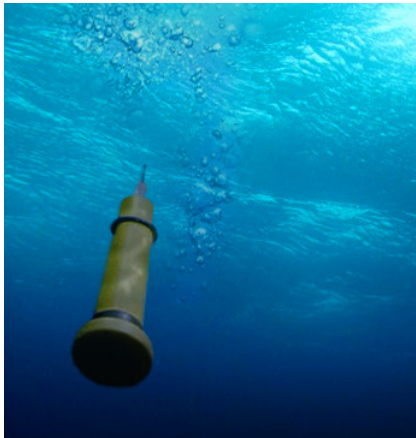


Can we infer vertical mixing rates for the surface mixed layer from float's ascent rates?

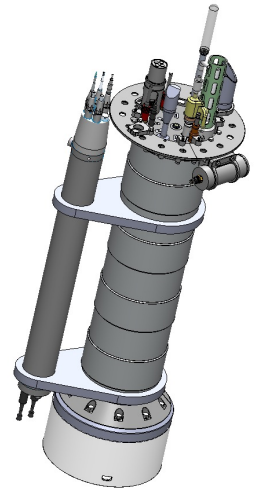
BGC Apex (UW)



Magdalena M Carranza
MBARI Postdoctoral Fellow

Gordon Research Seminar on Ocean Mixing
Mount Holyoke, MA
Jun 5 2022

Coastal Profiling Float (MBARI)



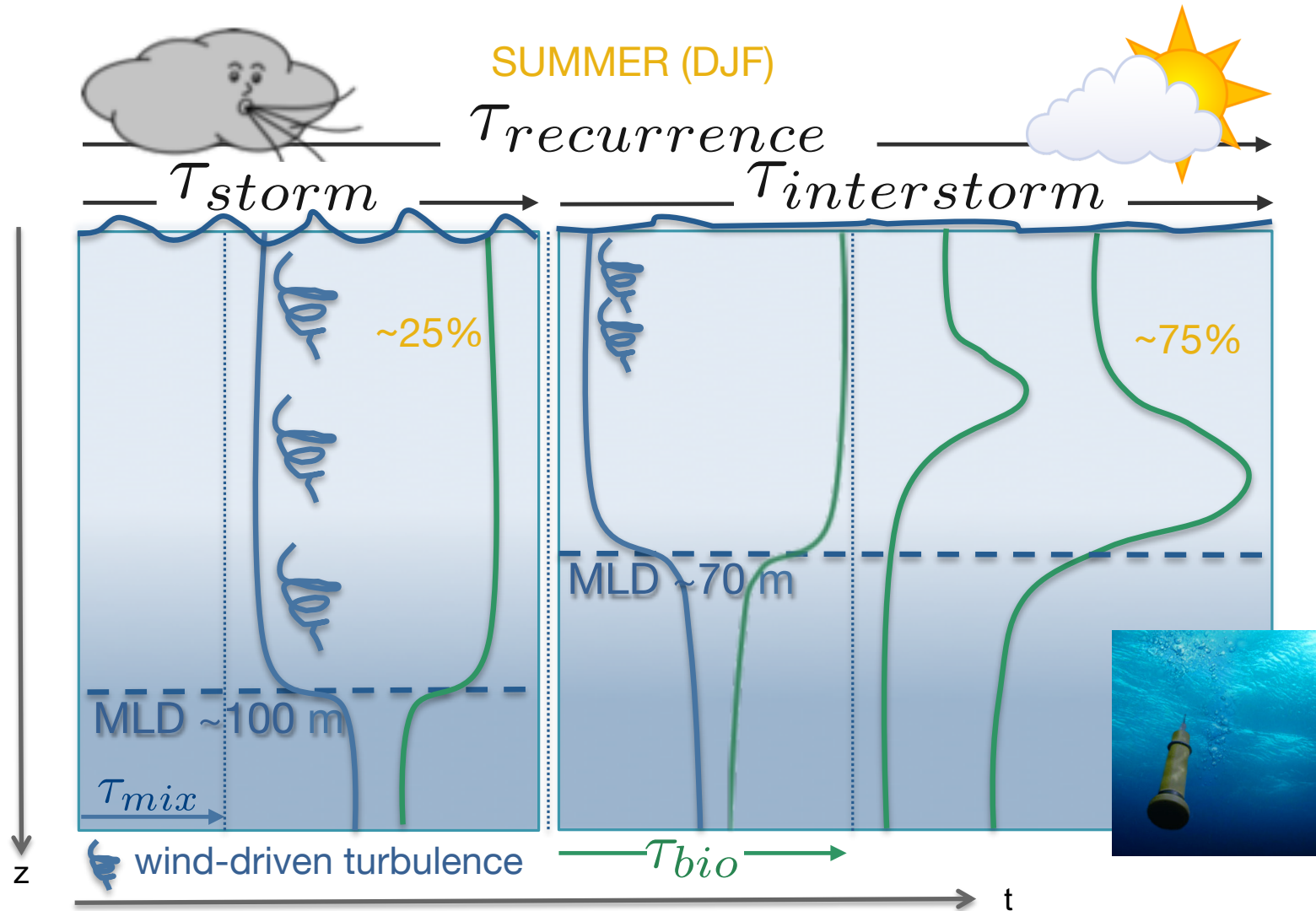
Contributors:

Rob Pinkel (SIO), Dana Swift (UW), Caitlin Whalen (UW)
Andrea Fassbender (now at NOAA), Gene Massion, Yui Takeshita, Ken Johnson (MBARI)
Judah Goldberg, Evan Cervelli (Rockland Scientific Team)

MIXED layer (from a past mixing event)

vs

MIXING layer (actively turbulent)



Biogeochemical properties can show structure in the surface mixed layer and more often times do show gradients

Turbulent fluxes:

$$\sim \frac{\partial}{\partial z} \left(K_z \frac{\partial P}{\partial z} \right)$$

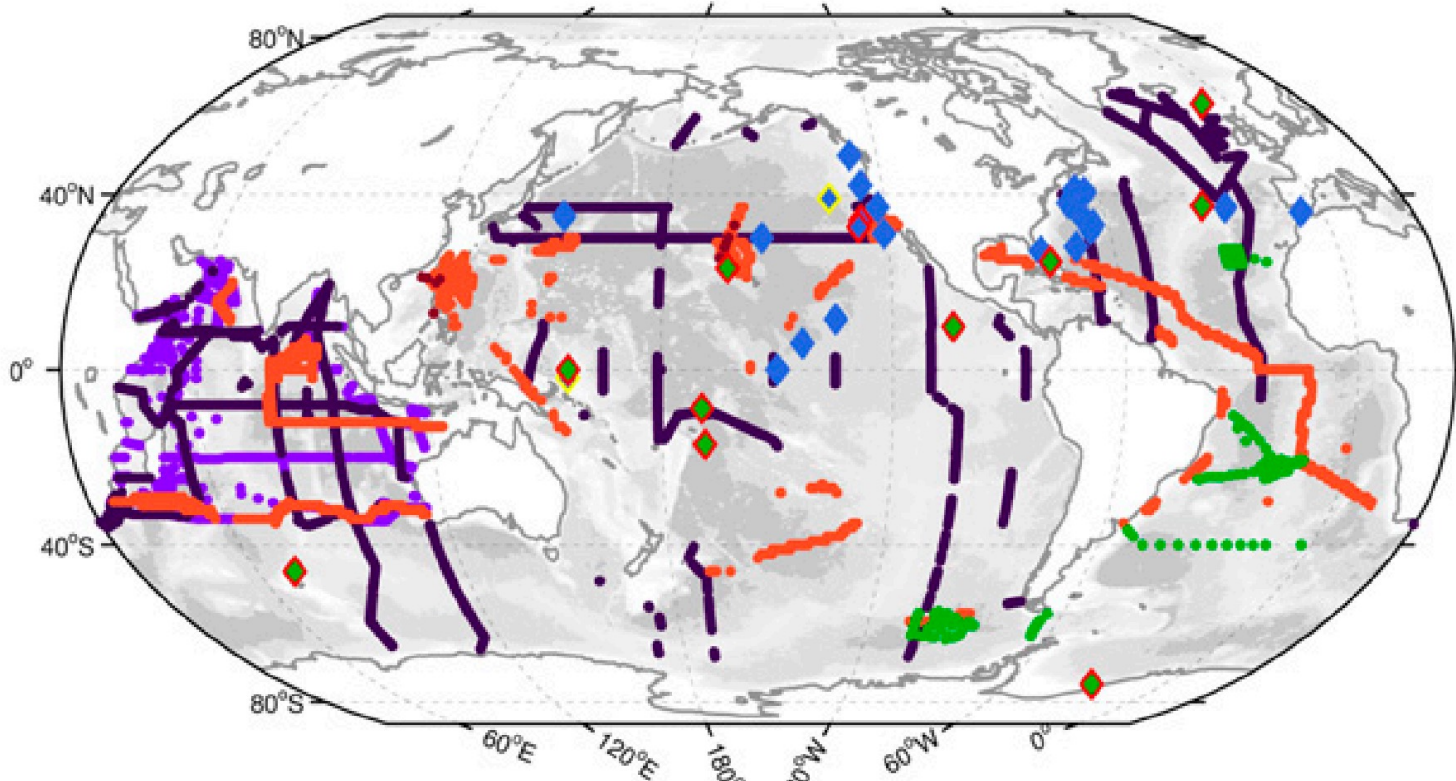
$K_z(z,t)$?

Turbulent diffusivity

Vertical
gradients
from BGC
Argo floats

SOCOM BGC float data in the Southern Ocean, Carranza et al. (2018)

Observations of Turbulence

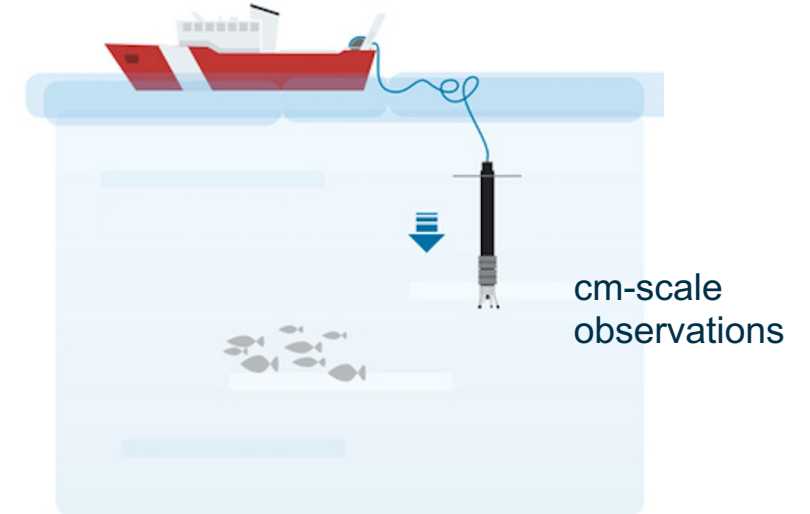


acoustic measurements (◆, ◆)

(c) Observations of mixing

Waterhouse et al. 2014

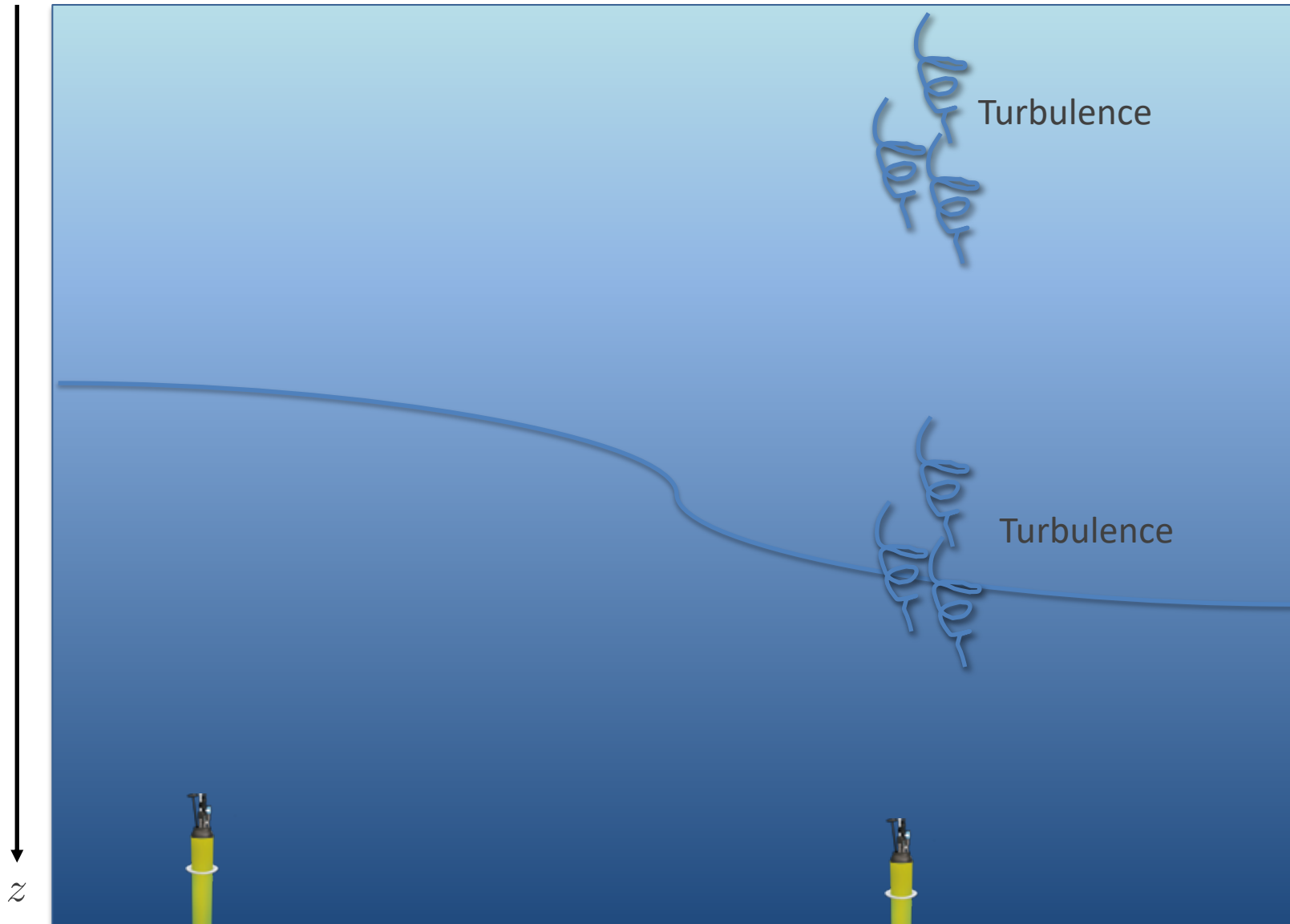
microstructure measurements (◆, ◆)
Vertical Microstructure Profilers, VMPs
→ very expensive, and thus sparse



Mixing rates in the top surface layer
are sparse !!!

