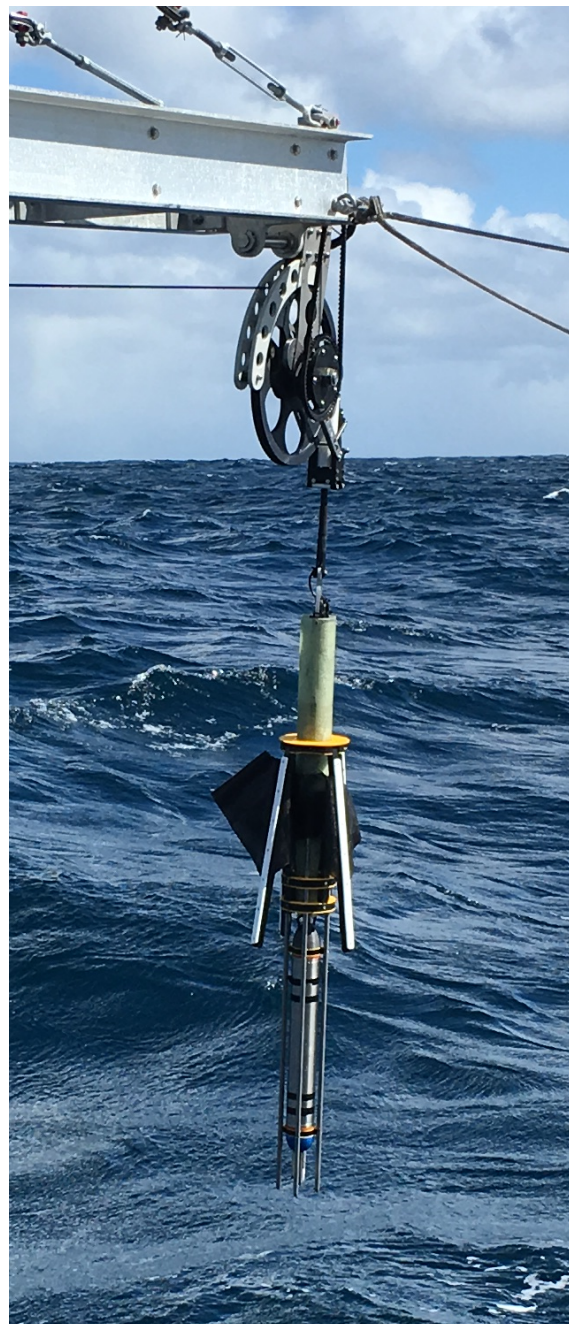
- All probes made and calibrated in-house at SIO
- modern ARM-based 24-bit electronics, 32Kb RAM.
- 422 Serial port or battery/SD card
- Accelerometer X,Y,Z
- 3.3 V power
- ~ 0.3 Watt and decreasing

Epsi

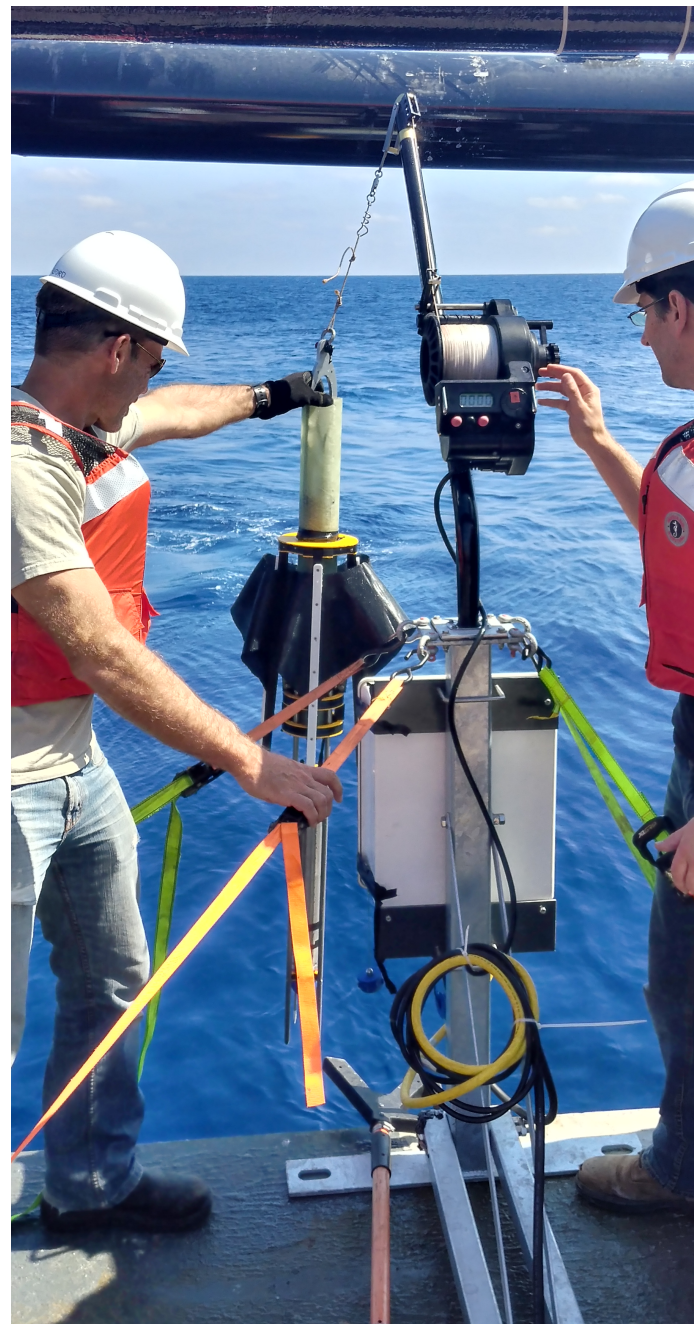
Inexpensive/
modular/low
power



With our fast
winch for rapid
profiles to 2000
m

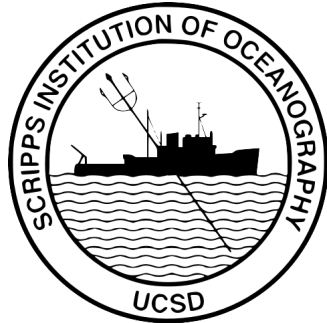


With a fishing reel
for very cheap
simple
measurements



On a wire walker (or
float or glider) for
autonomous
turbulence
measurements





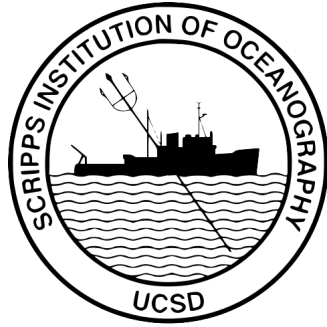
The Epsi-fish

- 3D printed
- Inexpensive
- SBE49 CTD
- Deployable standalone (fishing reel) or real-time streaming and powered (FCTD2 winch)

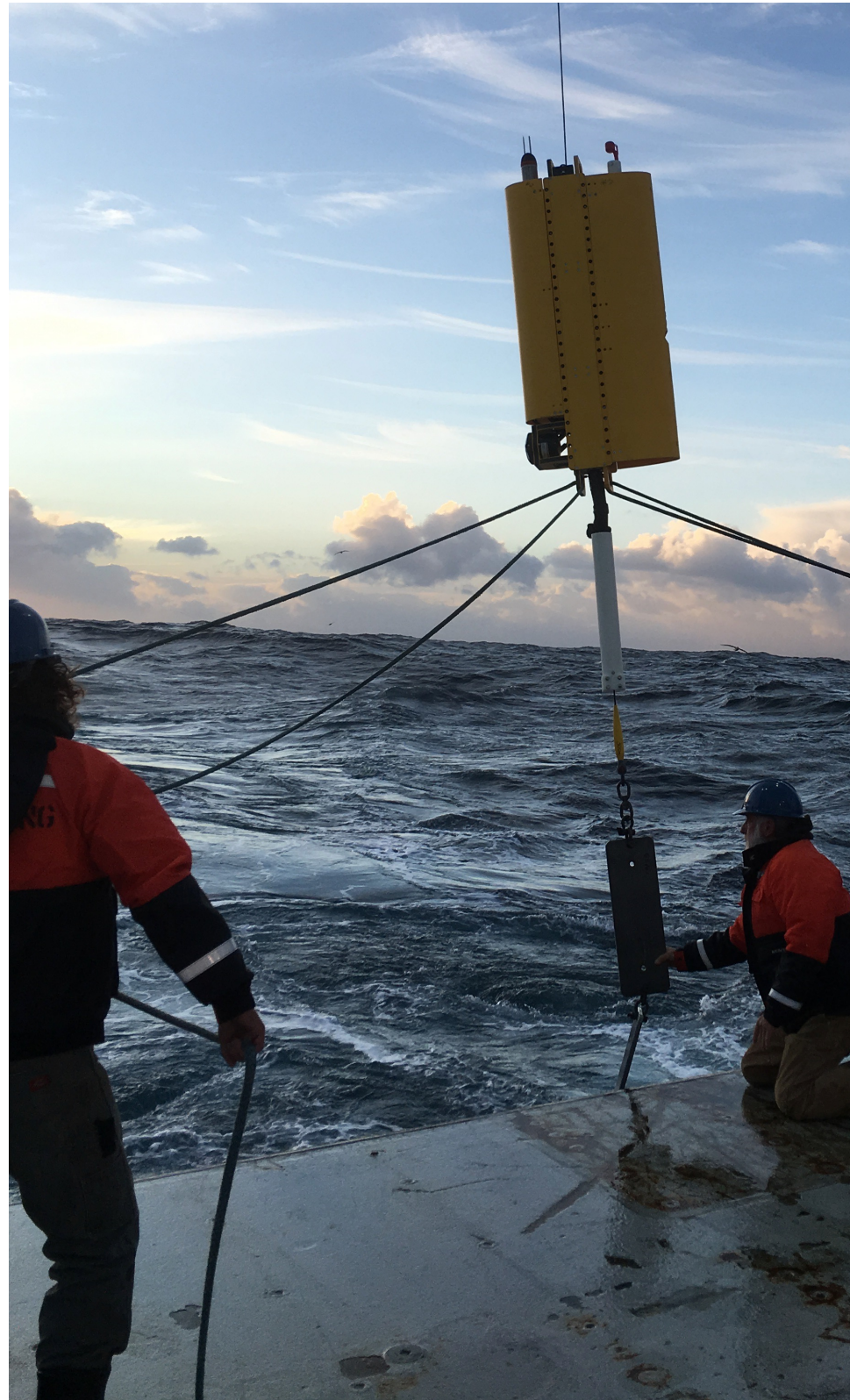




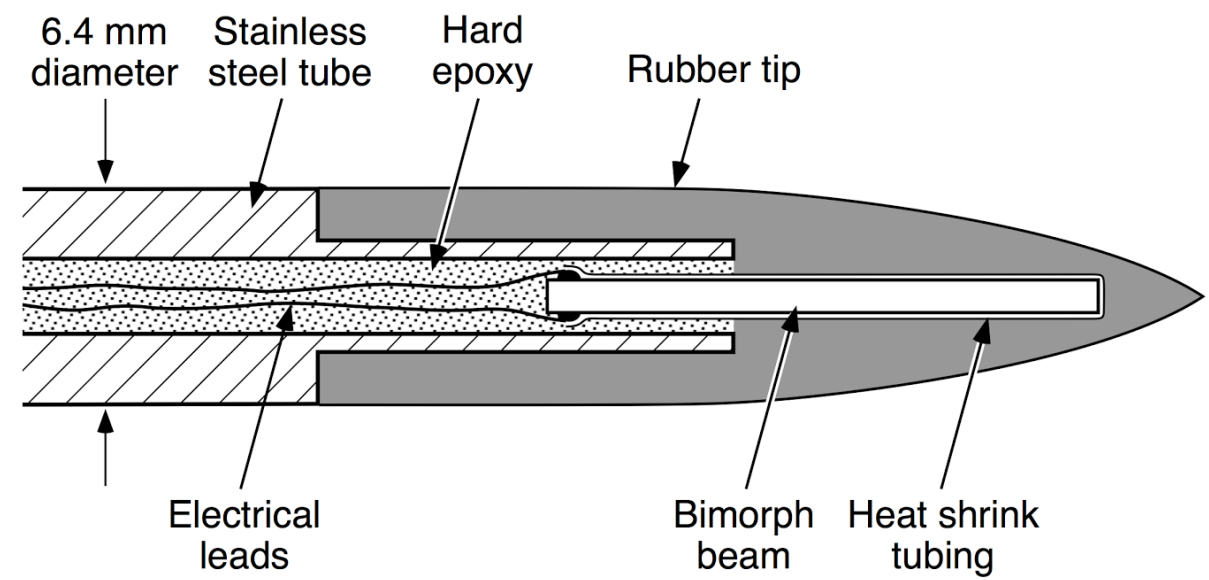
Epsi-WW: autonomous deployments



- Internal or external power
- Sampling on upcasts
- Rapid profiles (~20 minutes per 250 m)

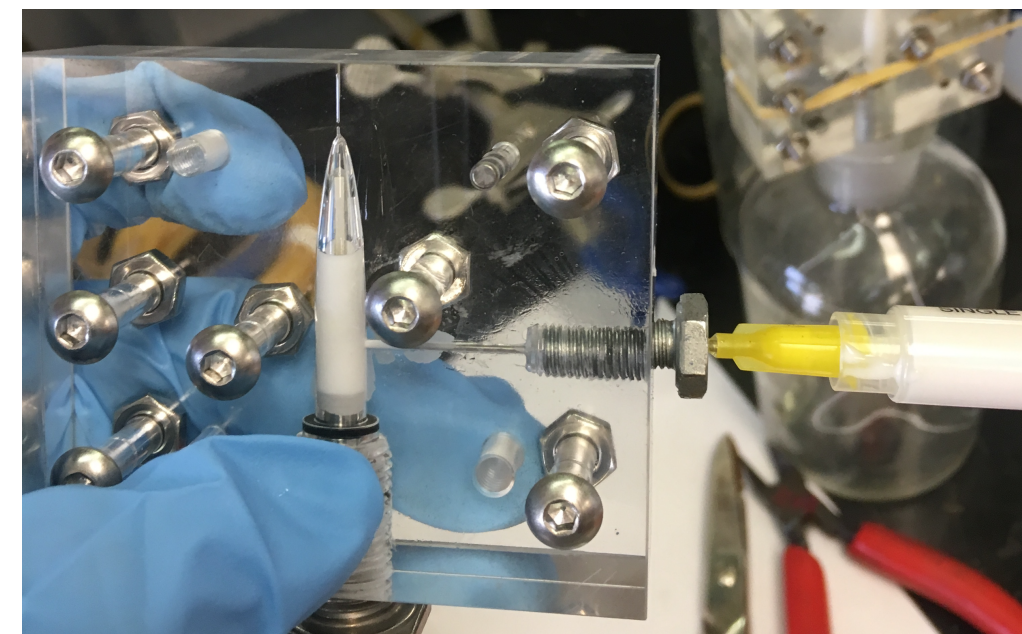
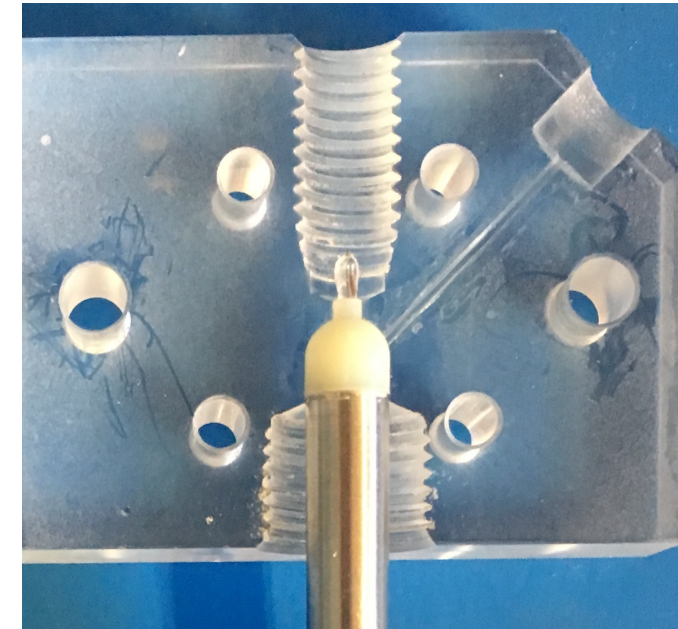


Probe fabrication



- Fabrication time
shear probes: 24 hours (silicon curing)
FPO7: 14 hours (Epoxy curing)
- Dimensions:
stainless sting: ~15 cm
bimorph beam: 2.8 cm
FPO7: 0.9 cm
- Epoxy and Silicon curing under pressure to remove bubbles.

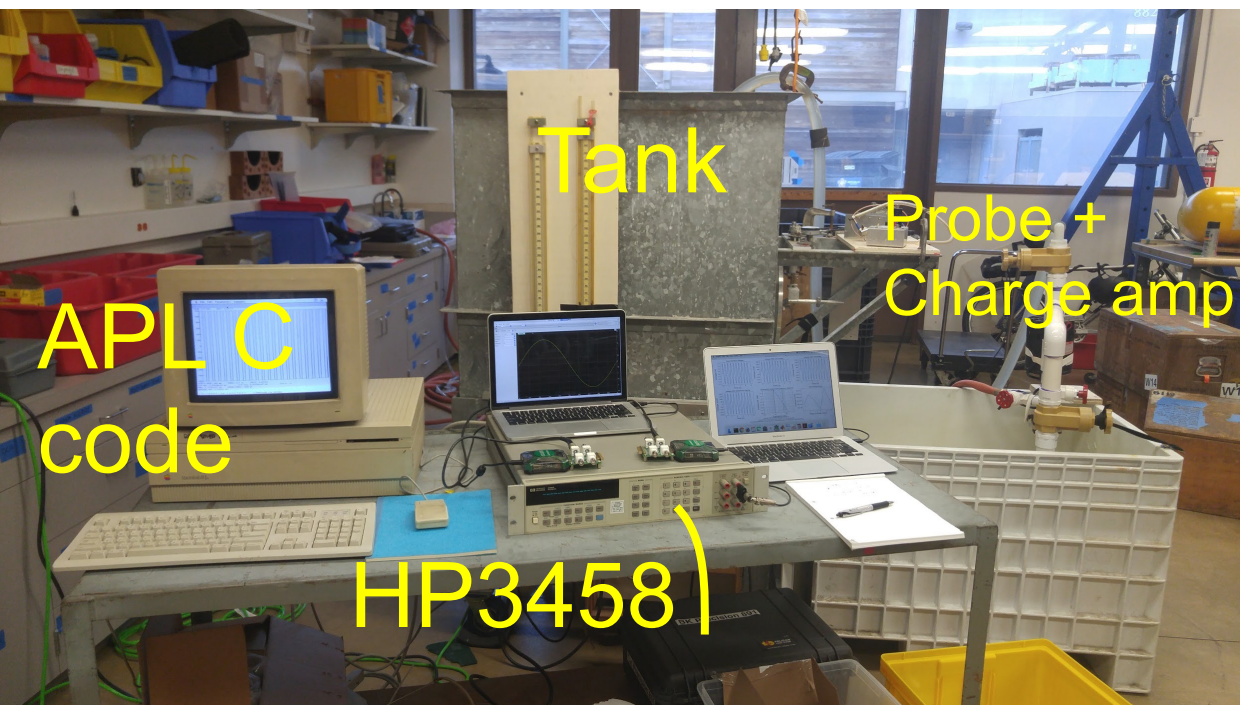
Resistance through
a stainless sting
protected by epoxy
resin



Piezoelectric bimorph beam in a stainless
sting protected by silicon

Shear probe calibration

- Shear probe calibration



- Upgrade of the previous calibration system: new digital encoder + new processing(python)
- Good correlation old vs new system
- Automated database link to Matlab Epsilon processing



Epsi-fish fabrication

Epsi-fish profiler:

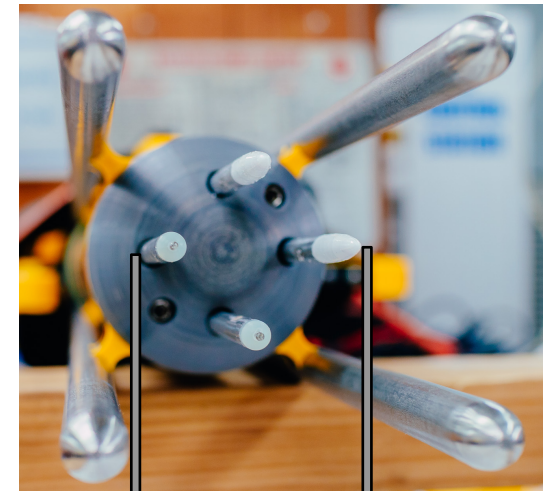
- drag for fall speed~ 0.6 m/s
- Drag synchronizer
- Inexpensive/3D printed
- combining SBE49 and EPSI into one vehicle

SBE49

Epsi

57 inches

57.70



4 cm



1st Deployment

San Diego, November 8th 2017, SPROUL

MMP-FastCTD winch



MMP-epsi comparison

New features tested:

- New shear probes
- New FPO7
- New free falling epsi-fish profiler
- New MADRE board
- EPSI + SBE49
- Free Falling EPSI deployed from FastCTD winch
- MMP deployed from FastCTD winch
- MMP - EPSI comparison



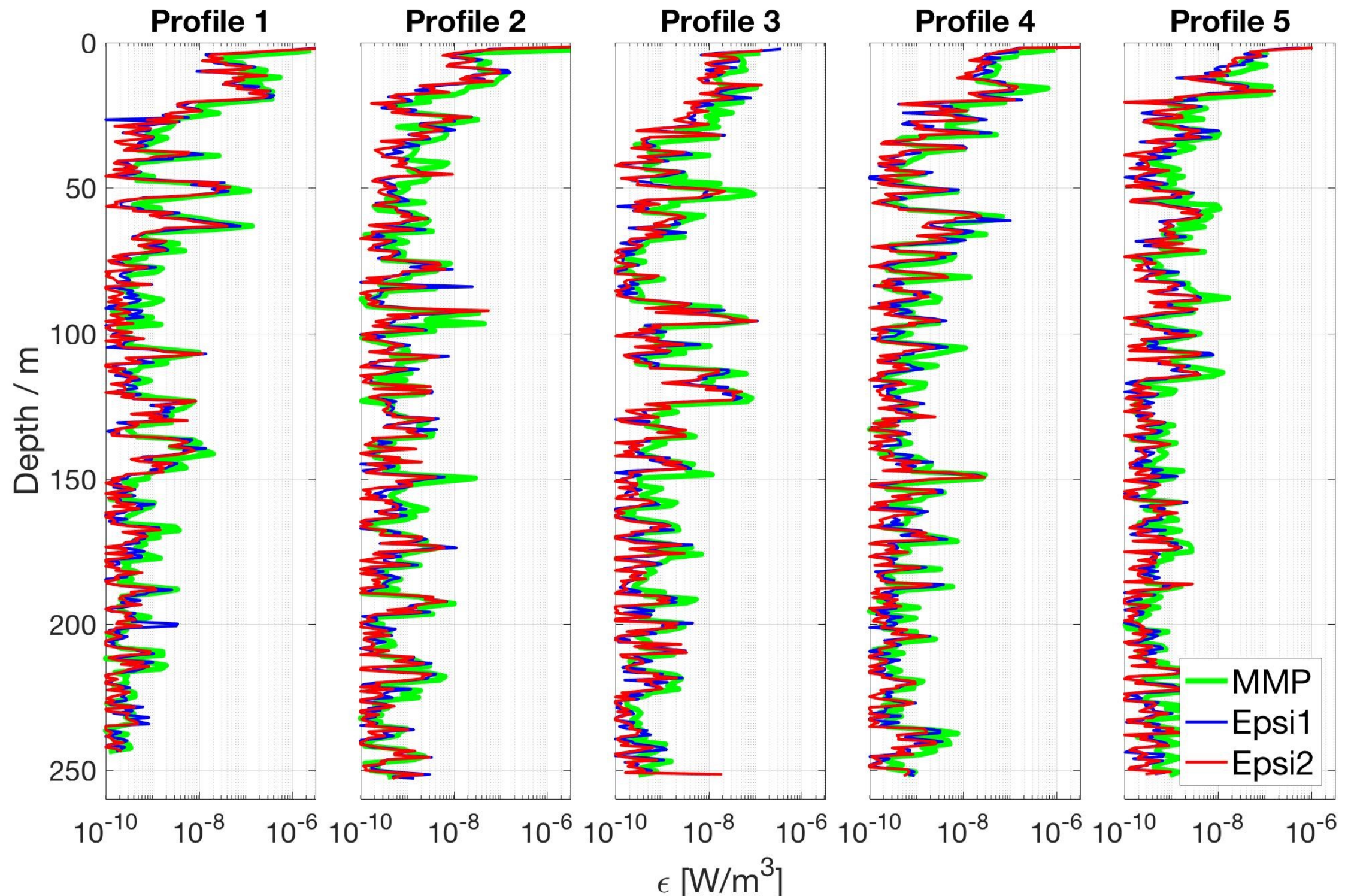
EPSI-FastCTD winch

Validation of Epsilon measurements

MMP-EPSI comparison:

Epsilon computed from
EPSI matches MMP

— MMP
— EPSI S1
— EPSI S2

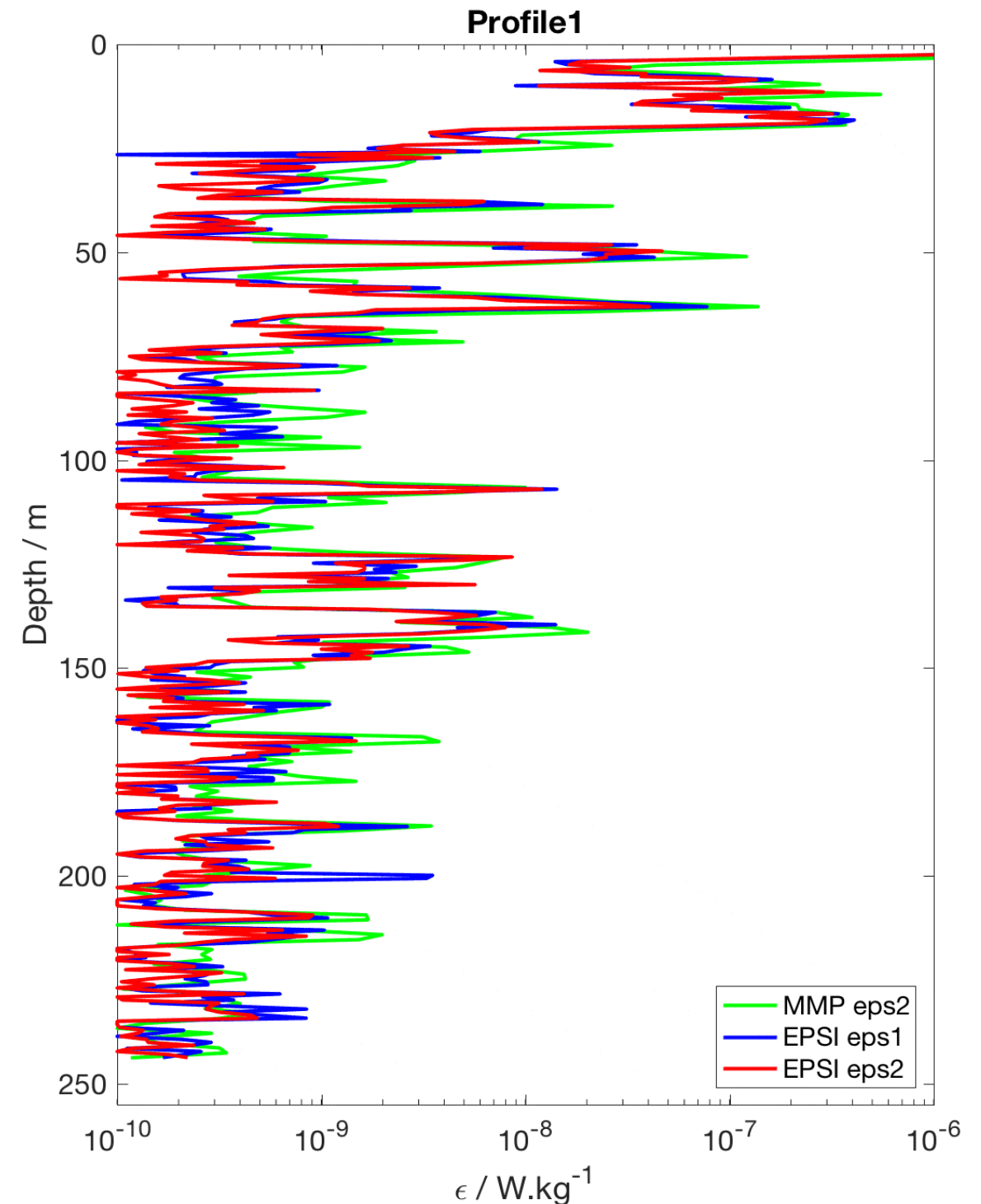


1st Deployment

MMP-EPSI comparison:

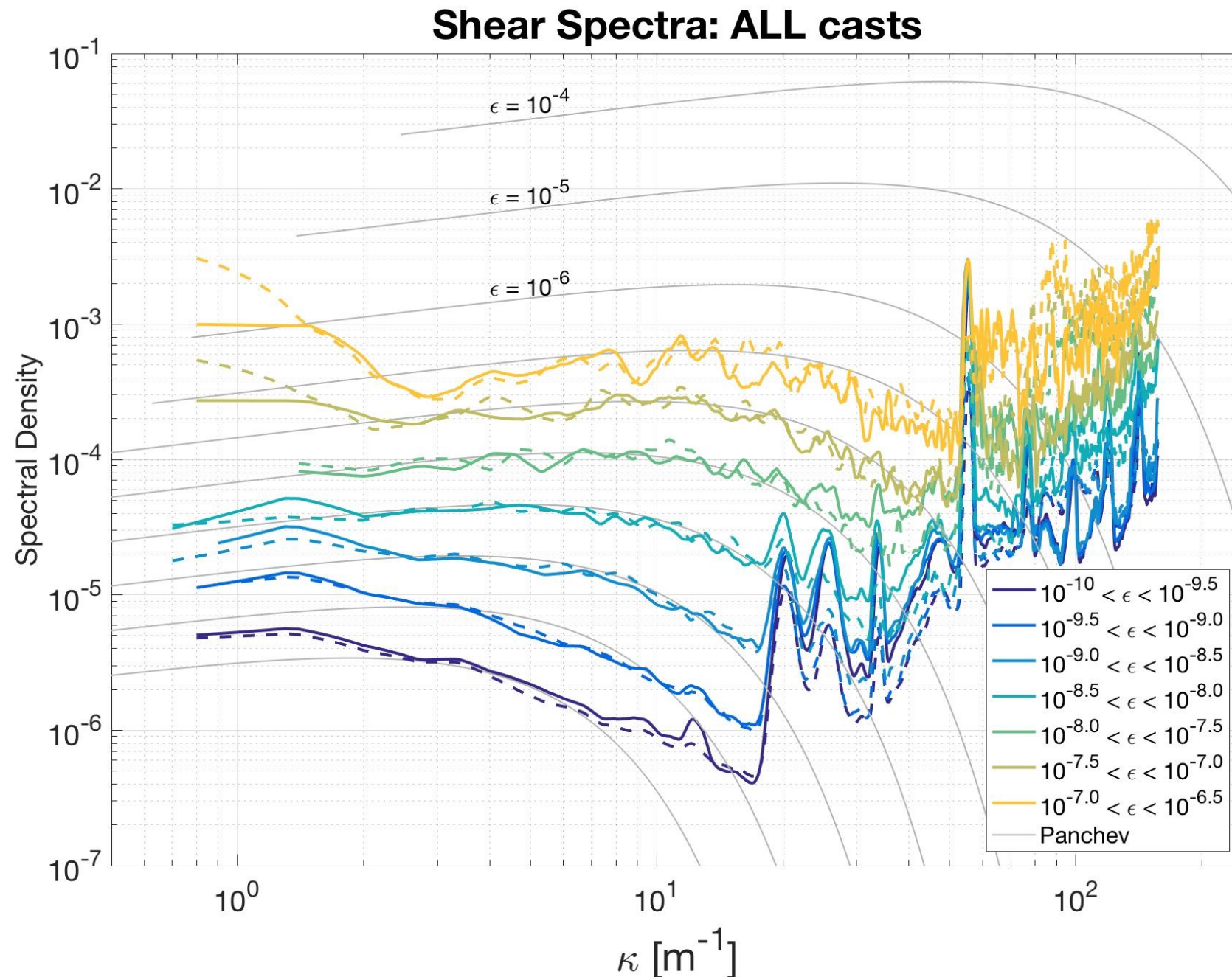
- epsilon EPSI follows epsilon MMP values
- Epsilon value between:
 10^{-10} and 10^{-6} W/kg

Because of a such a good correlation between MMP and ESI, an average of the EPSI shear spectra binned by Epsilon values is expected to describe the panchev theoretical distribution of shear :
characterisation of the epsilon range by EPSI

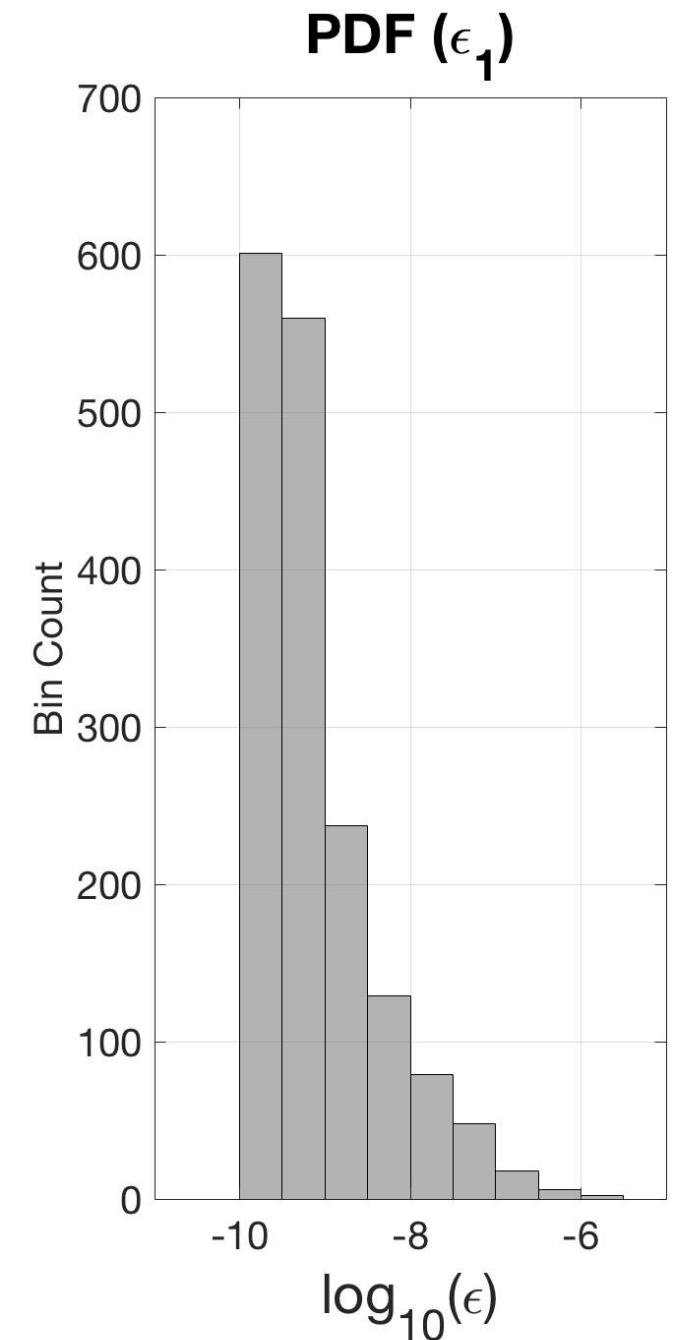


Turbulence range with stand alone EPSI

Shear / Panchev Comparison



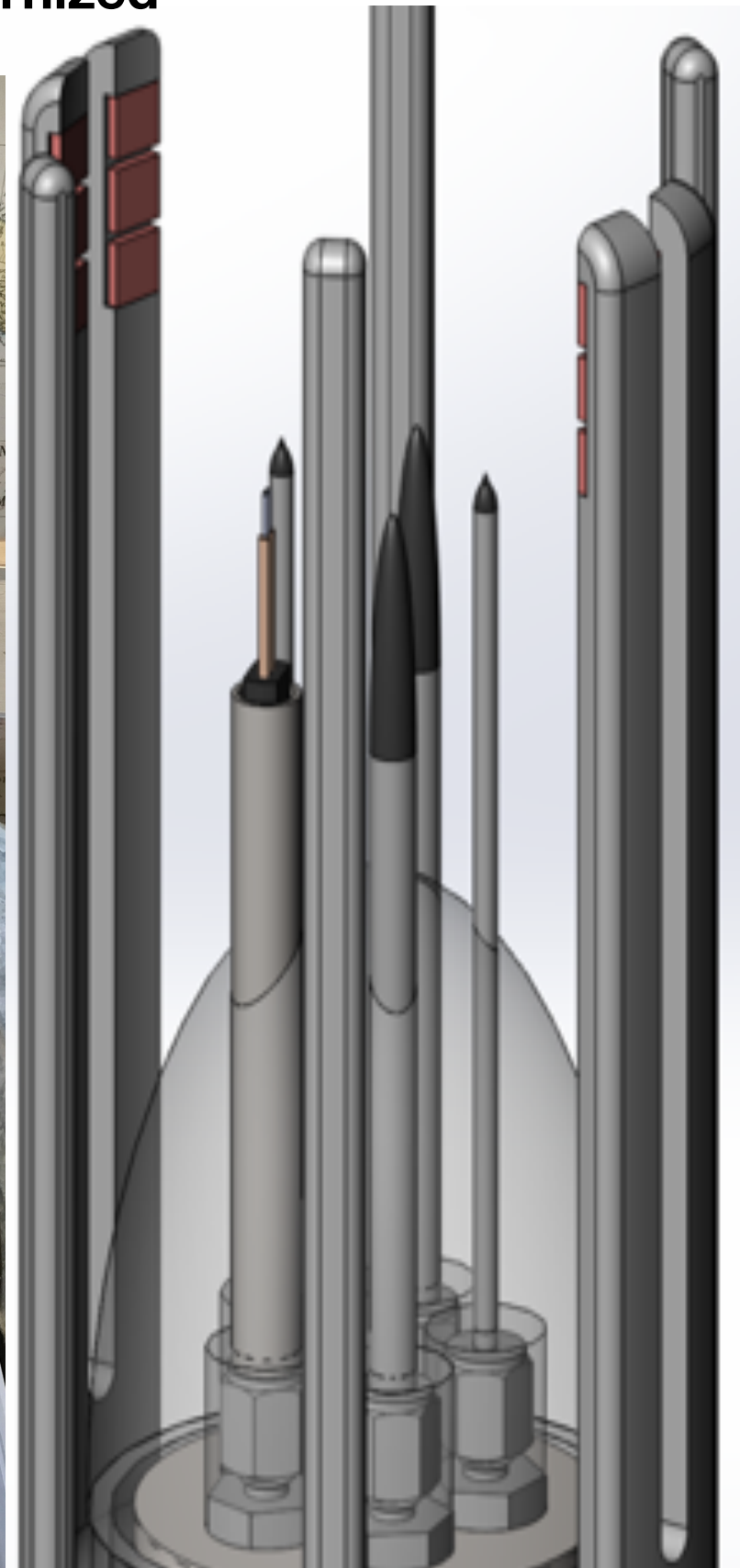
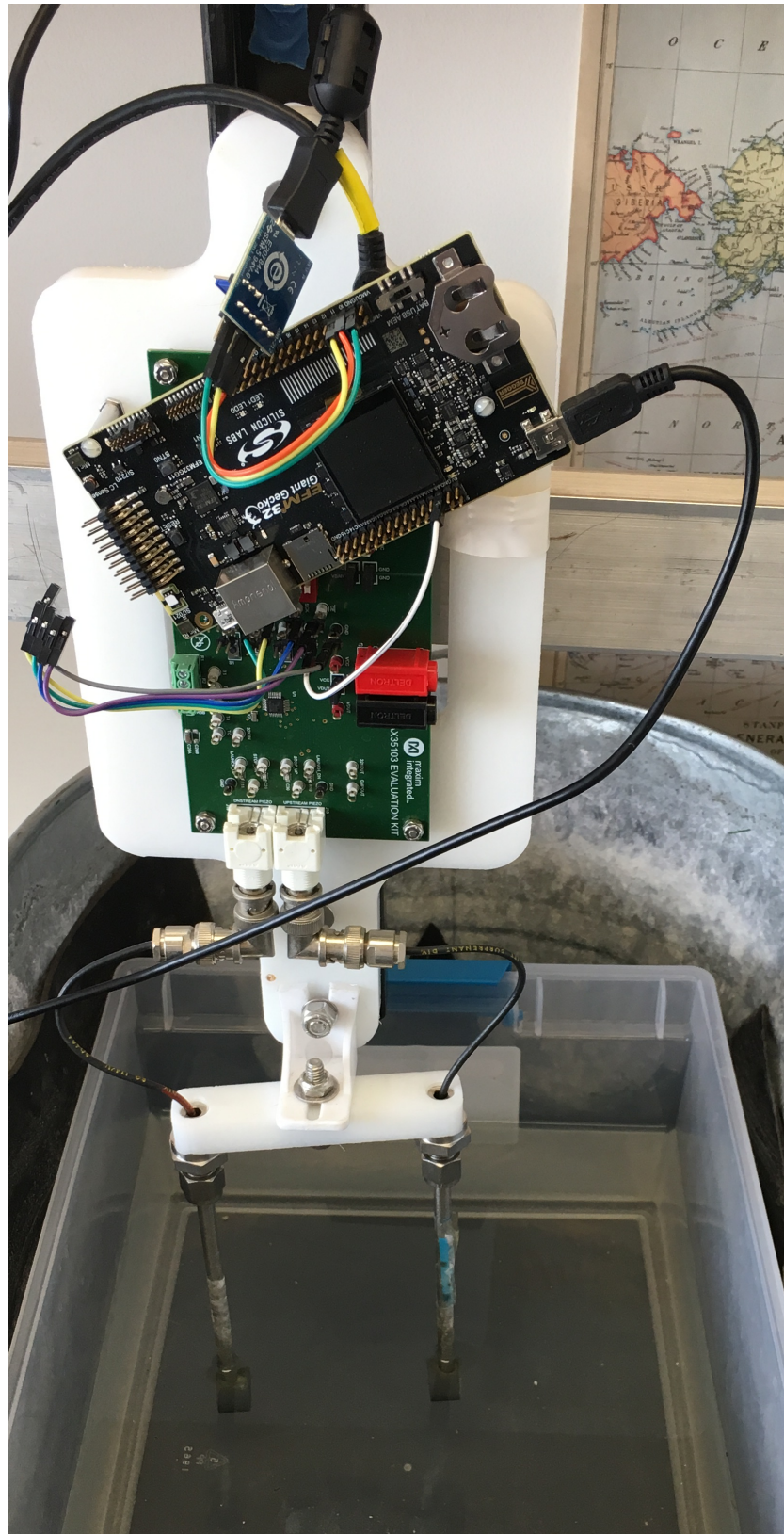
Shear spectra agree with Panchev spectra across several decades of epsilon.



Why go to all this trouble?

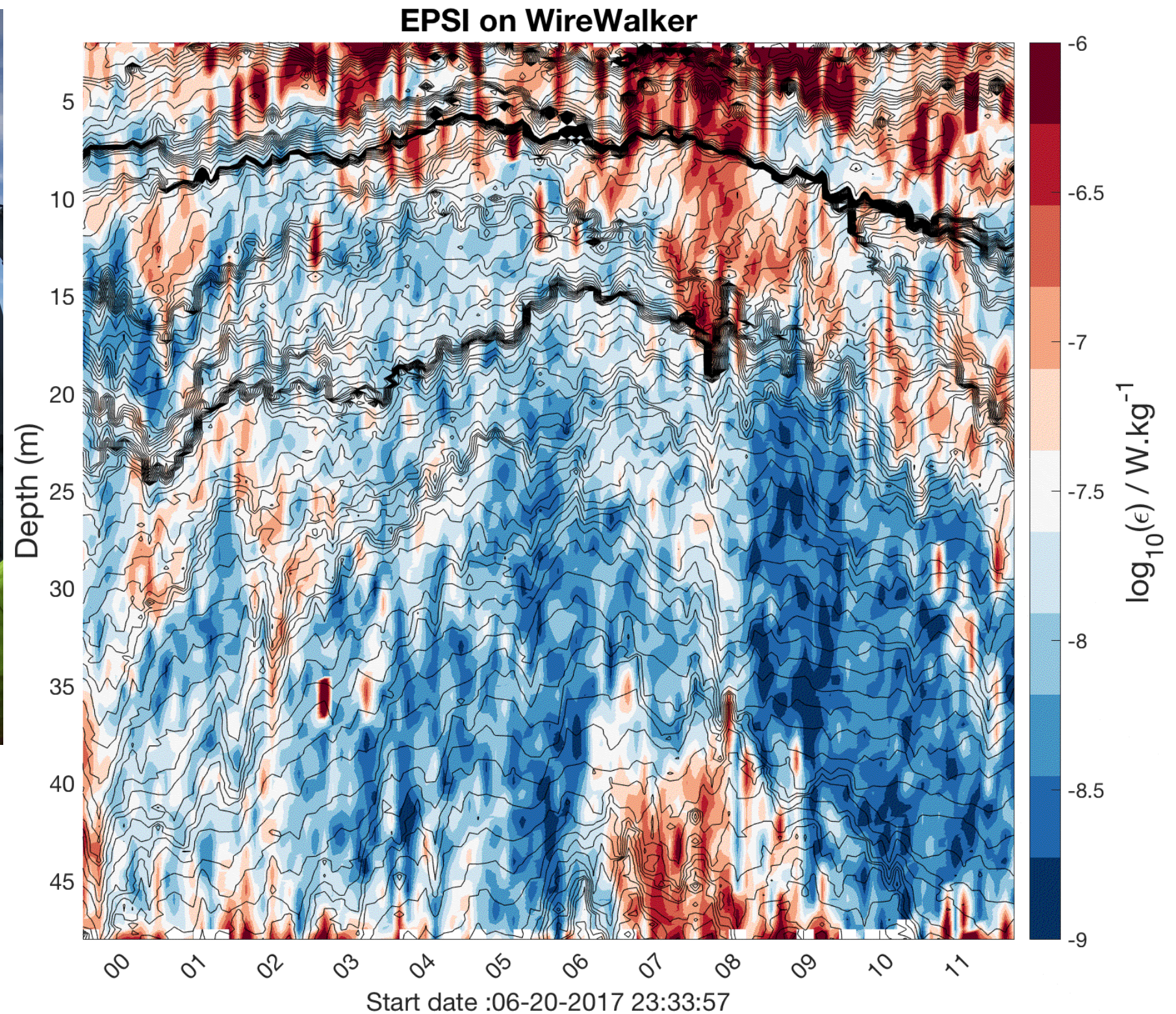
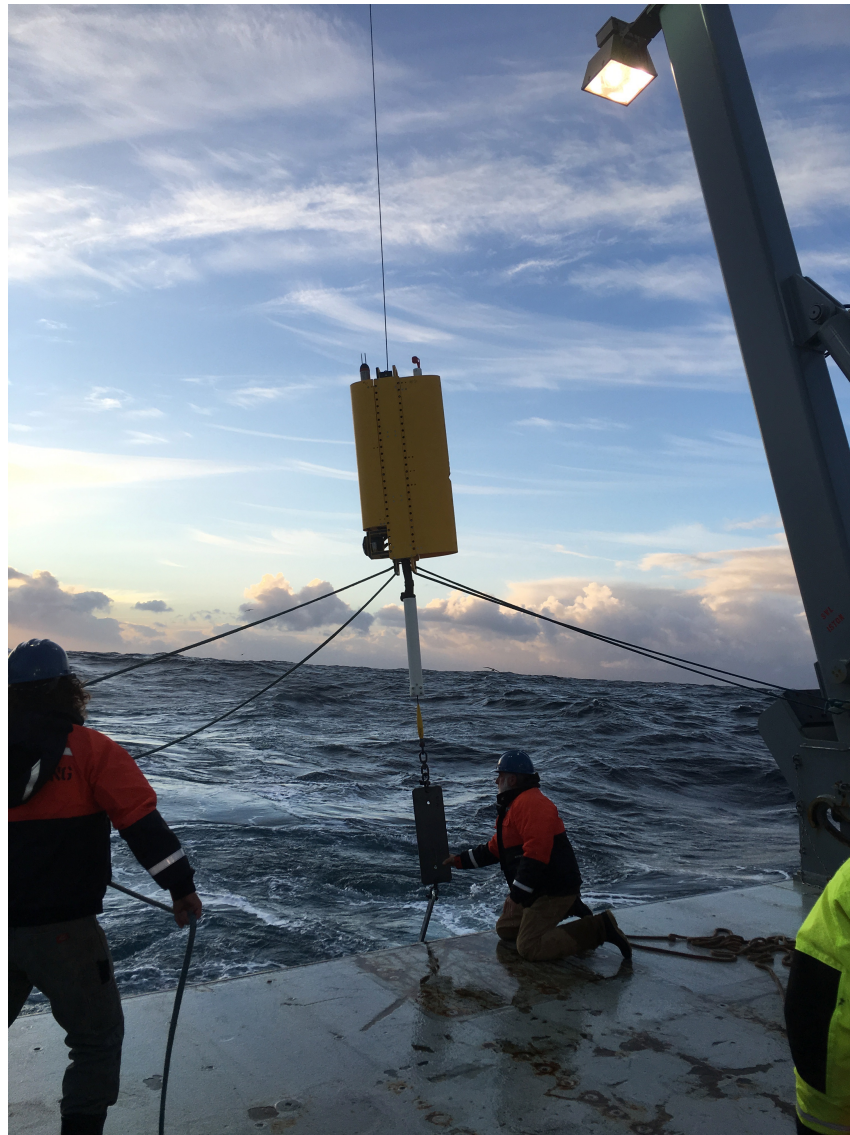
The travel time current meter, modernized

- Based on the MAVS
- Modern electronics from gas flow applications
- 1.3 MHz
- RMS errors 0.03 cm/s for 10-cm path
- 3D arrays of T/R transducers are envisioned for “tomography” of turbulence in future
- Acoustic CTD promising as well





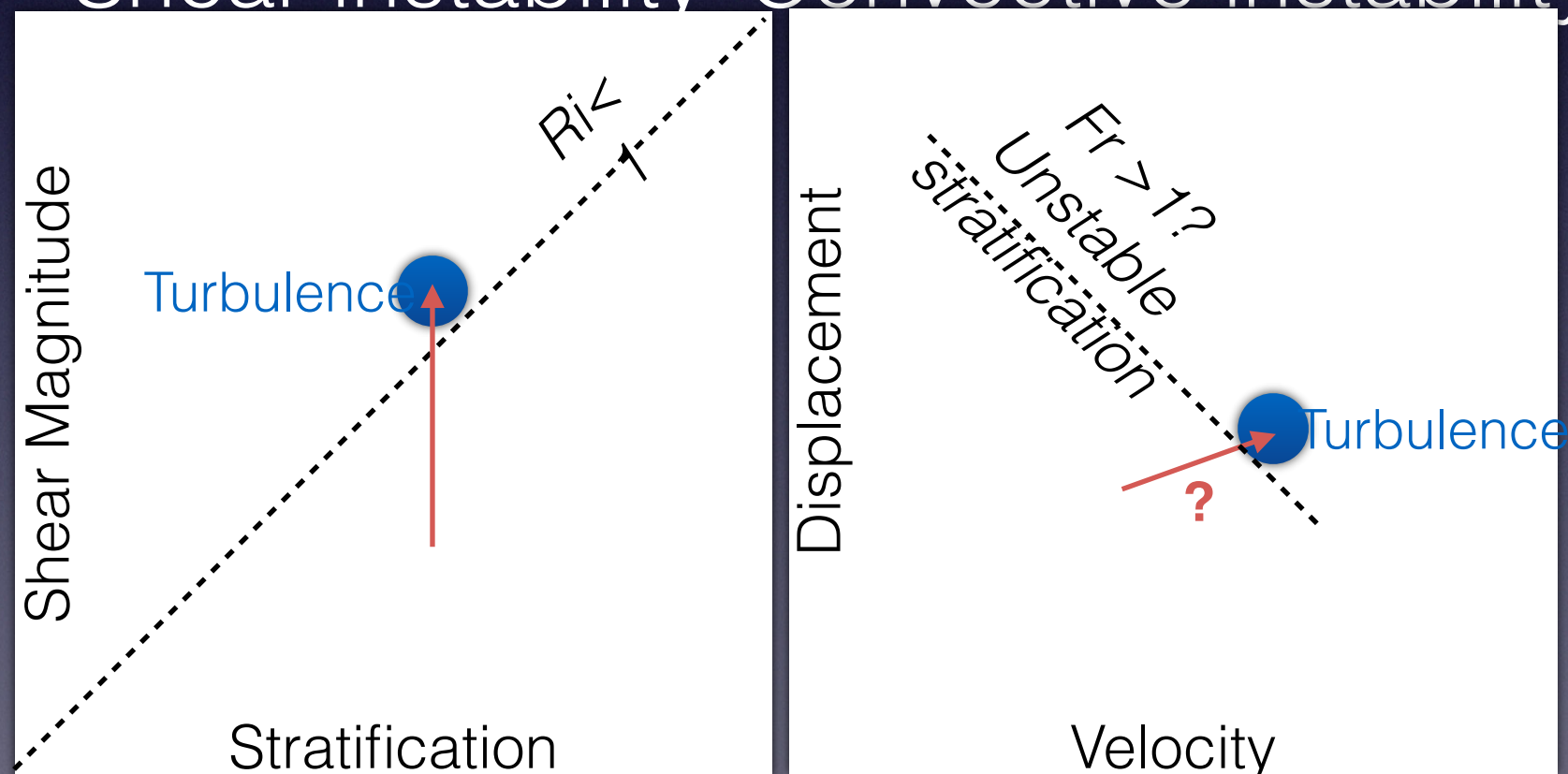
Epsi on Wirewalker



Shear and convective instability: Phasor diagrams

- Plot shear versus stratification and/or velocity versus displacement. Color by epsilon or K.
- Both the locus and the phasing of mixing give useful information.

