Measuring Ocean Turbulence

Jim Moum
Jonathan Nash
Bill Smyth
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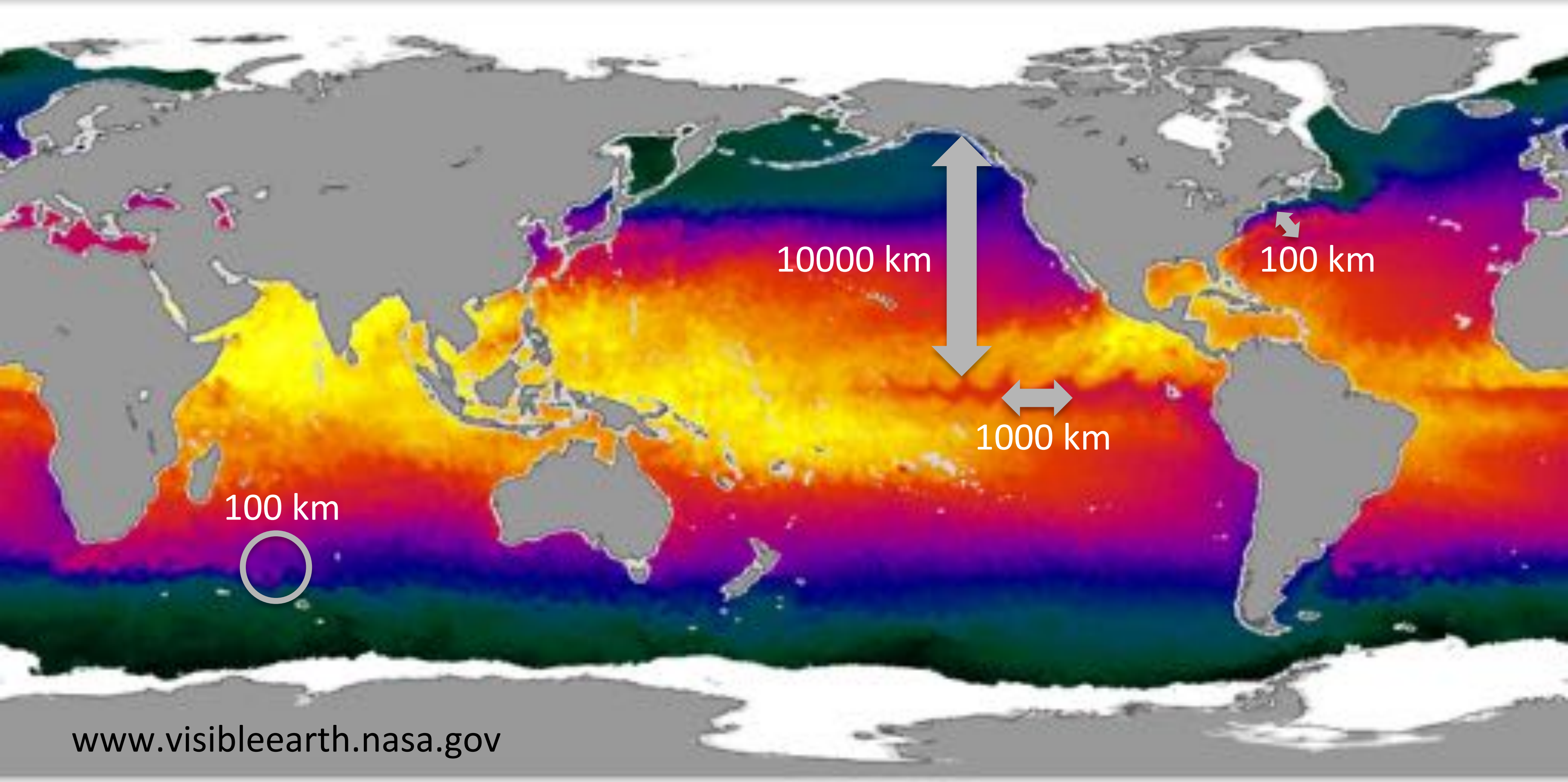
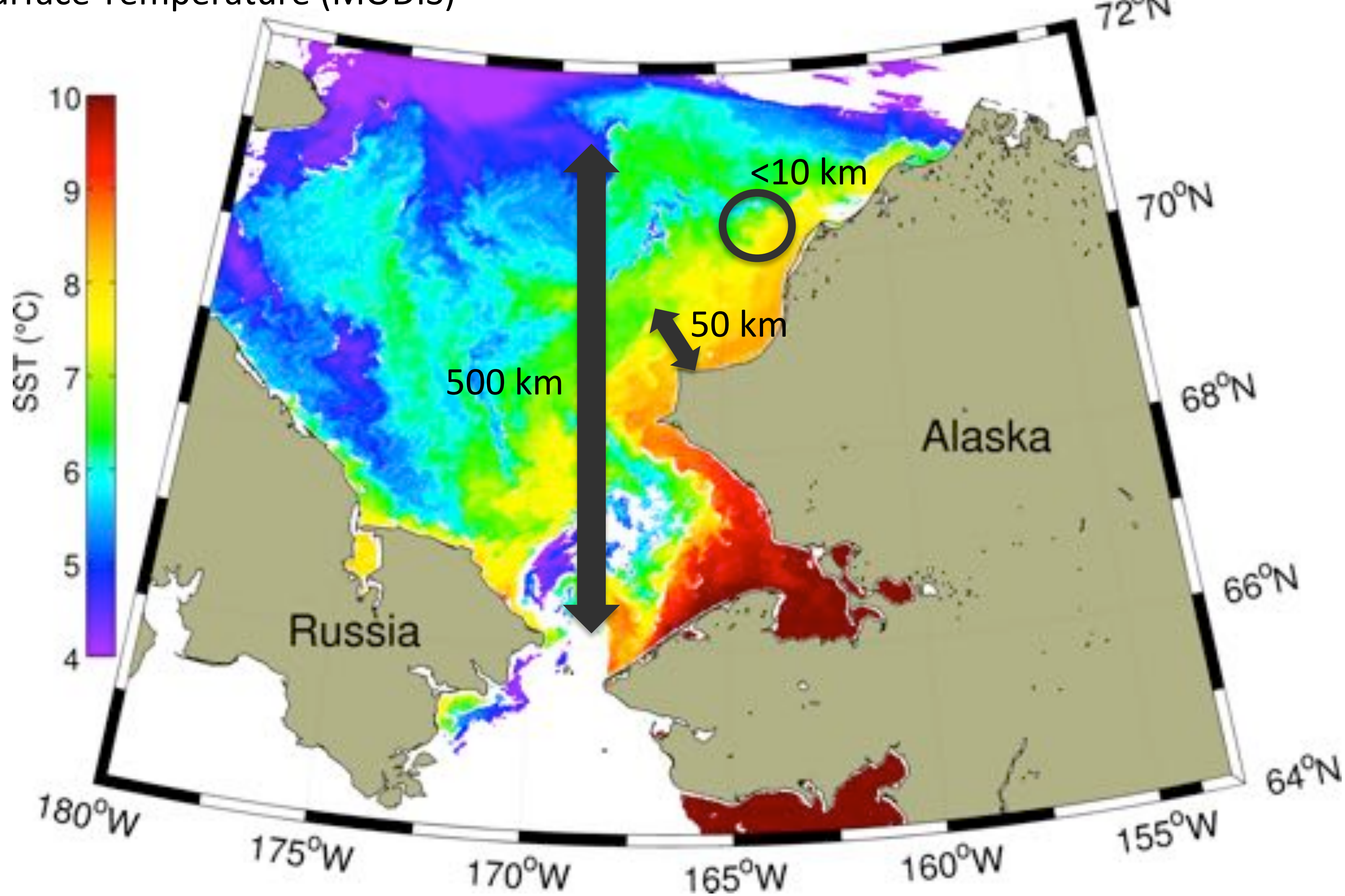
Spatial Scales in the Ocean

Sea Surface Temperature from NASA's Aqua Satellite (AMSR-E)



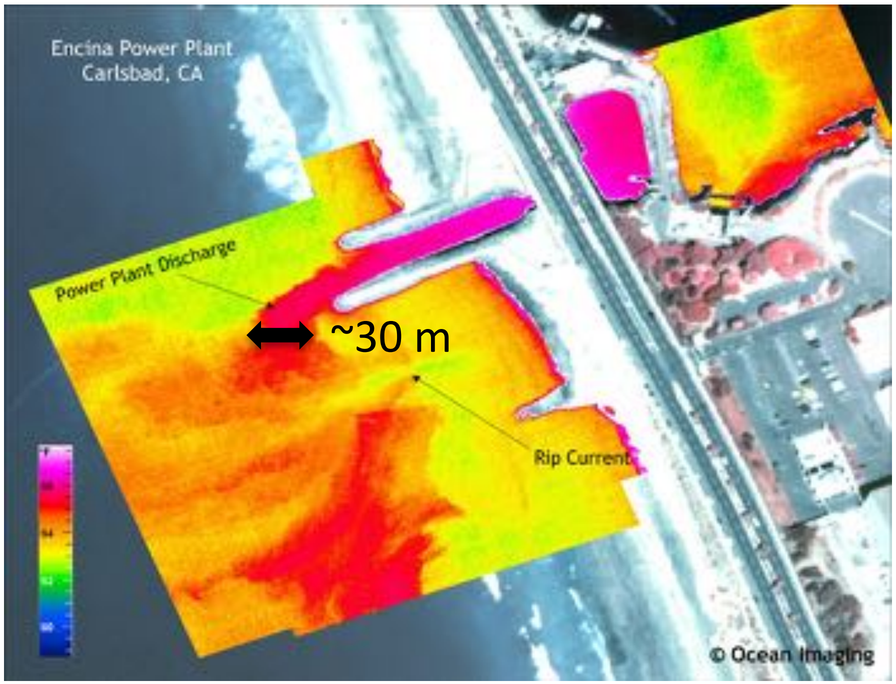
Spatial Scales in the Ocean

Sea Surface Temperature (MODIS)

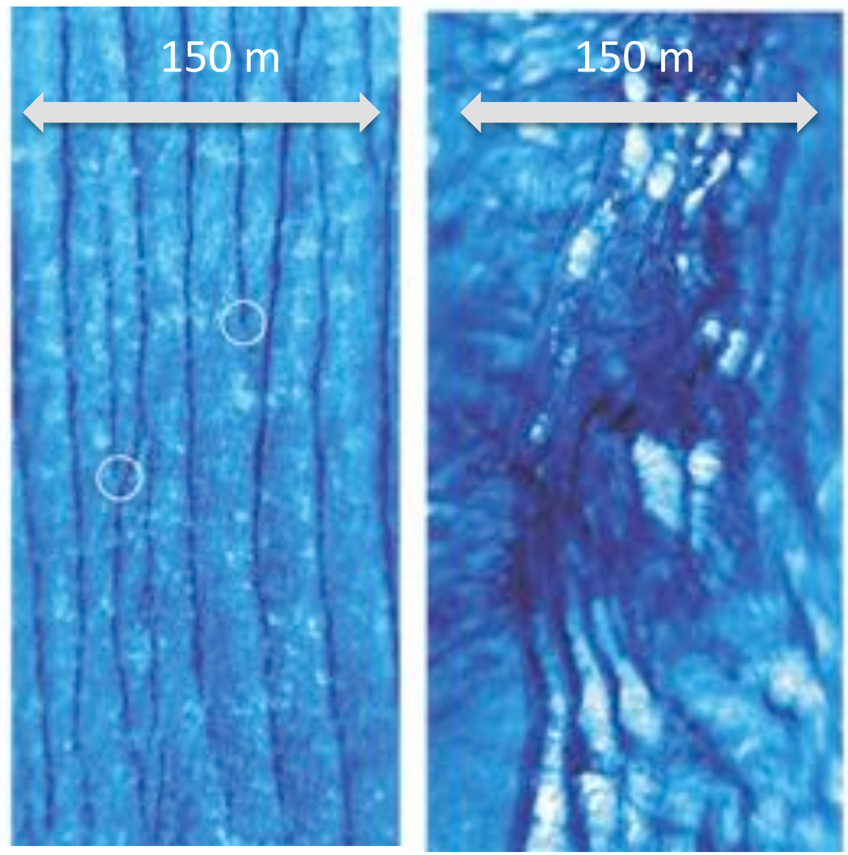


Spatial Scales in the Ocean

Sea Surface Temperature (Field Infrared Imagery)