Large Eddy Method (LEM):

eddy velocity scale from variance in the float's ascent rates



Large Eddy Method: vertical velocity (w) variance

eddy velocity scale + length scale $\longrightarrow$ eddy diffusivity, K_z

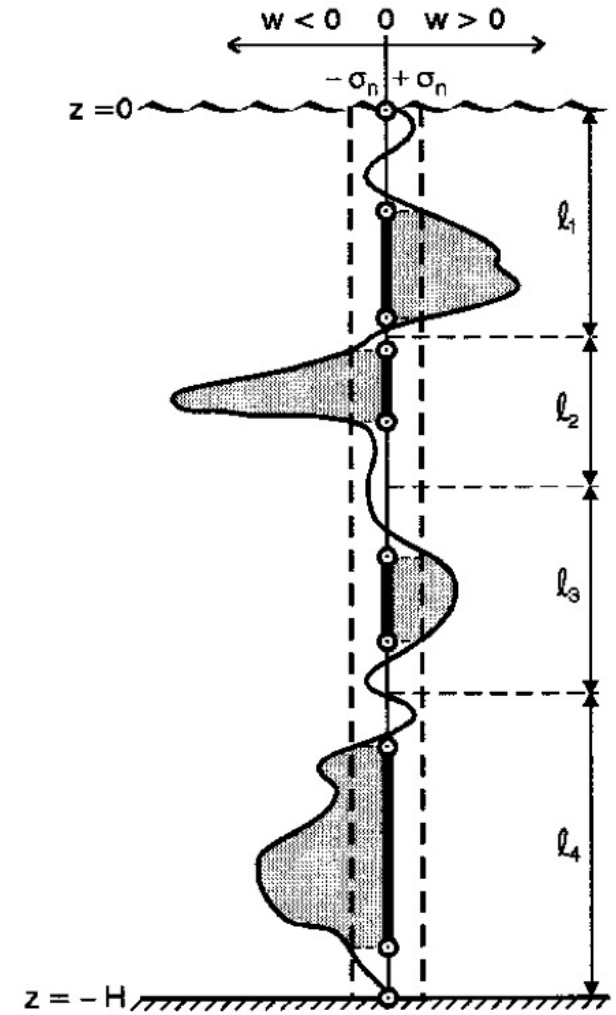
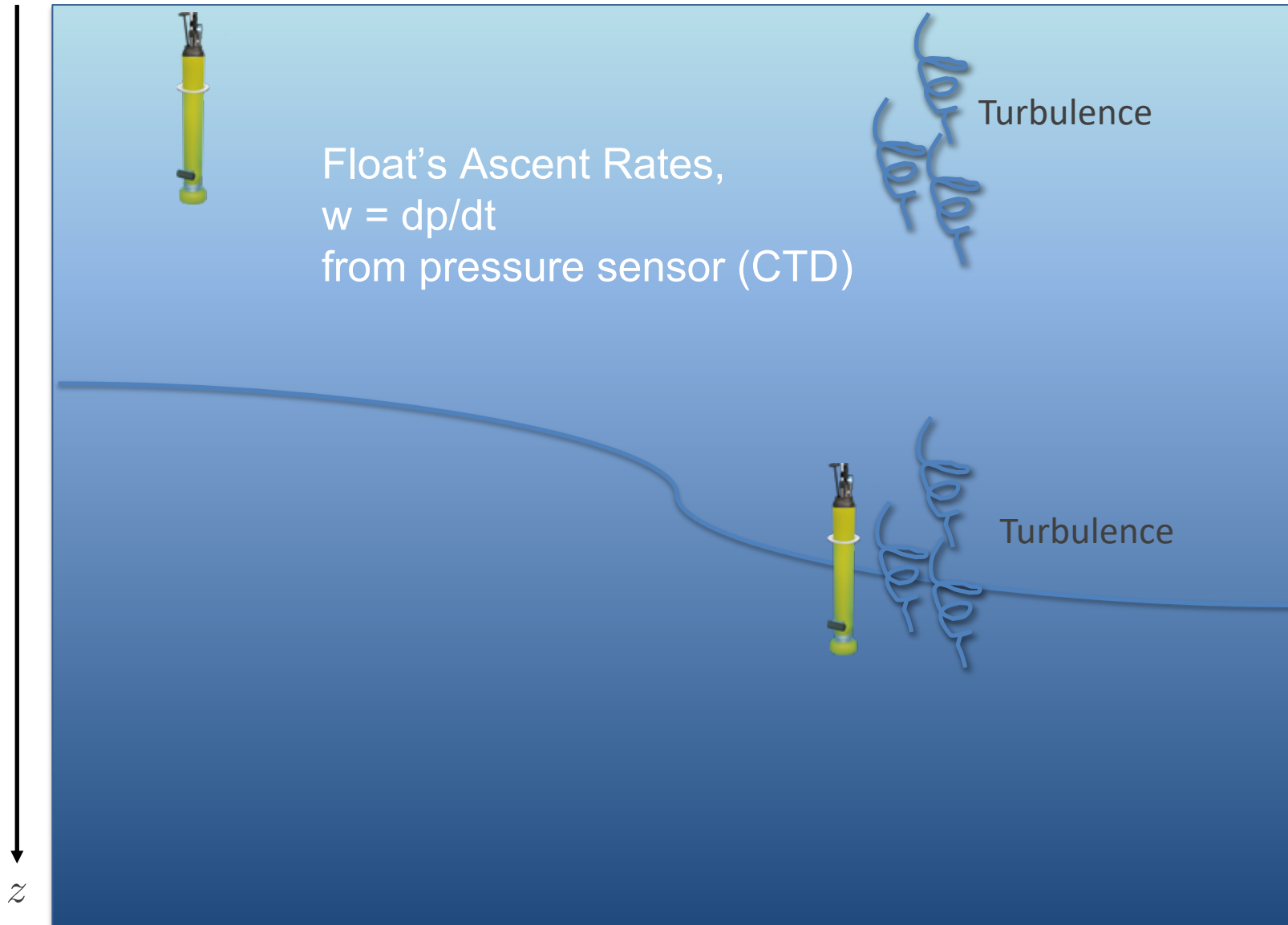
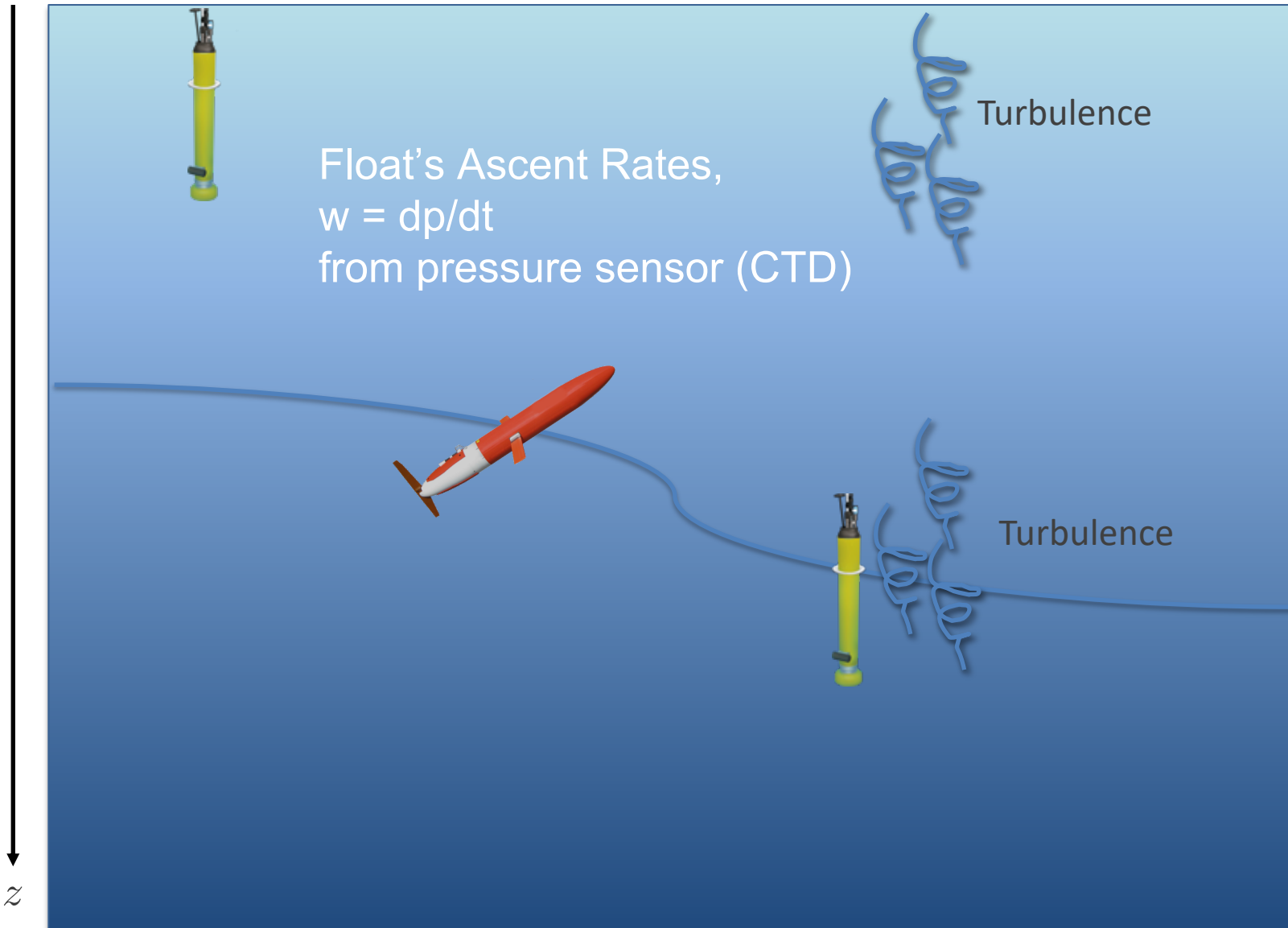


FIG. 6. Schematic of the zero crossing algorithm used for local determination of a (vertical) length scale associated with the large eddies of the turbulent velocity field. For discussion see text, section 3.

Gargett (1994,1999)

Large Eddy Method: vertical velocity (w) variance

eddy velocity scale + length scale $\longrightarrow$ eddy diffusivity, K_z



Challenges:
Buoyancy engine introduces variability

Metadata not always available:

- 1) Time step between measurements at depth to compute w
- 2) Engineering data to model ascent through still water

Filtering techniques look promising!

Large Eddy Method (LEM) requirements:

Eddy Length Scale, l :

- Thorpe Length (L_T , from high resolution density profiles, Thorpe 1977)
- Zero-crossing of a w' profile (Gargett, 1999)
- Ozmidov Length (L_{Oz} , largest turbulent eddy that is unaffected by stratification)
- $L_T \sim L_{Oz}$ even in the weakly stratified mixed layer (Dillon, 1982)

Vertical Velocity Scale, q' :

- removing any platform induced motion from w_{ctd}
- removing non-dissipative w signals (upwelling, internal waves, surface waves, etc)

Calibration Coefficient:

- From estimates of ϵ , against a direct measurement of epsilon
- will take up differences between measurements of l and L_{Oz} , choices made in the high-pass filtering of w , or varying N , etc.