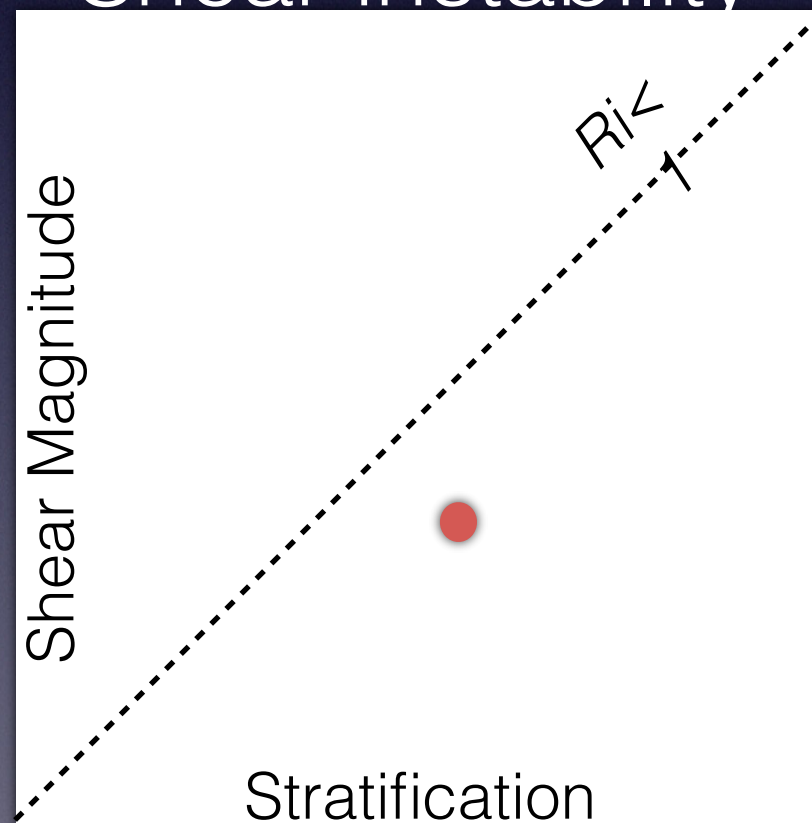
Shear instability Convective instability



The idea

- Plot shear versus strain and/or velocity versus displacement. Color by epsilon or K.
- Both the locus and the phasing of mixing give useful information.

Shear instability

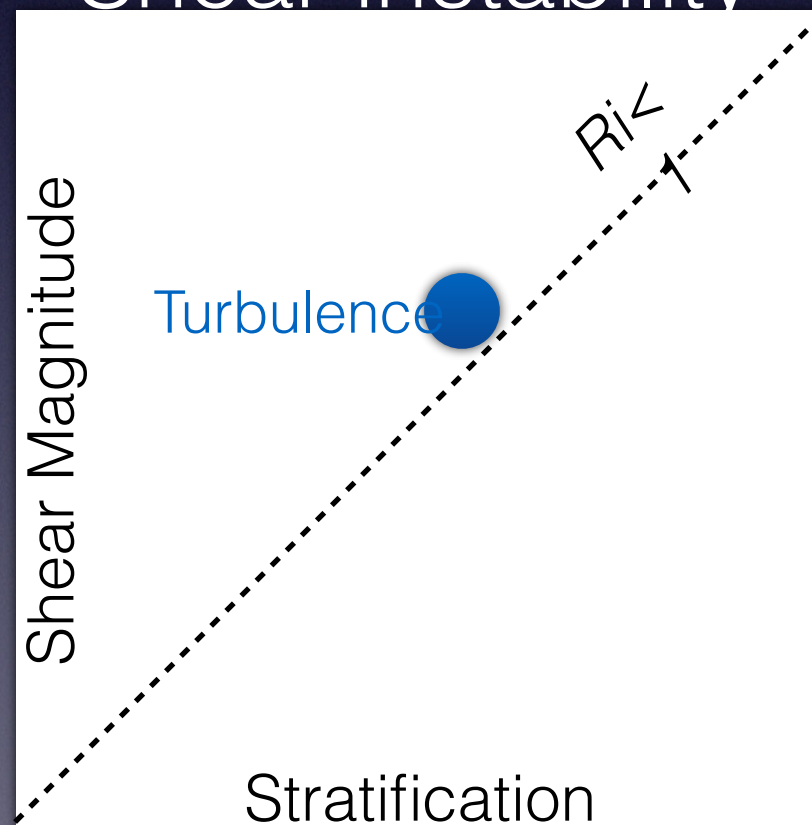


Stable mean flow

The idea

- Plot shear versus strain and/or velocity versus displacement. Color by epsilon or K.
- Both the locus and the phasing of mixing give useful information.

Shear instability

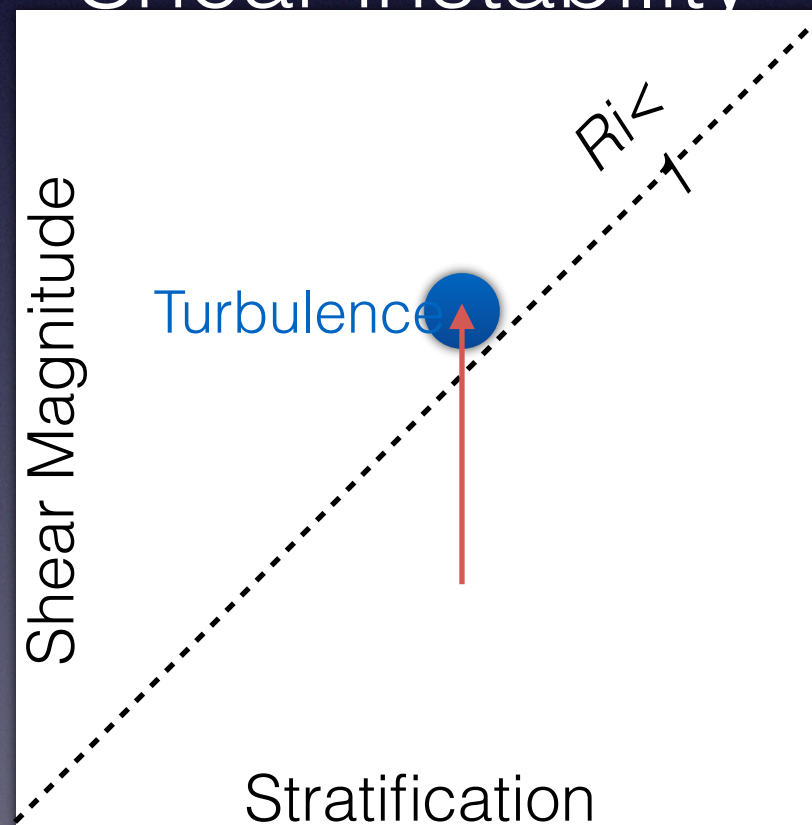


Unstable mean flow

The idea

- Plot shear versus strain and/or velocity versus displacement. Color by epsilon or K.
- Both the locus and the phasing of mixing give useful information.

Shear instability

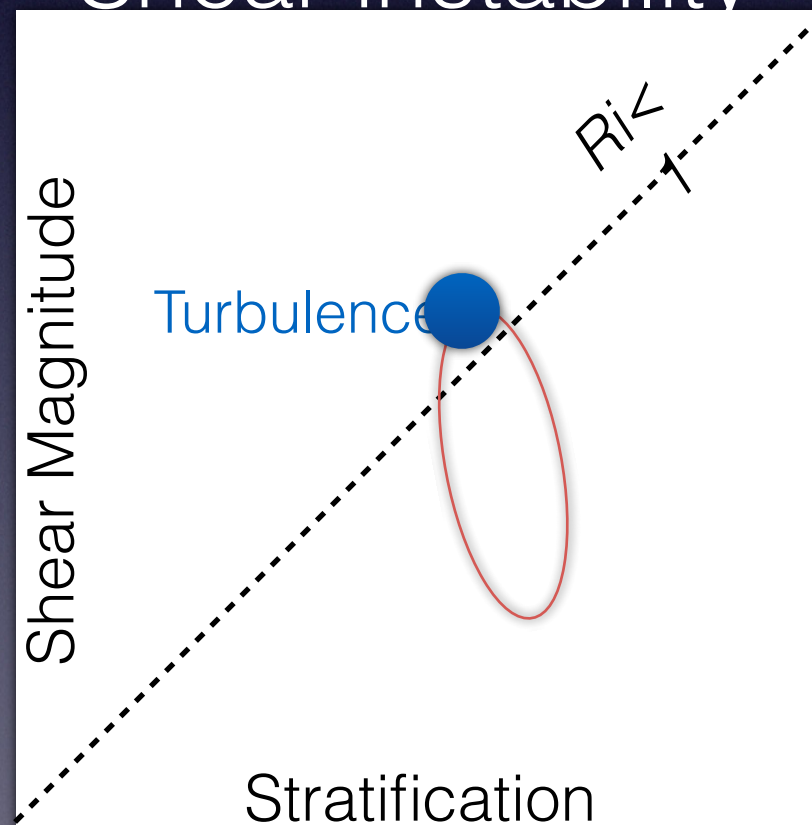


Modulated mean flow

The idea

- Plot shear versus strain and/or velocity versus displacement. Color by epsilon or K.
- Both the locus and the phasing of mixing give useful information.

Shear instability

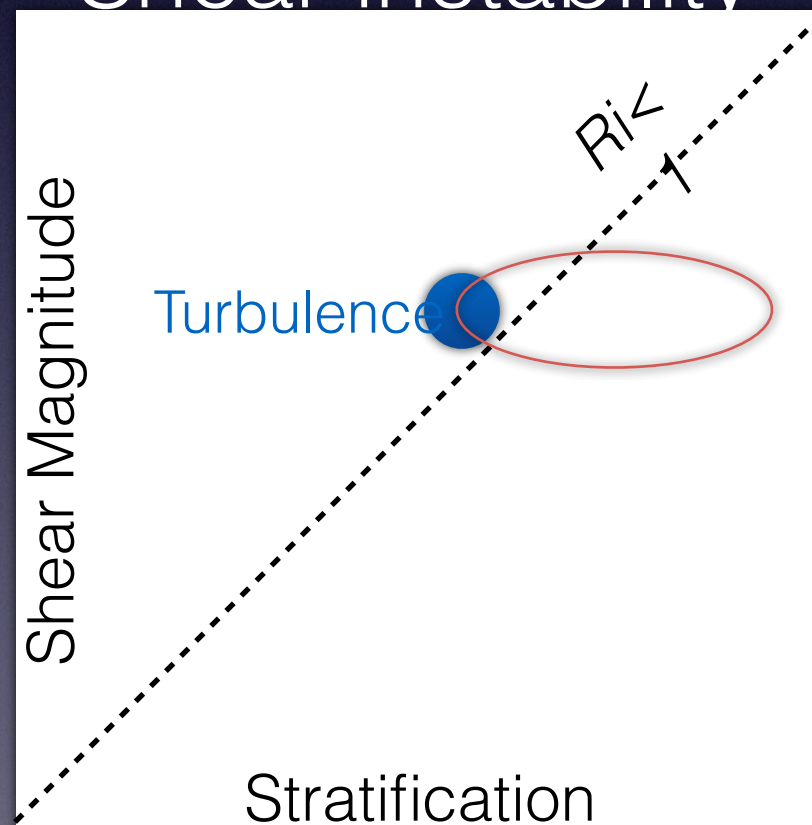


Breaking internal tides

The idea

- Plot shear versus strain and/or velocity versus displacement. Color by epsilon or K.
- Both the locus and the phasing of mixing give useful information.

Shear instability



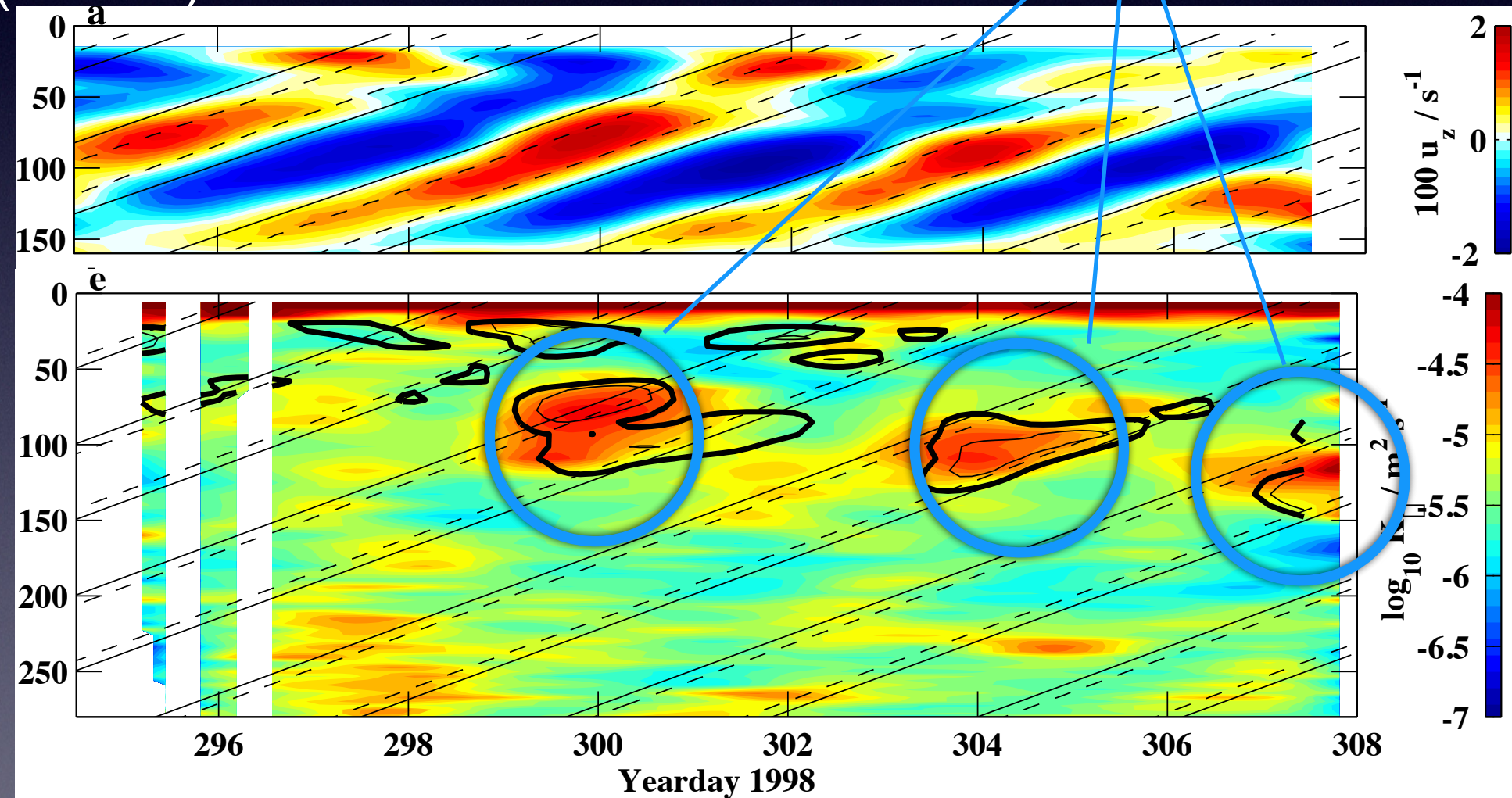
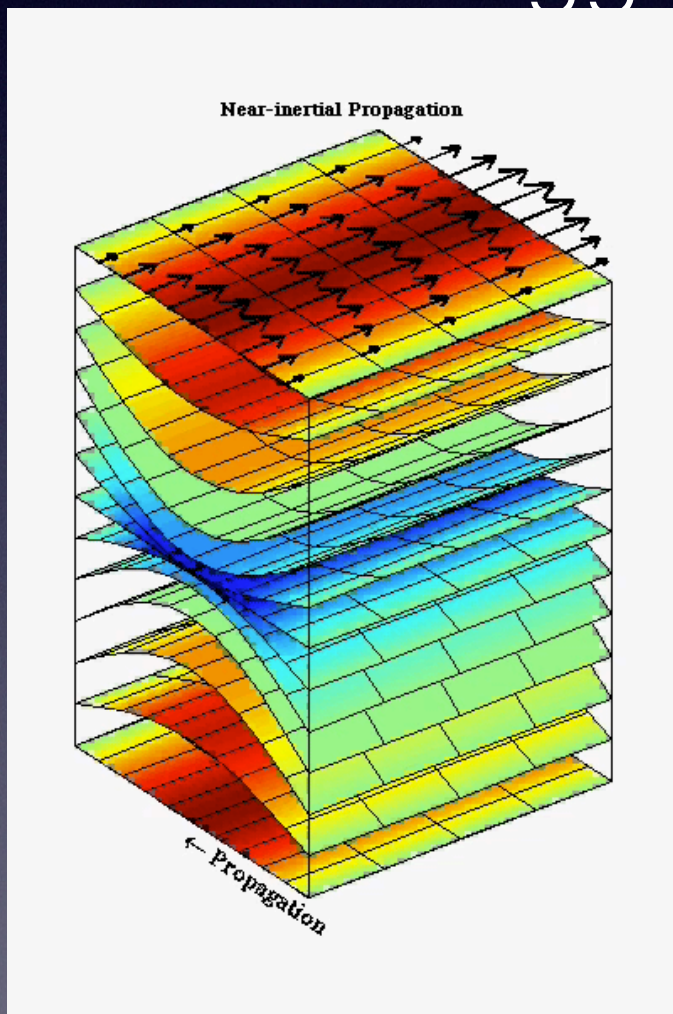
eaking near-inertial waves

Example 1: Banda Sea near-inertial waves

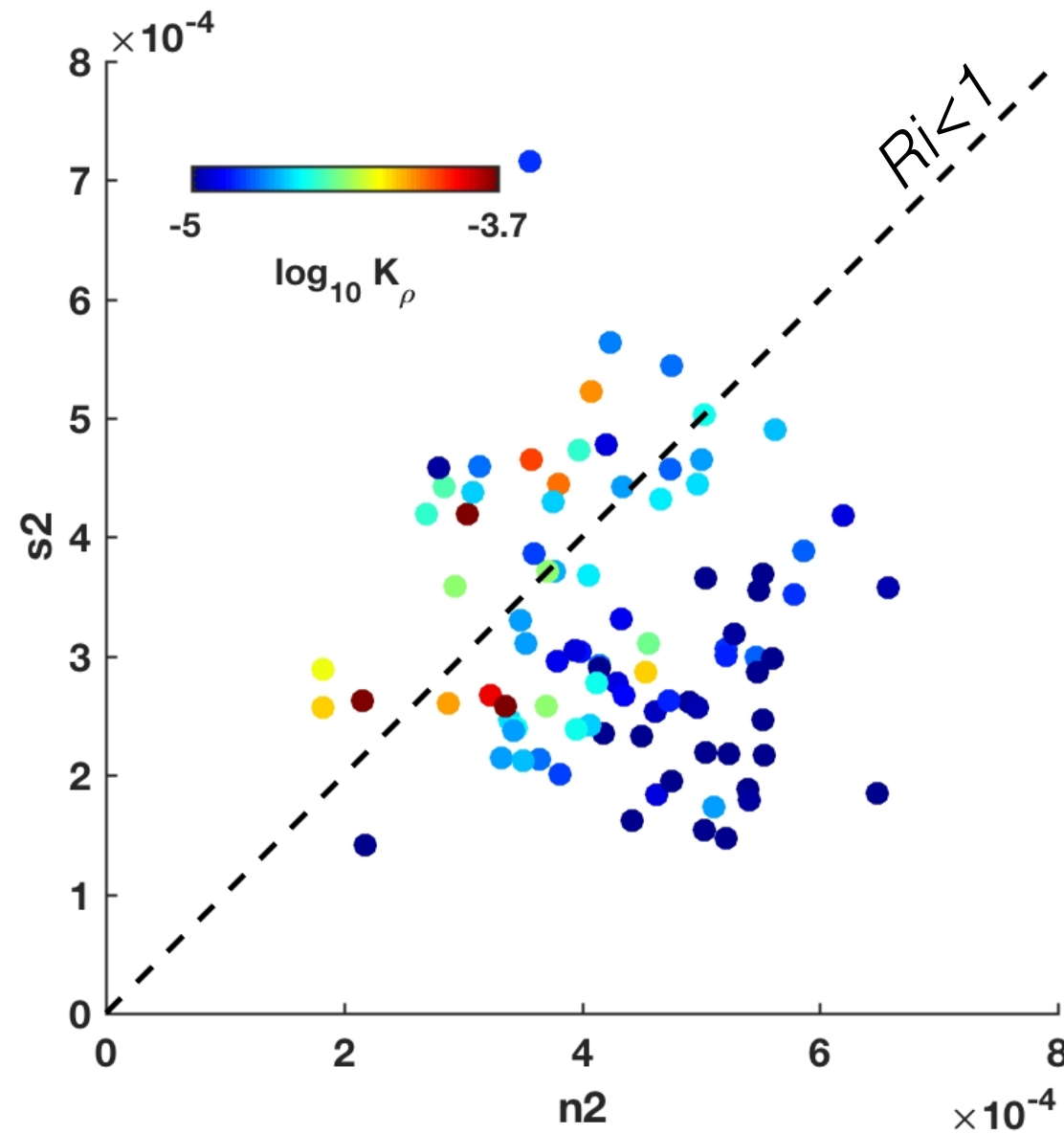
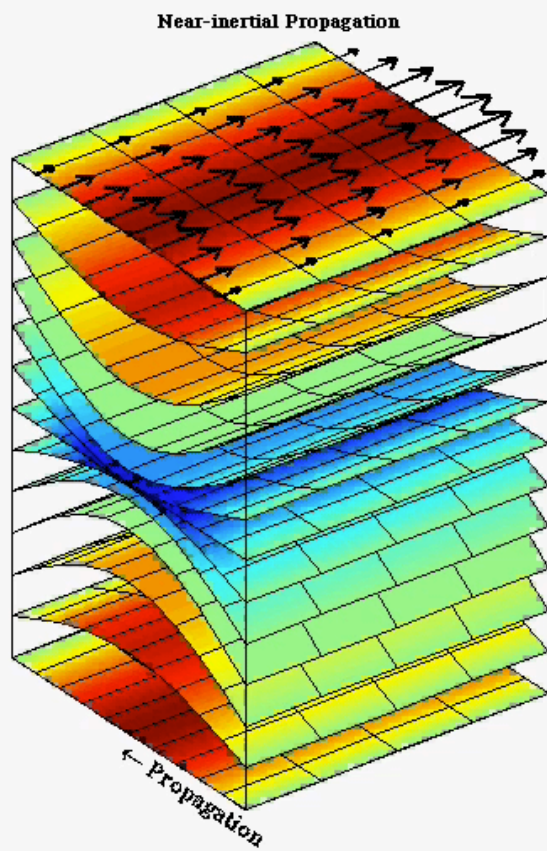
Weak stratification