Plant Discharge, Ocean Imaging

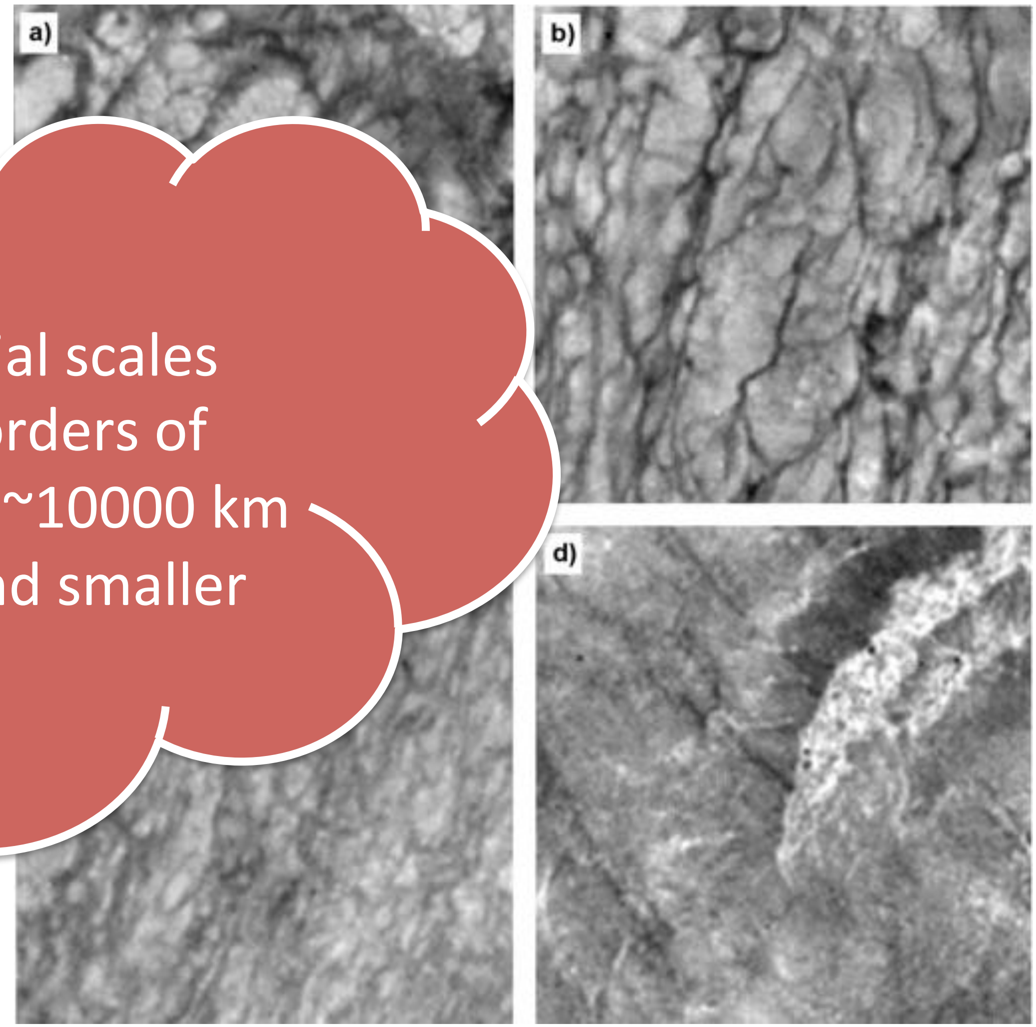


Langmuir and Internal Waves, NRL

Spatial Scales in the Ocean

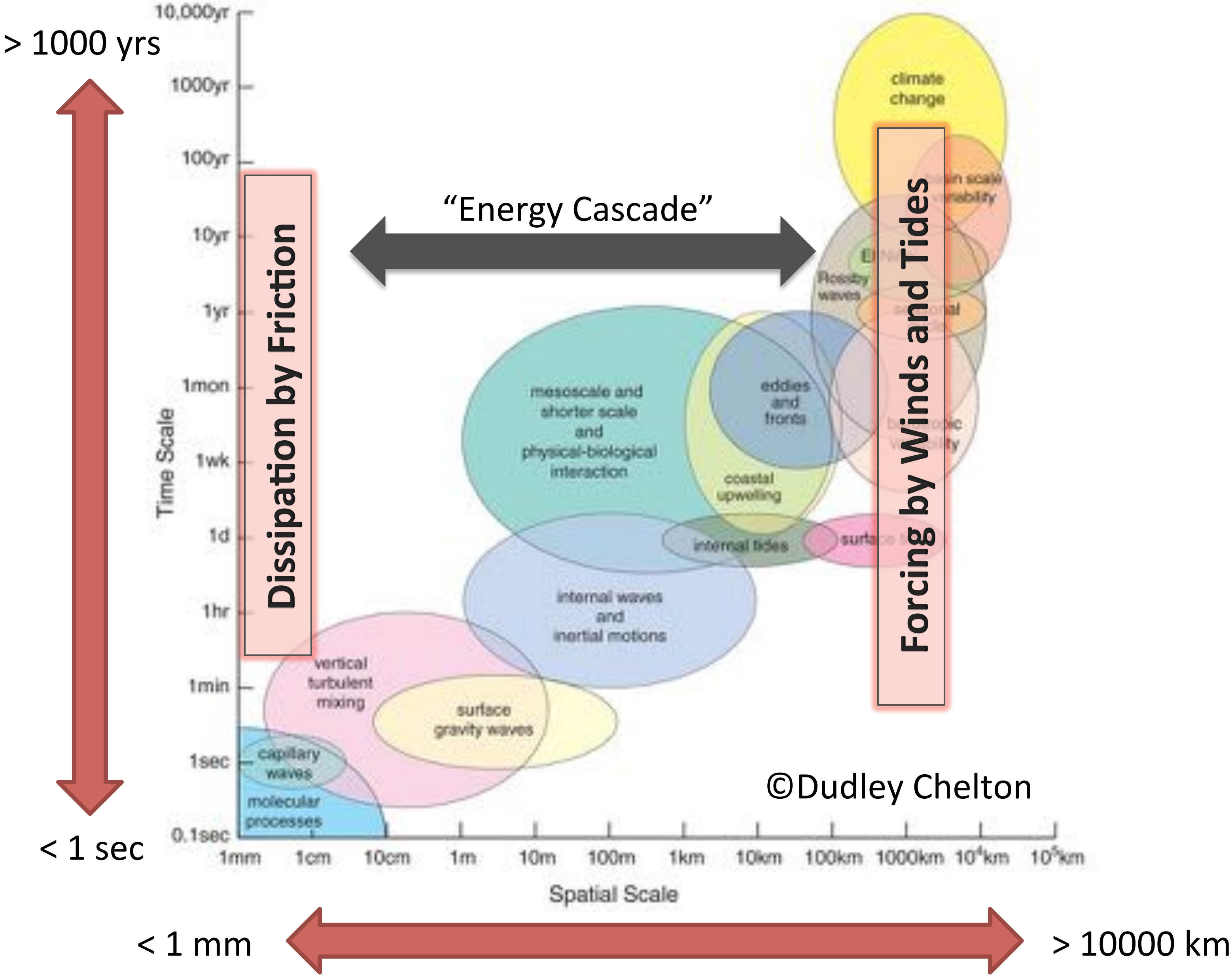
Sea Surface Temperature (Field Infrared Imagery)

Relevant spatial scales range many orders of magnitude from ~10000 km to submeter and smaller

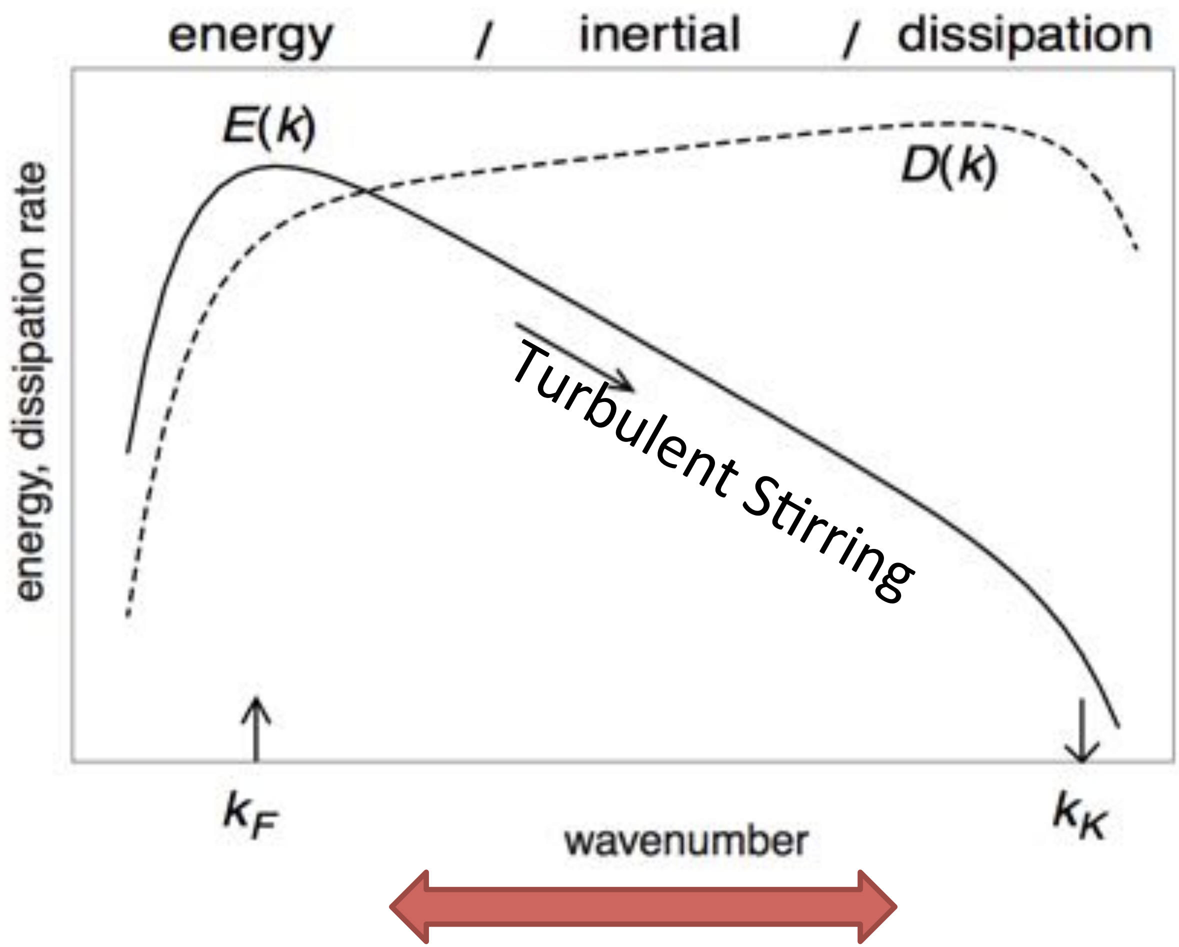


Breaking Waves under Variable Wind, Veronis et al., 2008

Spatial Scales in the Ocean



Re number in the ocean is typically very large!



"Big whorls have little whorls
That feed on their velocity
And little whorls have lesser whorls
And so on to viscosity."
-L.F. Richardson (1922)

The larger the Reynolds Number (UL/ν) the greater the distance between the energy subrange and the dissipation subrange.

Parameterizing Turbulence
The Quest for Improved Ocean Prediction

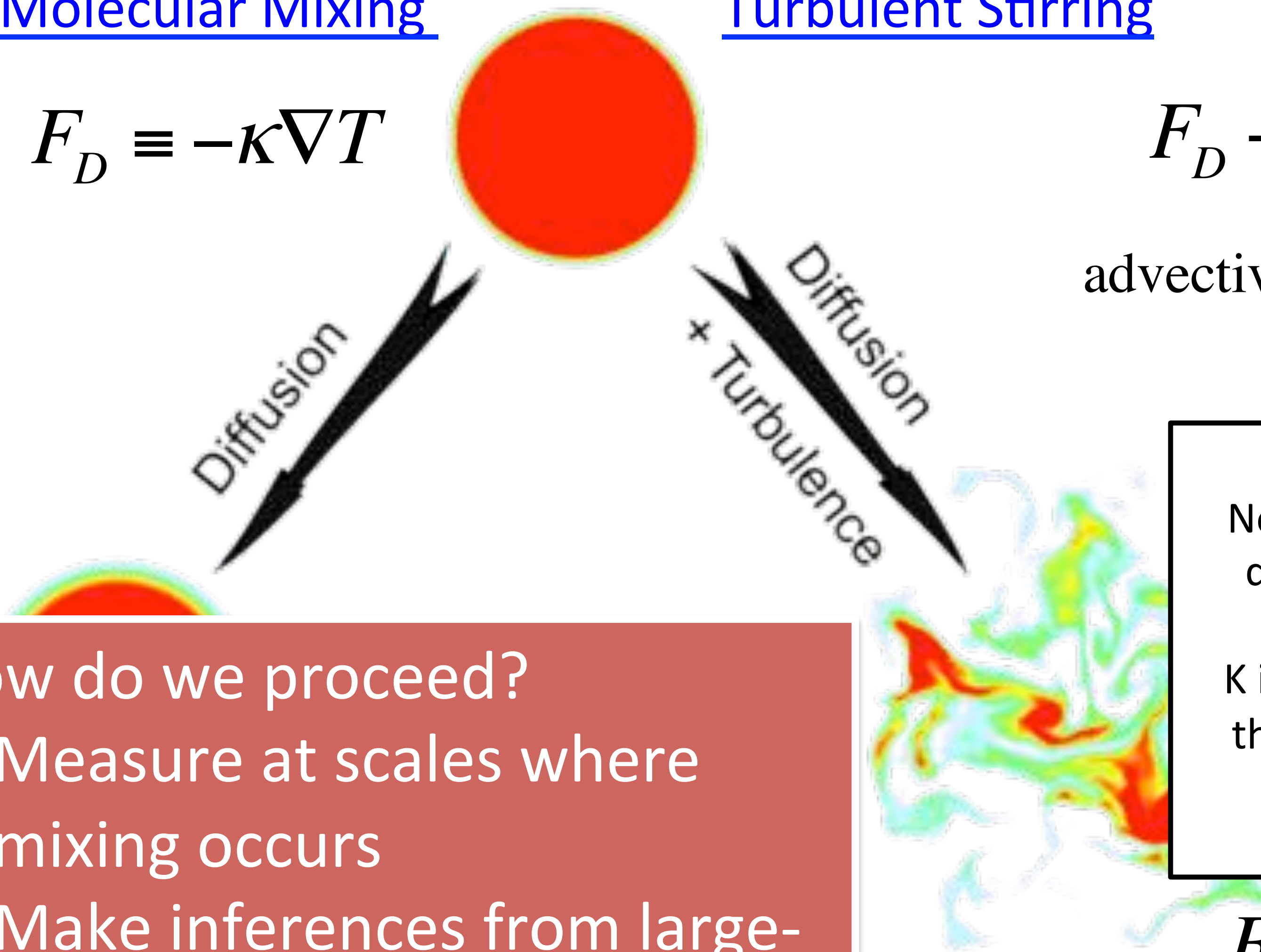
Molecular Mixing

$$F_D \equiv -\kappa \nabla T$$

Turbulent Stirring

$$F_D + F_{Advective}$$

$$\text{advective terms} \sim u\frac{\partial T}{\partial x}$$



Nonlinear Terms depend on the flow→
K is a property of the flow not the fluid!!!

$$F \equiv -K \nabla T$$

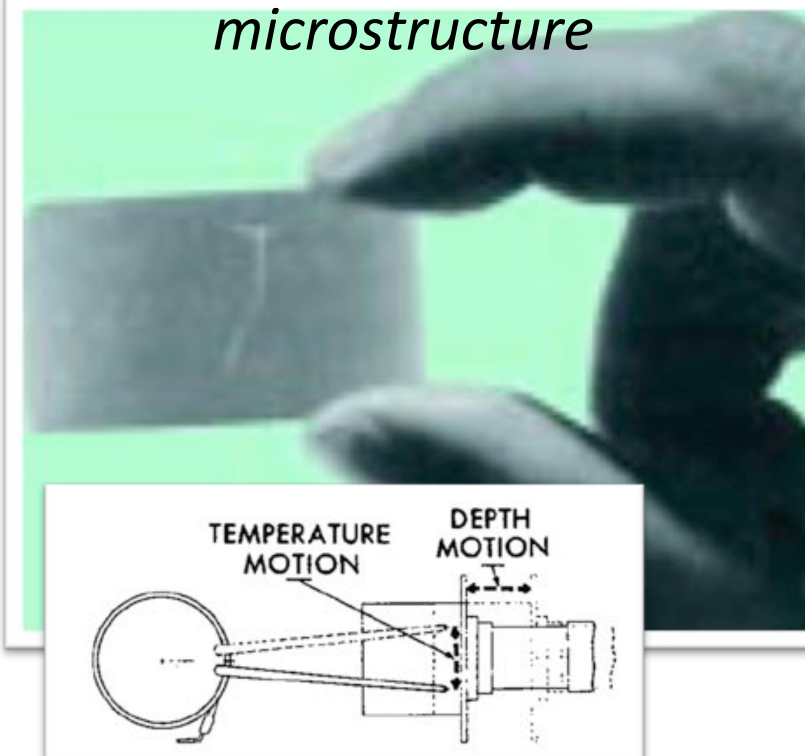
How do we proceed?

1. Measure at scales where mixing occurs
2. Make inferences from large-scale properties & flow

Bathythermograph: continuous measurement of ocean temperature

A bathythermograph, Spilhaus, 1938

"stiction" attributed to friction by the recording stylus rather than ocean microstructure

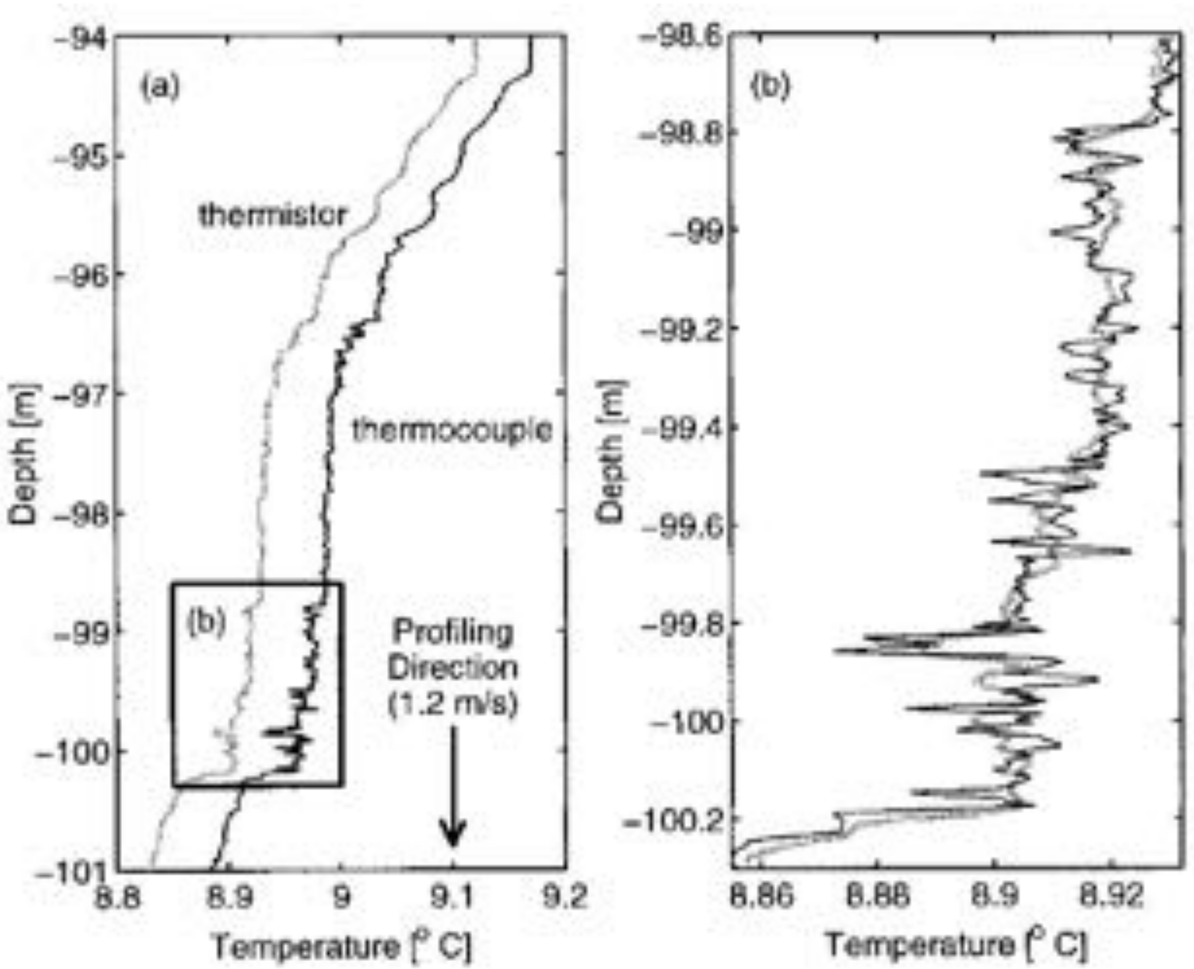


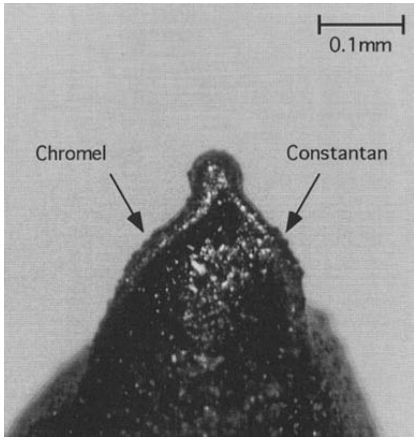
BT were lowered through the ocean on a wire, measuring ocean temperature based on the expansion/compression of copper tubing filled with xylene. Pressure changes in the tubing were transmitted to a spring and stylus, which recorded the signal on a glass slide. Water pressure caused the glass slide to shift in depth, leaving a trace of temperature with depth, "a temperature profile". Prior to this time temperature was measured at discrete depths with reversing thermometers.

mid-1930s to 1970s

Direct Measurements

Thermistors & Thermocouples: high-resolution of ocean temperature





Used on…

- Profilers
- Towed bodies
- Submarines

By the early 1950s, temperature measurements from thermocouples and thermistors had sensitivities of a few thousandths of a degree Celsius.