Vertical velocities from glider's CTD data and steady flight model

- ✓ Merckelbach et al. (2010) for a Slocum glider
- ✓ Frajka-Williams (2011) for a Seaglider
- ✓ Rudnick et al. (2013) for a Spray glider

Basic assumption:

$$w = w_{ctd} - w_{steady}$$

↓

water vertical velocity

$$w_{ctd} = \frac{dp}{dt}$$

↓

Low freq ~ flight

High freq ~ water motion

w_{steady} vertical velocity that the glider would have if going through still water

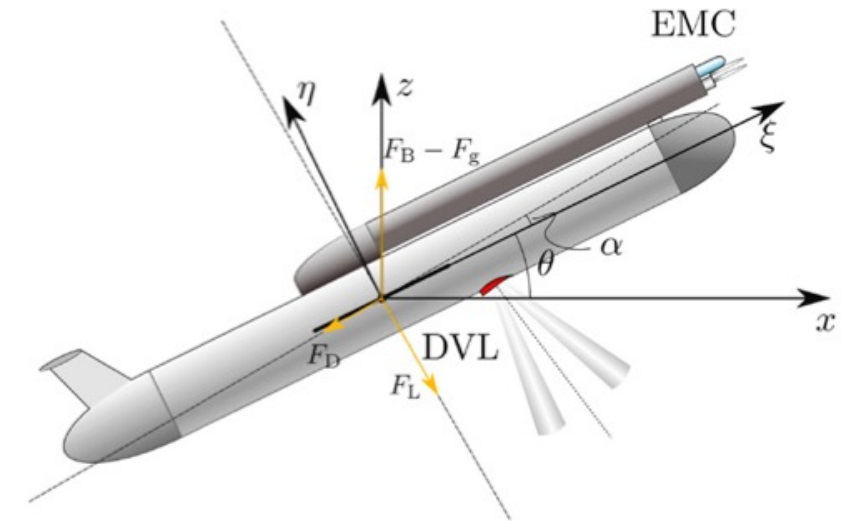
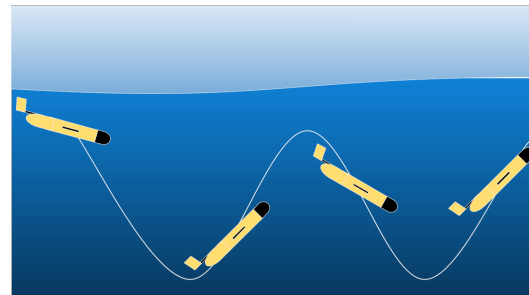


FIG. 1. Schematic representation of a glider, defining an orthogonal coordinate system with x and z axes, and an orthogonal glider referenced coordinate system (ξ, η) . The latter originates from the former after a rotation of the pitch angle. The glider path (dashed line) makes a small angle, equal to the angle of attack, with the glider's principal axis, which coincides with the ξ axis. The forces resulting drag, lift, and net buoyancy are drawn by the yellow vectors. The positions of the EMC sensor and the DVL are in blue and red, respectively. The DVL is mounted such that the principal axis of the DVL (dashed) makes an 11° angle with the η axis.

Dissipation rate estimates from w

Large Eddy Method (LEM):

$$\epsilon \sim \frac{(w')^2}{\tau} \sim \frac{(w')^3}{l} \left[\frac{m^2}{s^3} \right] \quad K_z \sim w'l, \left[\frac{m^2}{s} \right]$$

q' velocity scale of the largest (energy-containing) eddies

τ time it takes to overturn once

l their length scale

For stratified flow, $l \sim L_{Oz} = \sqrt{\frac{\epsilon}{N^3}}$ (Ozmidov Scale)

$$e = c_\epsilon N (w')^2$$

c_ϵ calibration coefficient (determined from MR casts)

N buoyancy frequency/stratification

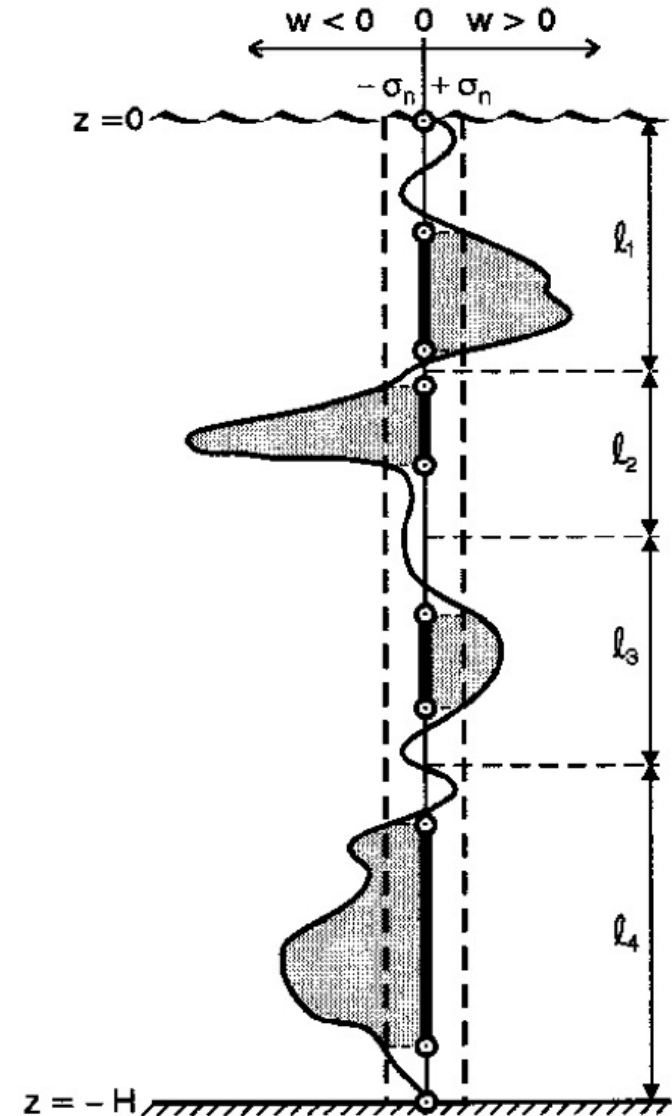


FIG. 6. Schematic of the zero crossing algorithm used for local determination of a (vertical) length scale associated with the large eddies of the turbulent velocity field. For discussion see text, section 3.

Vertical Velocities and TKE Dissipation Rates from EM-APEX floats

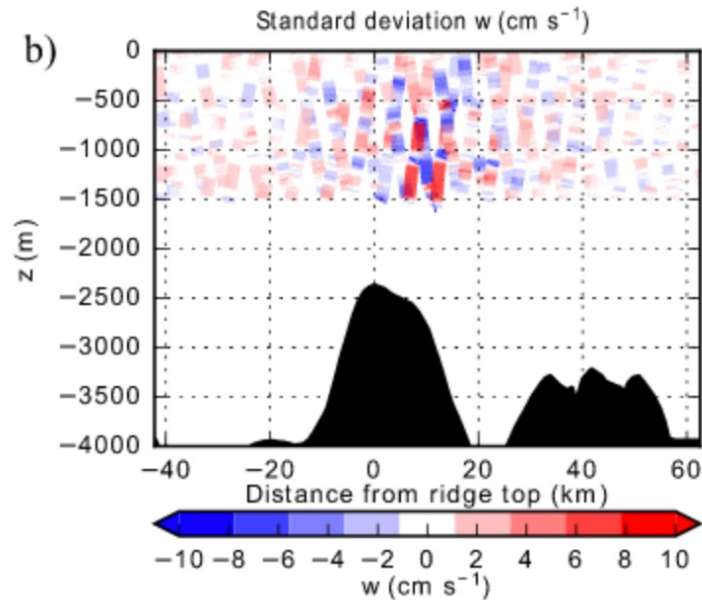


FIG. 6. (a) Mean horizontal velocity vector below 100m within the boxed region in Fig. 1. Arrow color denotes the standard deviation of vertical velocity measured below 100-m depth. Depth is contoured in 500-m increments. (b) A vertical section of vertical velocity from the same region. The observations from both floats

$$w_{\text{noise}} = 1 \text{ mm/s}$$

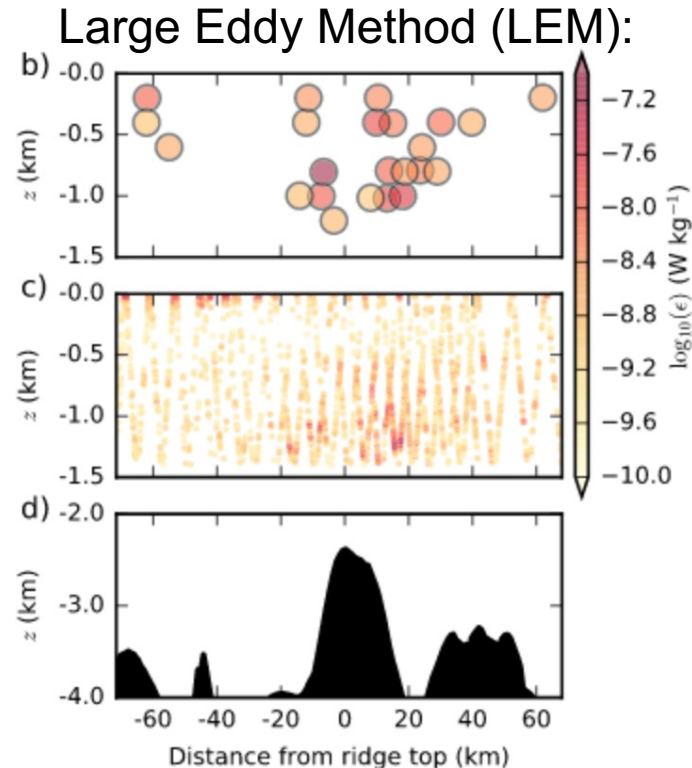


FIG. 12. (a) Depth-integrated TKED rate. (b) Thorpe-scale-derived estimate of the TKED rate on a logarithmic scale; the large circles denote 200-m bin averages. (c) LEM-derived TKED rate calculated on a 20-m sliding window. (d) Bathymetry. Measurements smaller than the noise threshold of the LEM, $c(w_{\text{noise}})^2 N$, where the noise velocity, $w_{\text{noise}} = 1 \text{ mm s}^{-1}$, has not been plotted. Similarly, portions of the water column where overturns are not detected have no associated Thorpe estimate.

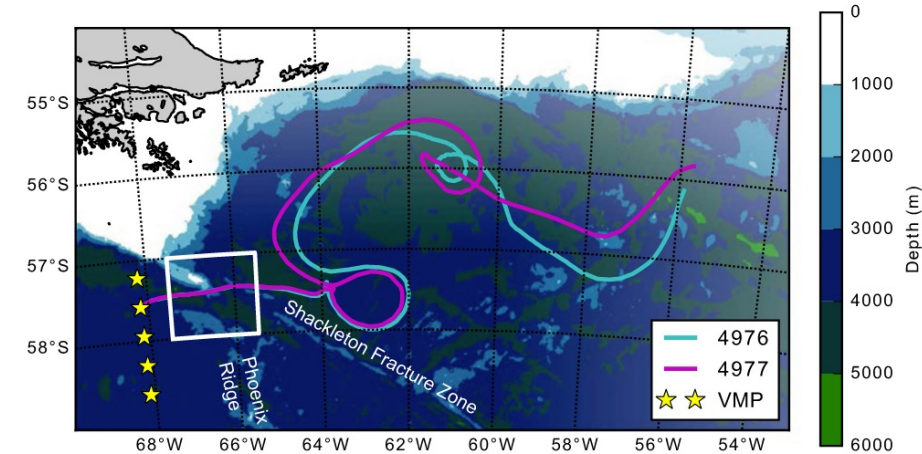


FIG. 1. Map of the northern Scotia Sea with float trajectories and vertical microstructure profiler stations (VMP) used in calibrating the float-derived dissipation rates. Lee-wave measurements were obtained within the boxed region, which is expanded in Fig. 6.

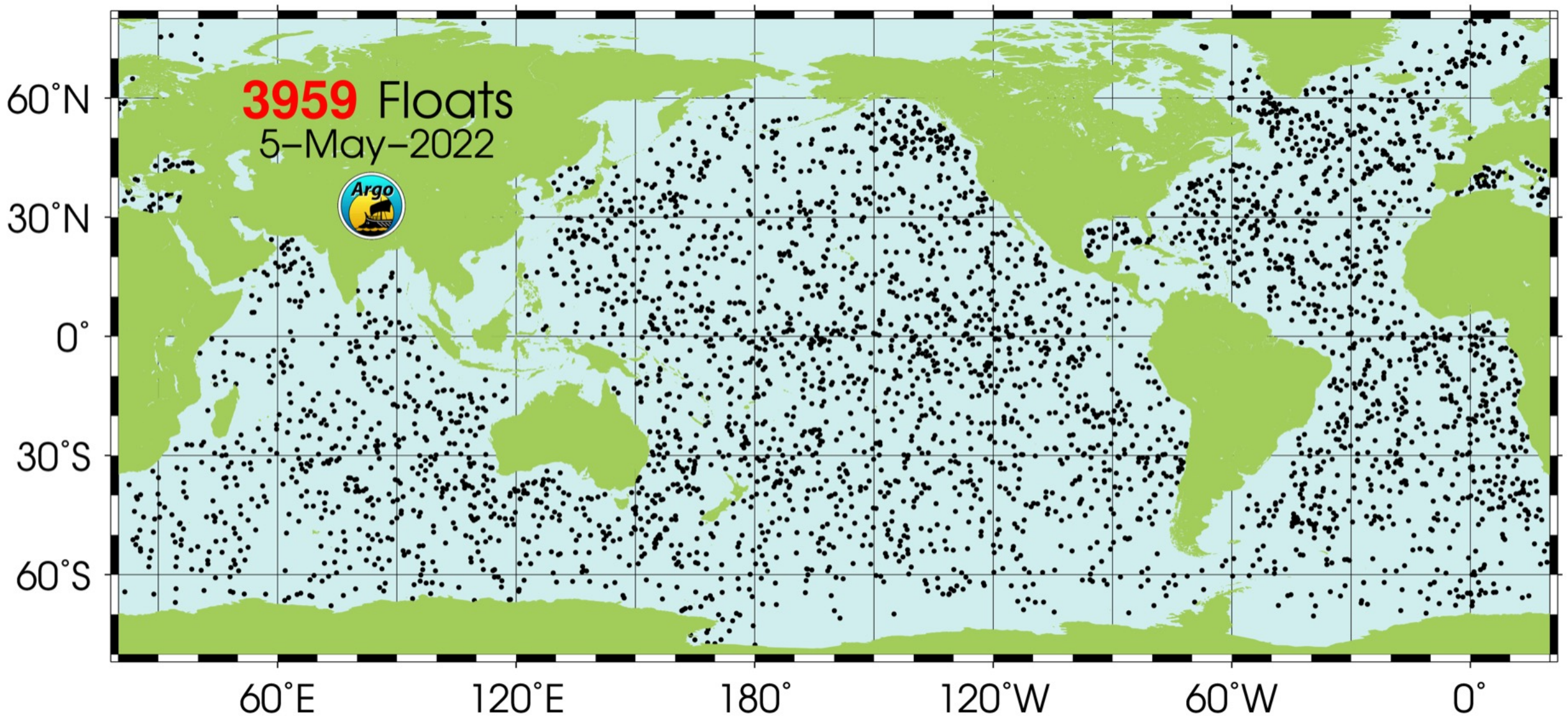
Comparison of ϵ against VMP casts:

$$C_e = 0.146$$

$$C_e = 0.123$$

(overall statistics)

Potential for Scalability to the entire Argo array



How Apex floats work?