→ low Ri →
turbulence

Alford and Gregg (2001)



Example 1: Banda Sea near-inertial waves



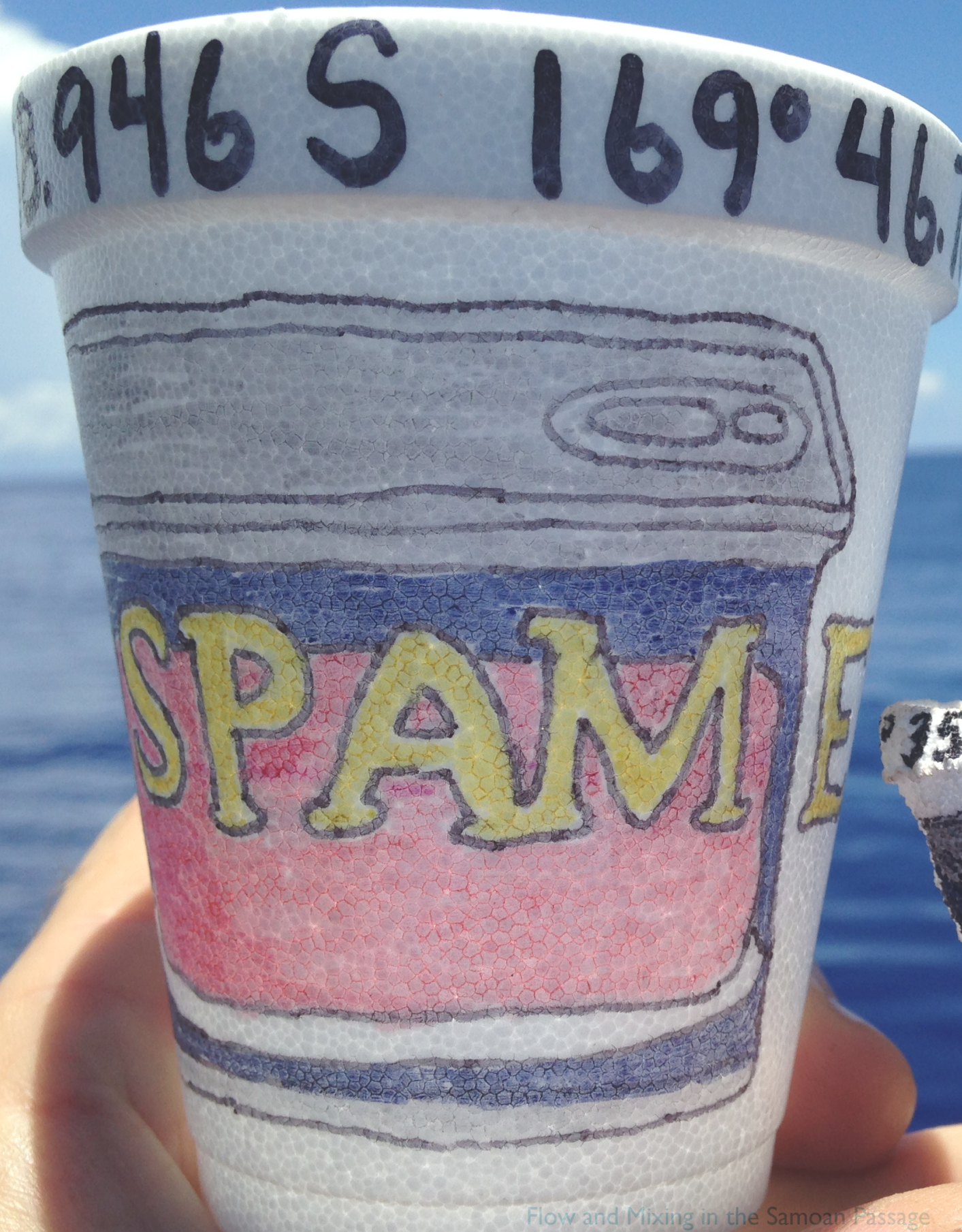
THE SAMOAN PASSAGE ABYSSAL MIXING EXPERIMENT

Goals

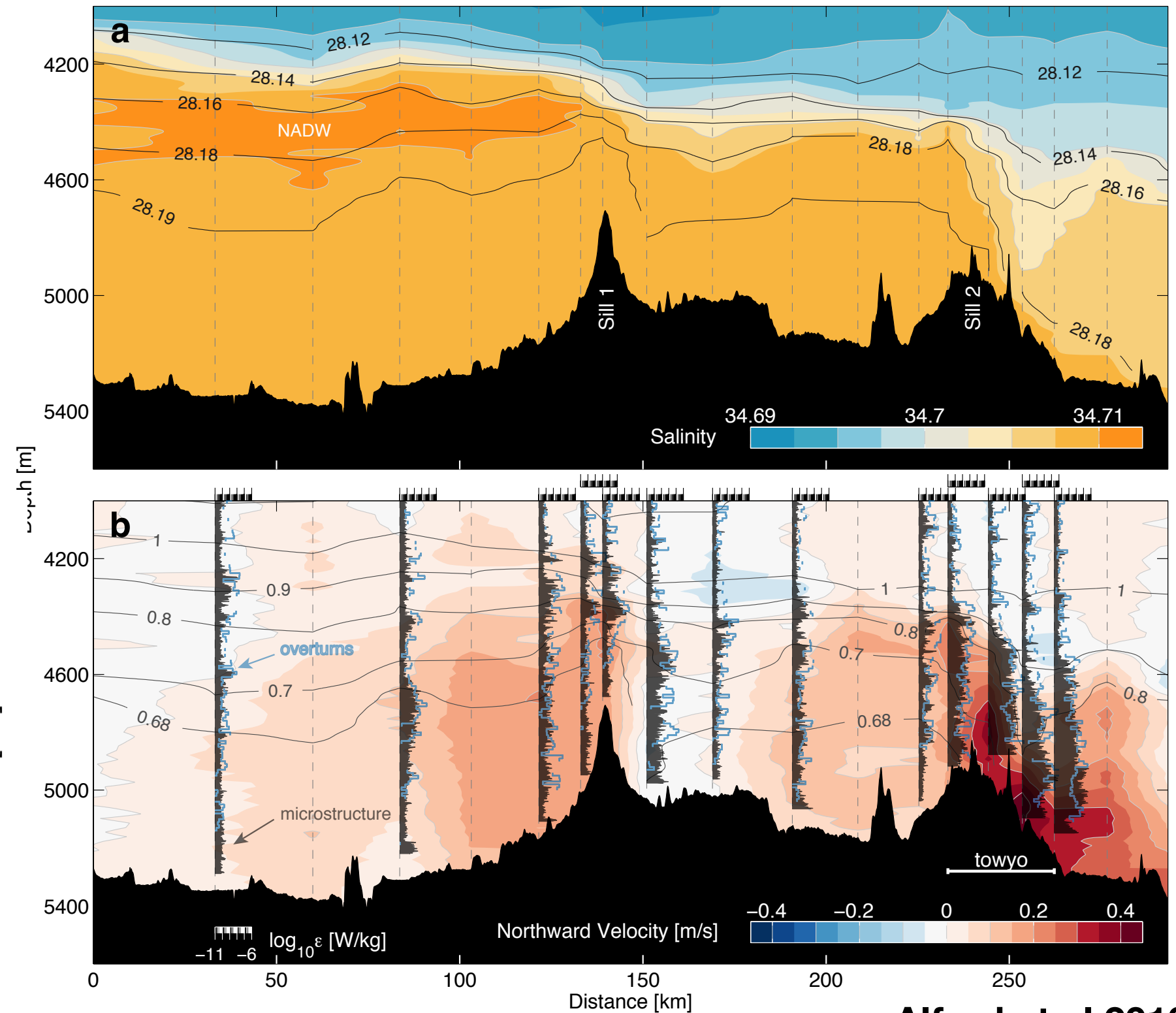
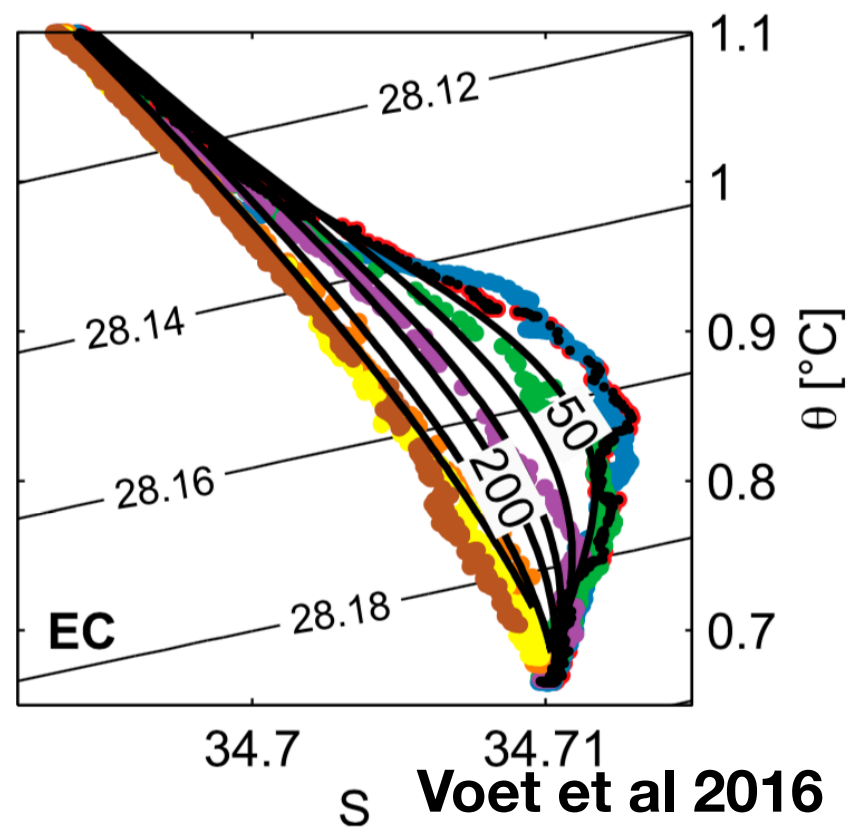
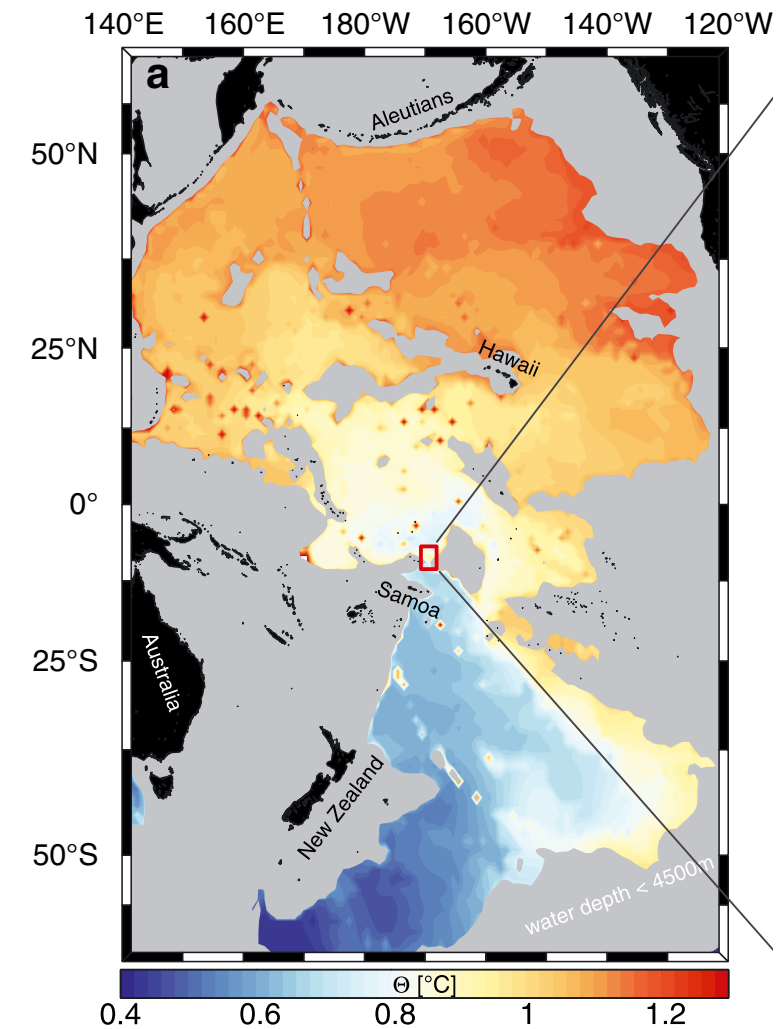
Compare volume transport to WOCE measurements 20 years ago

Map flow pathways

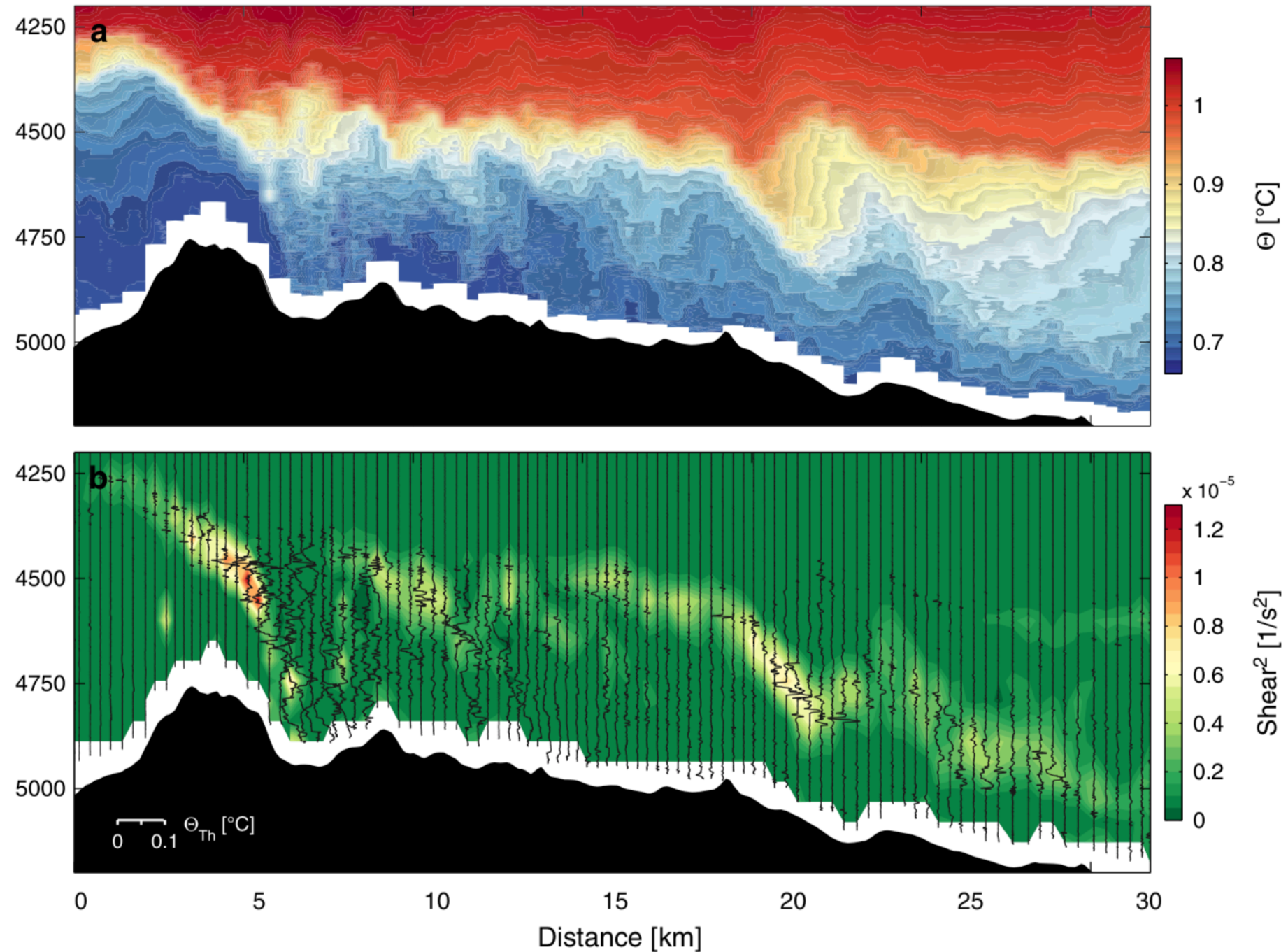
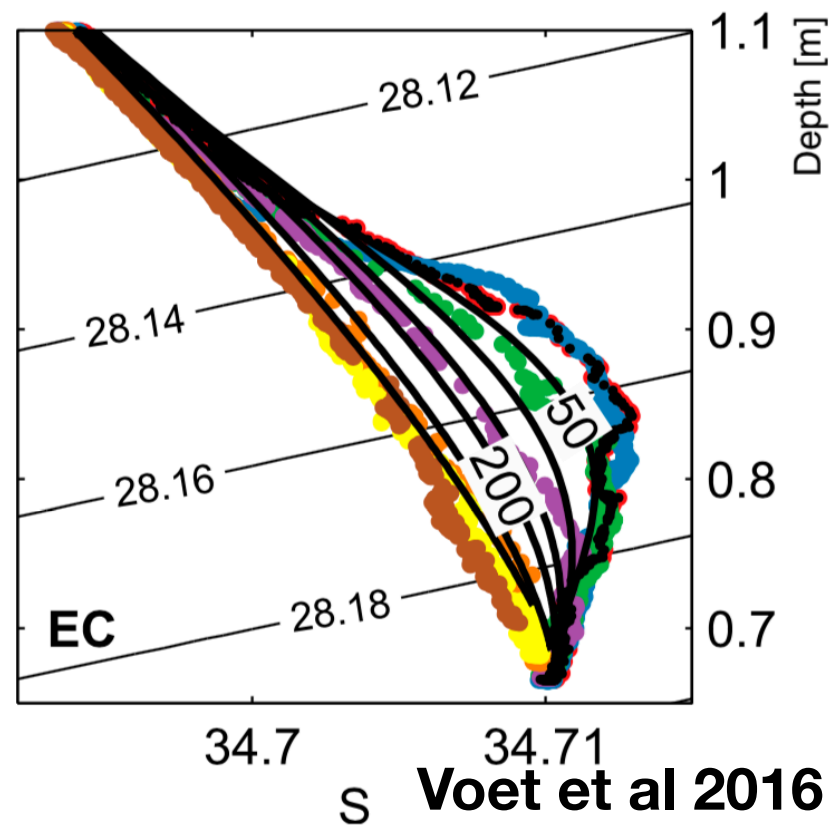
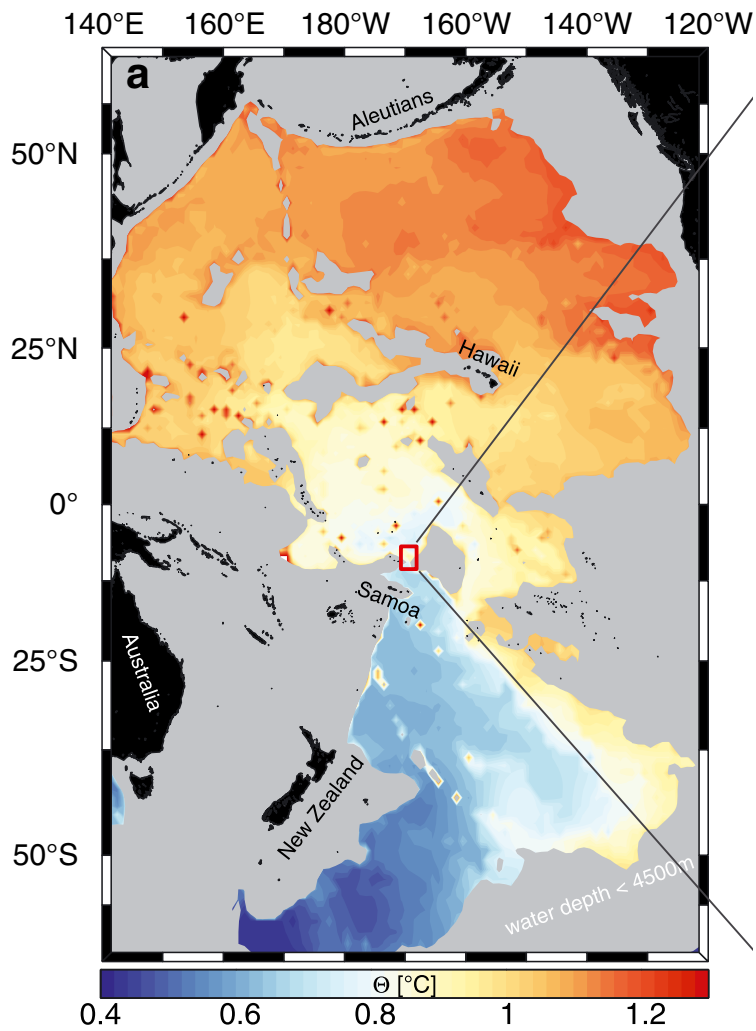
Quantify turbulence and mixing, determine causes.