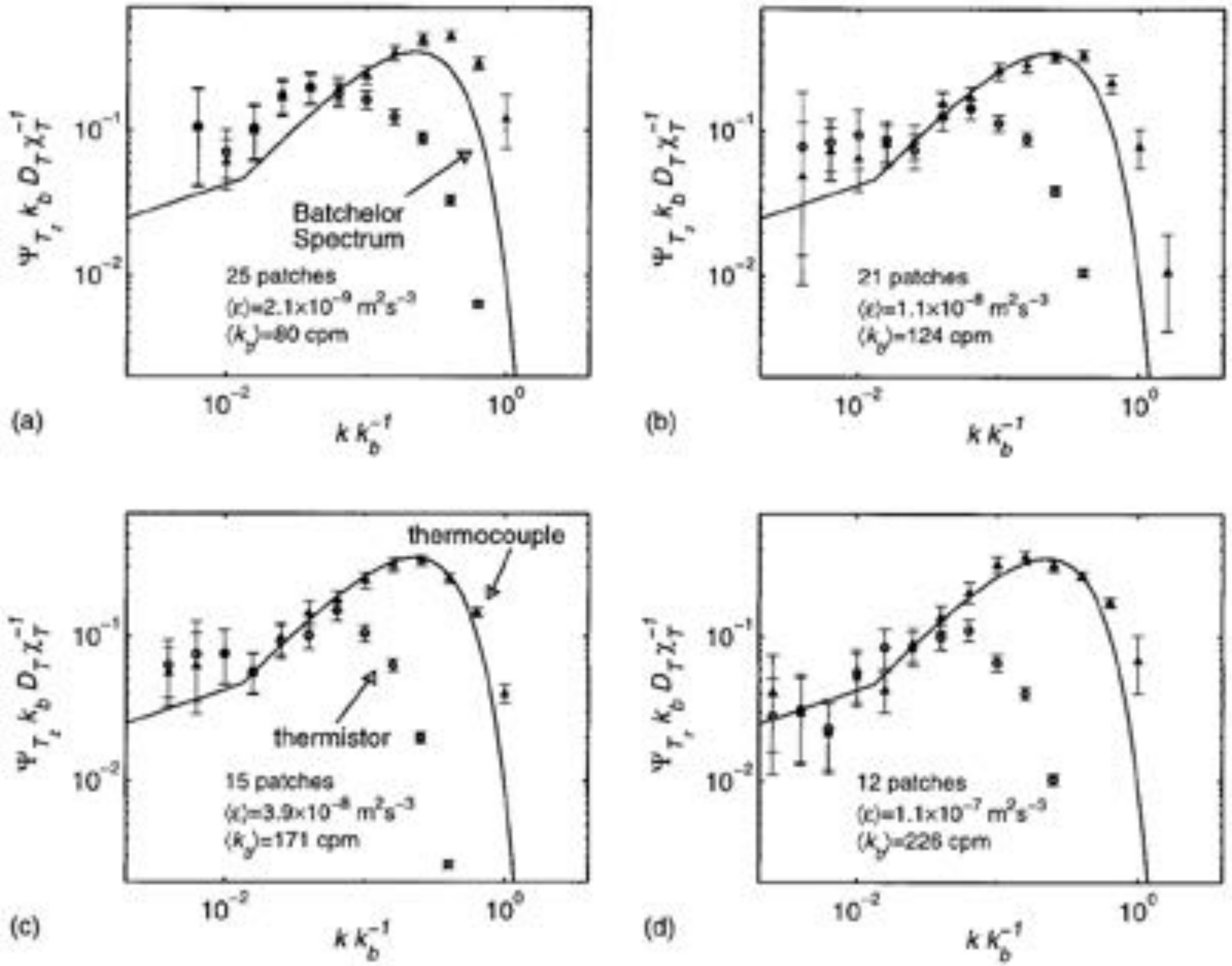
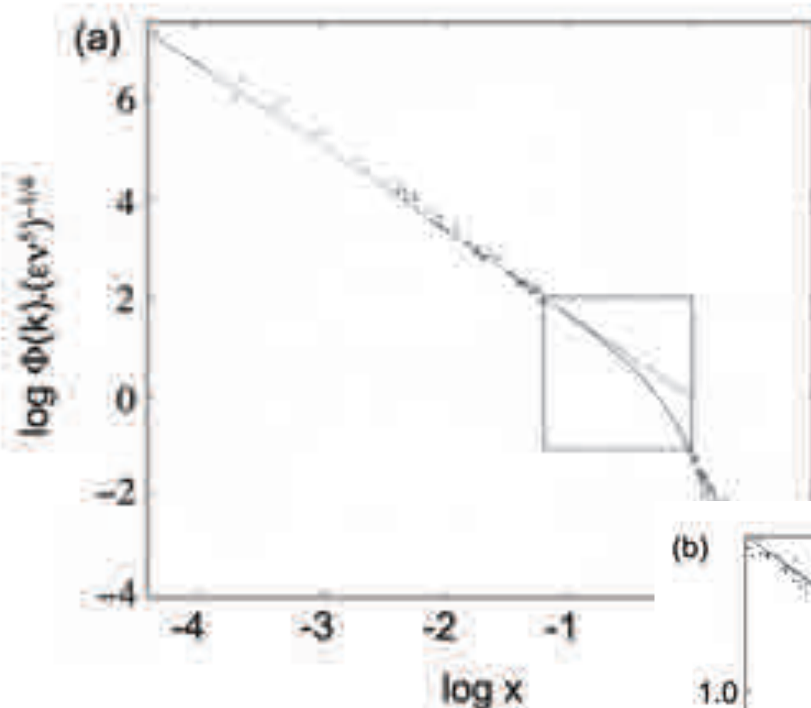


FIG. 9. Mean nondimensional temperature gradient spectra $\Psi_{T_z} k_b D_T \chi_T^{-1}$ for four different ranges of ϵ defined by Batchelor wavenumber (in cpm): (a) $k_b < 100$, (b) $100 < k_b < 150$, (c) $150 < k_b < 200$, and (d) $k_b > 200$. Spectral estimates from thermistor measurements are represented by open circles; triangles represent those from the thermocouple. Error bars represent 95% bootstrap confidence limits. Profiles were made at 1.2 m s^{-1} and no corrections for frequency response have been applied. The solid lines represent Batchelor spectra with $q = 3.7$ calculated for the mean ϵ and χ_T of the included patches.

Hot-Film Anemometer: velocity microstructure

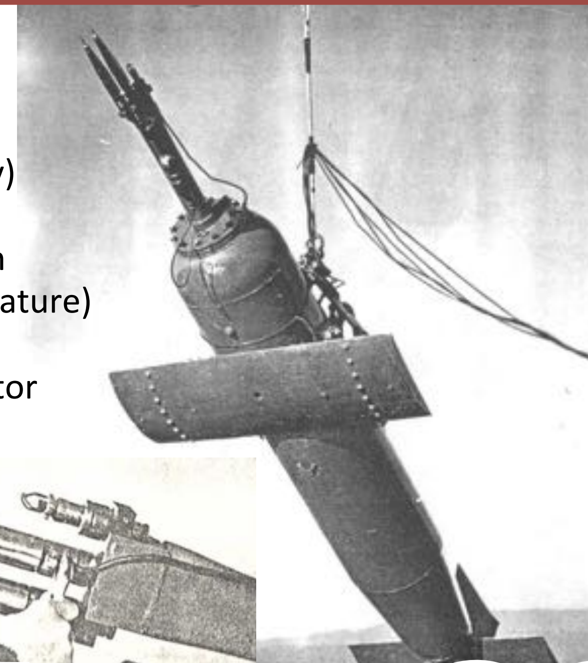
Direct Measurements

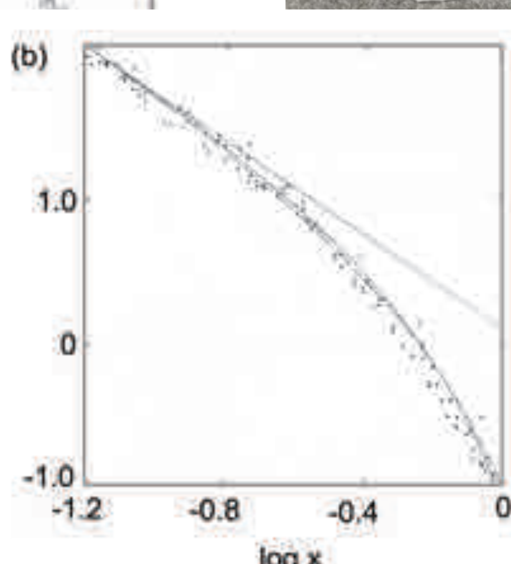


hot film
(velocity)

cold film
(temperature)

thermistor





resolution of the inertial subrange and confirmation of theory

Navy Sponsored Development
"stratification might effectively suppress any turbulence that did occur, causing a turbulent submarine wake to stand out (Stewart, personal comm.)"
-from Gregg 1991

Grant, Stewart, and Moilliet [1962]

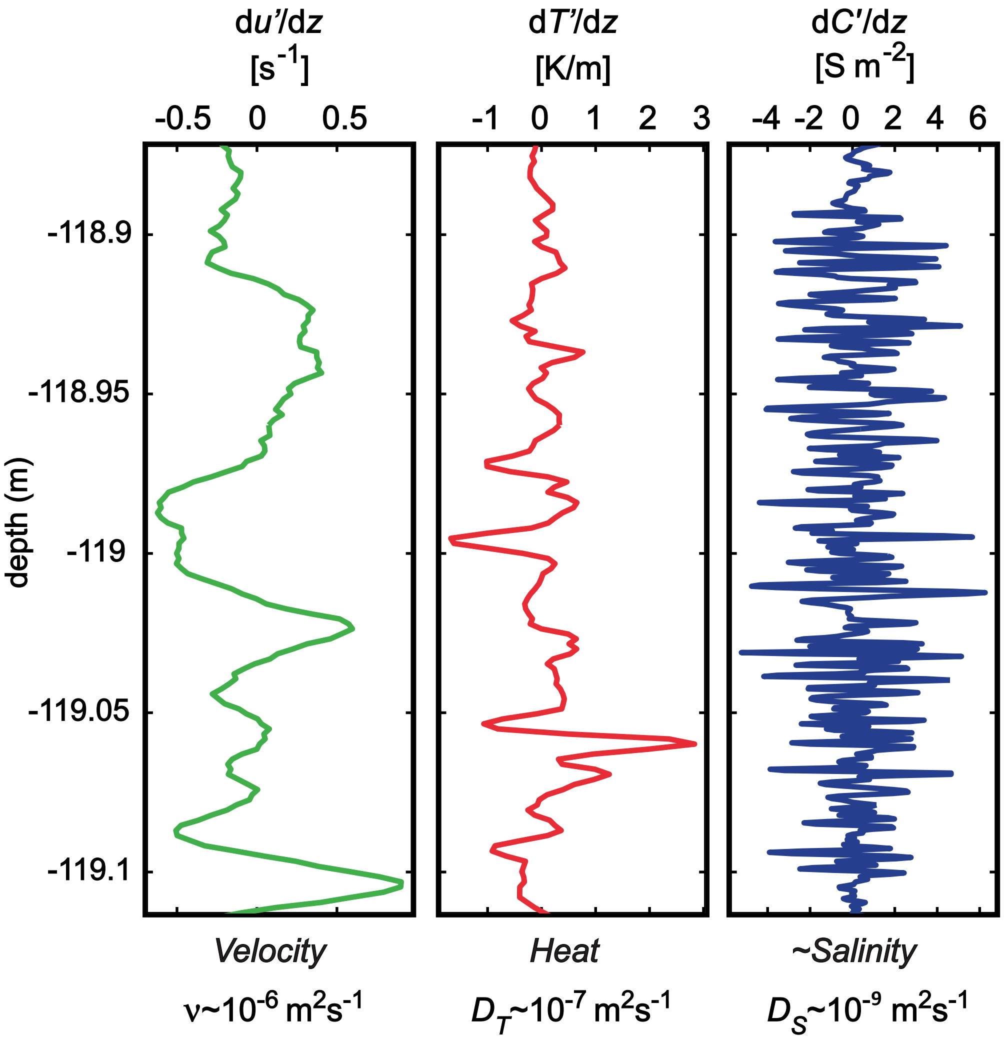
Free-falling Turbulence Profilers

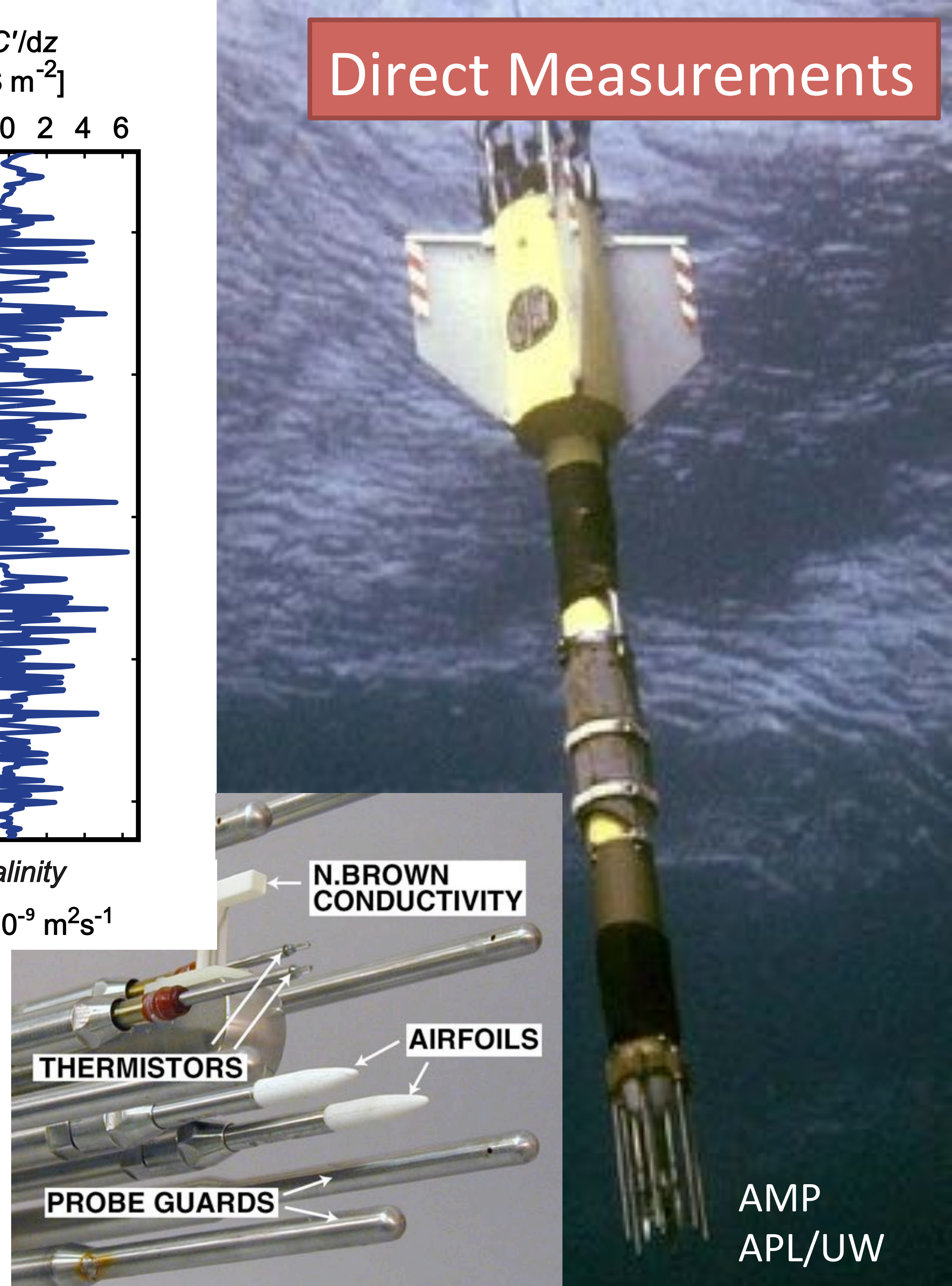
- The MSR had glass rod thermistors (sensitivity 10 µ°C) that originally recorded internally on paper charts!