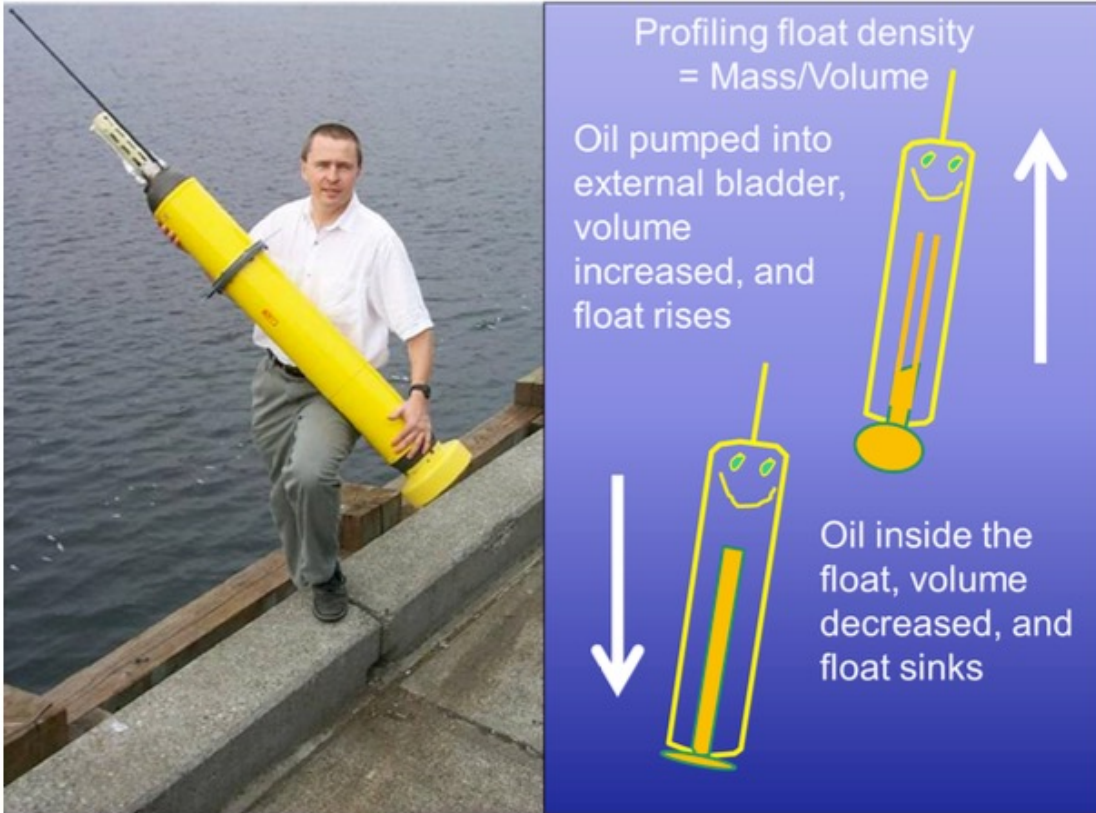


Figure 1: (left) A Teledyne Webb Research APEX (Autonomous Profiling Explorer) float. (right) A schematic of the operation of the float buoyancy engine.

Buoyancy engine:

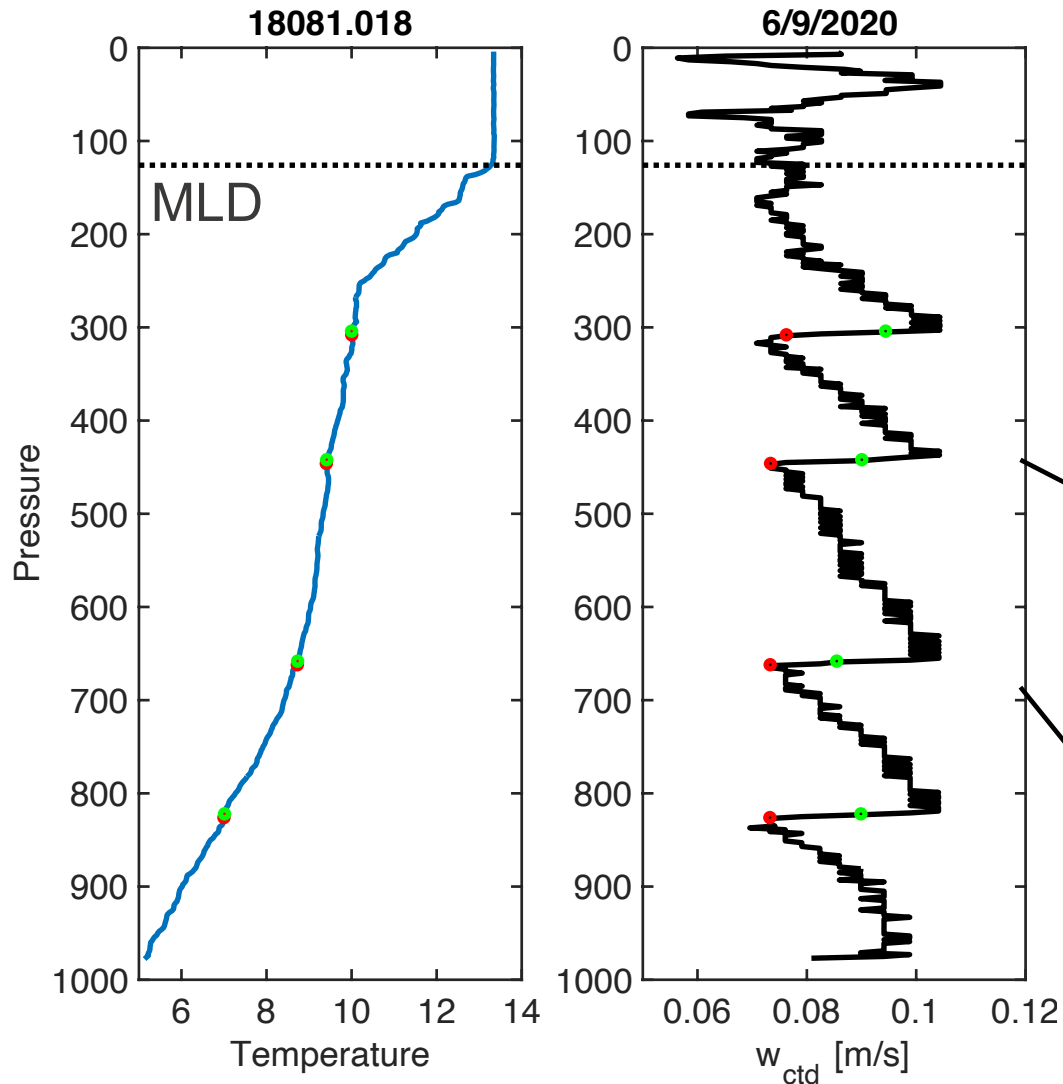
Oil is pumped into/out of the bladder to change its volume

Carry a pumped SBE41cp CTD, sampling at 1Hz and returning binned pressure sensor data every 2m

$$w = \frac{dz * f_s}{N_{bin}} = \frac{dz}{dt}$$

Johnson (2017), Riser et al. (2018)

Example of ascent rate profile from an Apex float



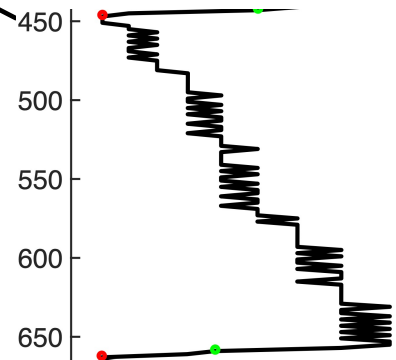
1) Buoyancy Pump Activity:

- pump on
- pump off

Low frequency
sawtooth pattern

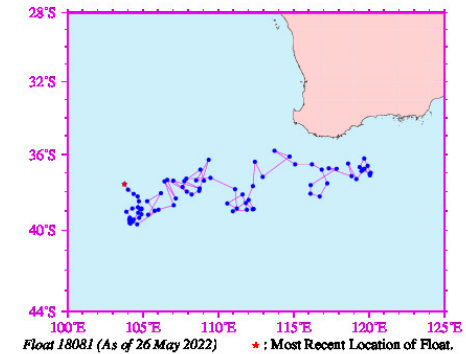
engineering data not always available!

2) Pressure sensor:



High-frequency noise

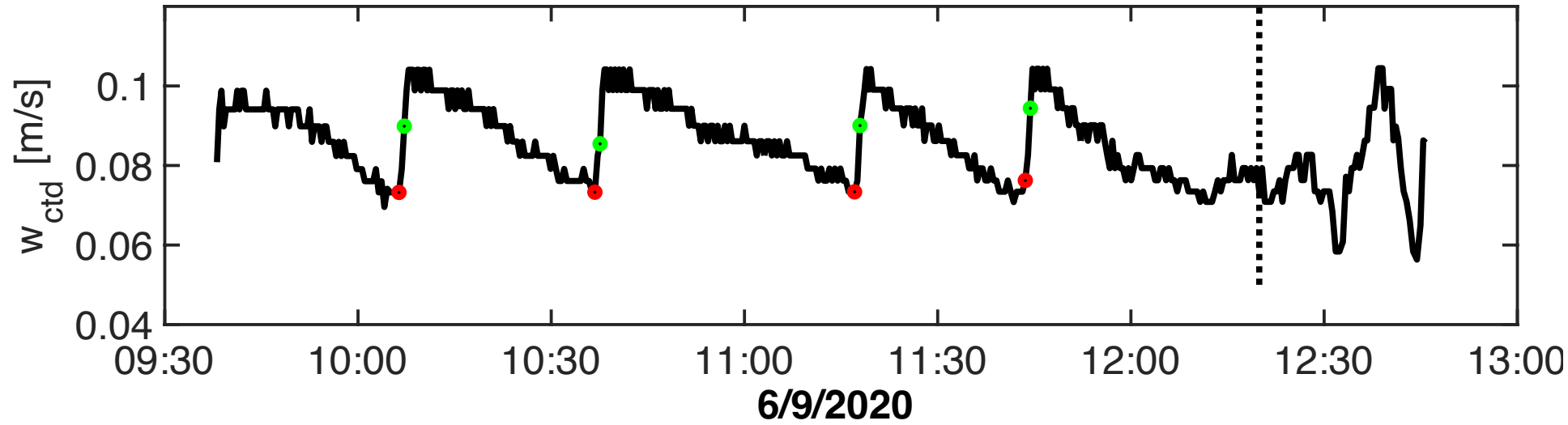
Can we filter out these effects to recover w ?



Can we filter out these effects to recover w ?