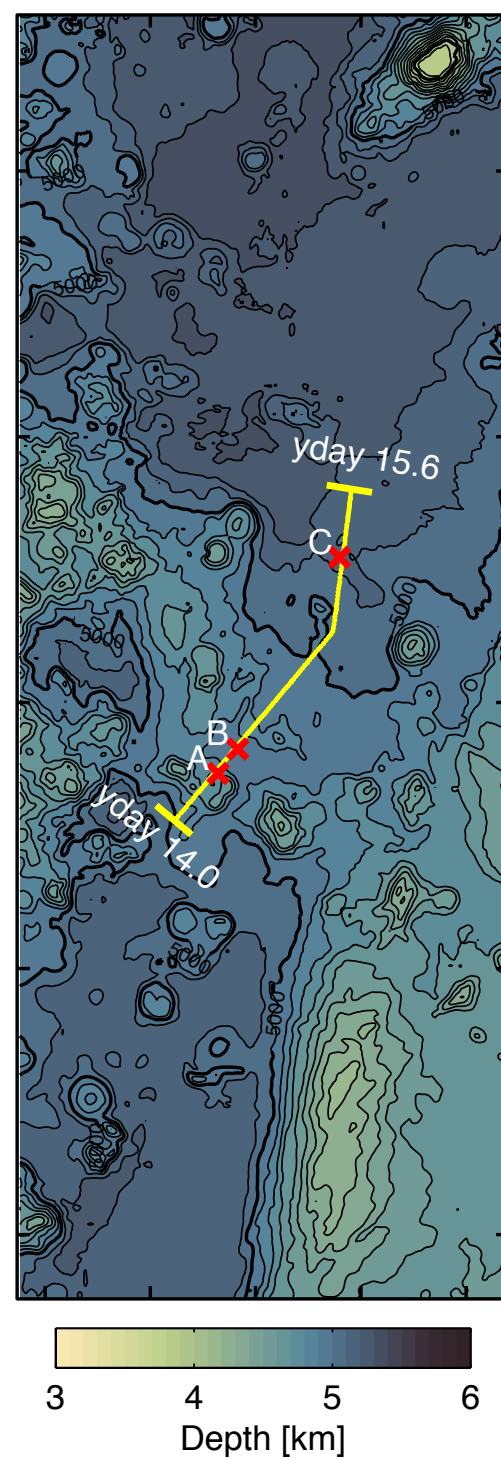
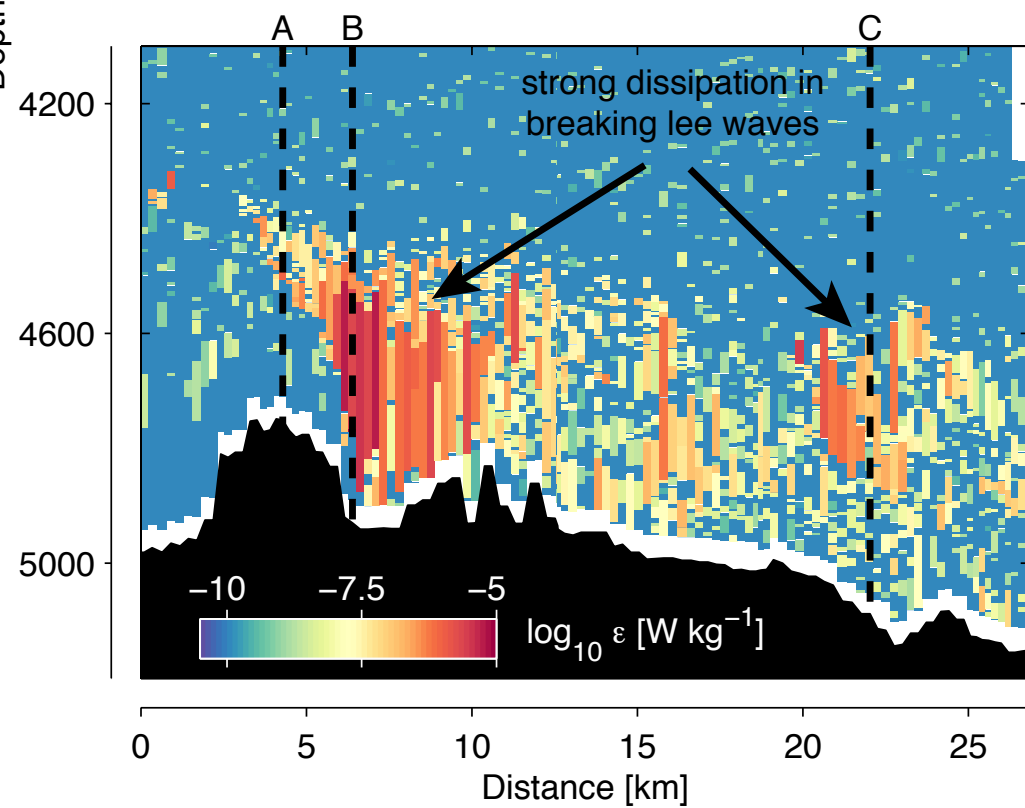
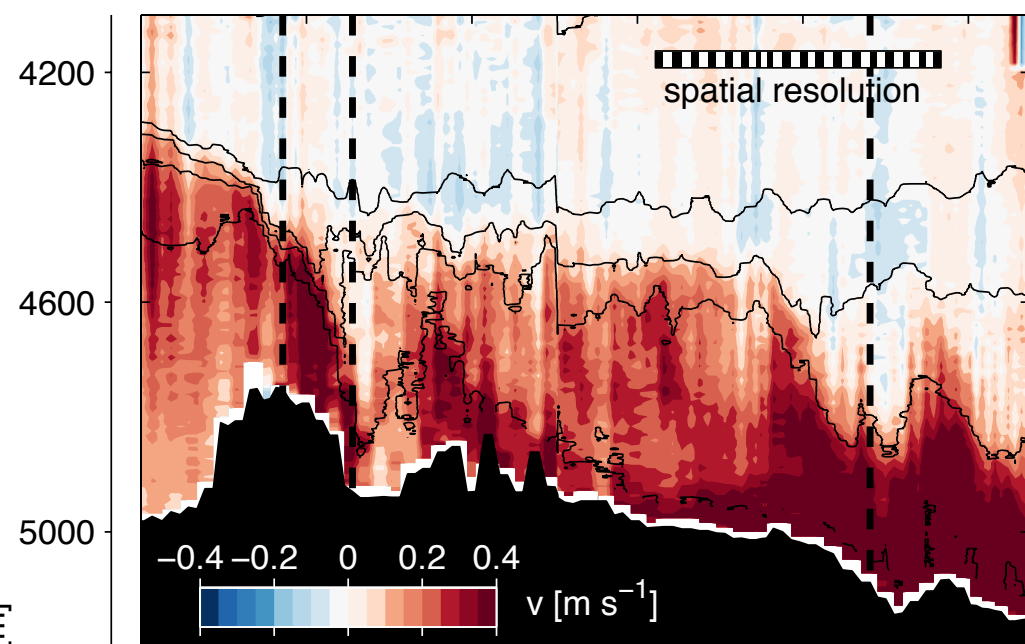
Example 2: Samoan Passage and abyssal mixing



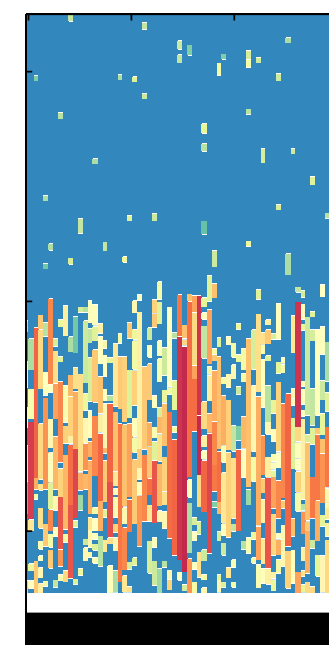
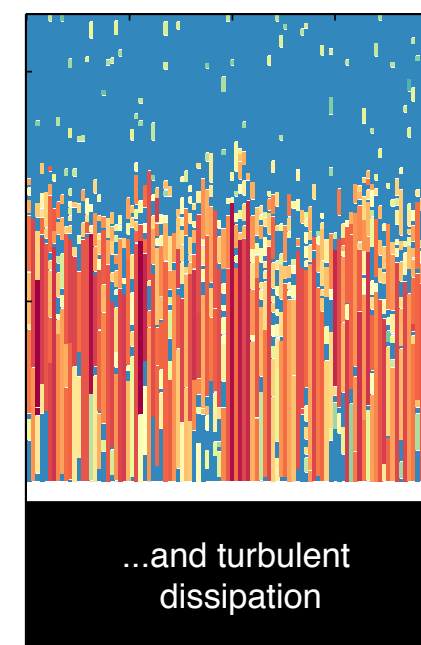
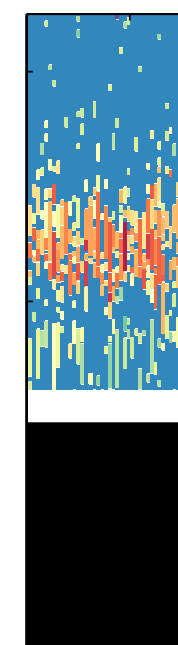
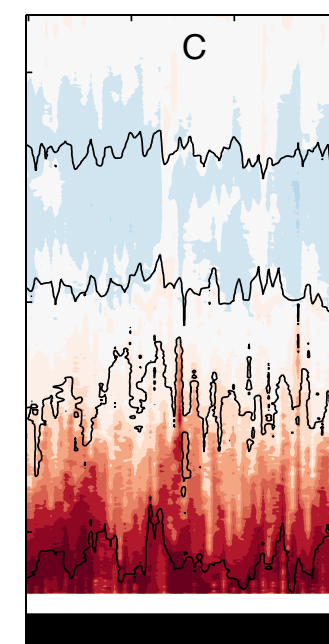
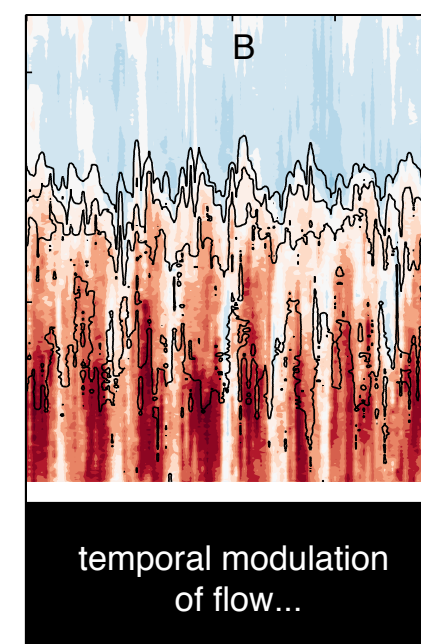
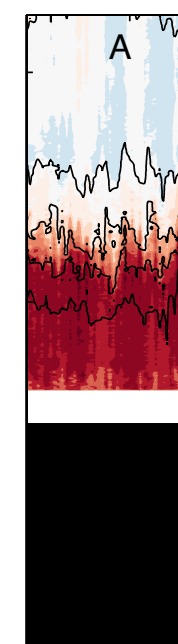
Example 2: Samoan Passage and abyssal mixing



TOWYO



MOORED PROFILER



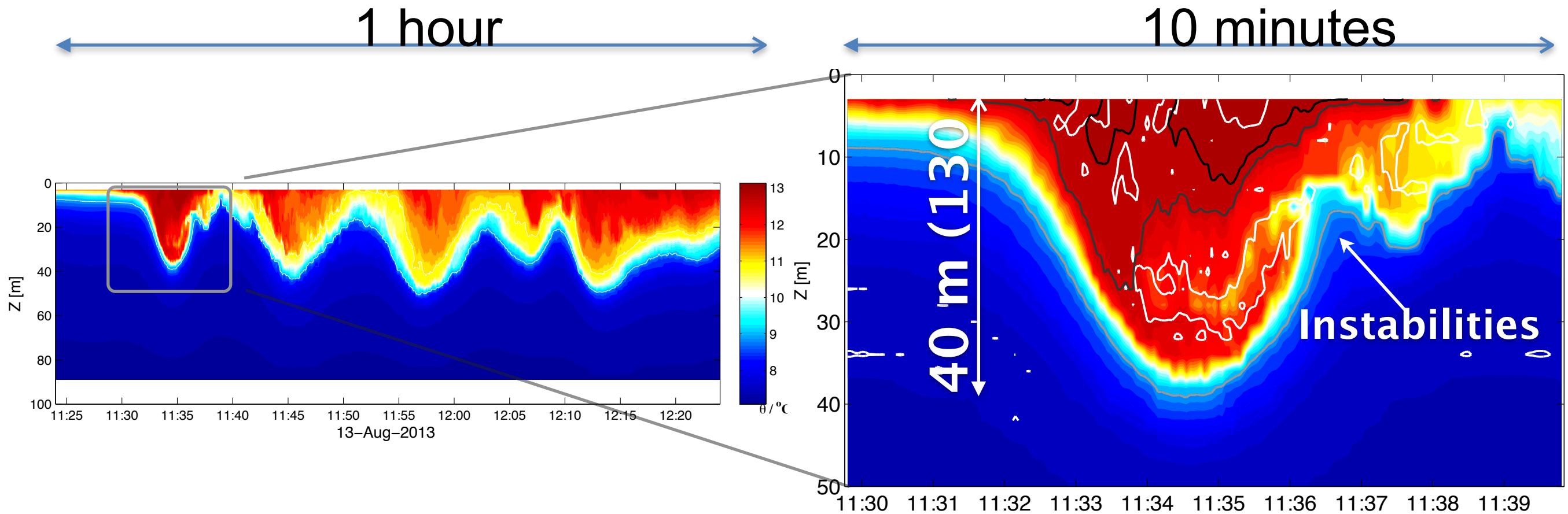
17 18

19 20 21 22 23

26 27 28 29

year day

Example 3: Coastal turbulence and biology

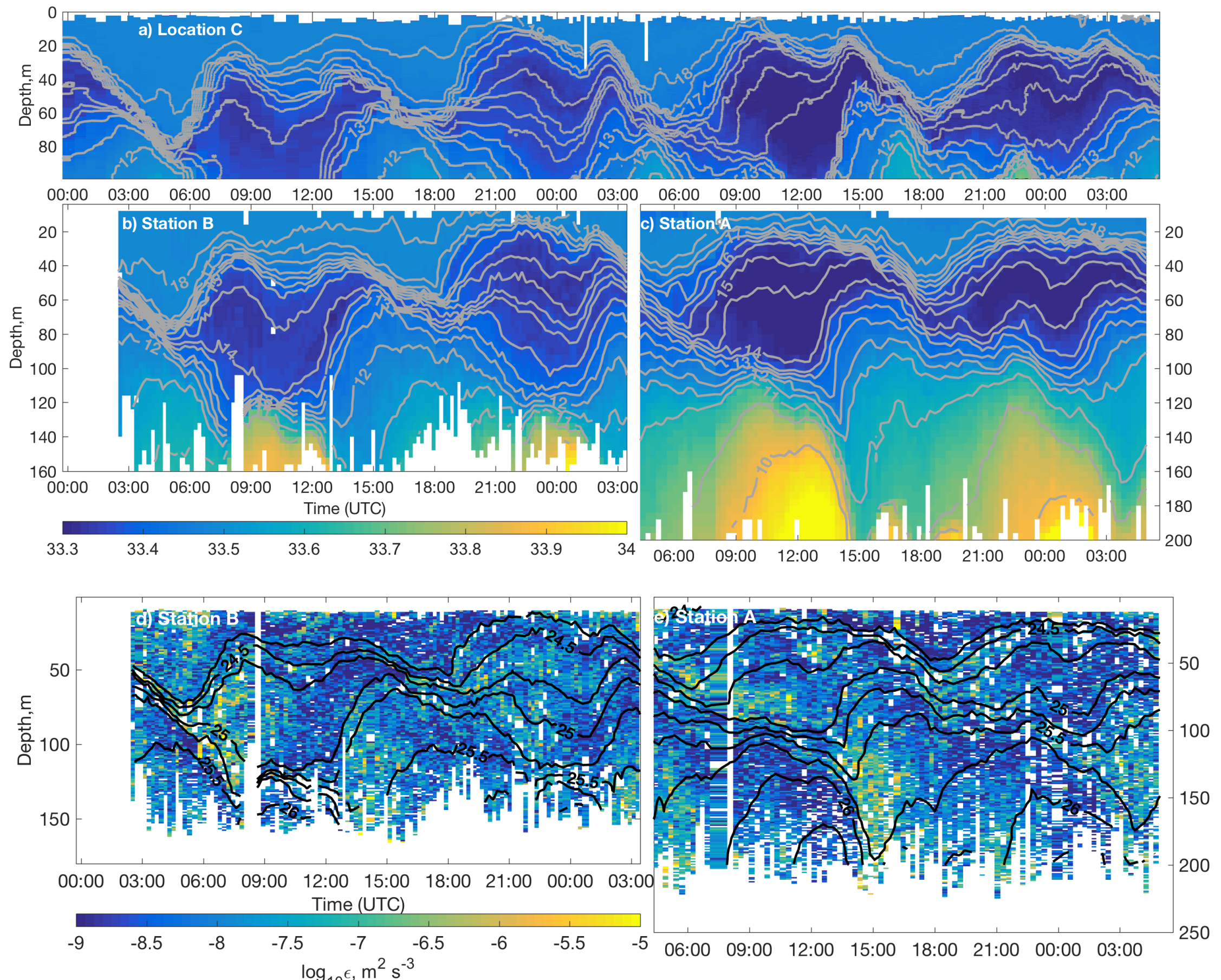


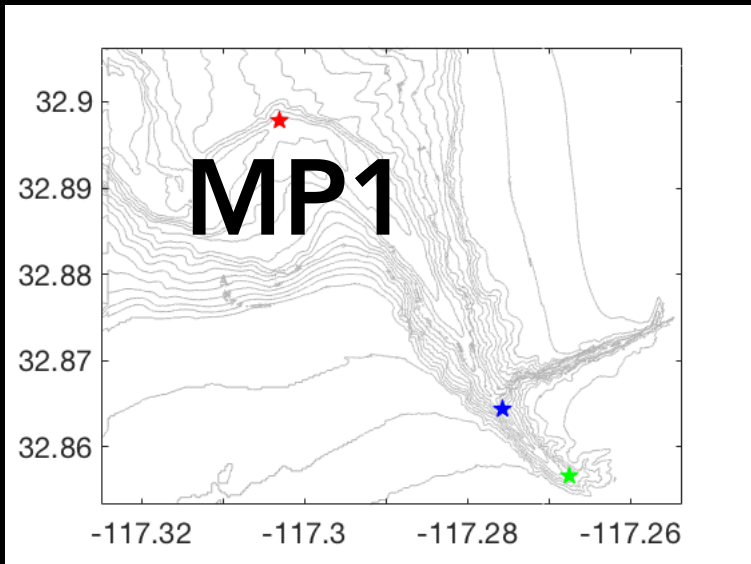
Zhang et al 2014

La Jolla Canyon



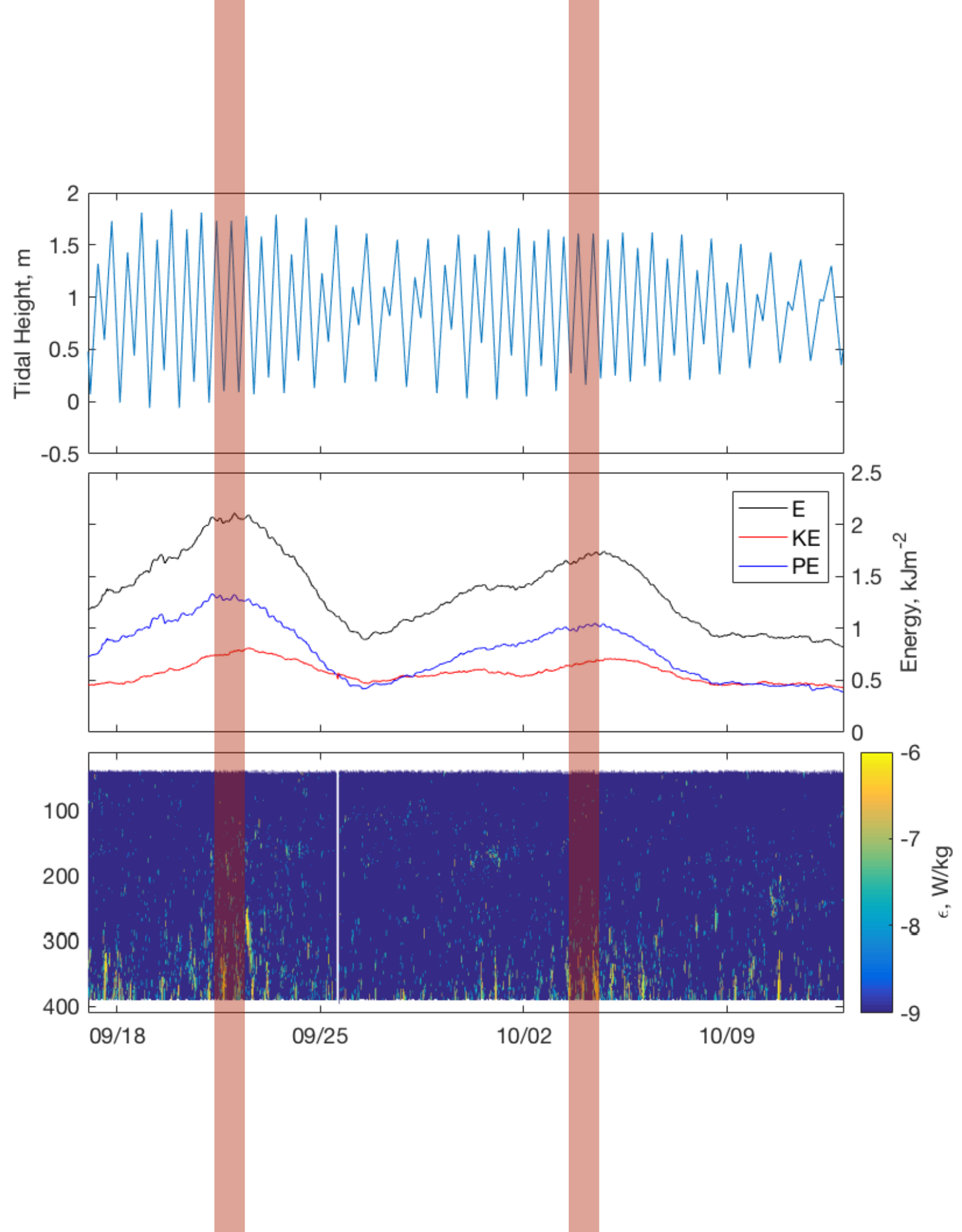
Example 2: Coastal turbulence and biology