- Airfoil turbulent velocity sensor for use in the ocean was pioneered by Tom Osborn (Cox's student) in the mid-1970s. The airfoil senor is superior to the hot-wire approach in the ocean due to strong turbulence and large temperature changes.

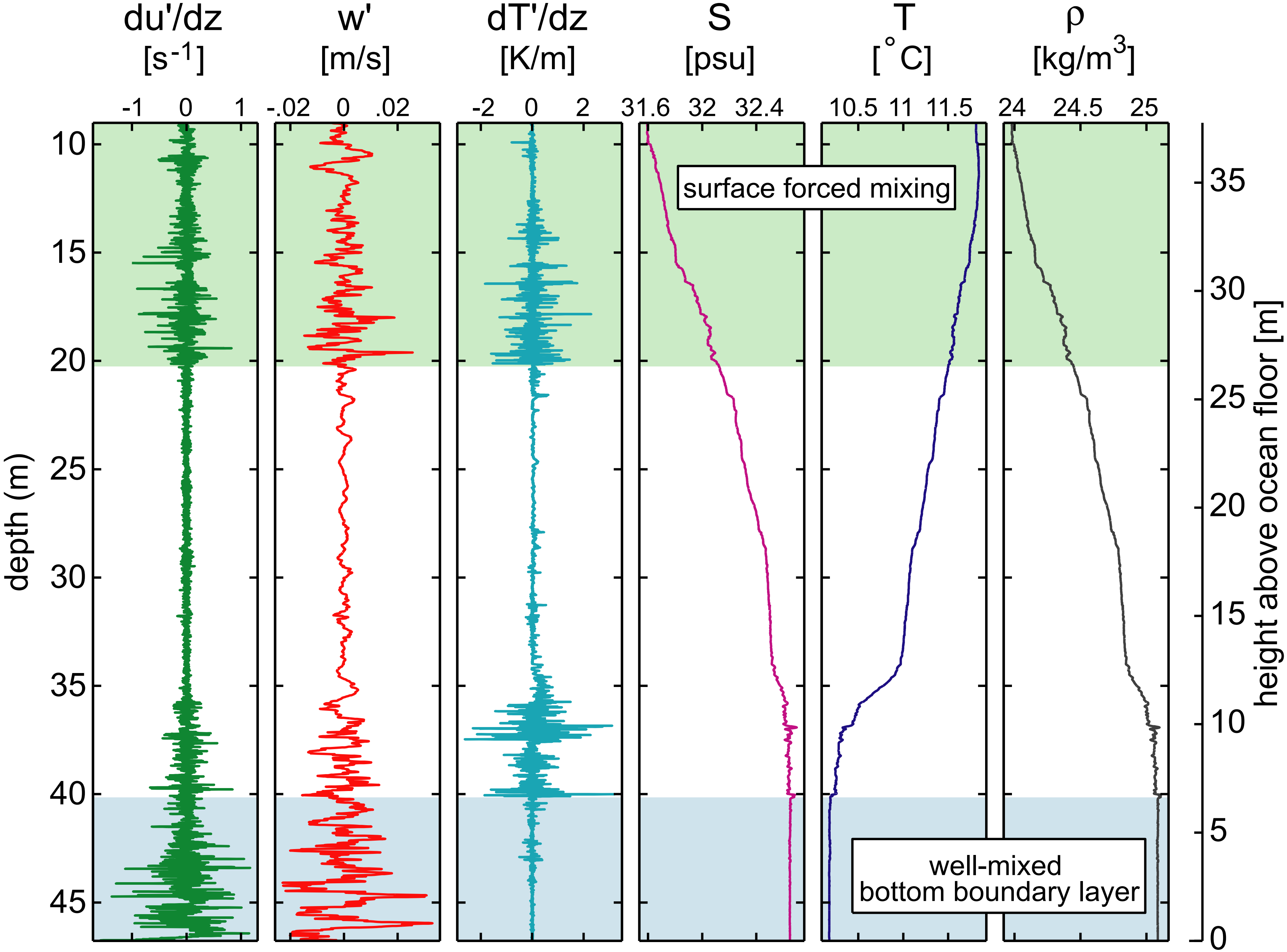
- Several groups developed different instrument systems in tandem during the mid-1970s through the 1980s.
  - Gregg APL (AMP)
  - Caldwell & Moum OSU
  - Toole & Schmitt WHOI

Direct Measurements






Direct Measurements
OSU’s Chameleon
Ocean Mixing
OSU



“Typical” profiles of turbulence over a small bank *(Nash & Moum 2001)*

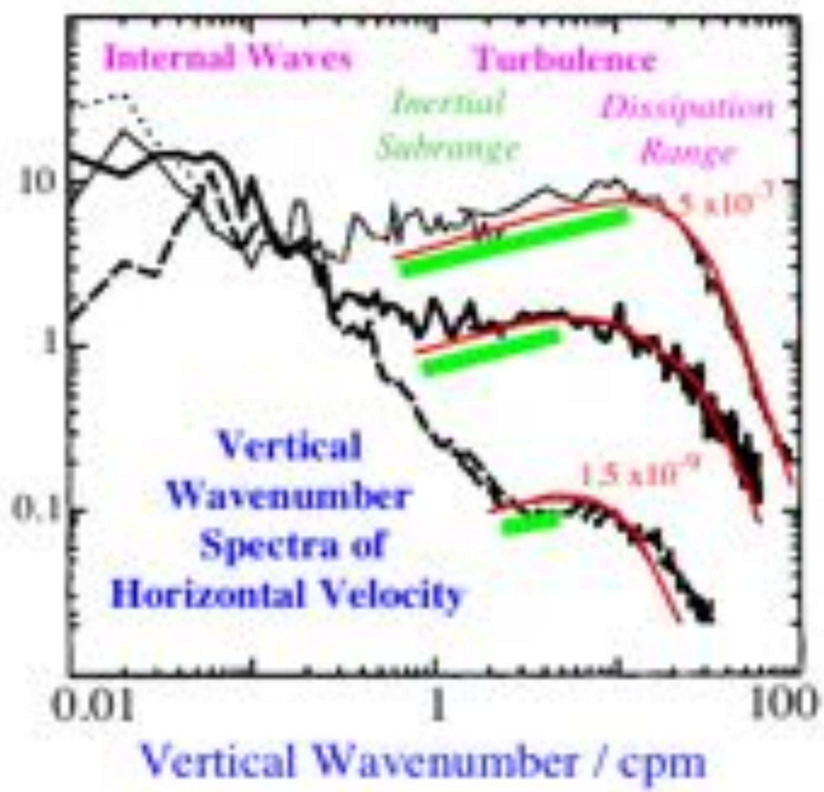
Measuring ε, TKE dissipation rate

"Measure Velocity gradients, Fit Universal Spectra"

Eulerian

Inertial Subrange (Velocity)

$\Phi_u(k)=\alpha\varepsilon^{2/3}k^{-5/3}$



Eric D'Asaro Applied Physics Lab, UW

From TKE dissipation rate (ε) we can estimate the effective turbulent diffusivity by assuming a balance between shear production, buoyancy flux, and dissipation (Osborn 1980)

$$K_\rho = \frac{R_f \varepsilon}{(1 - R_f)N^2}$$

$$K_\rho = \frac{\Gamma \varepsilon}{N^2}$$

Other Approaches: Dye Injections

Direct Measurements

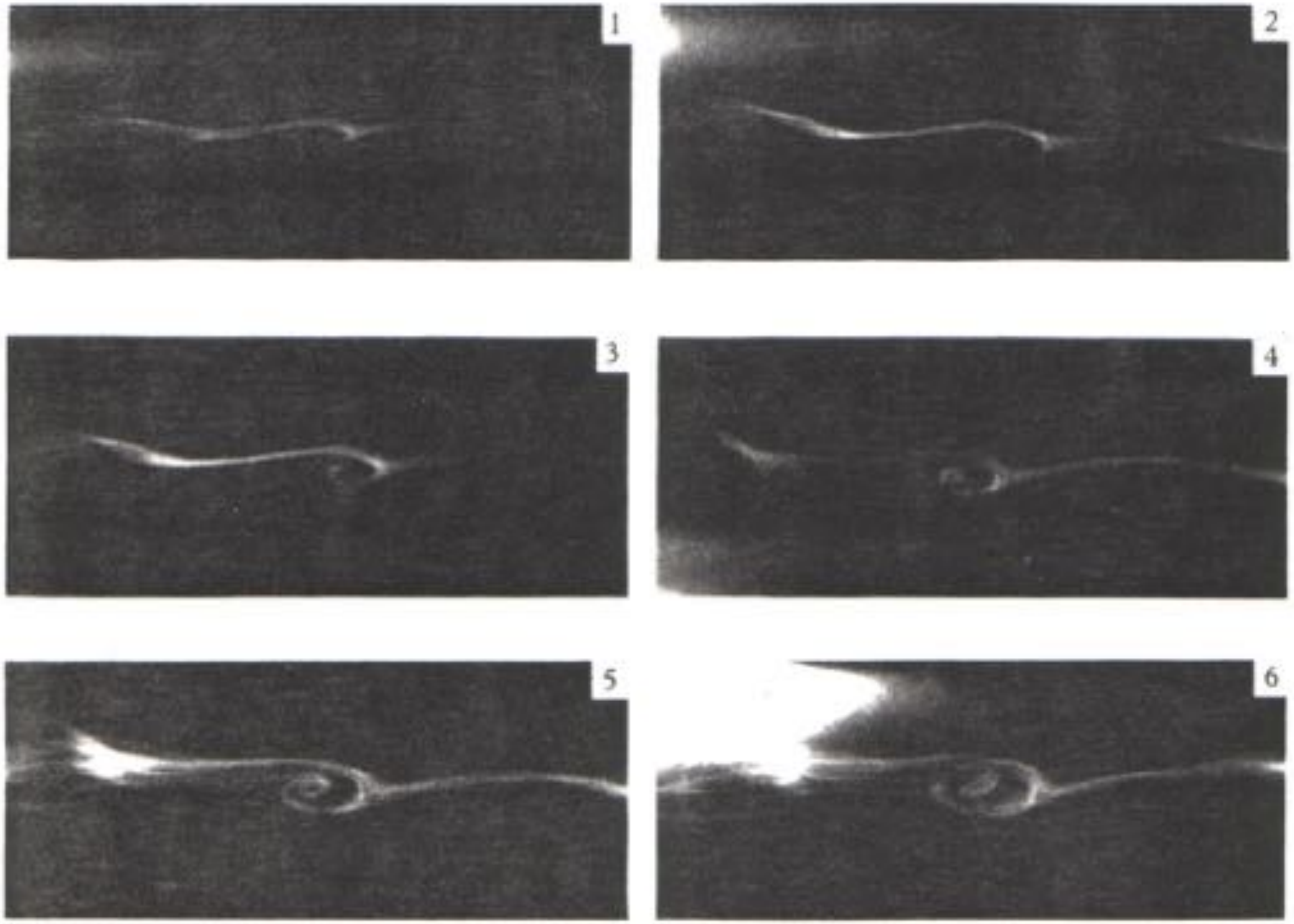


FIGURE 14. Stages in the growth of an exceptionally large breaker (λ, 250 cm; $2a$, 60 cm). Note the 10 cm markings on the scale at bottom right.

Woods 1968

Direct Measurements

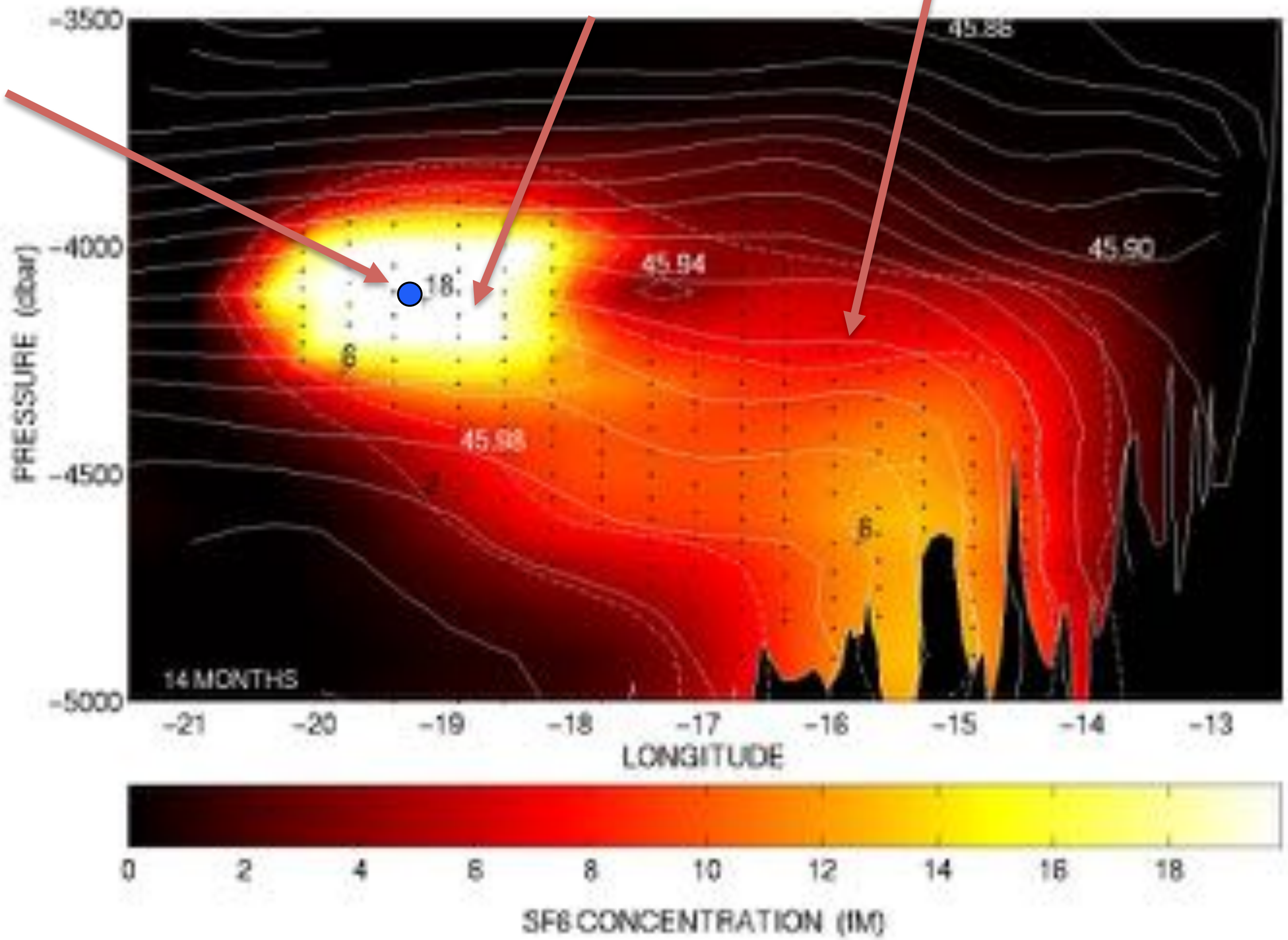
Large scale dye injections to determine the integrated effect of mixing