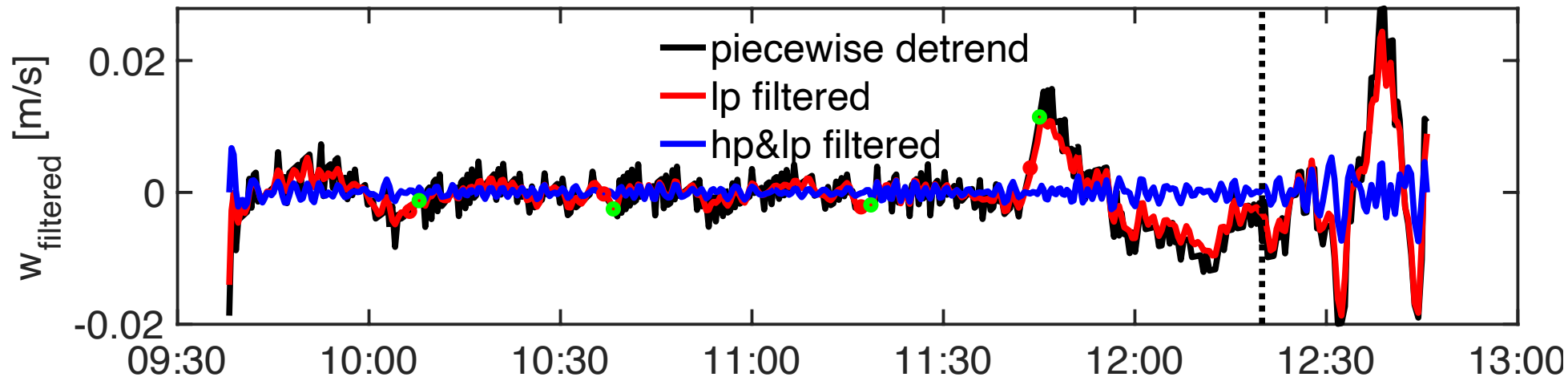
18081.018 6/9/2020

MLD ~ 125 m



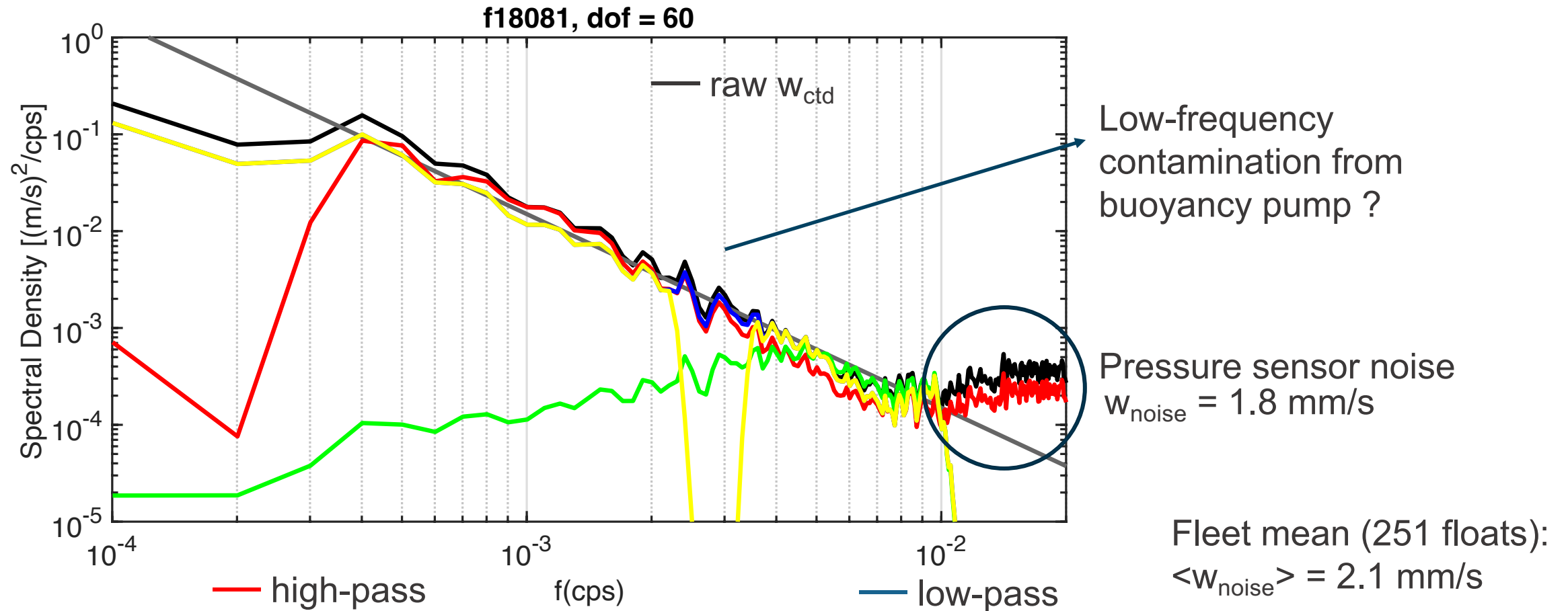
Buoyancy Pump

● pump on
● pump off

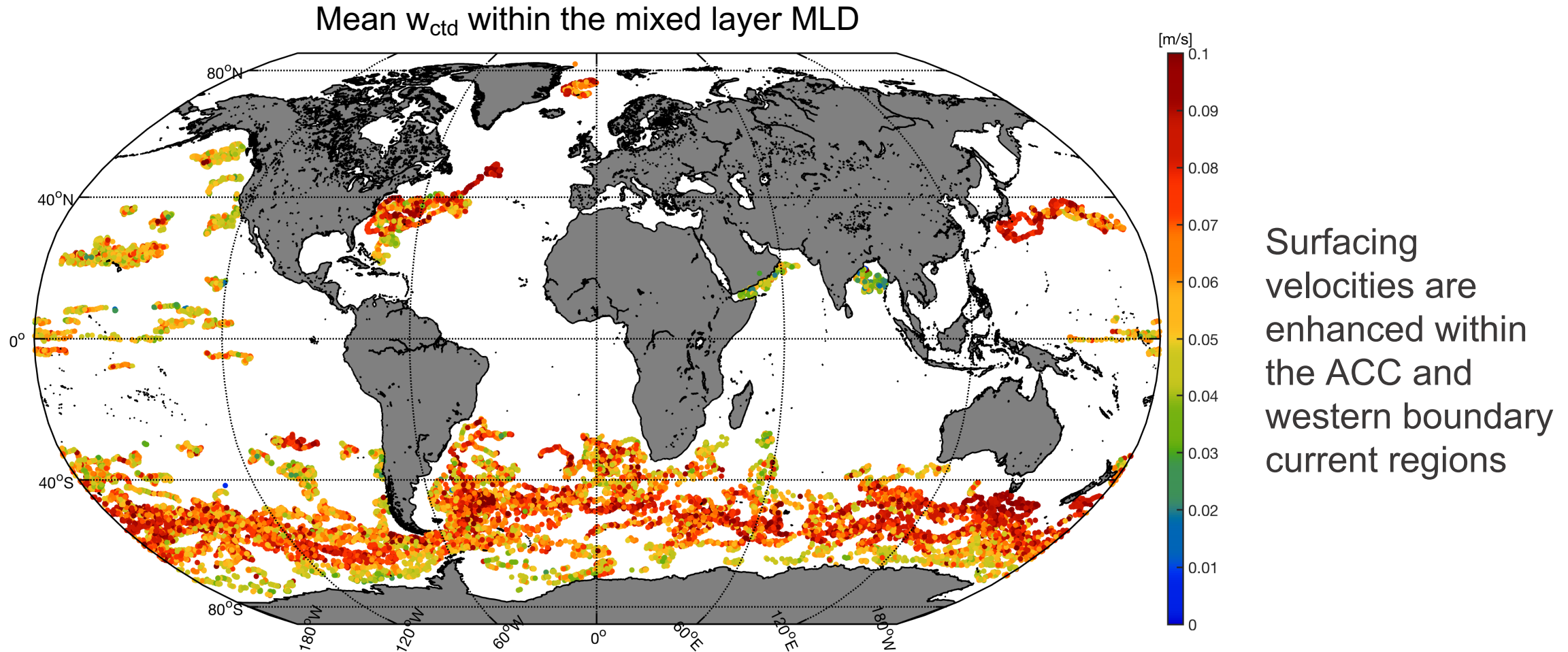


Engineering data
not always
available!

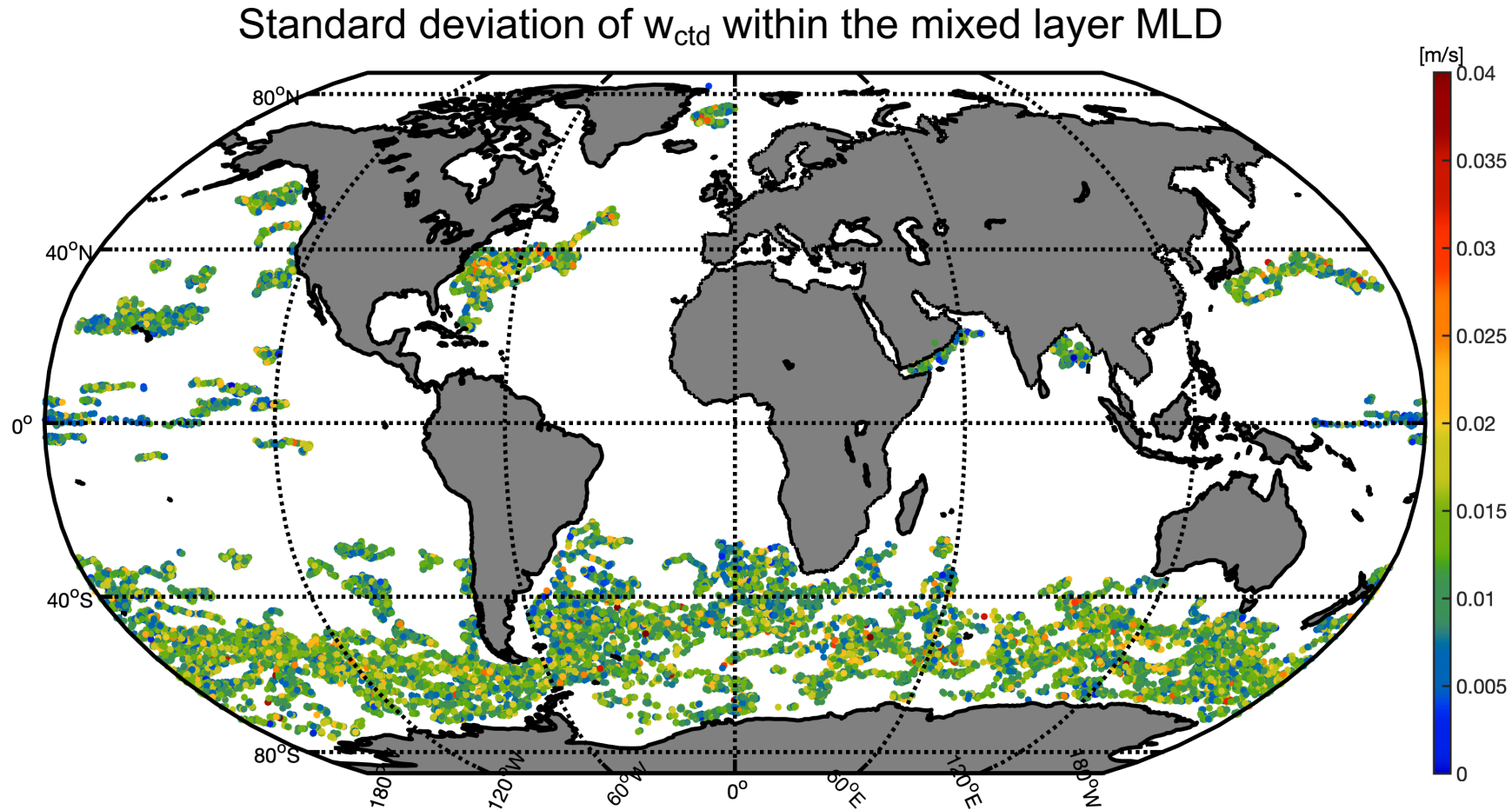
Can we filter out these effects to recover water velocity, w ?