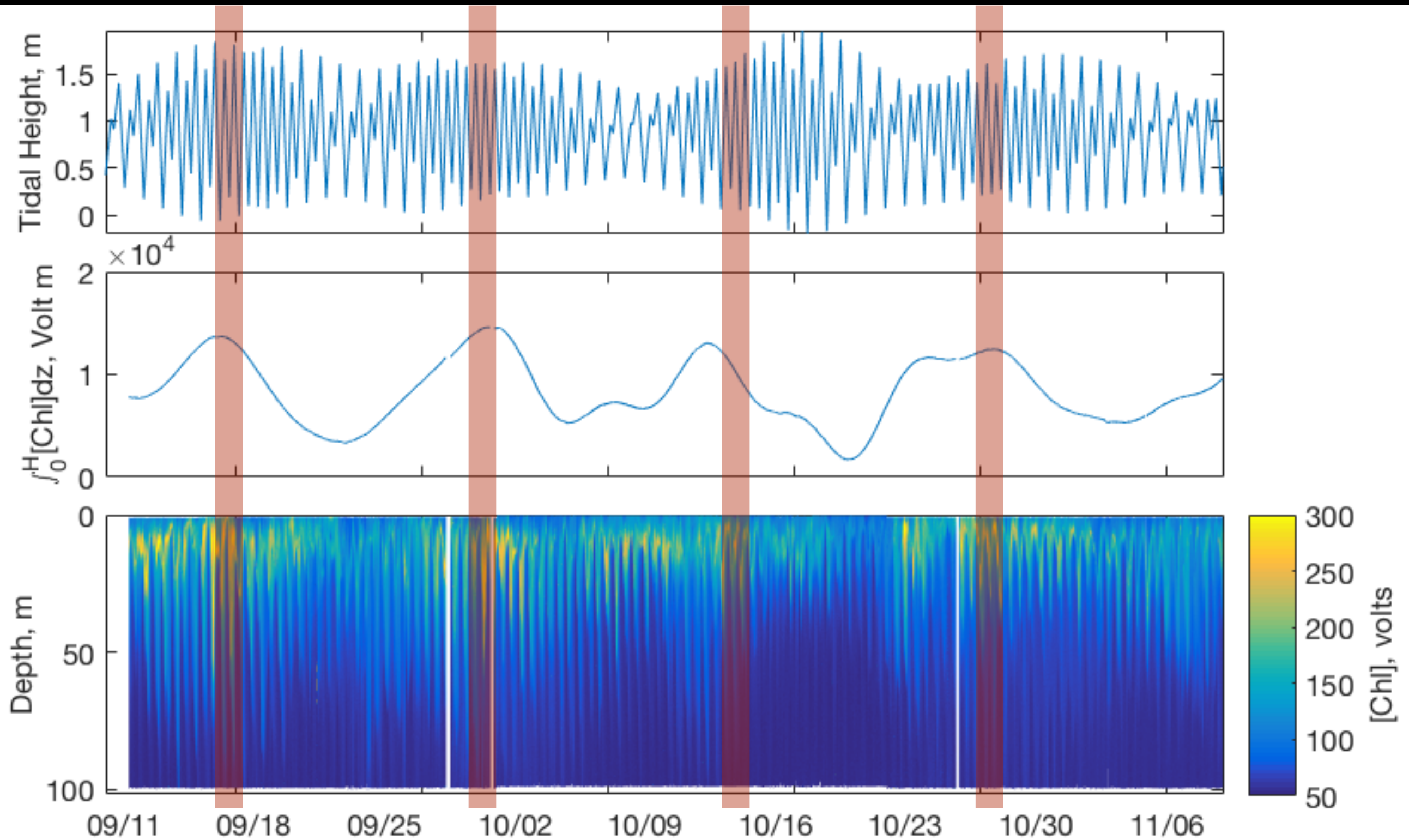


SPRING-NEAP TIDAL
CYCLE

INTERNAL
WAVE
ENERGY AND
MIXING

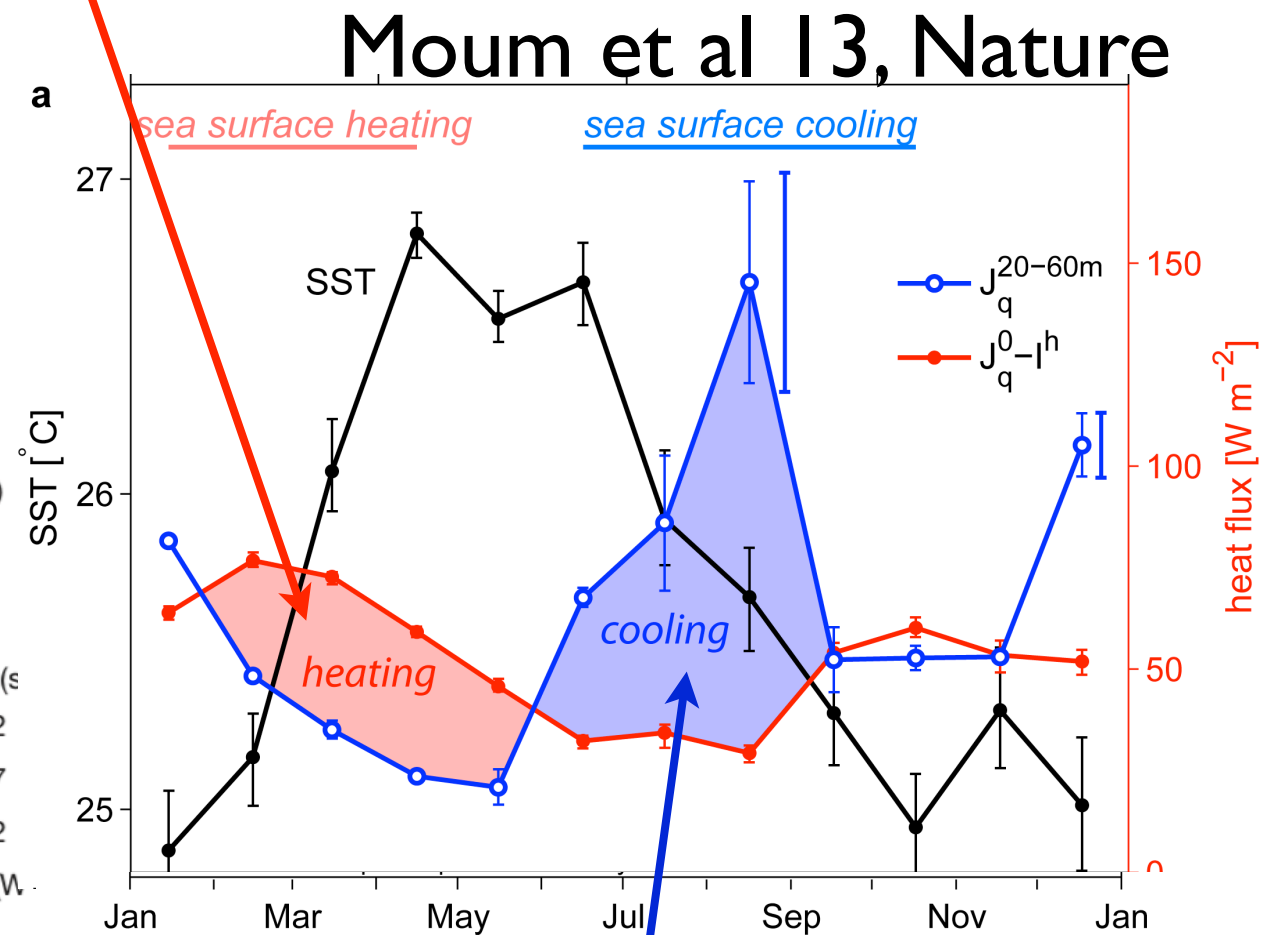
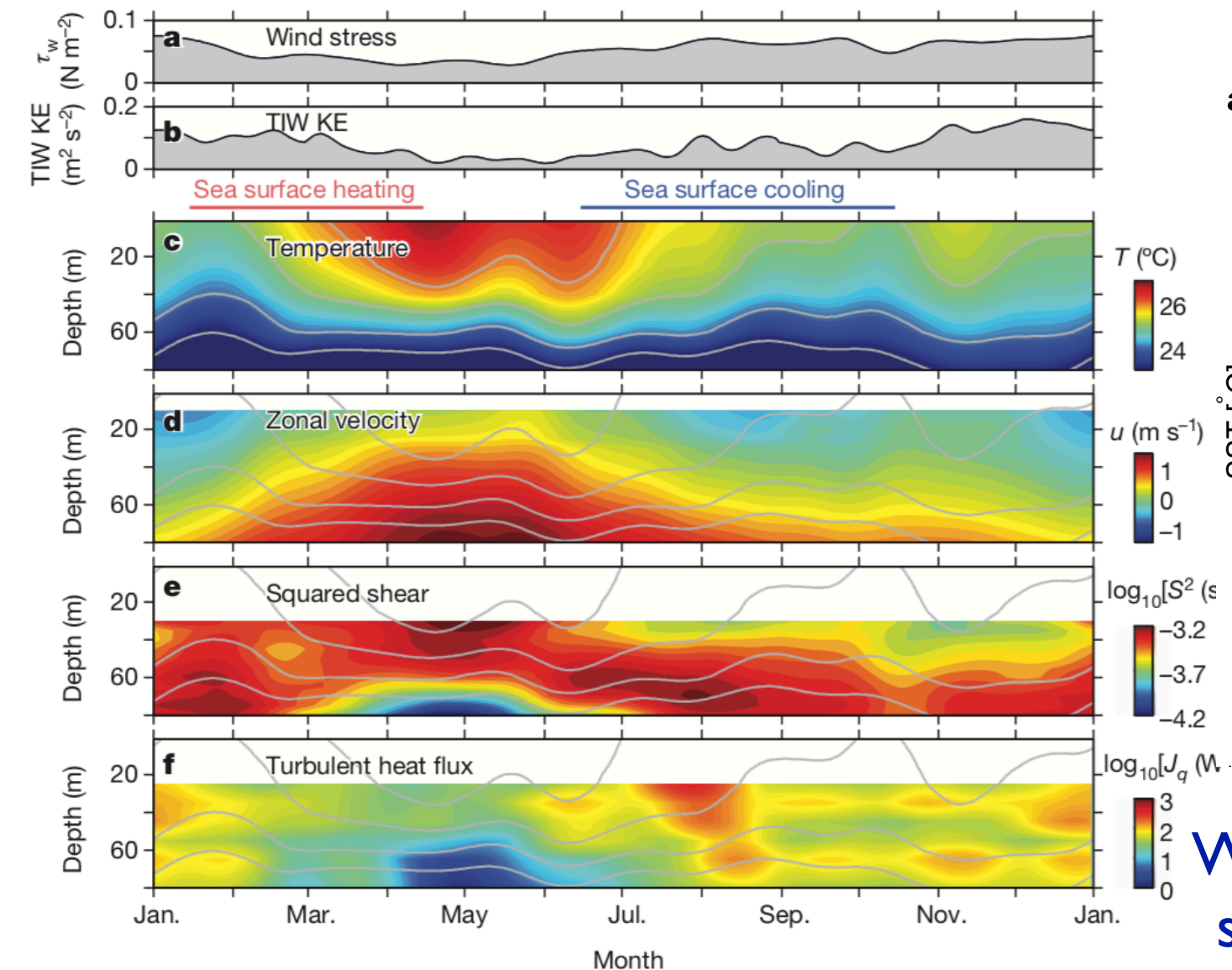


SPRING-NEAP CYCLE IN CHLOROPHYLL FLUORESCENCE



Example 3: equatorial cold tongue SST

When downward turbulent heat flux is weak, surface heat flux 'wins' and upper ocean WARMS



When downward turbulent heat flux is strong (extra shear from TIWs in the autumn), there's a divergence of downward heat flux and upper ocean COOLS

Example 4: Arctic Mixing

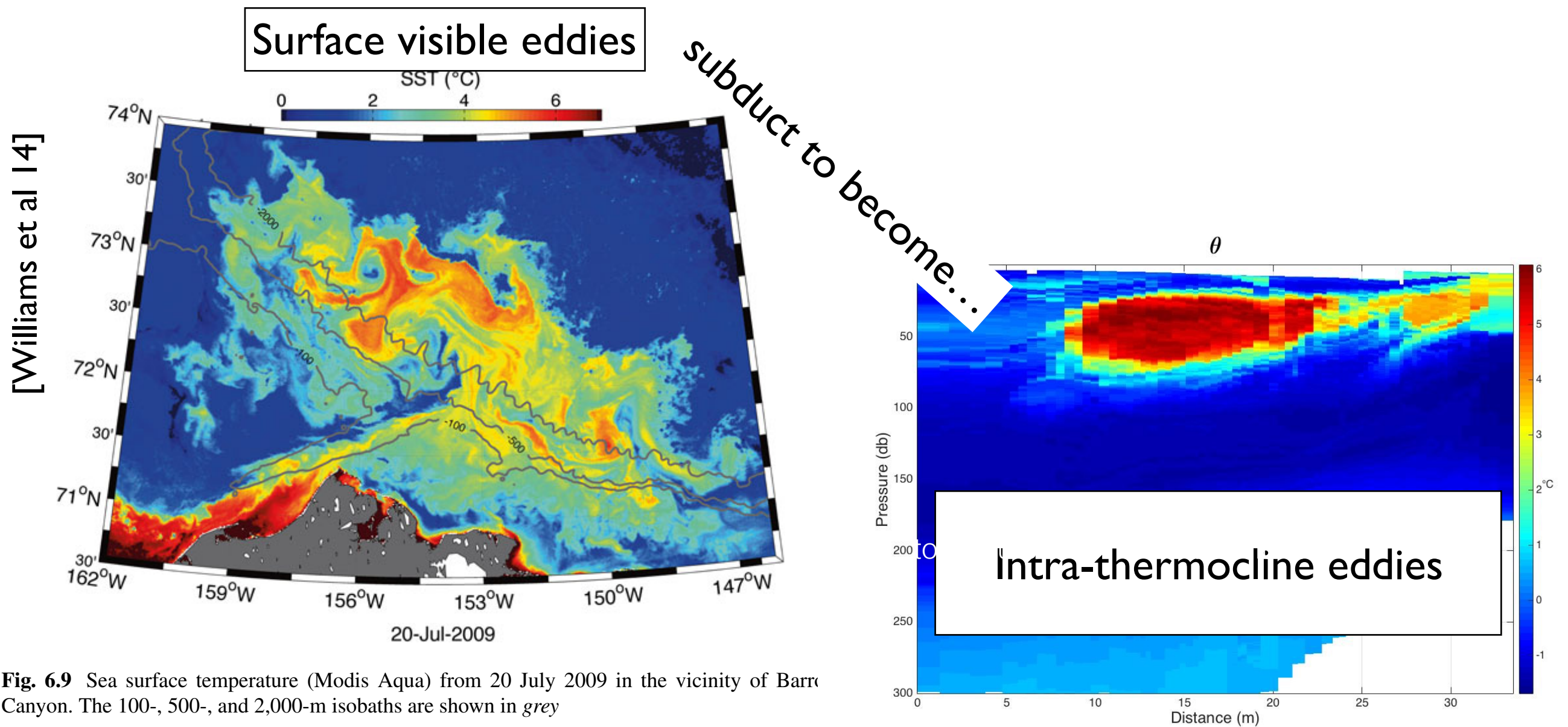


Fig. 6.9 Sea surface temperature (Modis Aqua) from 20 July 2009 in the vicinity of Barr Canyon. The 100-, 500-, and 2,000-m isobaths are shown in grey

Related observations by Timmermans et al 08, 15, Zhao et al 14, Zhao and Timmermans 15

Heat content of Arctic inflows increasing

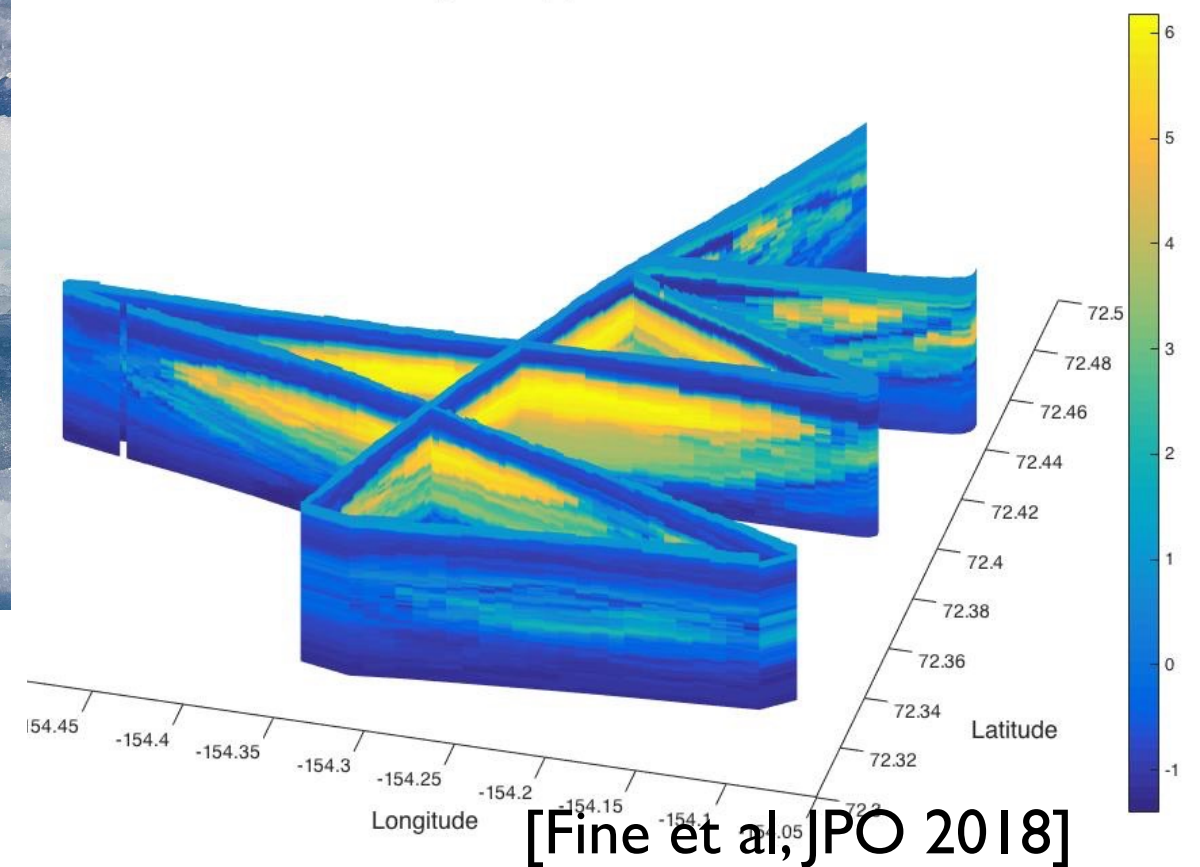
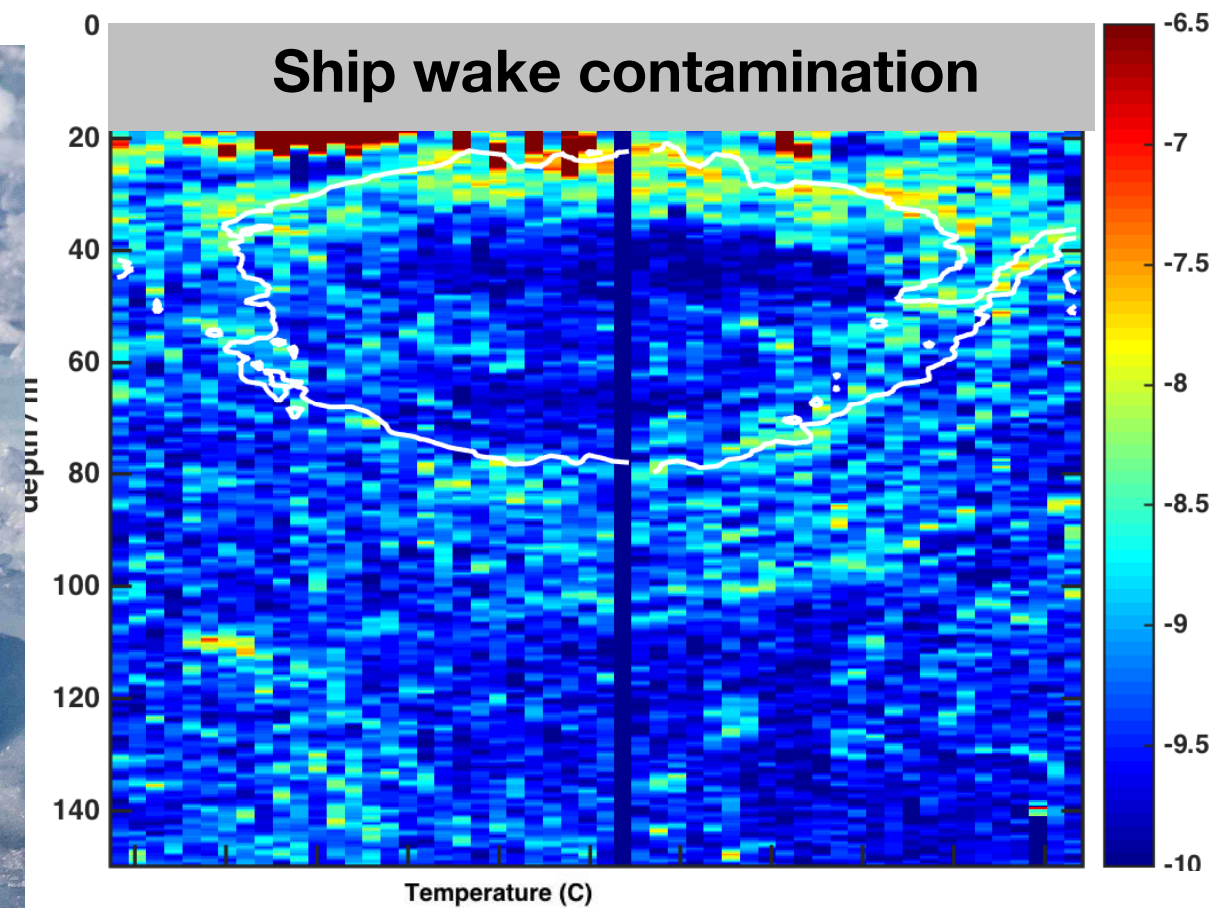
[Fine et al, JPO 2018]

ArcticMix 2015: MacKinnon, Alford, Mickett

Measuring turbulence in the Arctic

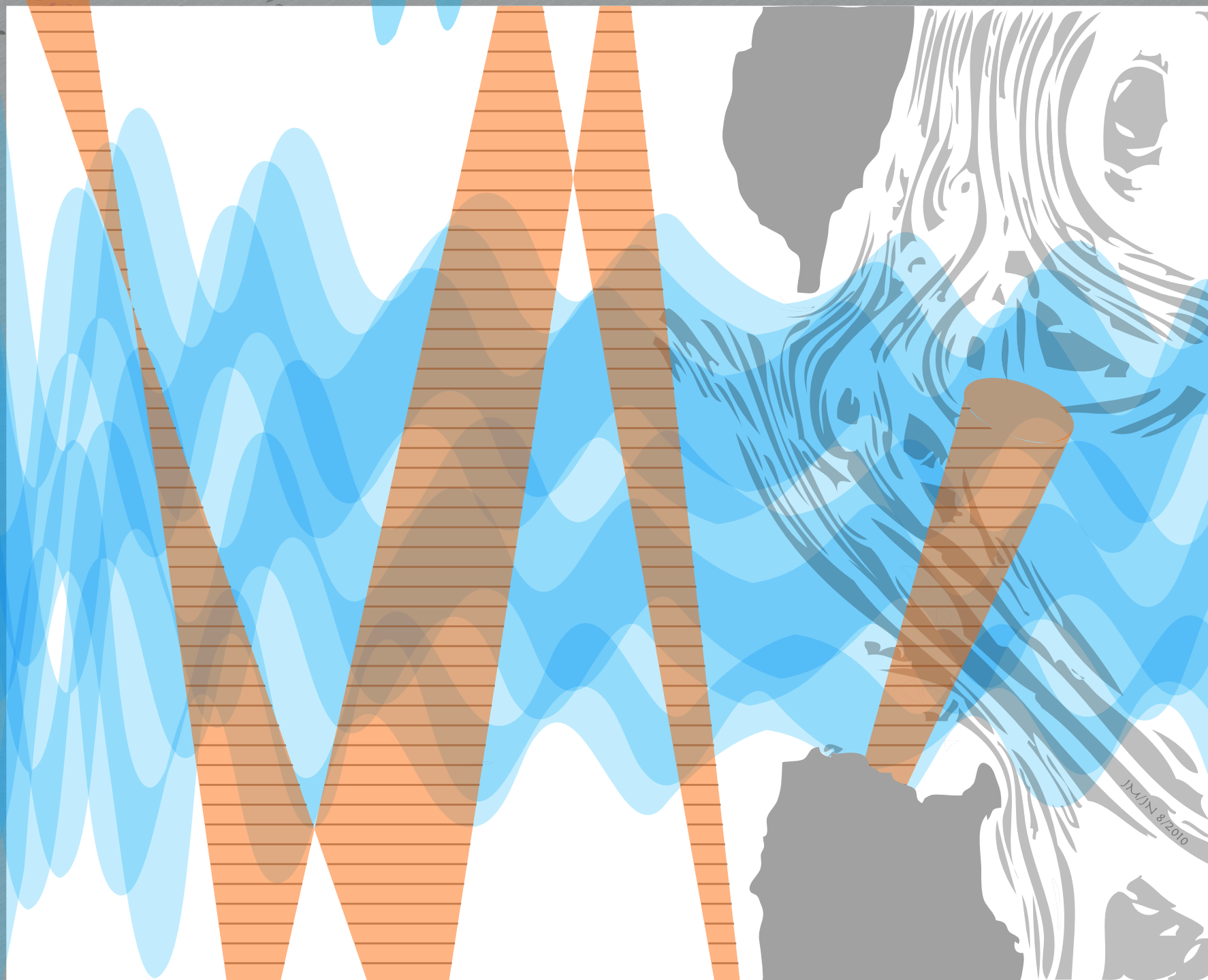


Photo courtesy of Jen MacKinnon



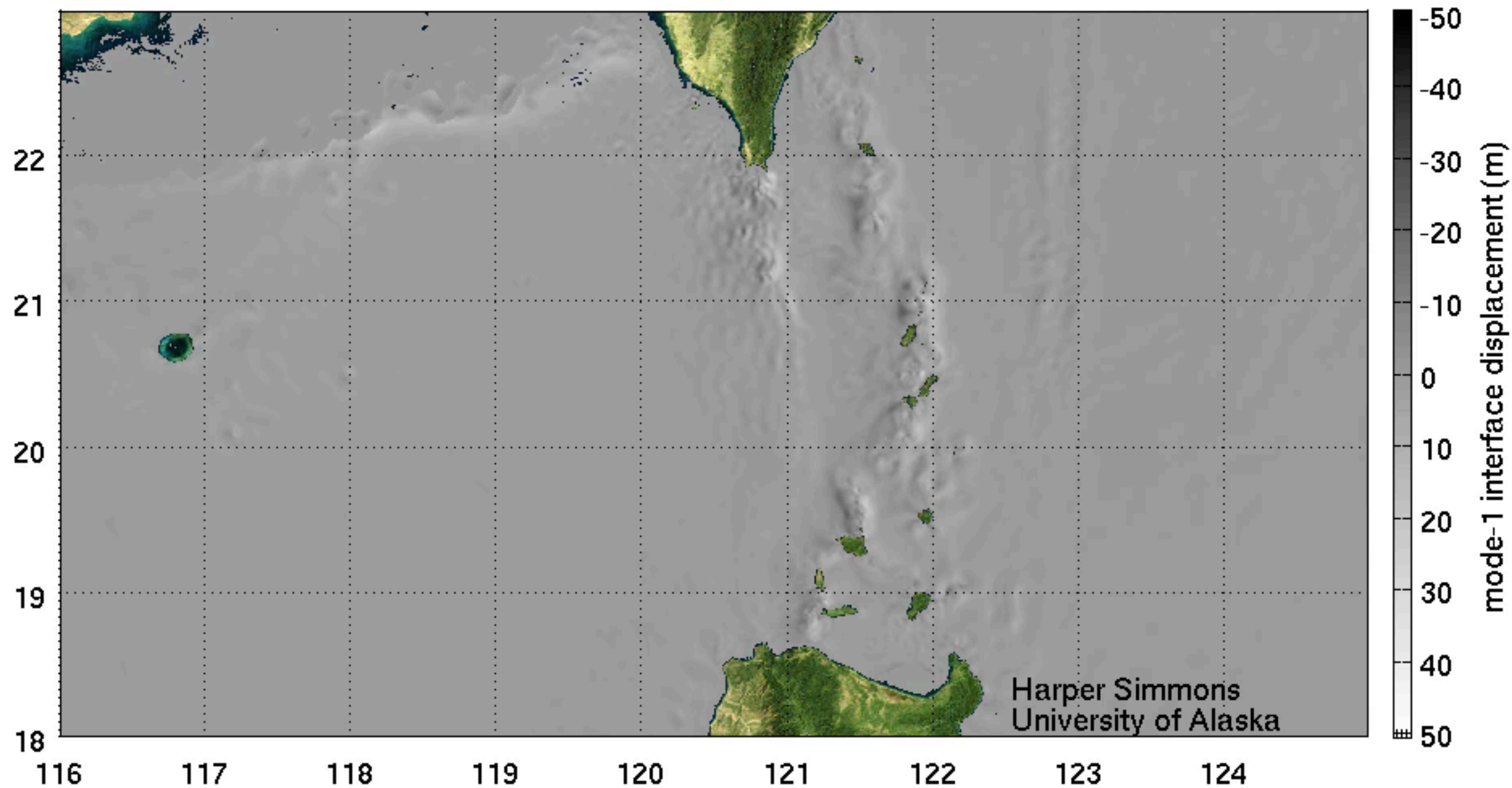
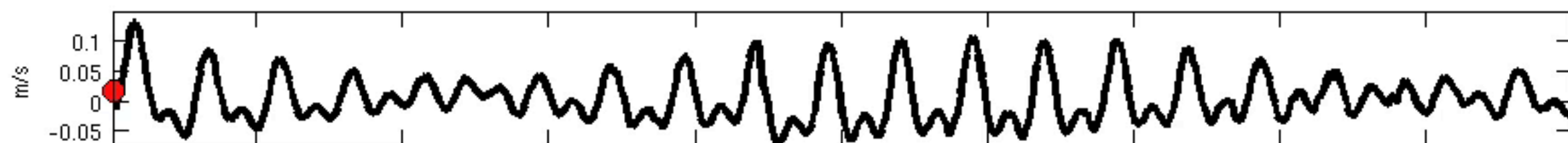
[Fine et al, JPO 2018]