Brazil Basin result after 14 months

concentrated dye
- weak mixing

diffuse dye
– strong mixing

initial injection point

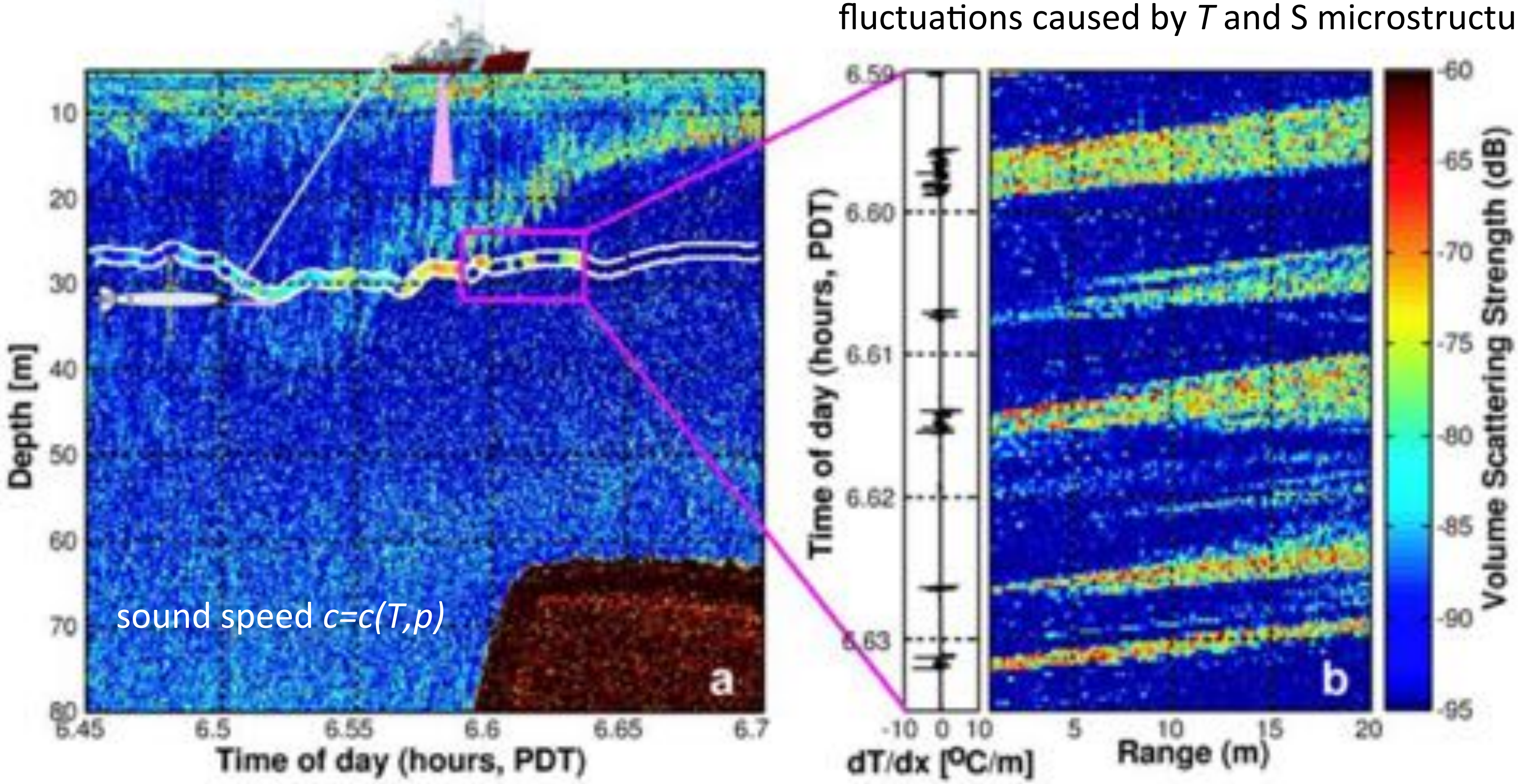


Ledwell, WHOI

Other Approaches: High-Frequency Acoustics

Direct Measurements

scattering from small-scale sound speed fluctuations caused by *T* and S microstructure

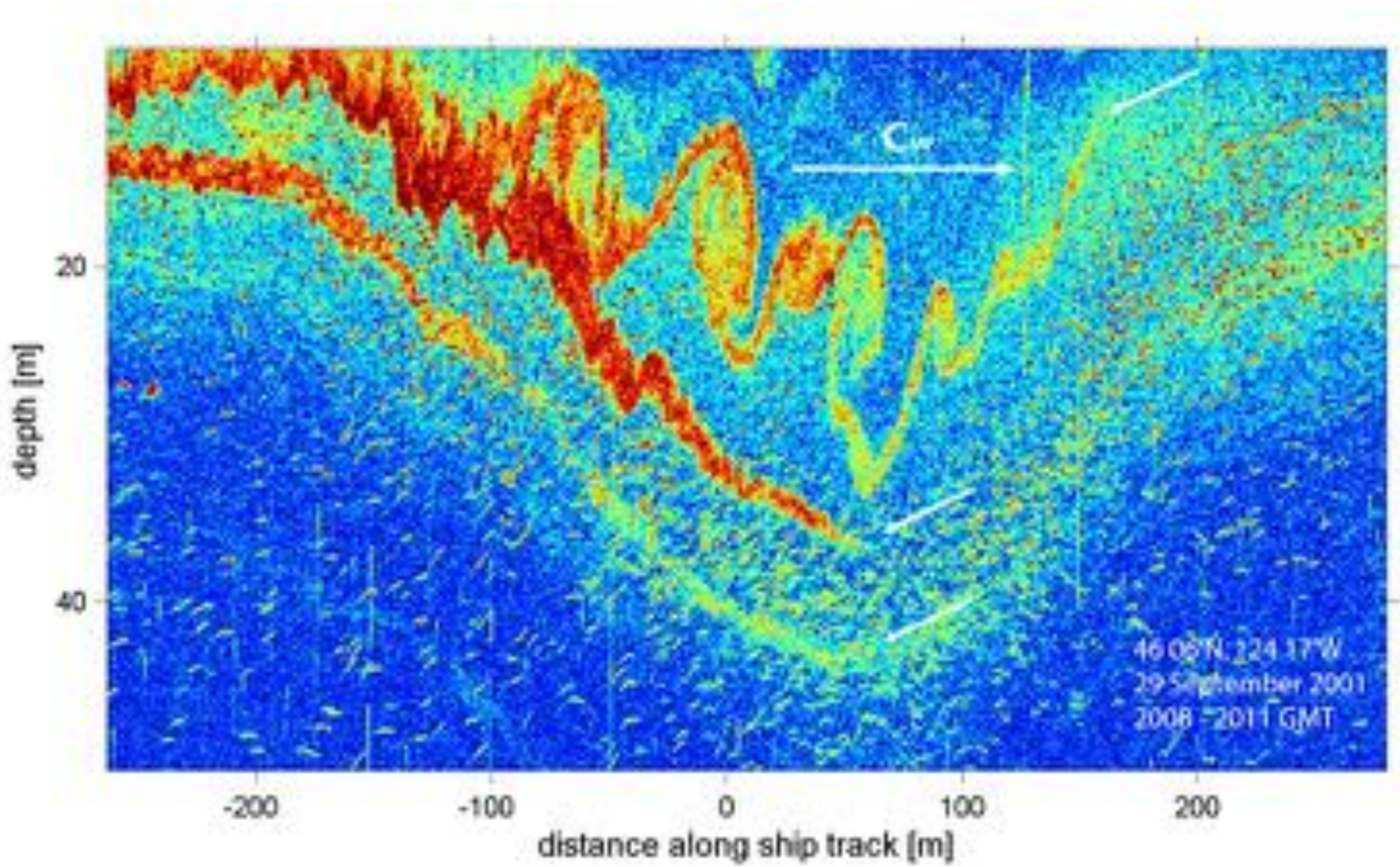


Ross and Lueck 2003

Figure 1. (a) Sketch of experimental setup (not to scale) overlaying an echogram from the 100 kHz ship-board sounder. The pink beams emanating from the ship and the towed vehicle represent the 100 and 307 kHz sounders, respectively. White line is the approximate path of the towed vehicle (ship-board sounder data is lagged to line up with vehicle data) and the colored circles are predicted backscatter at 100 kHz as estimated from microstructure data. (b) Echogram from 307 kHz vehicle-mounted sounder for time and depth of the pink box in a. Each horizontal line shows the echo from one ping. As time progresses downwards and range is distance ahead of the vehicle, parcels of water travel diagonally across the figure, from right to left. Temperature microstructure is shown on the left. Color scale on the right applies to both images.

High Frequency Acoustics for Flow Imaging

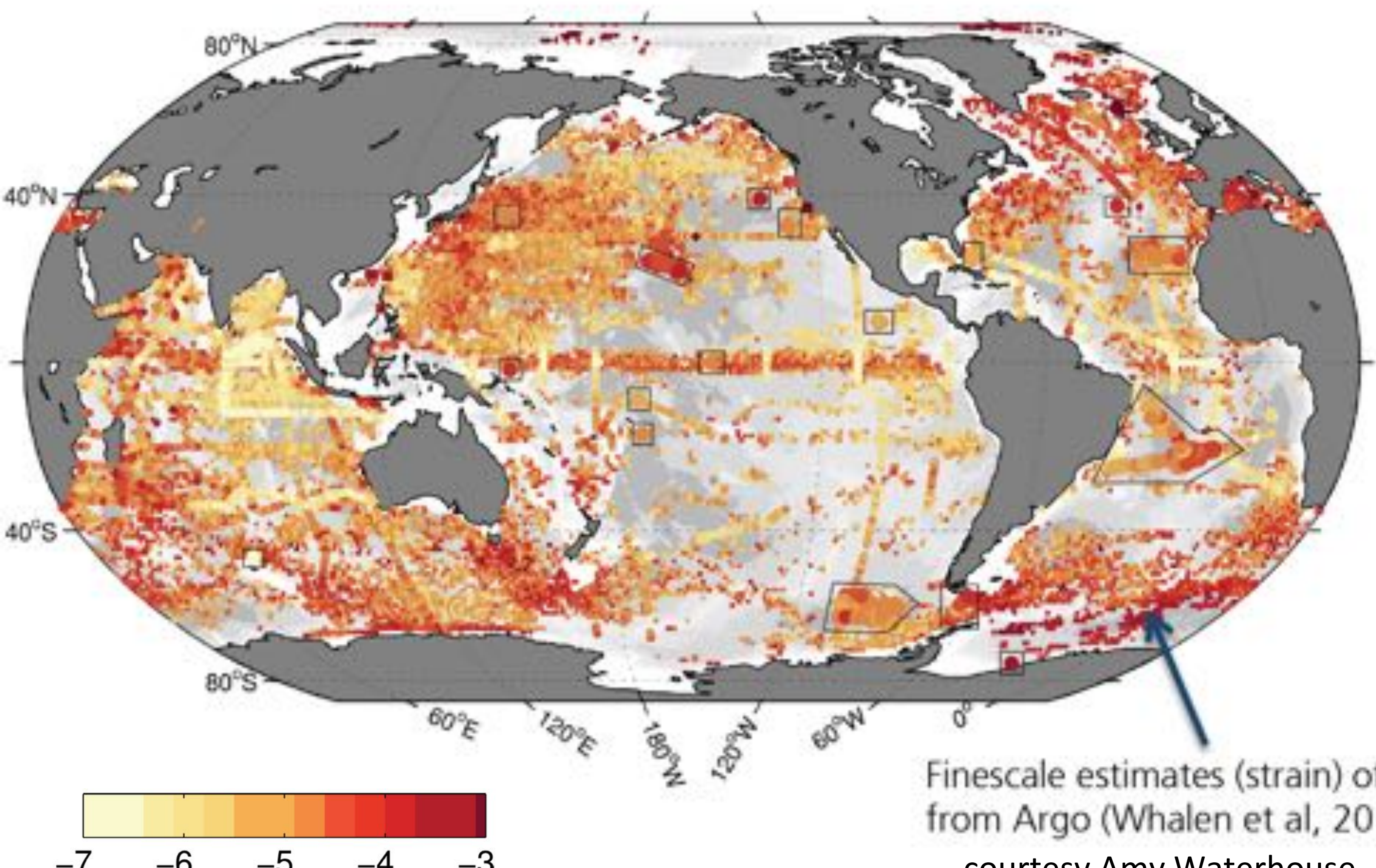
Direct Measurements



Moum et al. 2003

Boxes show historical locations from microstructure Profilers, all other estimates based on parameterizations.

Direct Measurements

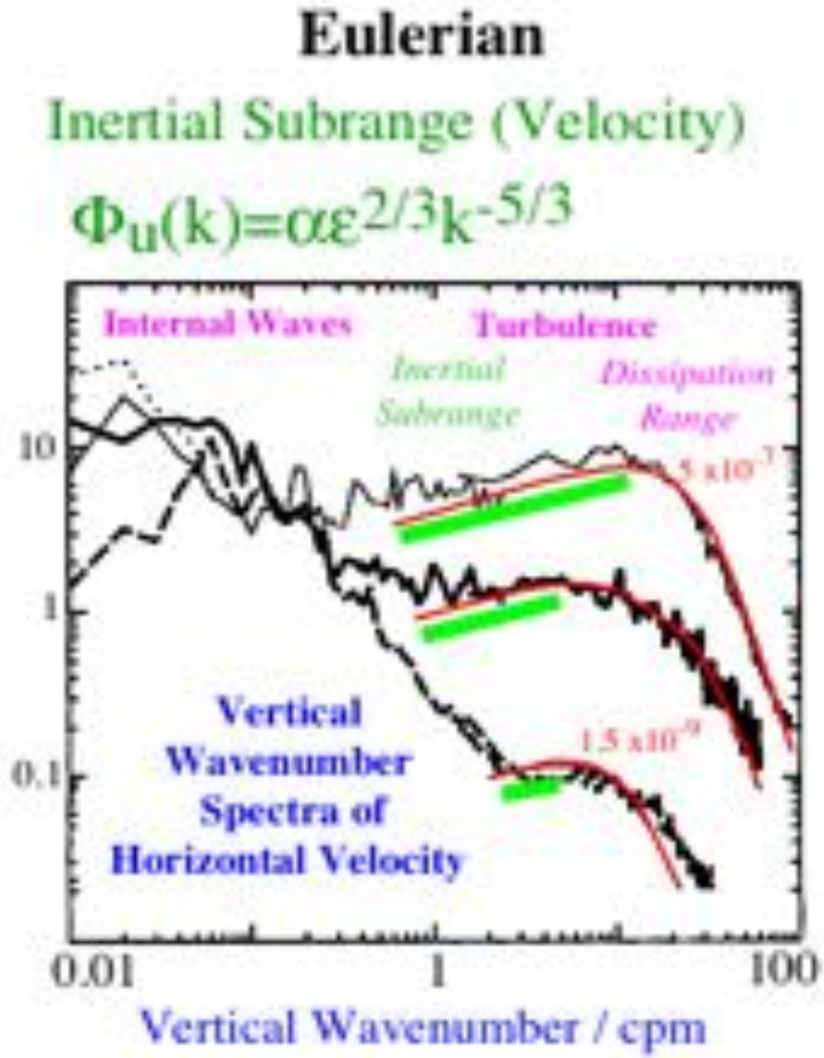


Finescale estimates (strain) of K from Argo (Whalen et al, 2012)

courtesy Amy Waterhouse

Measuring ε, TKE dissipation rate

"Measure Velocity gradients, Fit Universal Spectra"



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$$K_\rho = \frac{\Gamma \varepsilon}{N^2}$$