APEX Float's Ascent Rates: Mean Surfacing Velocities



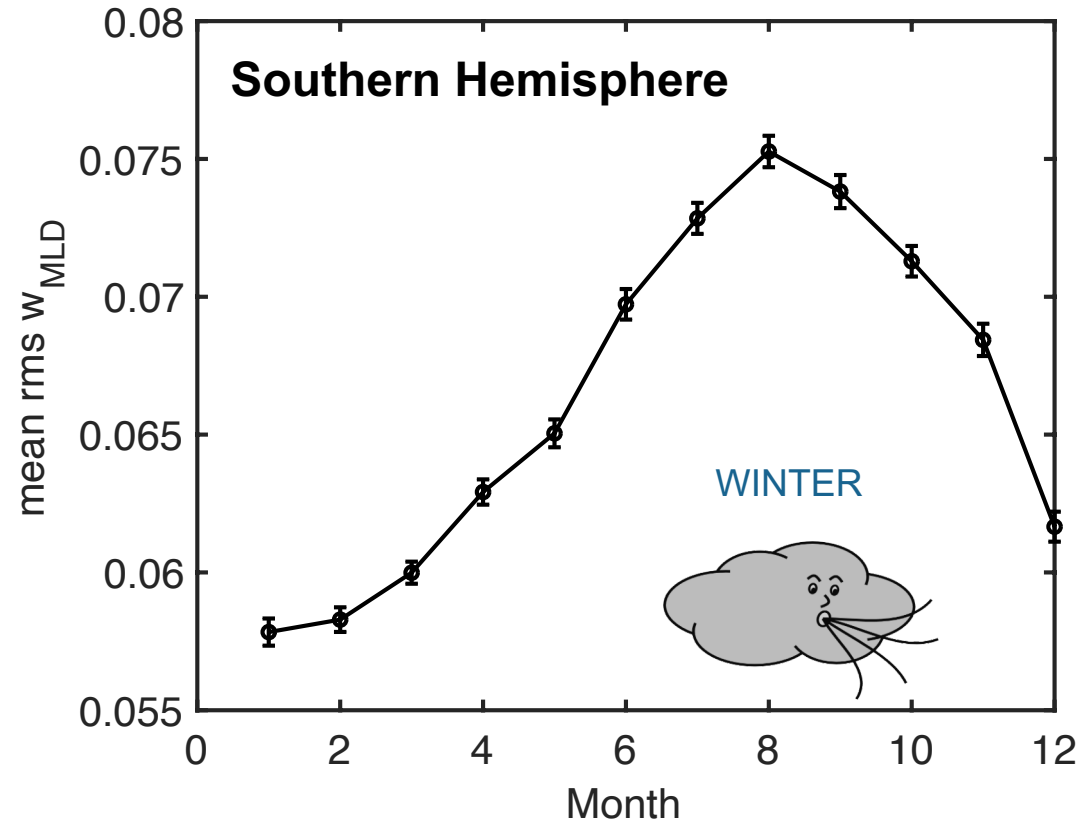
APEX Float's Ascent Rates



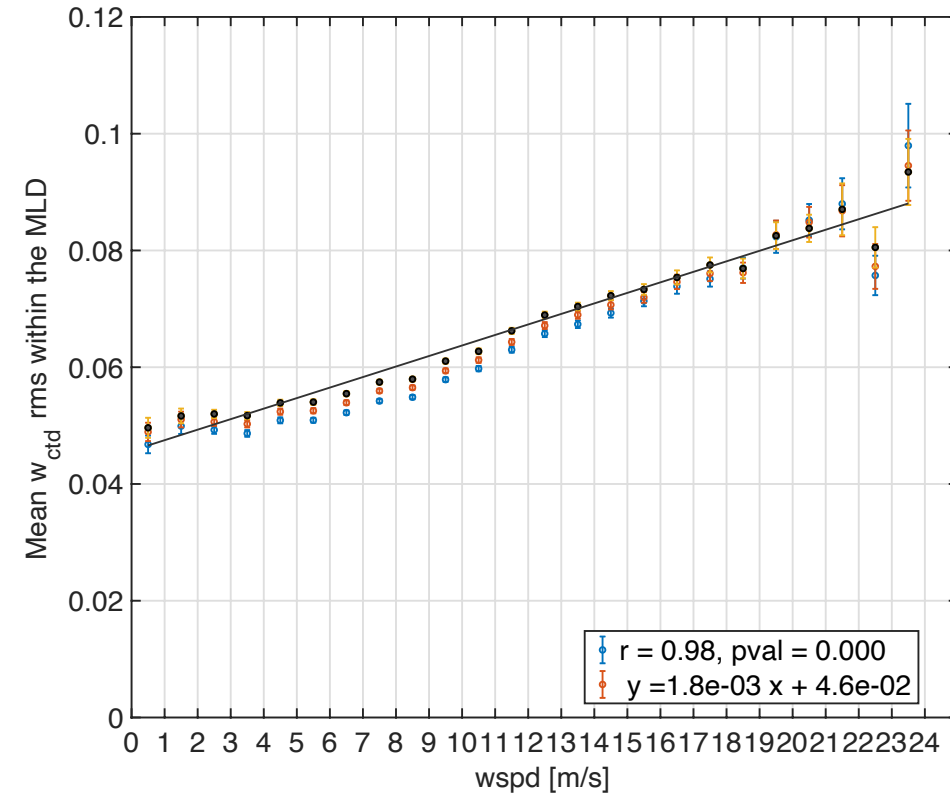
Spatial patterns consistent with regions where we expect elevated mixing

Seasonality and correlation with winds is consistent with expectations

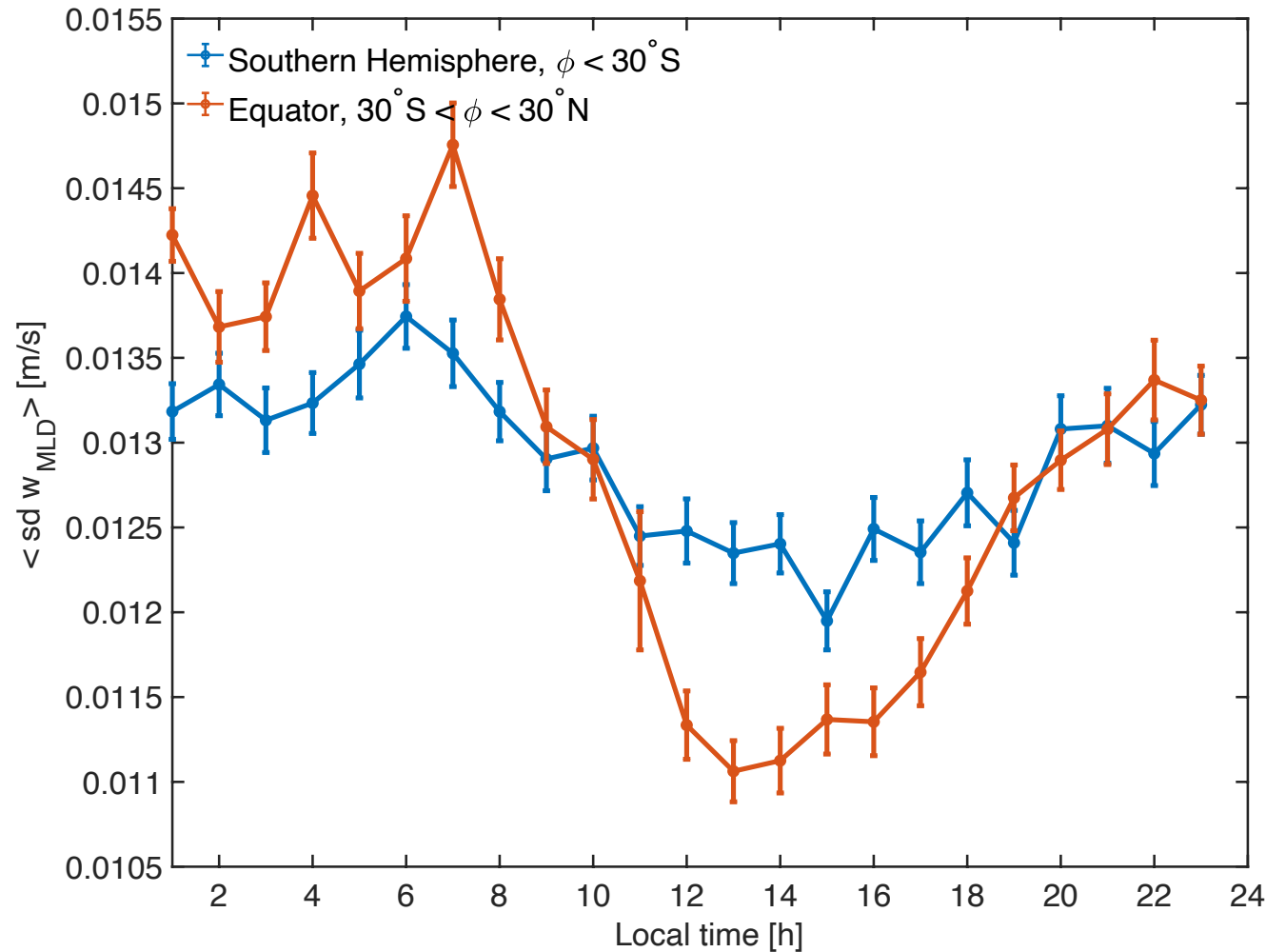
High w variance in wintertime



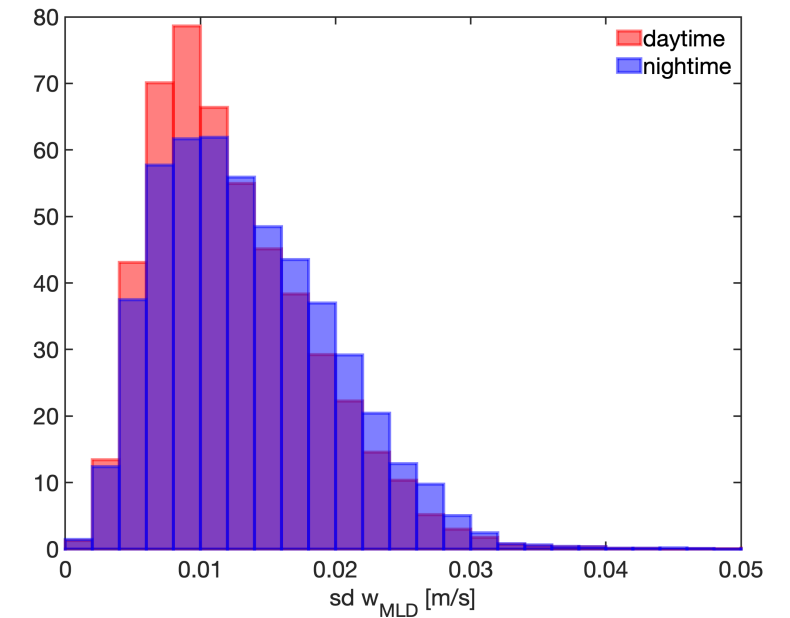
w variance increase with high winds



Diurnal variability in float's ascent rates (SD within the ML)



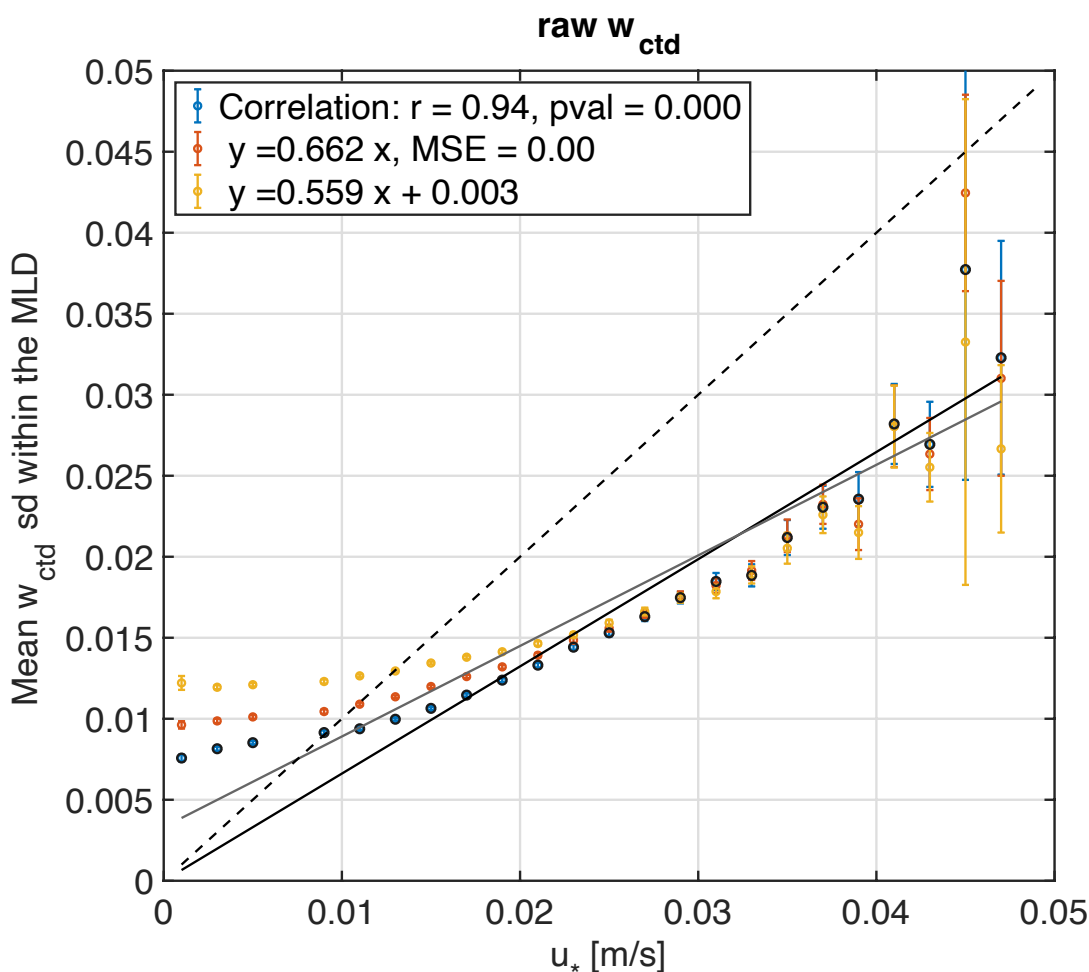
Larger diurnal amplitude in the Equatorial band ($\sim 4 \text{ mm/s}$), relative to higher SH latitudes



Scaling Arguments for rms w

$$w^* = < w^2 >^{1/2}$$

Wind-driven mechanical mixing
(Tseng and D'Asaro, 2004;D'Asaro and Daikiri, 2019)



MLD threshold sensitivity

- 0.005 kg/m³
- 0.03 kg/m³
- 0.125 kg/m³

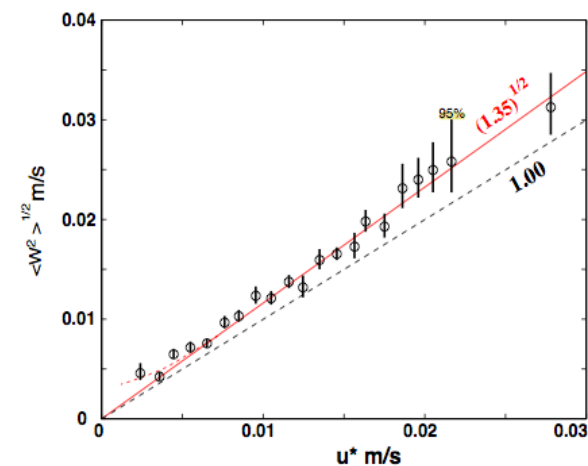


Figure 3. Root mean square vertical velocity σ_w as a function of friction velocity u_* . Line is $\sigma_w = \sqrt{1.35} u_*$.