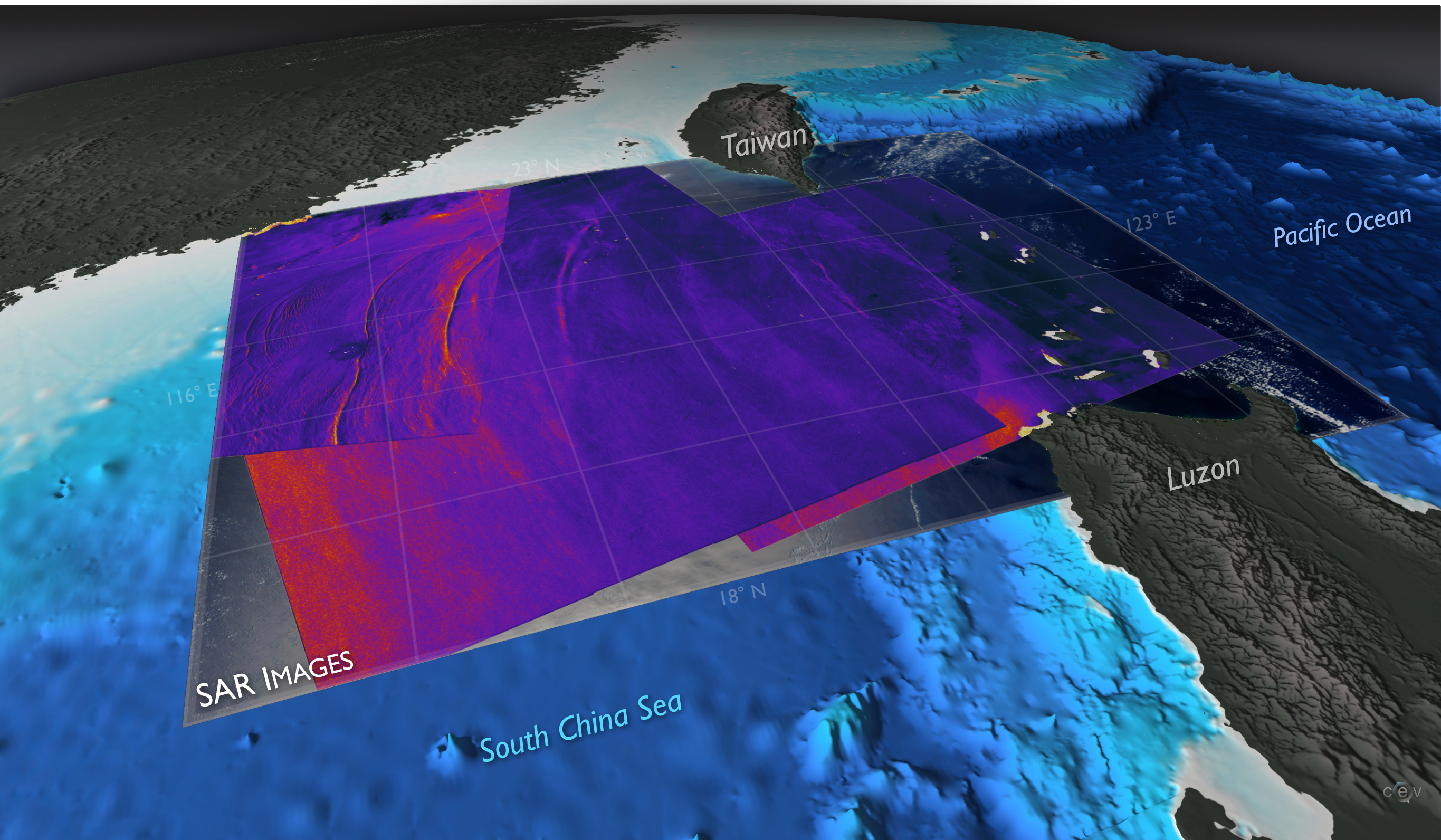
WISE 2010/11



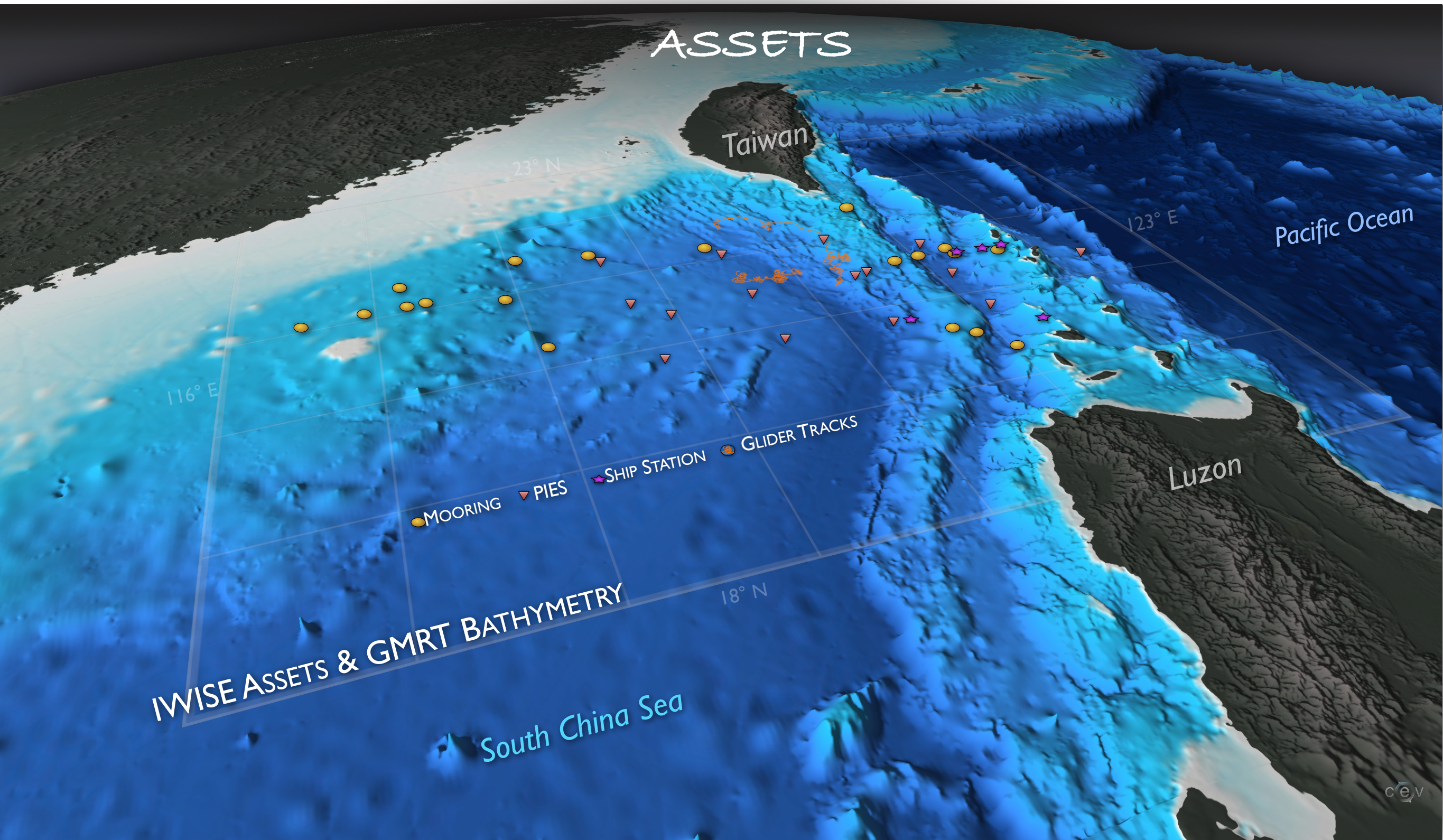
INTERNAL WAVES IN STRAITS EXPERIMENT, ONR
SOUTH CHINA SEA & LUZON STRAIT 2010/11

East-West Currents in Luzon Strait 05-June-2011 01:00Z

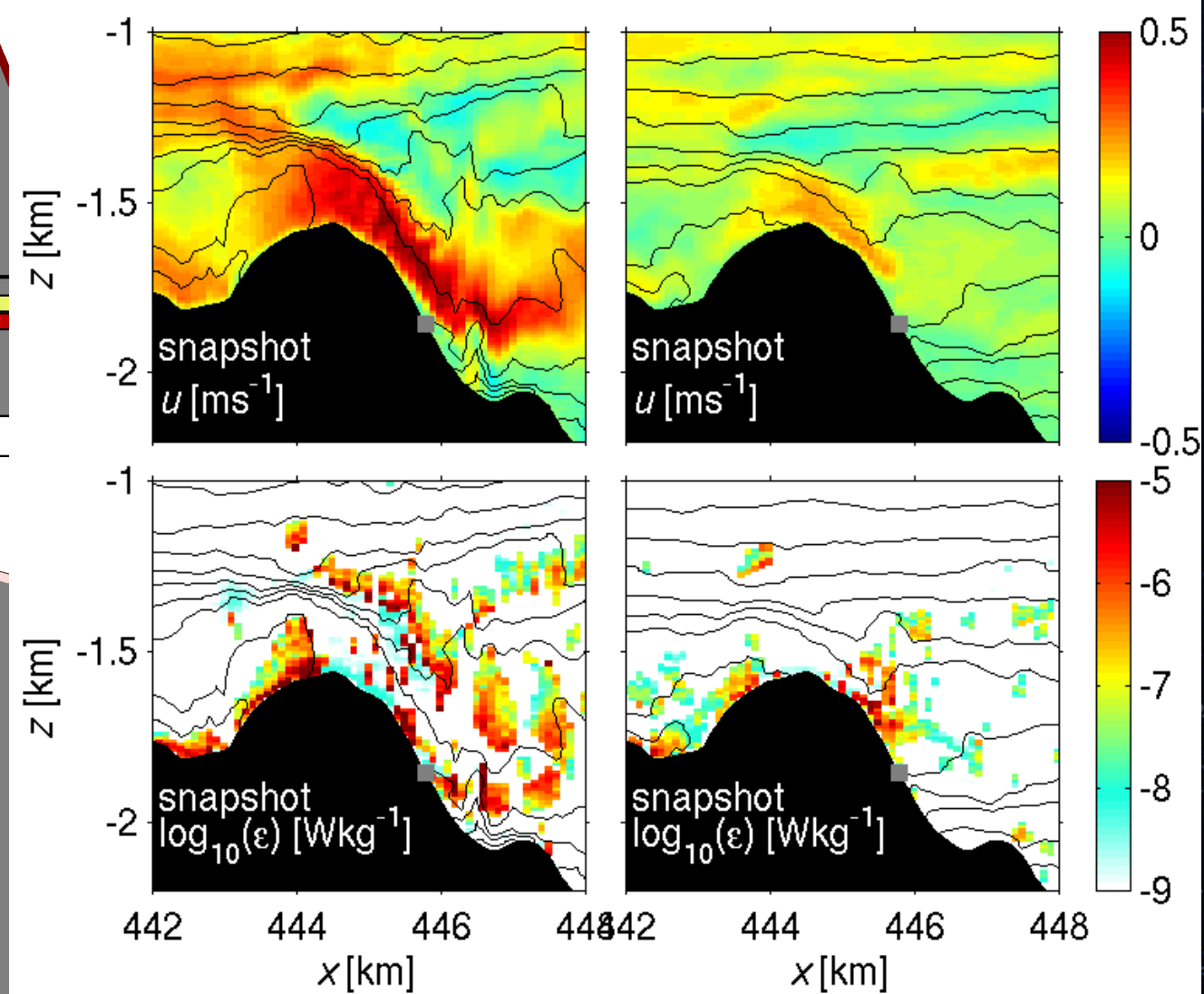
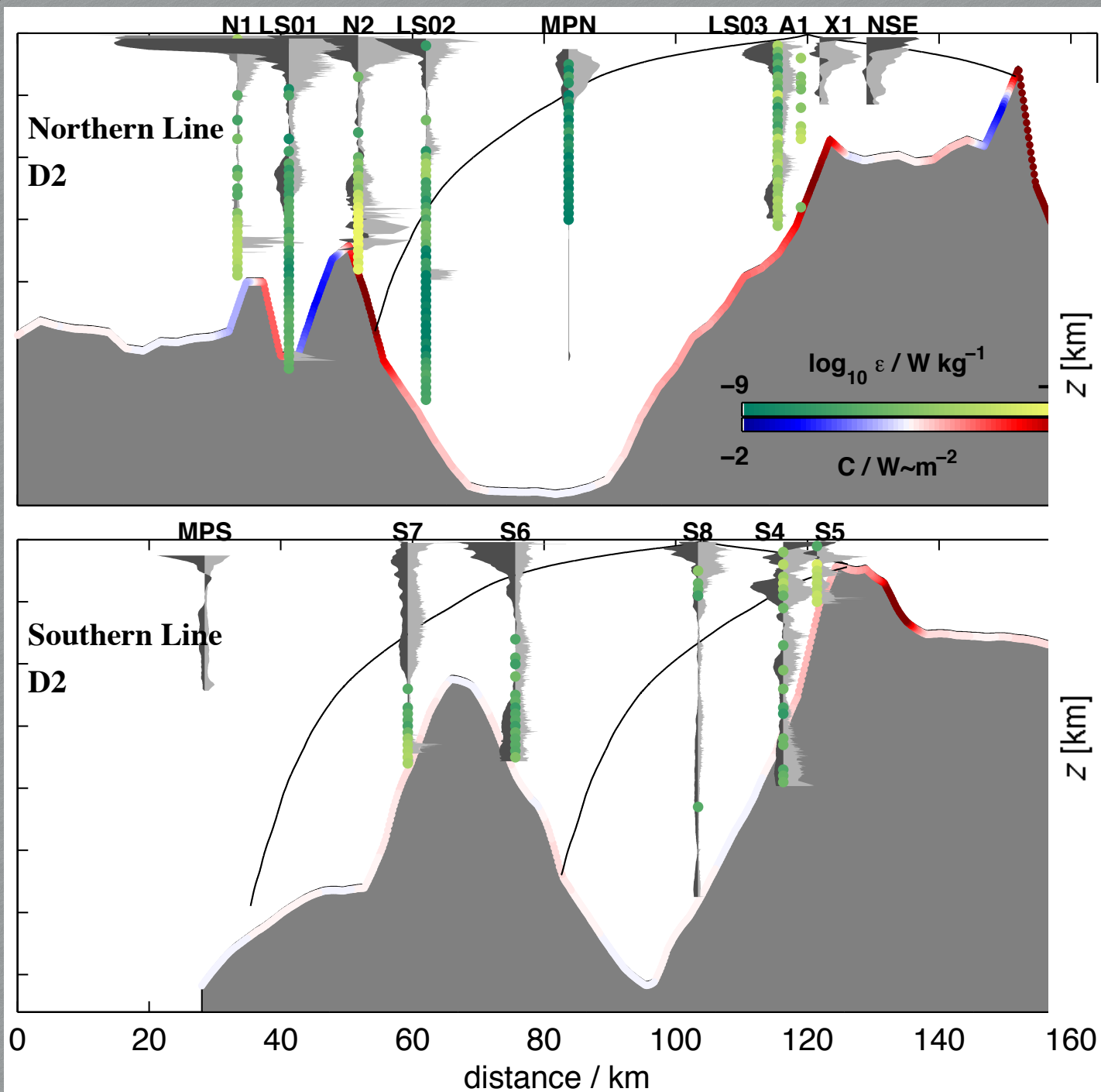




ASSETS

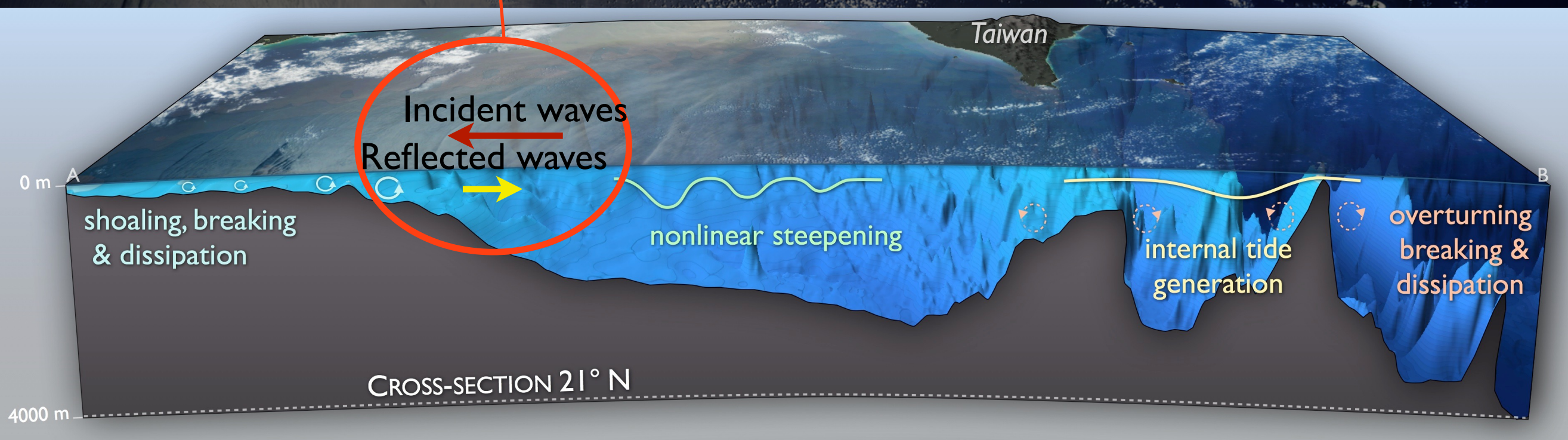
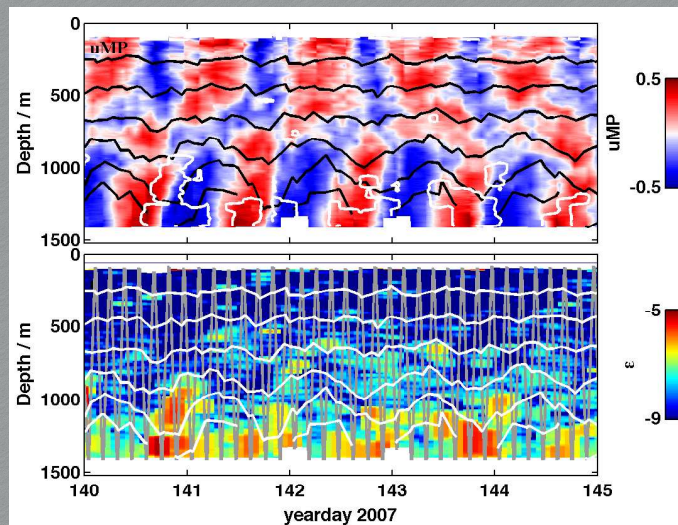