Internal Waves- Part of the Energy Cascade

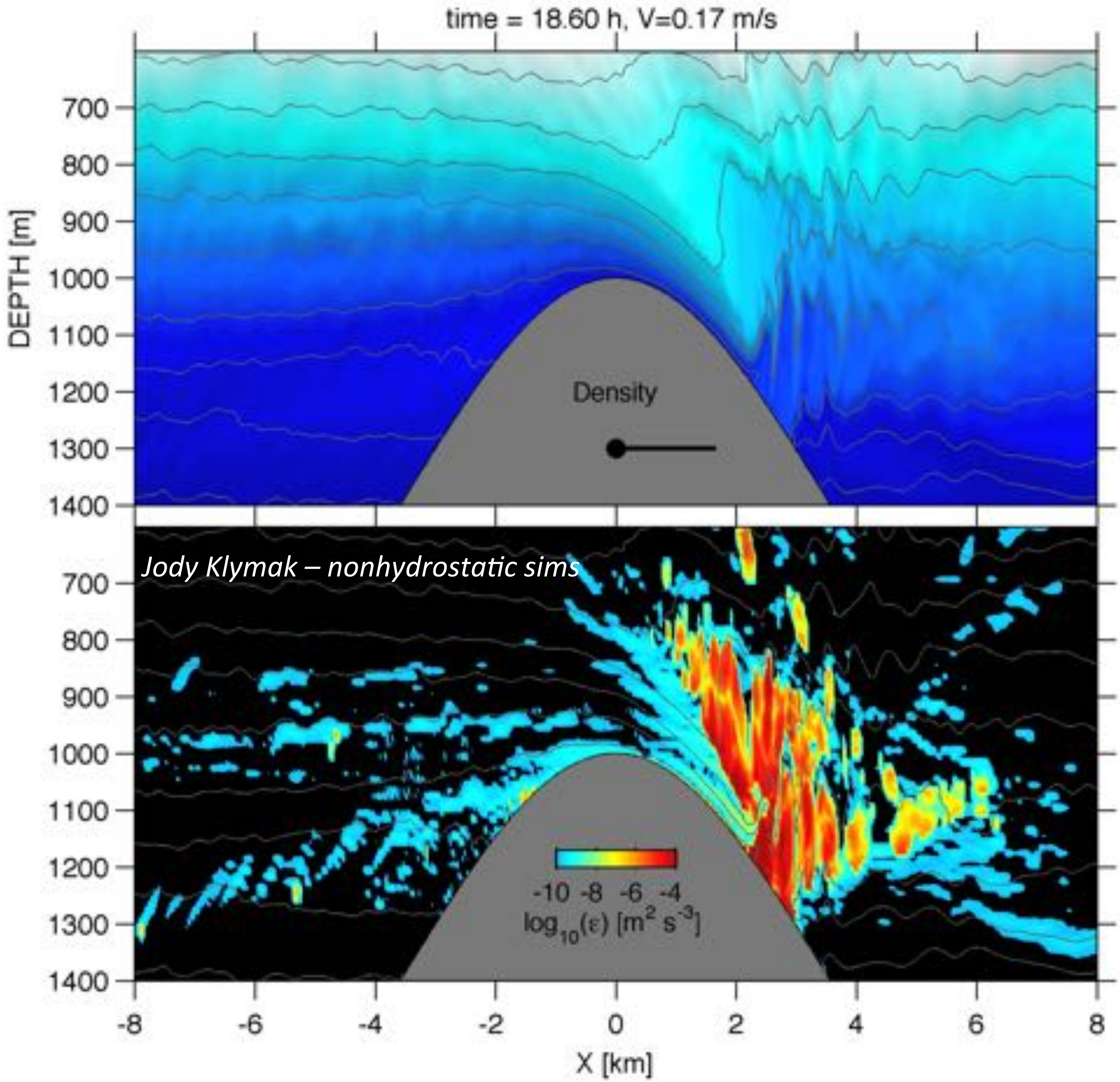
Inferences

Lee waves in oscillating flows over abrupt topography can directly break.

➔ turbulence may be well-constrained if all supercritical modes break

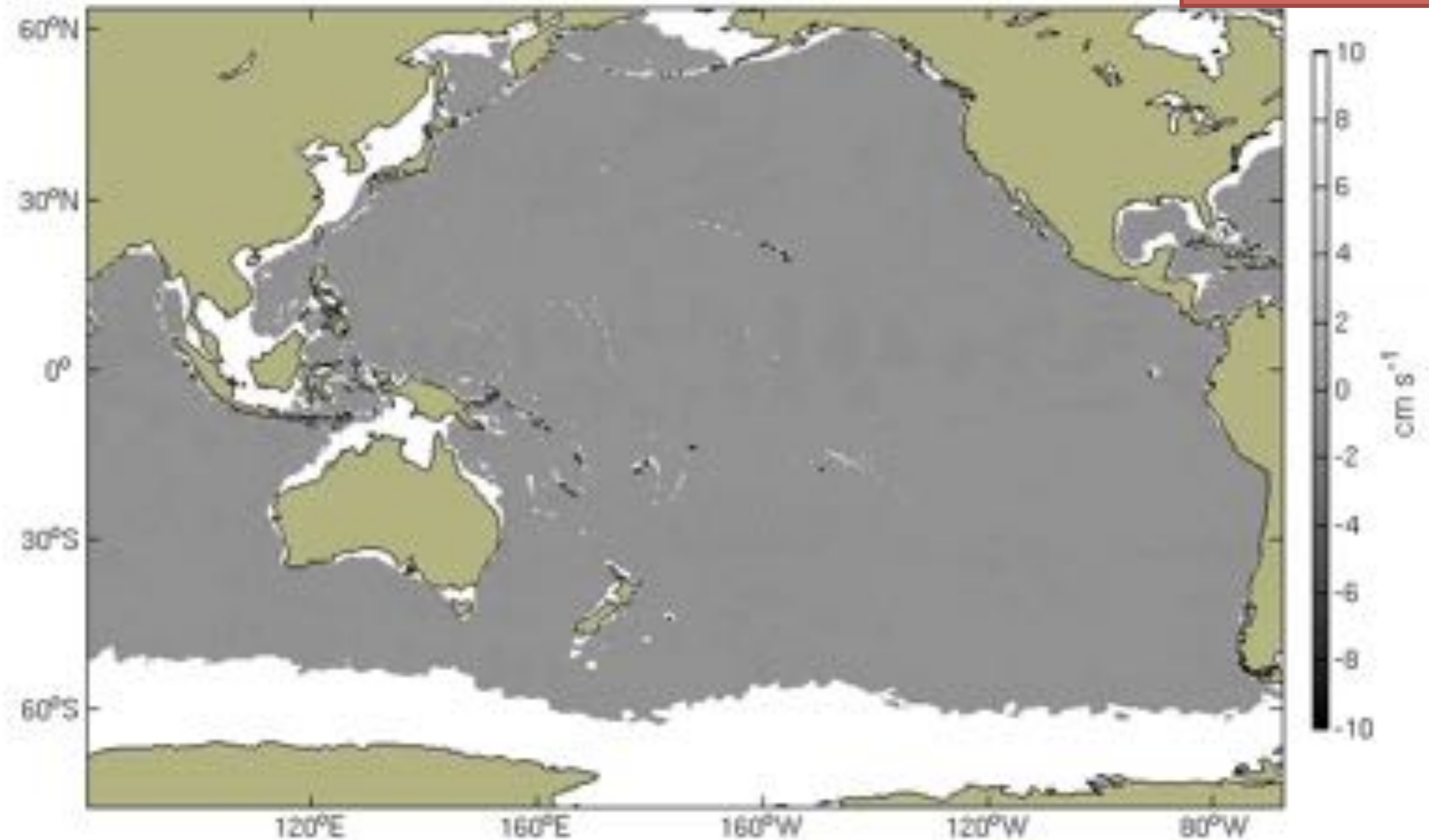
➔ Waves radiate away from generation sites

Klymak, Legg & Pinkel 2012 a,b



The Fate of the Waves that Get Away

Inferences

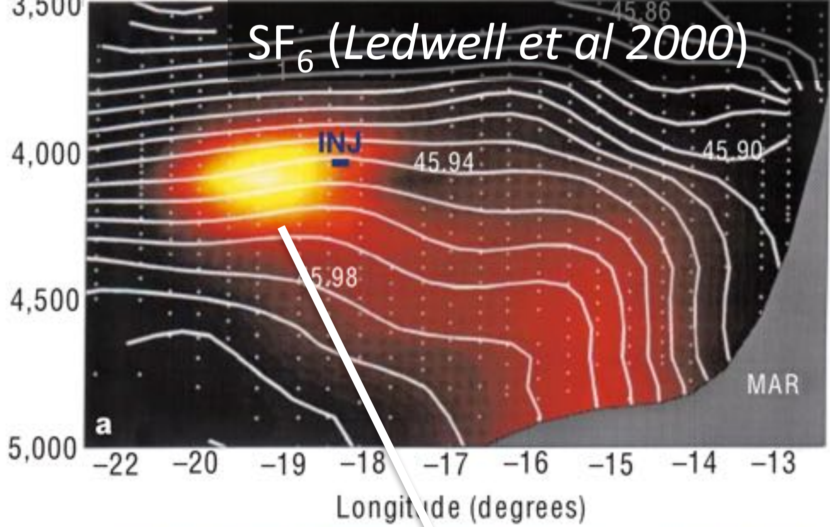


Harper Simmons (University of Alaska)

Generalized Ocean Layer Dynamics Model (Adcroft & Hallberg, GFDL)

50 layer, 1/8^{o} isopycnal, Boussinesq, hydrostatic, forced for 6 years w/ realistic winds (rel. vorticity; above), then the tides are turned on (8 constituents)

internal wave enhancement via topographic roughness

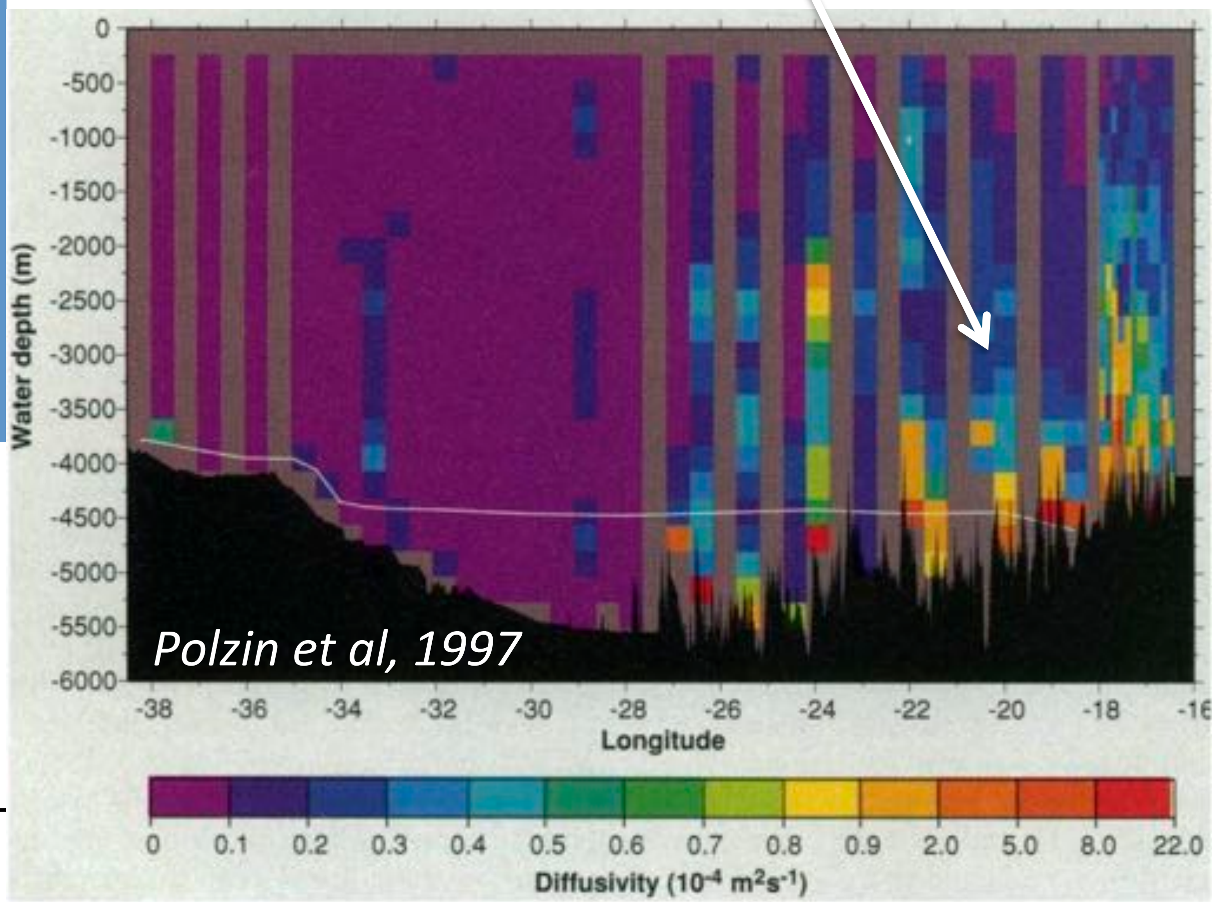


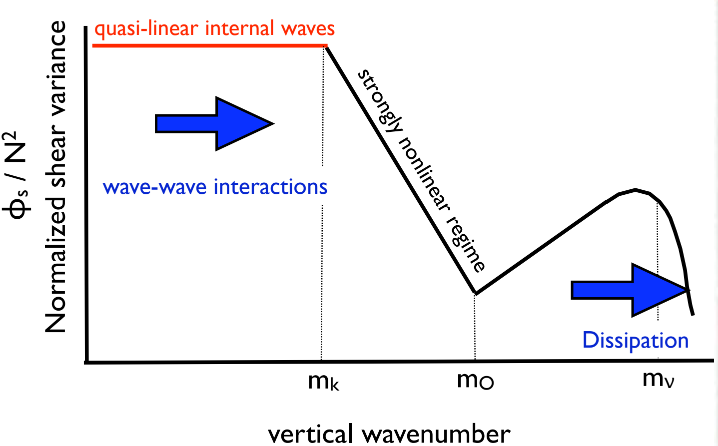
baroclinic generation from topographic roughness (e.g. *Bell, 1975*)

+

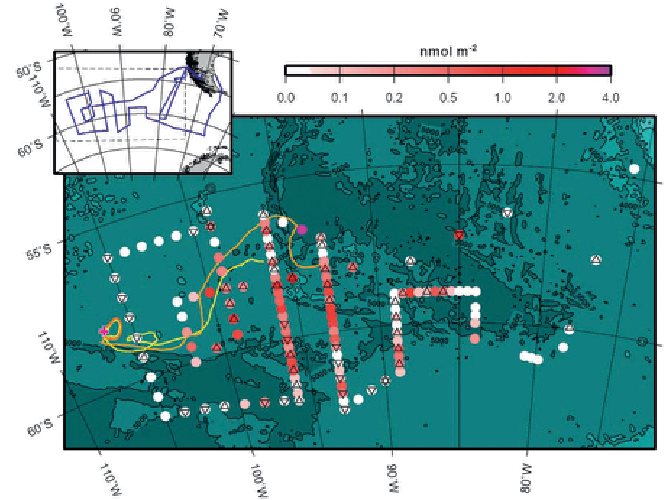
nonlinear wave transfers to high wavenumbers & turbulence.