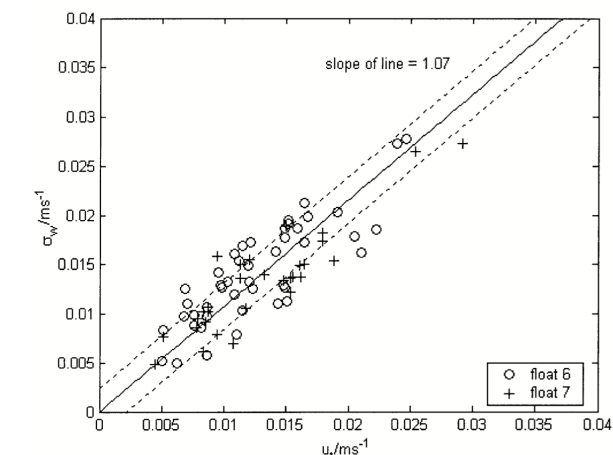
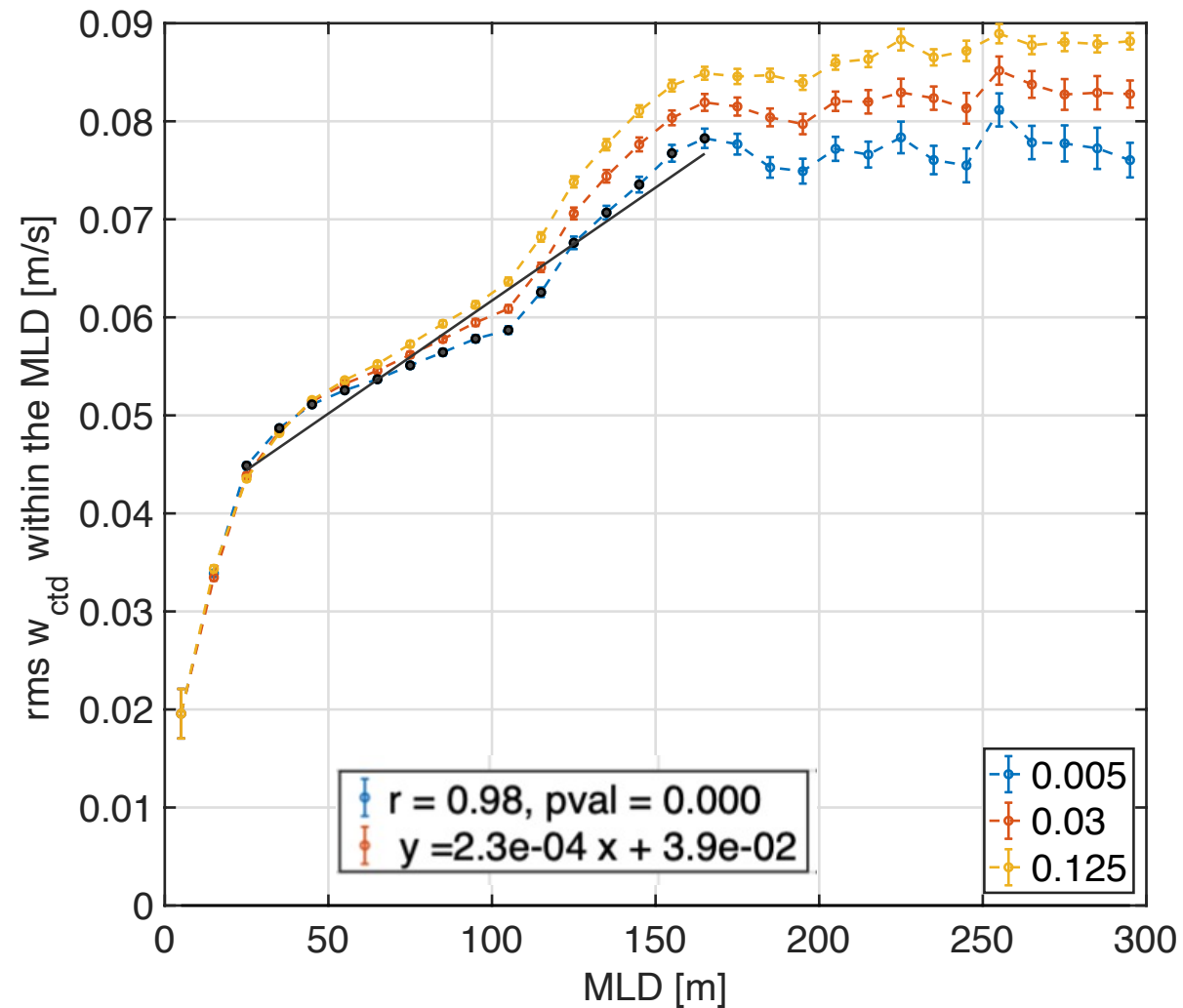
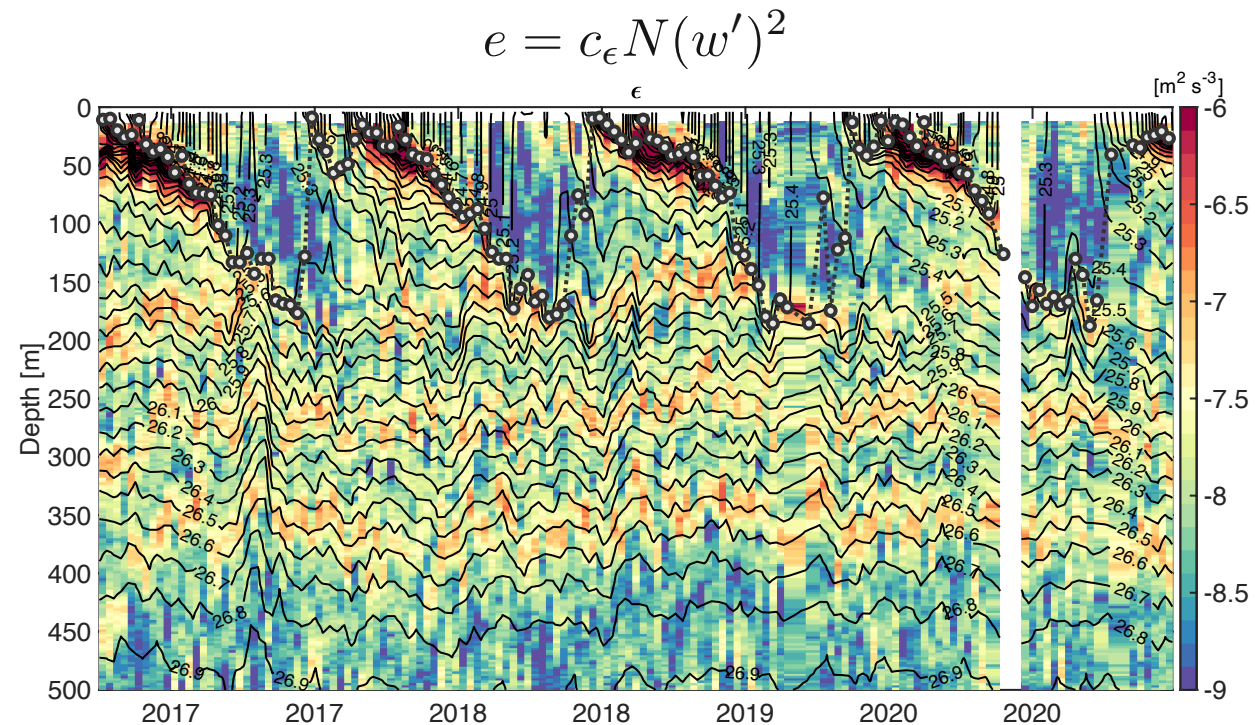
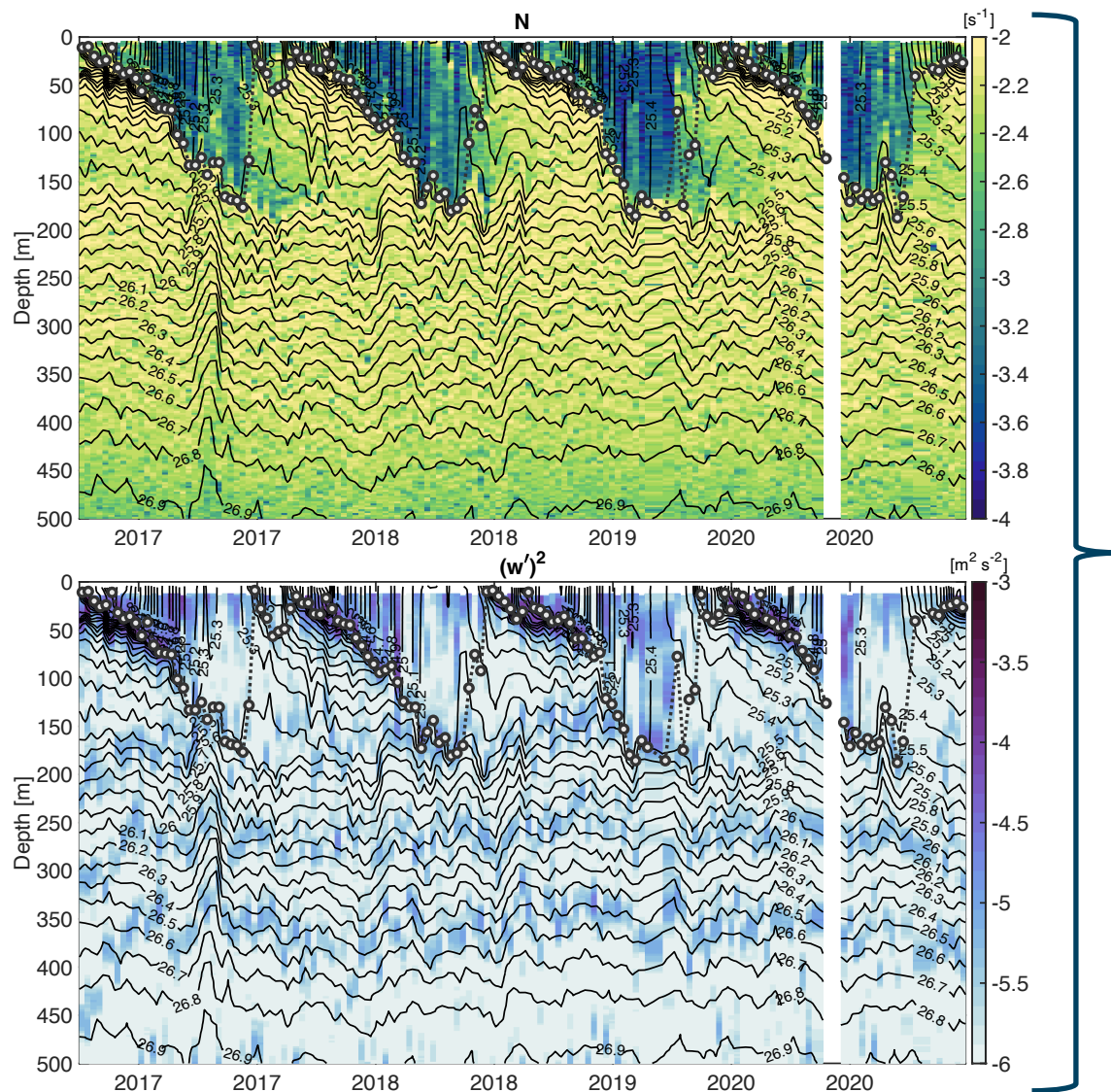


FIG. 3. Root-mean-square vertical velocity $\langle w^2 \rangle^{1/2}$ as a function of friction velocity u_* for Lagrangian float data within the mixed layer. The line has a slope of 1.07. The dotted lines indicate 1 standard deviation of measurement error in u_* .

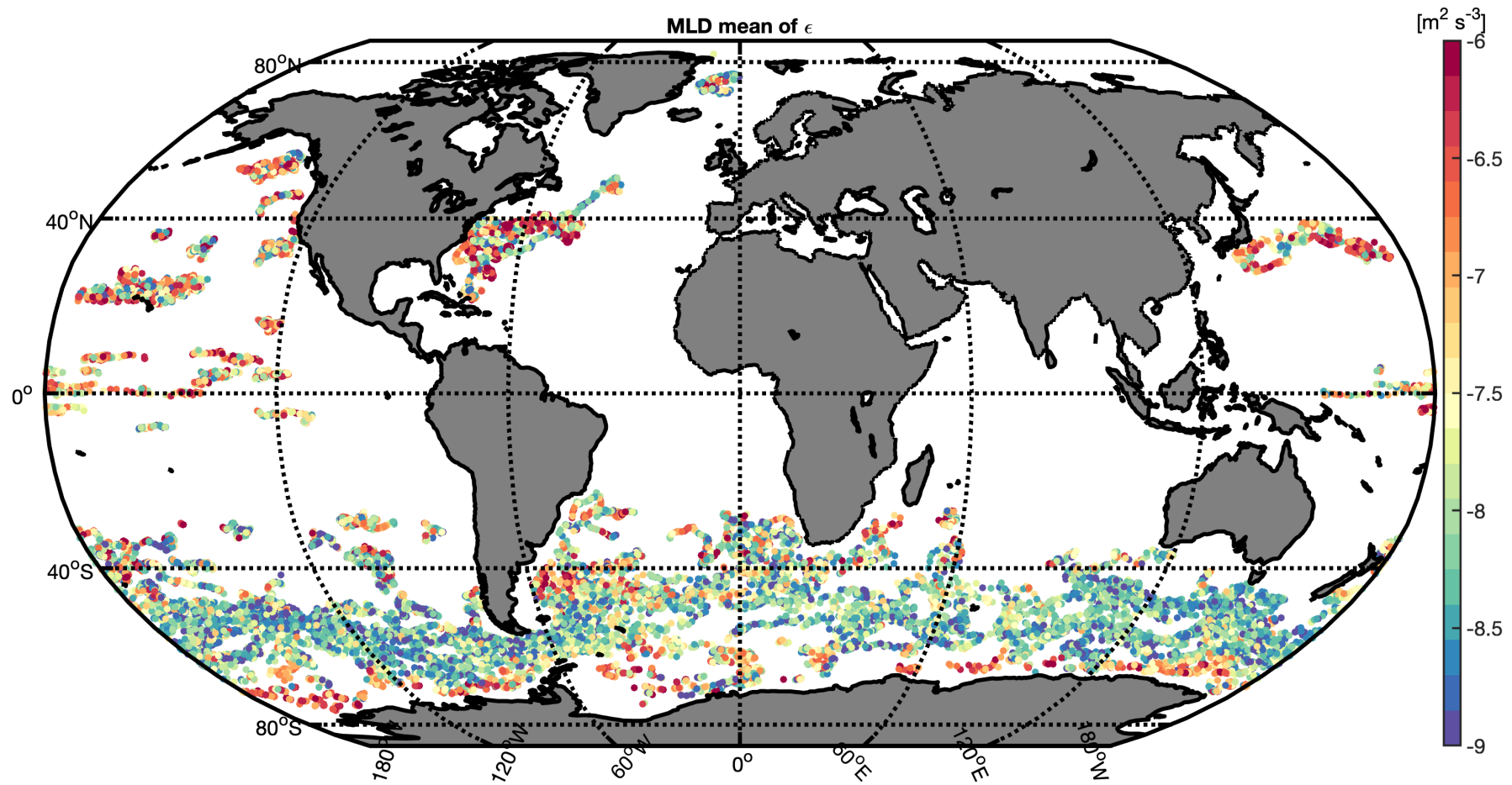
Is w variance larger for deeper mixed layers?