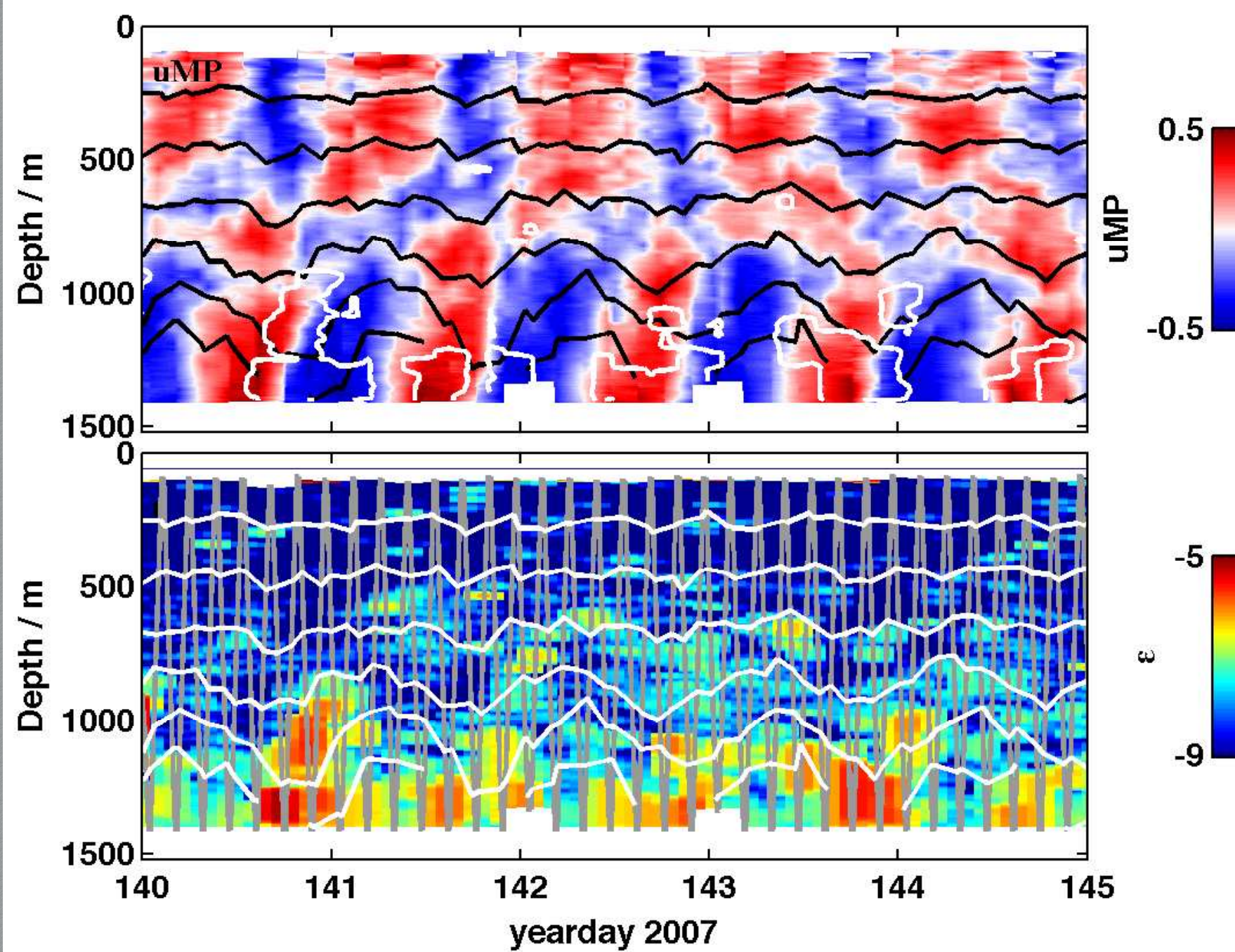
RESONANCE



Alford et al, JPO 2011

REFLECTION



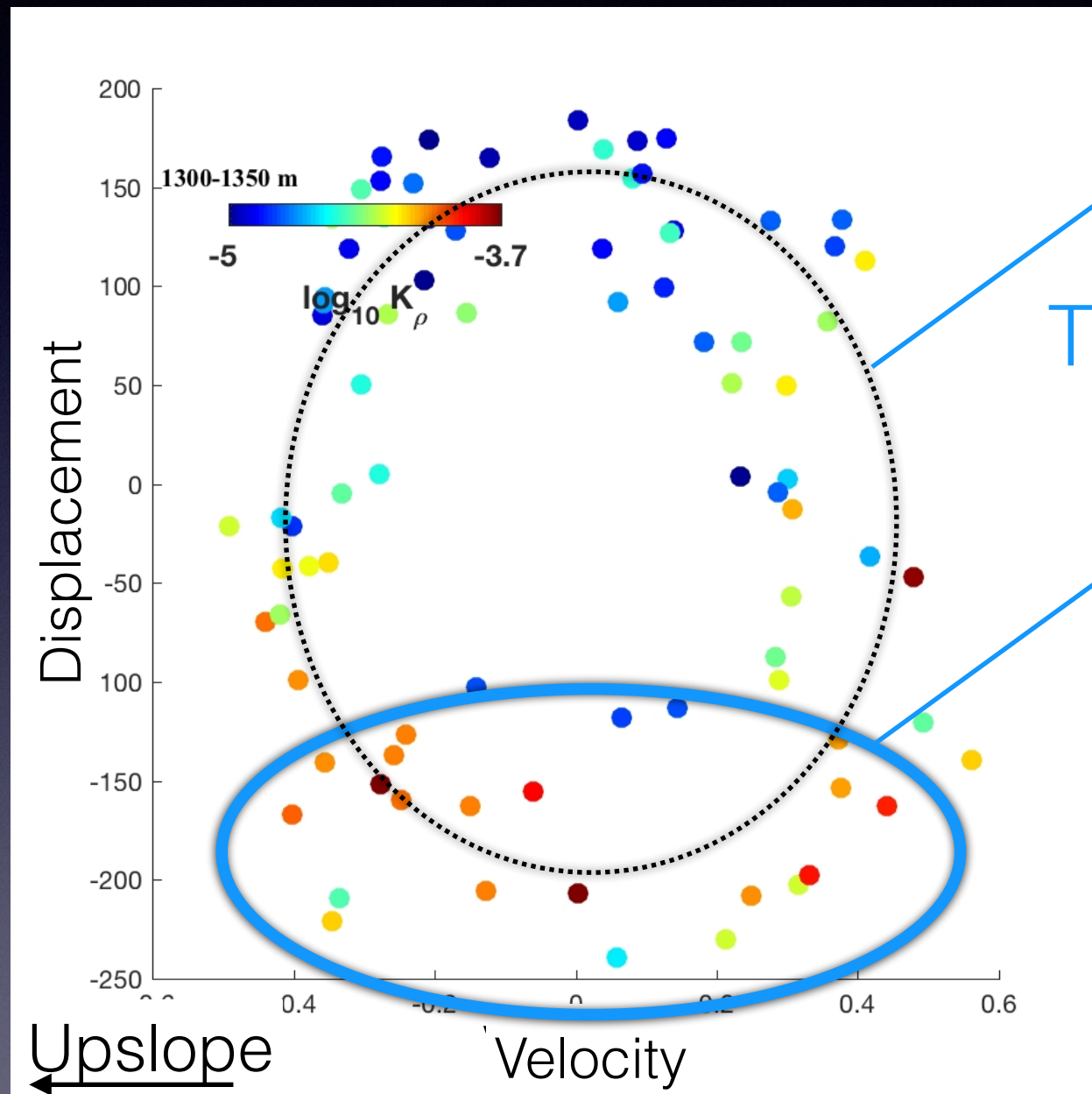


Klymak et al, JPO 2011

Convective Instability

Tidal flow - breaking hydraulic

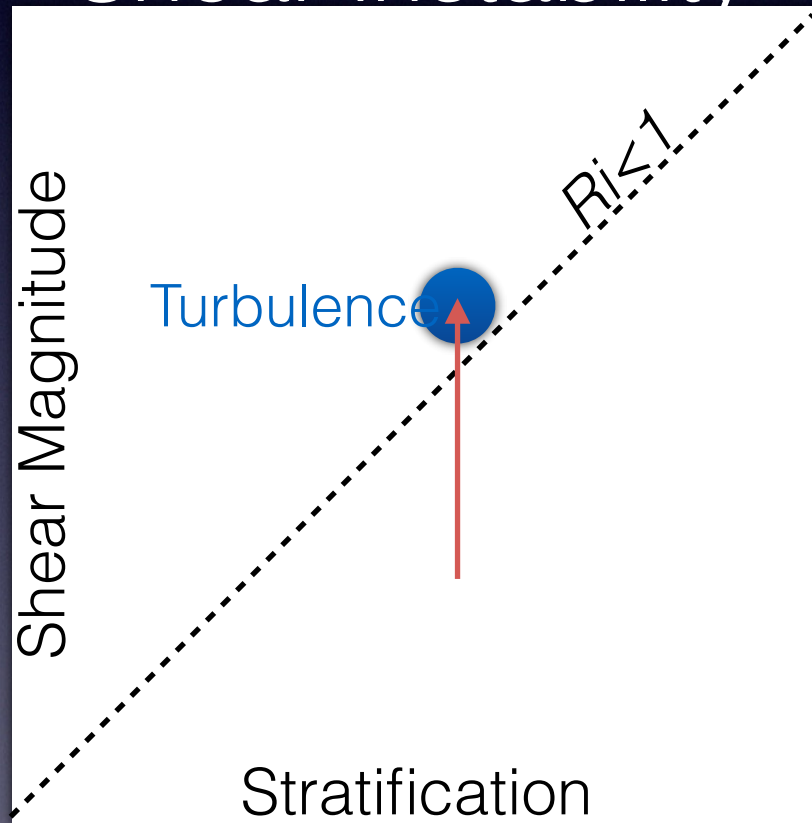
Circular



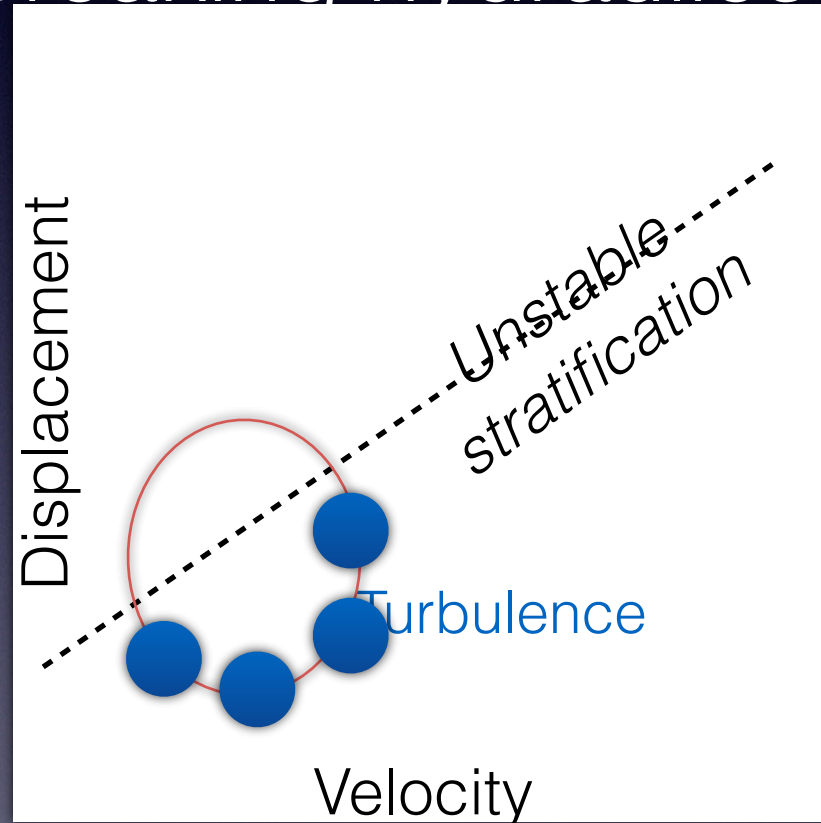
Circular locus $\rightarrow u$, displacement out of phase
Turbulence on downslope flow

- Locally generated internal tides
- Remotely generated internal tides
- Mean-flow hydraulic jumps

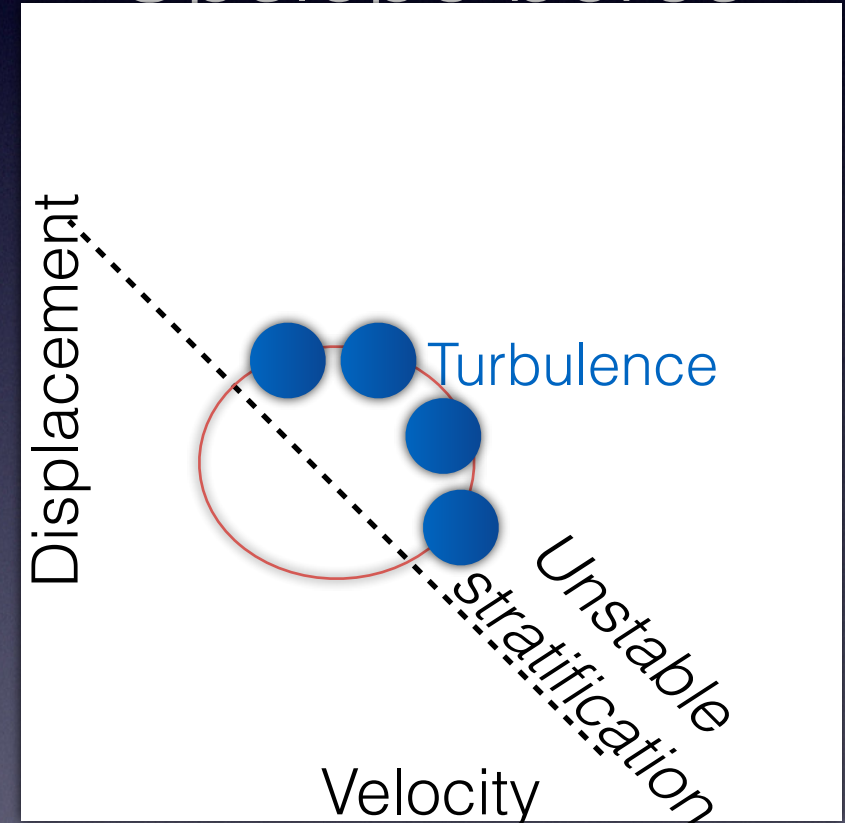
Shear instability



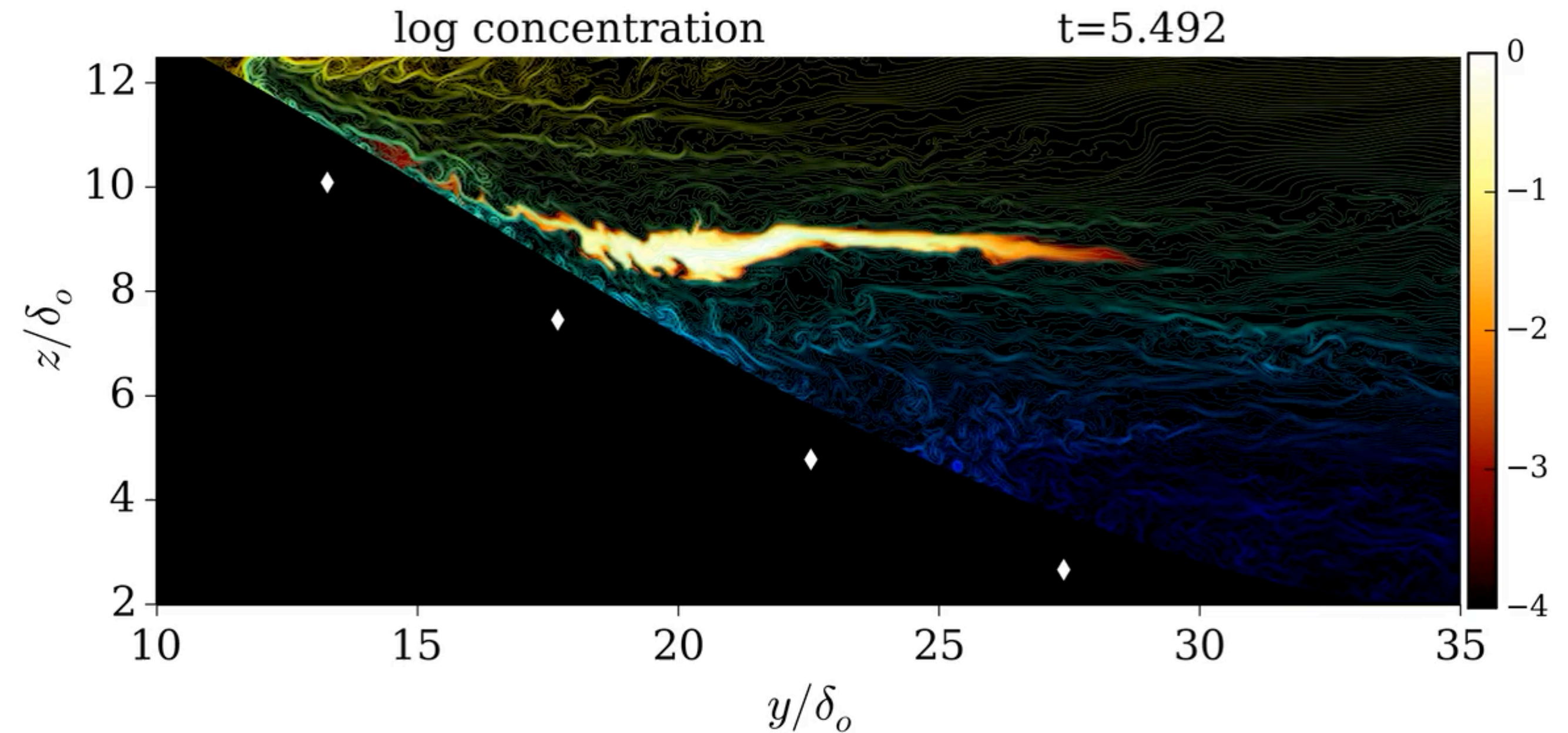
Breaking hydraulics



Upslope bores



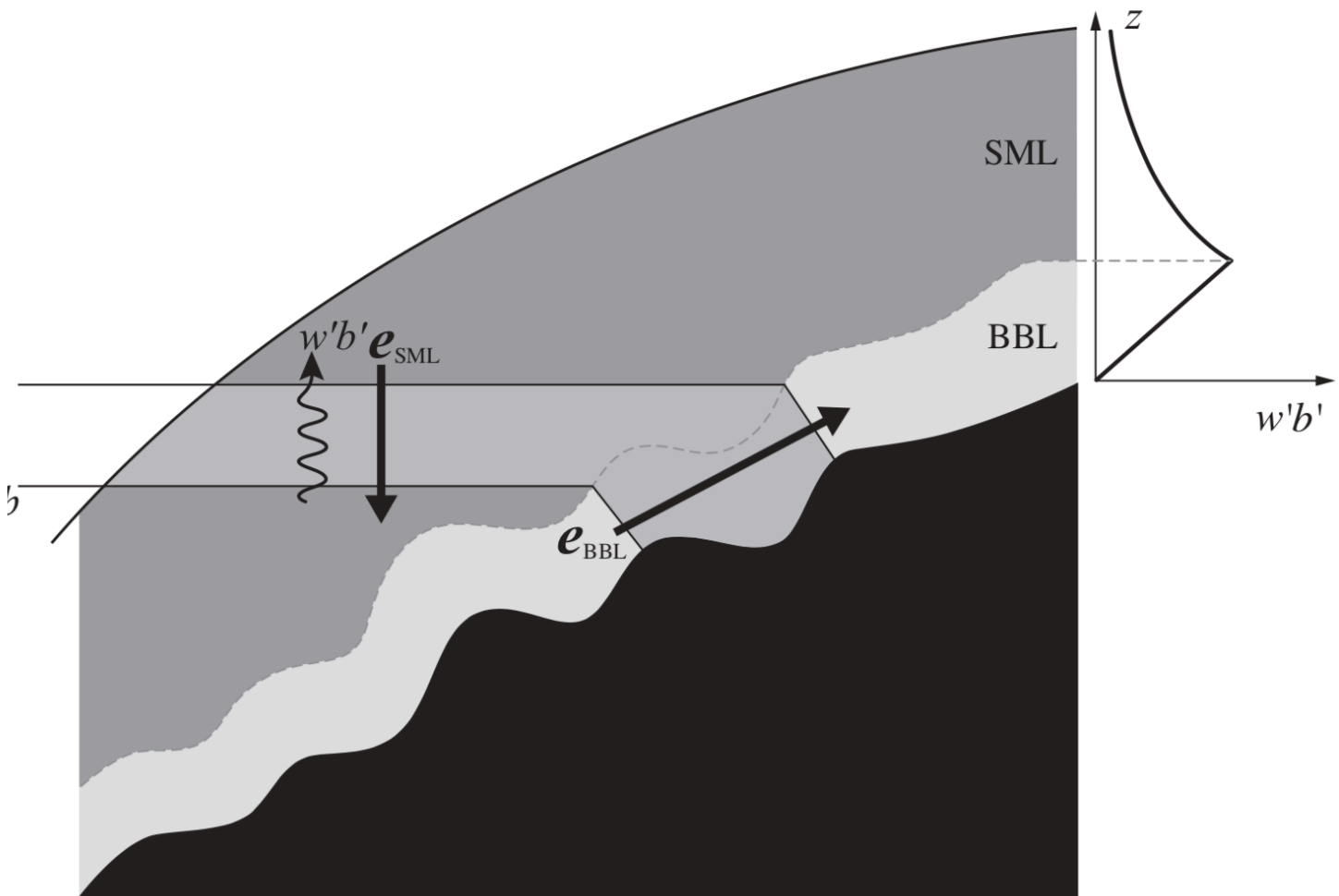
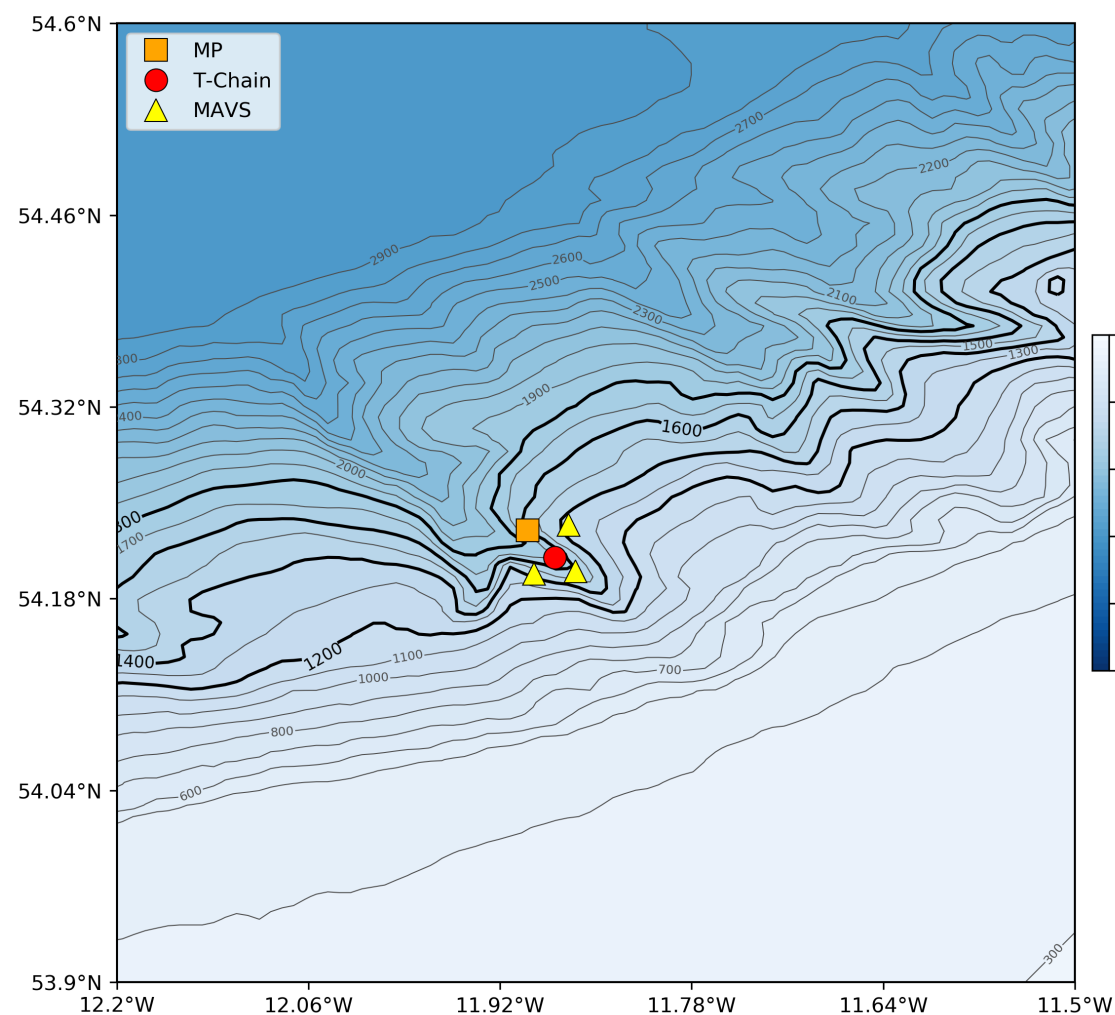
Exchange with the interior



BLT (boundary layer turbulence, and Raf's favorite sandwich)



- Put dye in the bottom boundary layer
- Directly measure both turbulence and the buoyancy flux

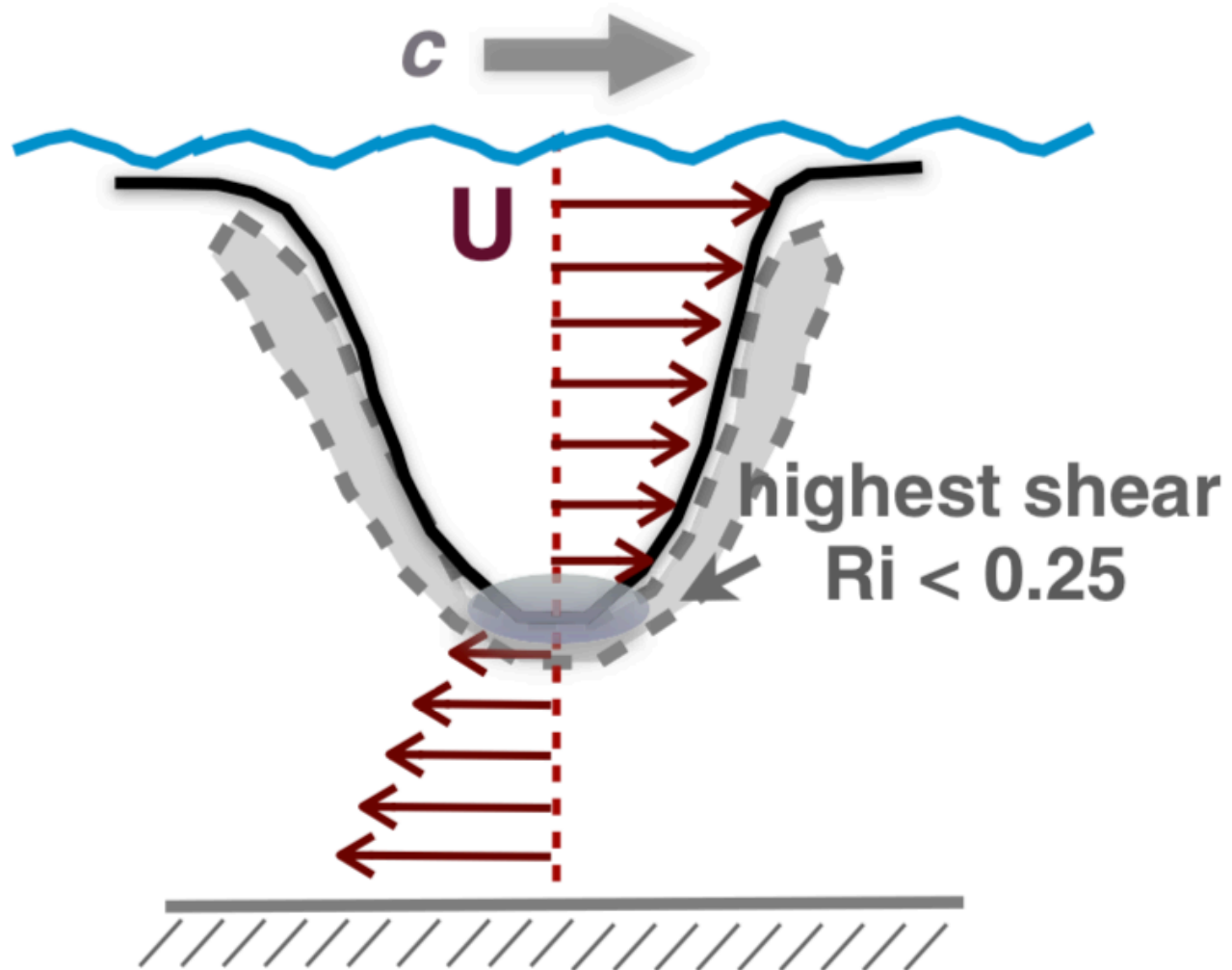


Conclusions

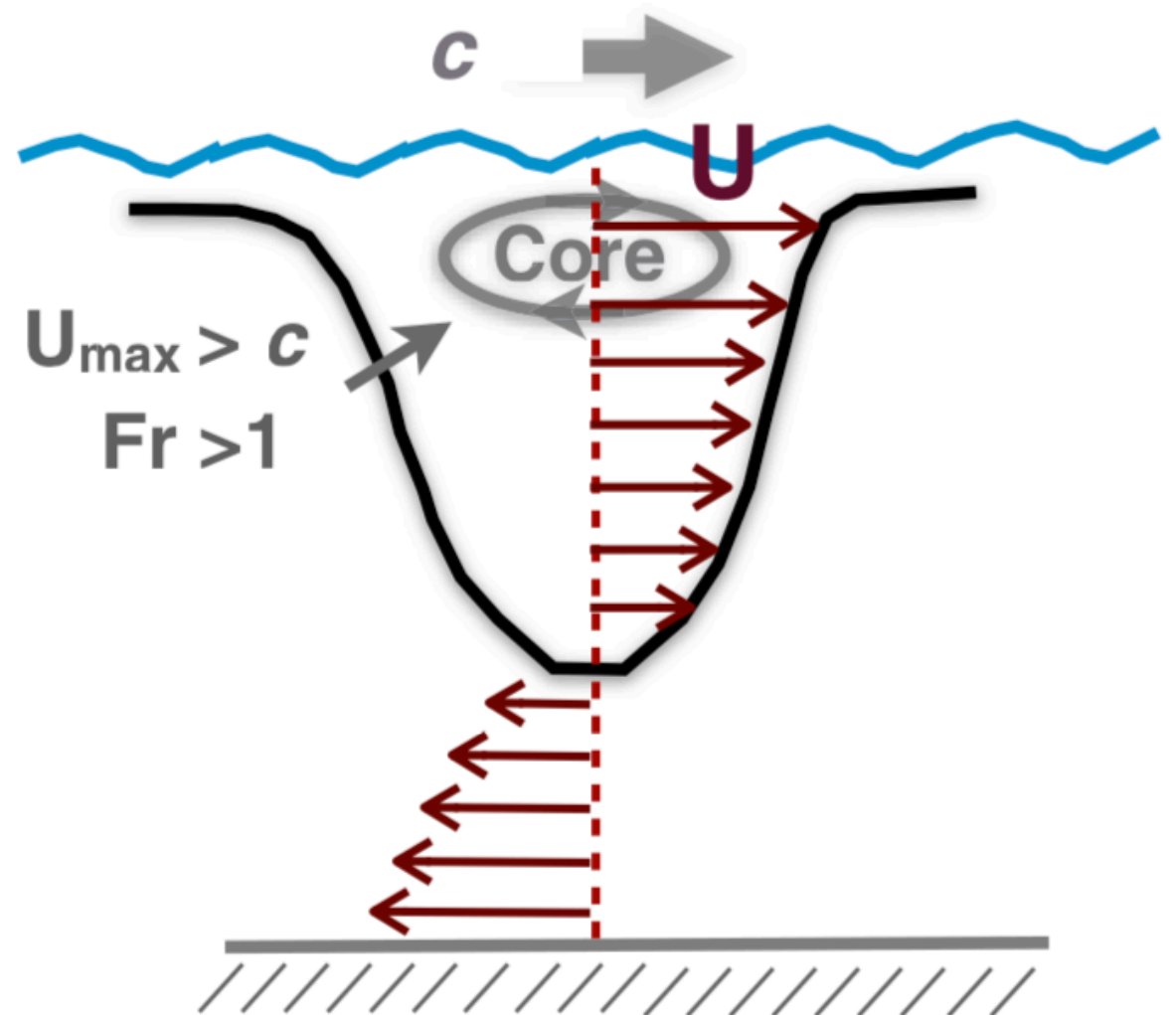
- Turbulence is a crucial parameter to measure in order better understand climate, regional models, and biogeochemistry.
- We must move to measure turbulence on the Argo array of autonomous floats as soon as possible.
- We must understand the physics of near-bottom turbulence and its exchange with the interior of the ocean.

Extra slides

Type I: Shear Instability



Type II: Convective Instability



Type I: 108 waves

Type II: 22 waves