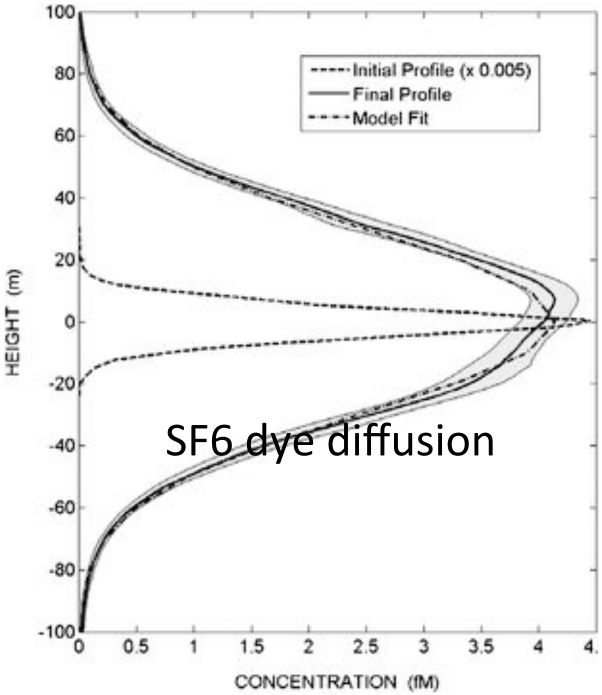
(*Polzin 2004,*etc)





…weak diapycnal diffusivity over smooth southern ocean topography

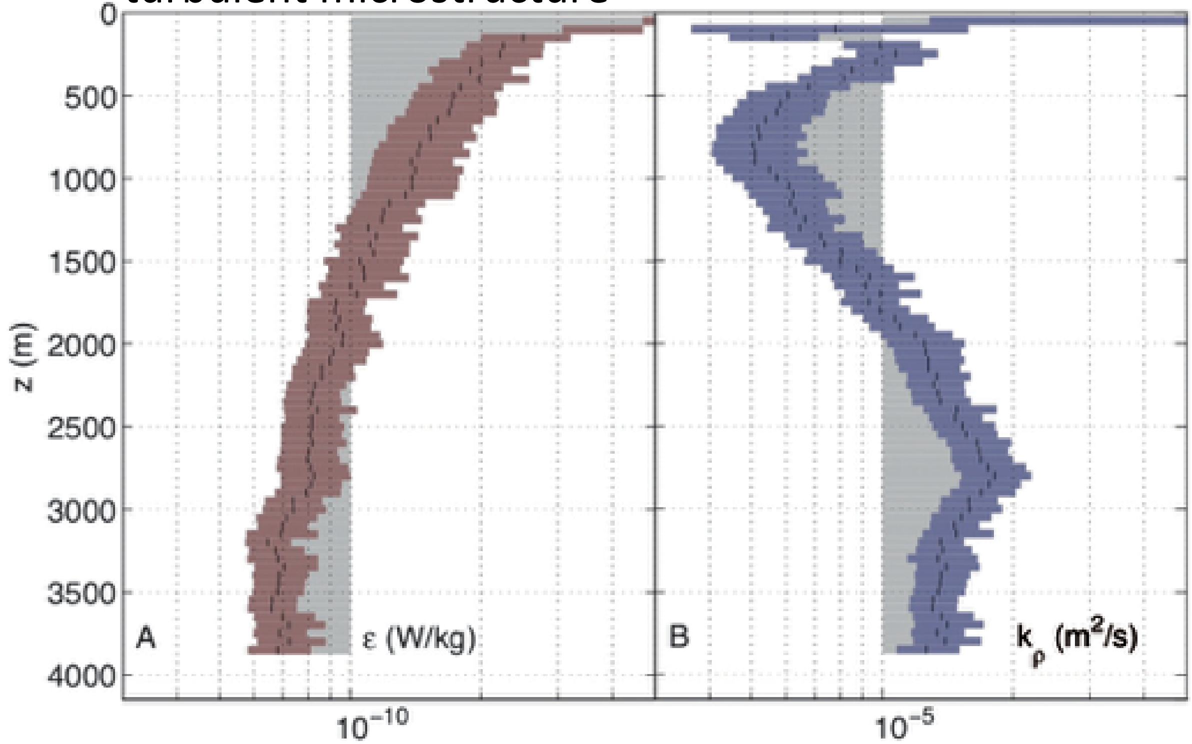




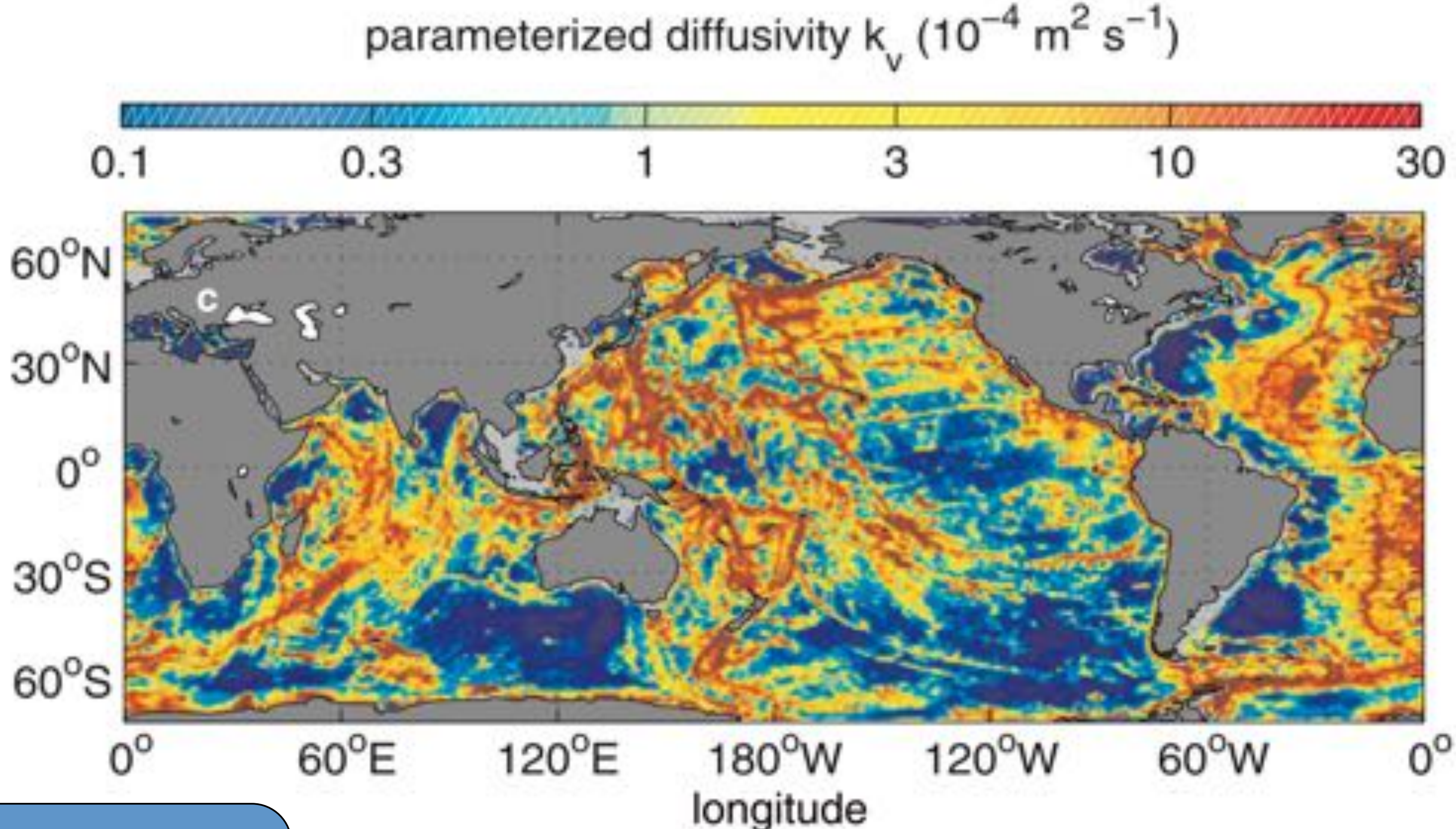
SF6 dye diffusion

Ledwell et al 2011 find "weak mixing" in the Southern Ocean Interior

turbulent microstructure



…towards a global map of turbulent viscosity/diffusivity



One component in isolation: mixing from the BT tide

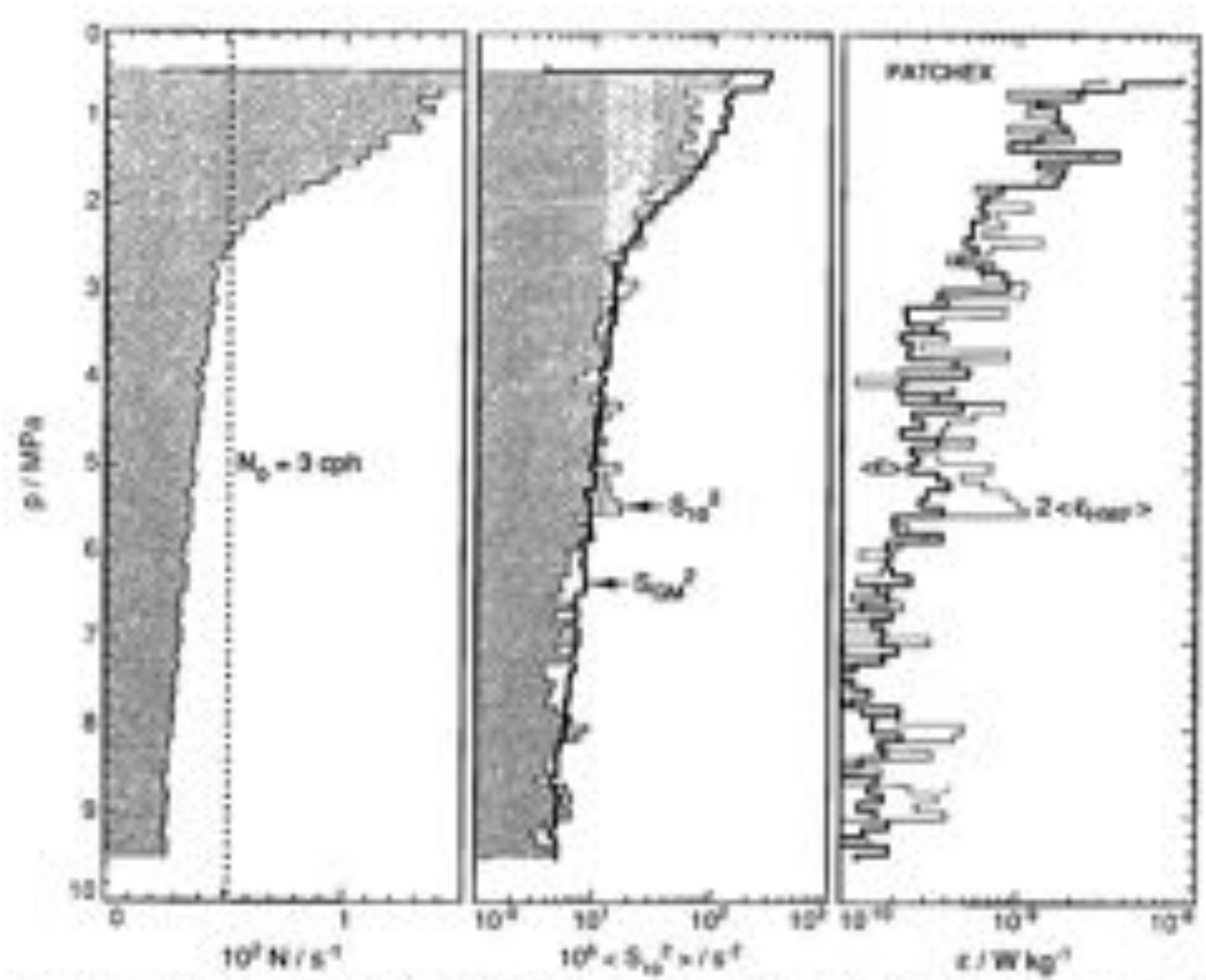
$$k_v \simeq \frac{\Gamma q E(x,y) F(z)}{\rho N^2}. \quad [\mathrm{m}^2\,\mathrm{s}^{-1}]$$

E=f(k,h,N) + ad-hoc F(z) & constant q

St Laurent, Simmons & Jayne ('02)

Finescale Parameterizations of Mixing

Inferences



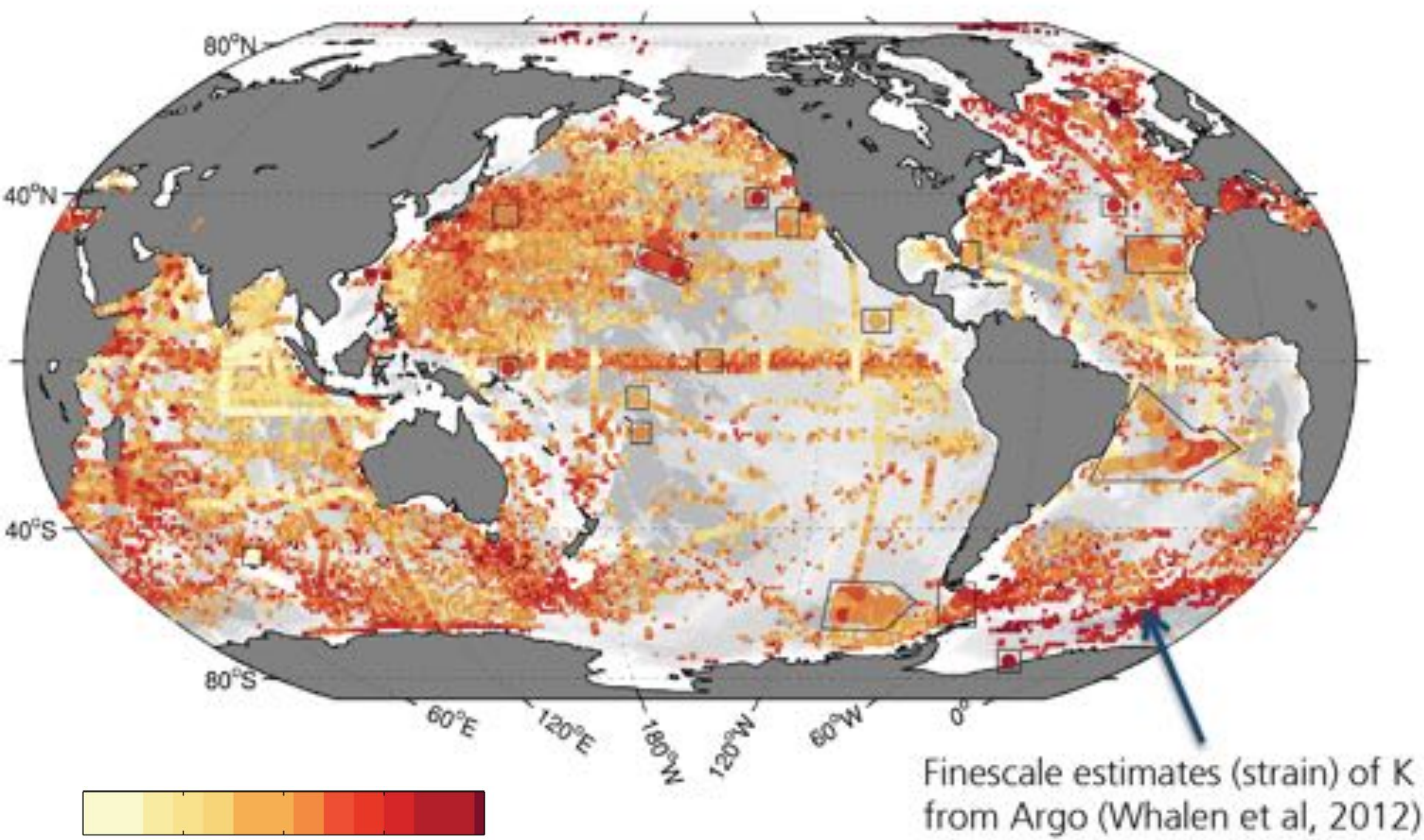
Black- Dissipation from a microstructure profiler

Grey- Parameterized based on Henyey et al., 1986

Gregg, 1989

Inferences

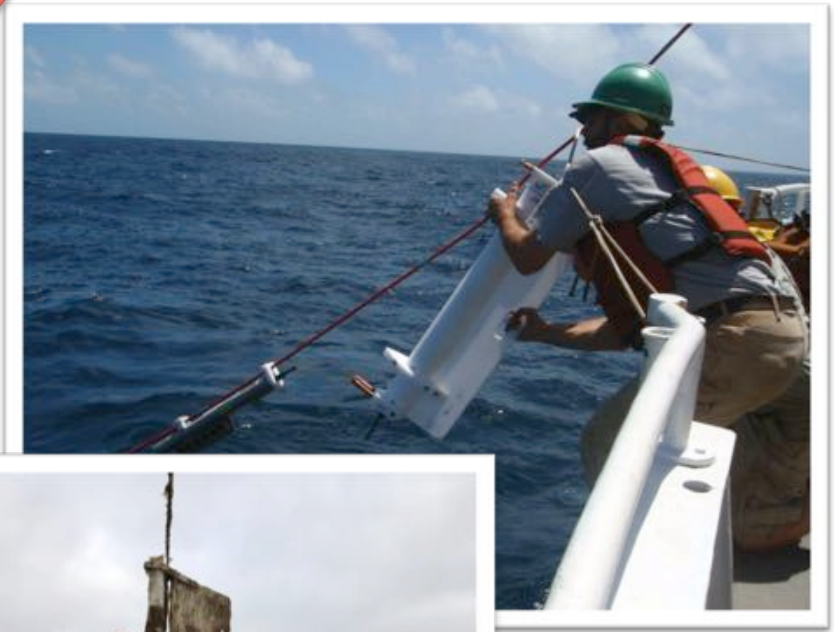
Boxes show historical locations from microstructure Profilers, all other estimates based on parameterizations.

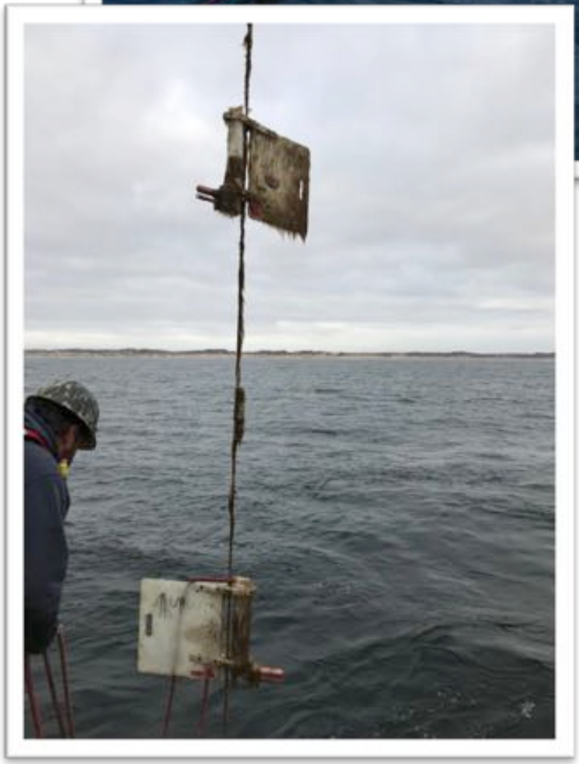


courtesy Amy Waterhouse

Moving Forward

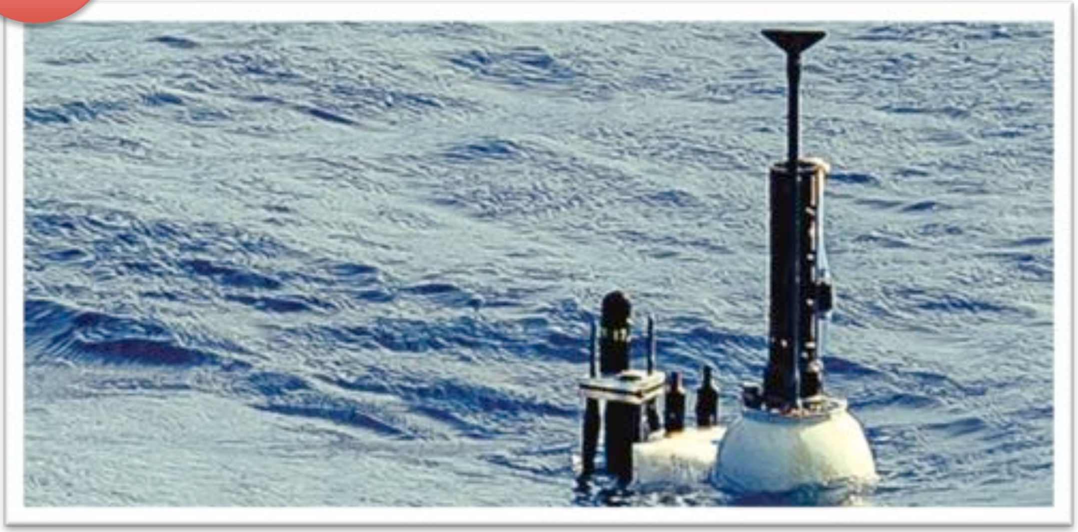
1. Extended Time Series





How do we proceed?
1. Measure at scales where mixing occurs
2. Make inferences from large-scale properties & flow

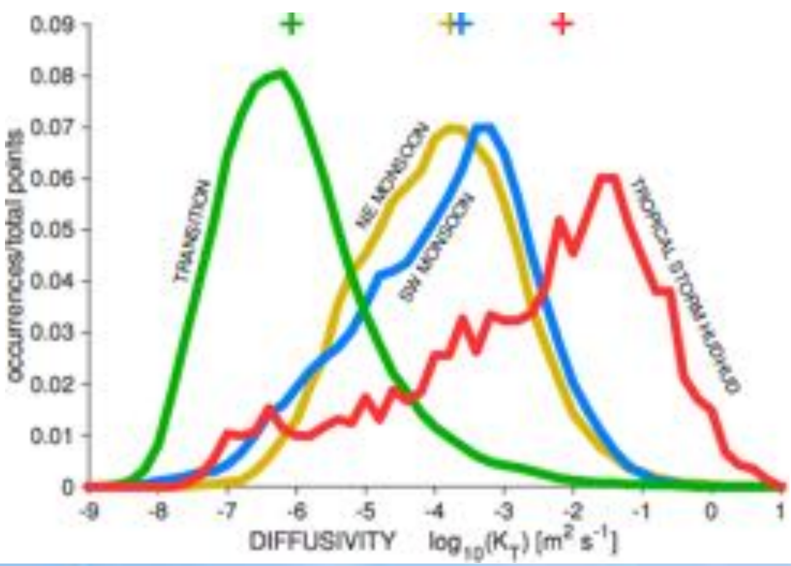
2. New (Autonomous) Platforms

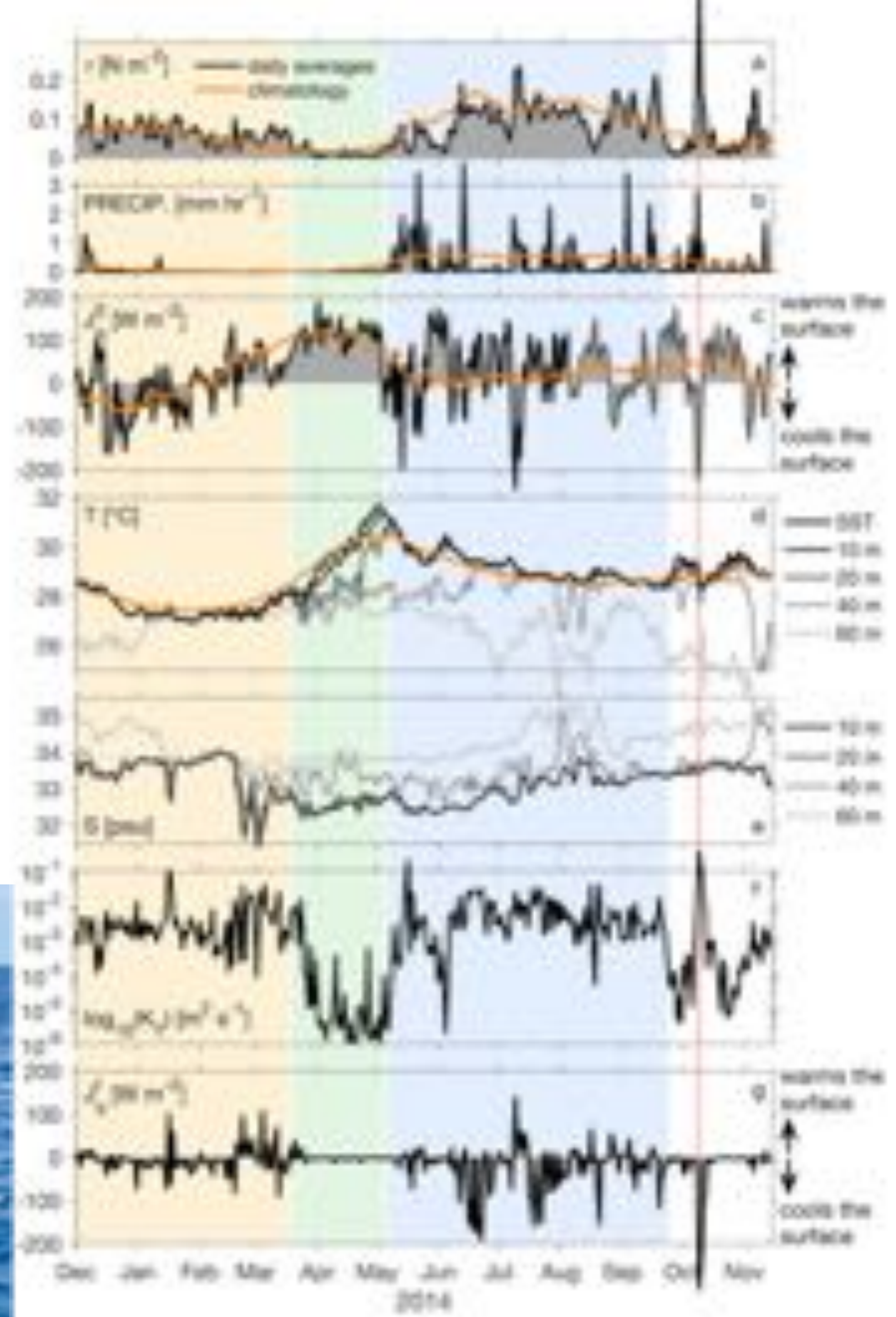


1.

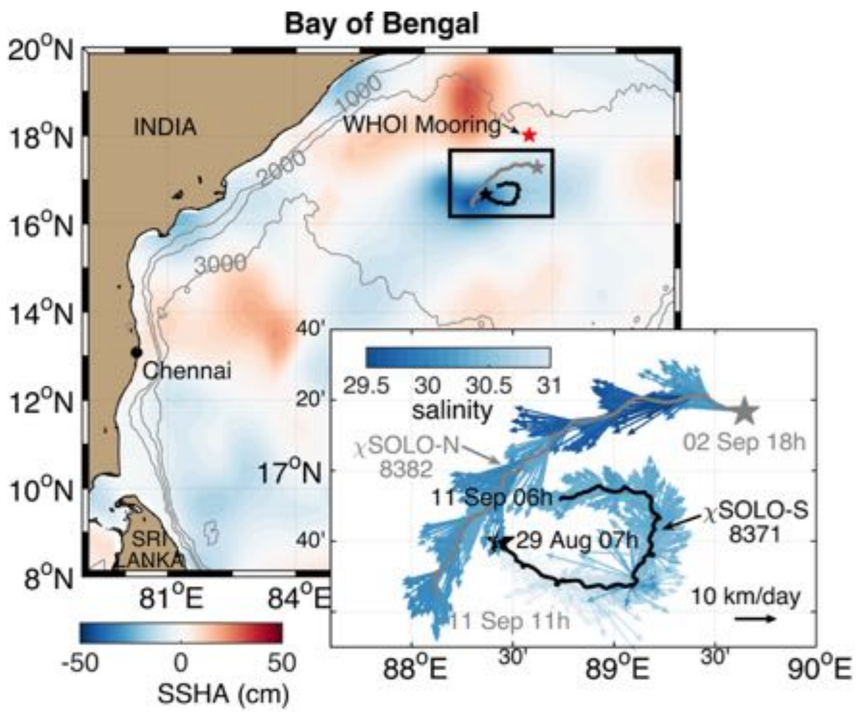
Extended Time Series: Moored χpods

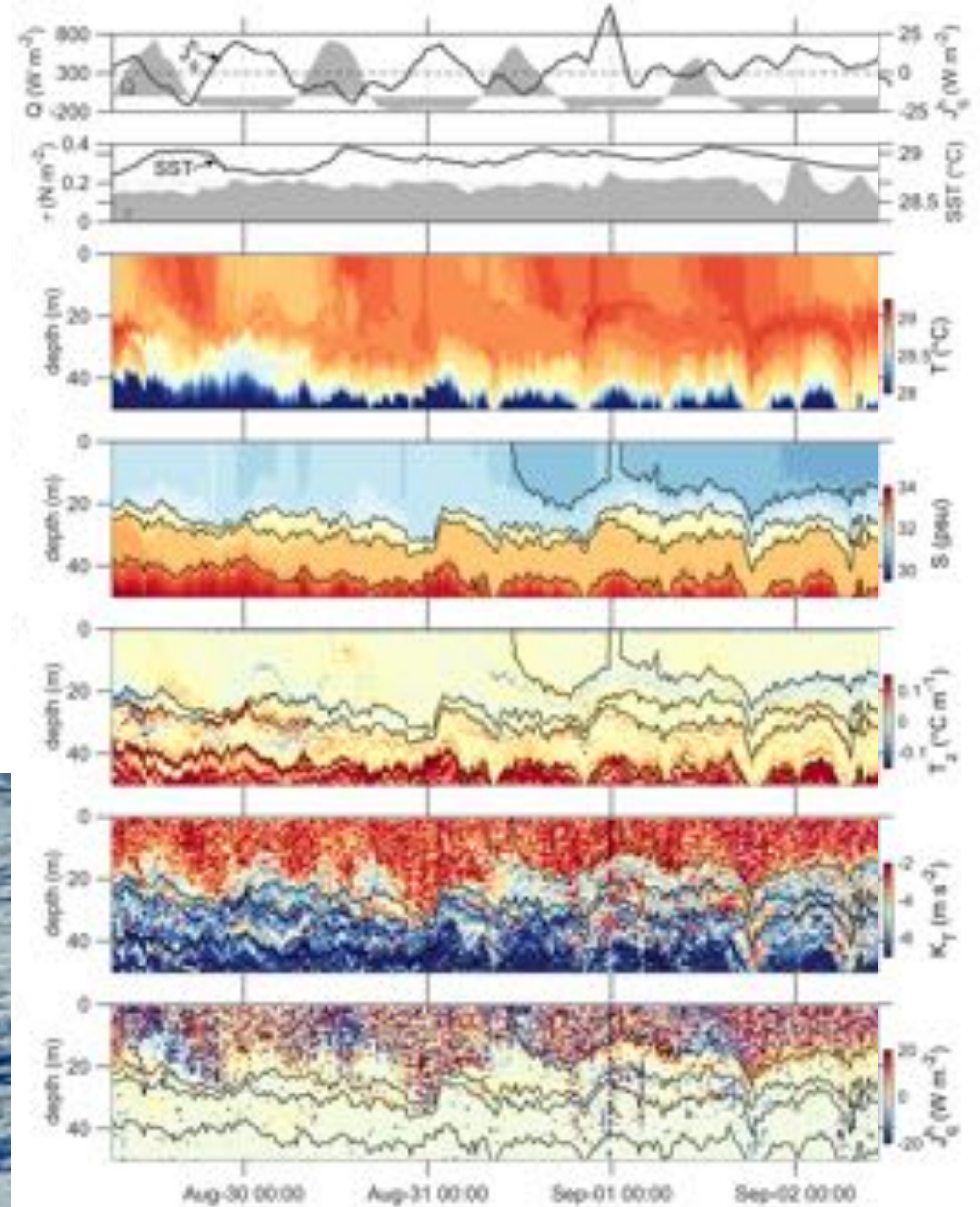
Example from RAMA Array

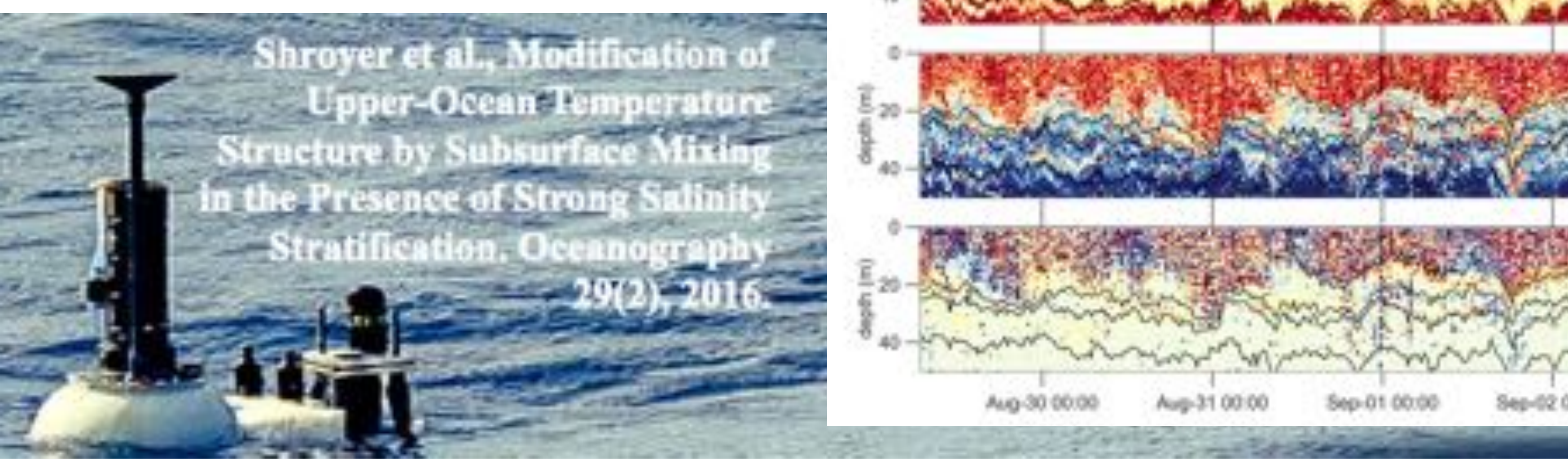




2. New Platforms: Toward Integration in the Global ARGO Array







Summary

1. Turbulence measurements in the ocean have benefited from a "long" history of multiple groups working to adapt and apply new methods in an operationally challenging environment.

2. Turbulence is a property of the flow. It is patchy and intermittent. Measurements need to be made so that turbulence is adequately sampled, and so that we can relate mixing back to process resolvable by models.

3. We need new measurement approaches to increase our sampling capabilities both in terms of time and space resolution. This basically means adapting sensing technology to new platforms (moorings, floats, gliders, drifters, etc.).