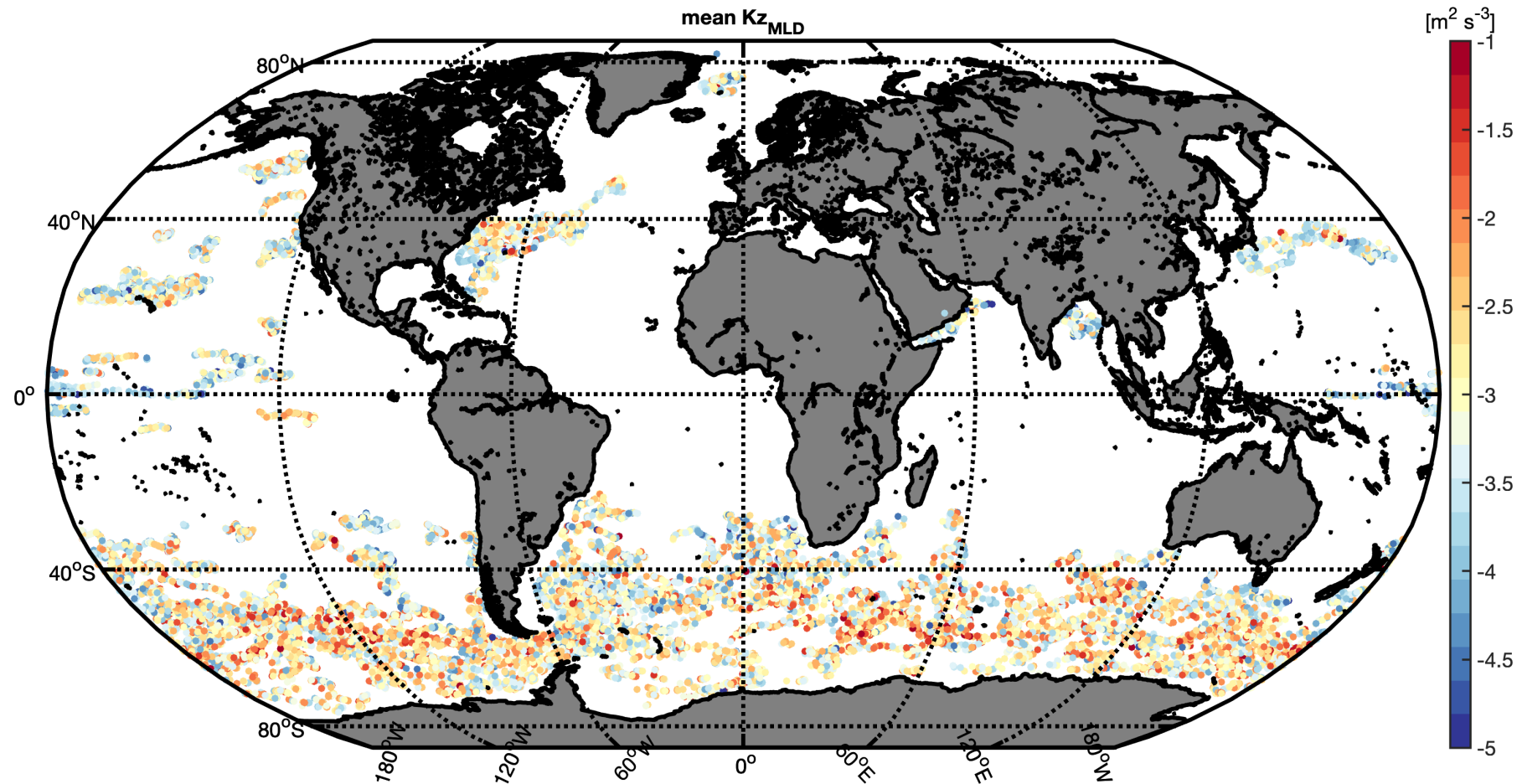
Dissipation rate estimates from LEM



Dissipation rate estimates within the mixed layer (ML)



Vertical eddy diffusivity, K_z , within the ML

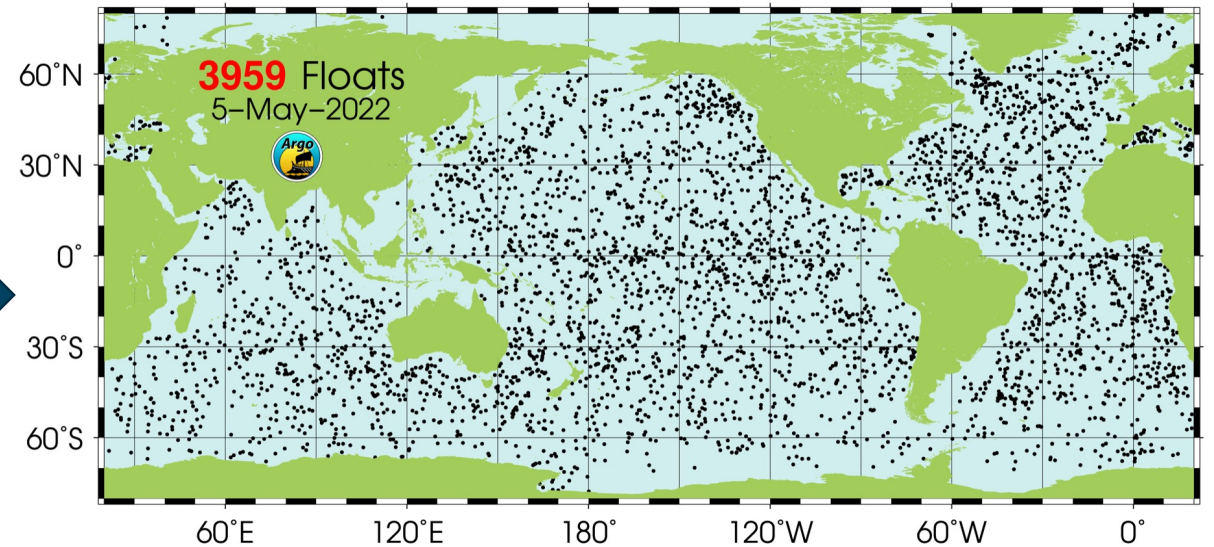


Remaining Issue



Calibration
Coefficient

Float ascent
rate variability

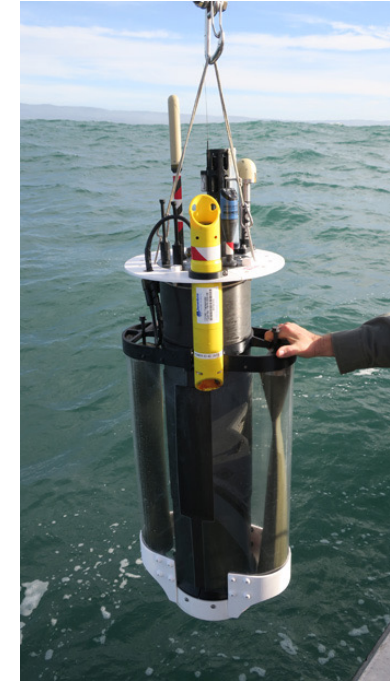
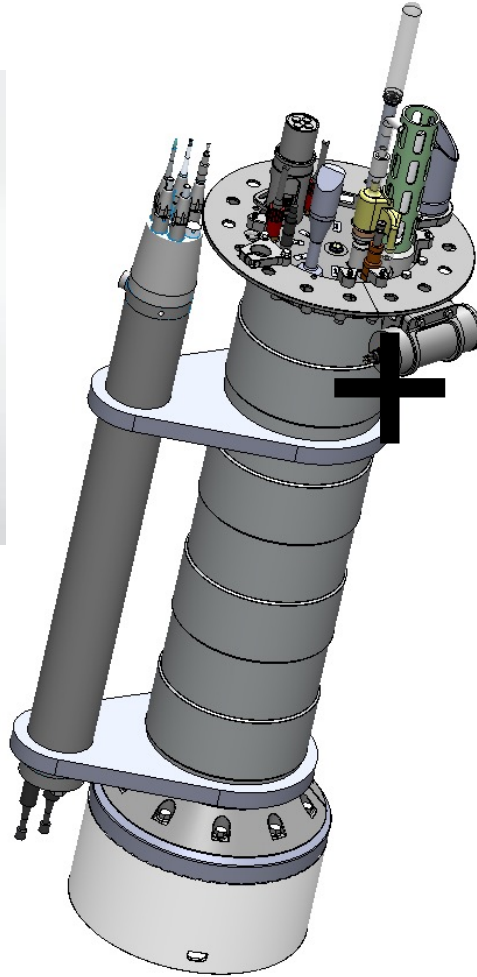


Global K_z estimate

New Technology: Microstructure Sensors on Autonomous Platforms



MicroRider
(direct measurements
of turbulence)



Coastal Profiling Float
(‘Pick-up truck float’)

CPF + MR integration

CPF + MR Deployments at Sea



09/24
MR arrival

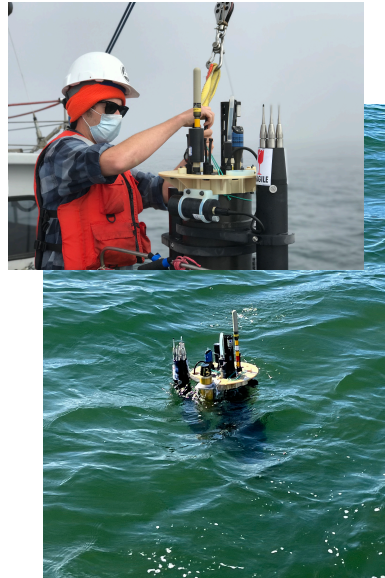
Pre-MR arrival tasks

- ✓ Profiling
Speed
- ✓ Buoyancy
Control off

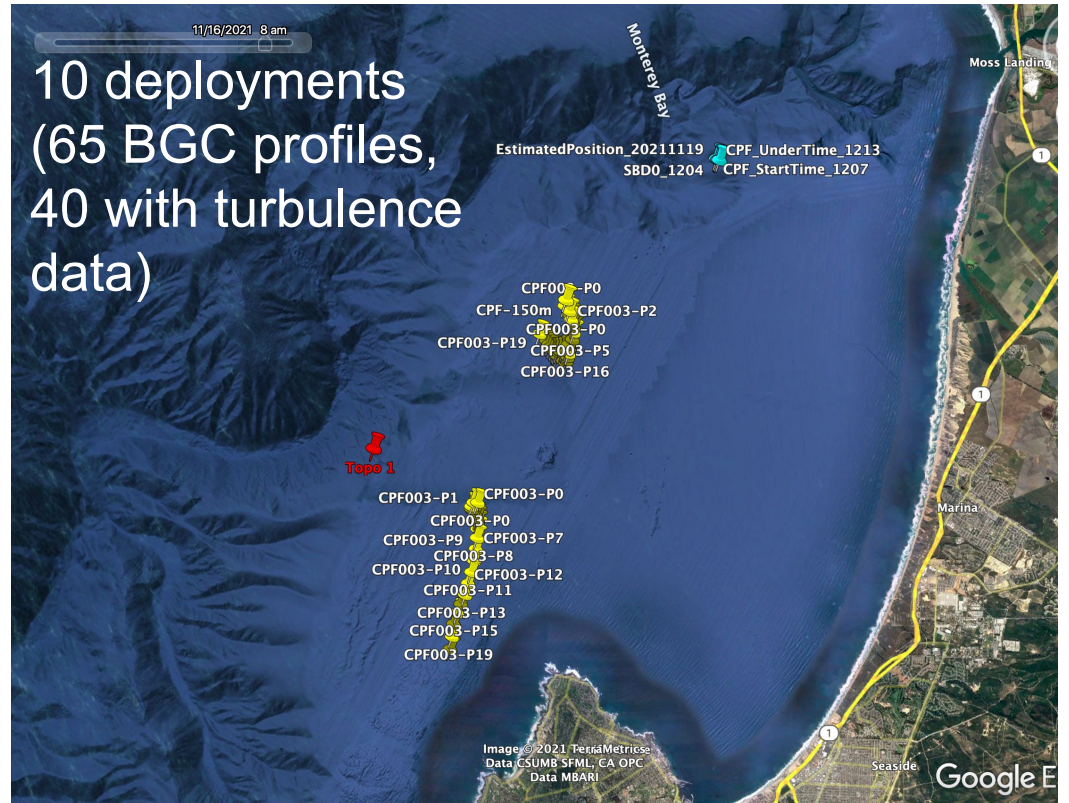
Tank Testing

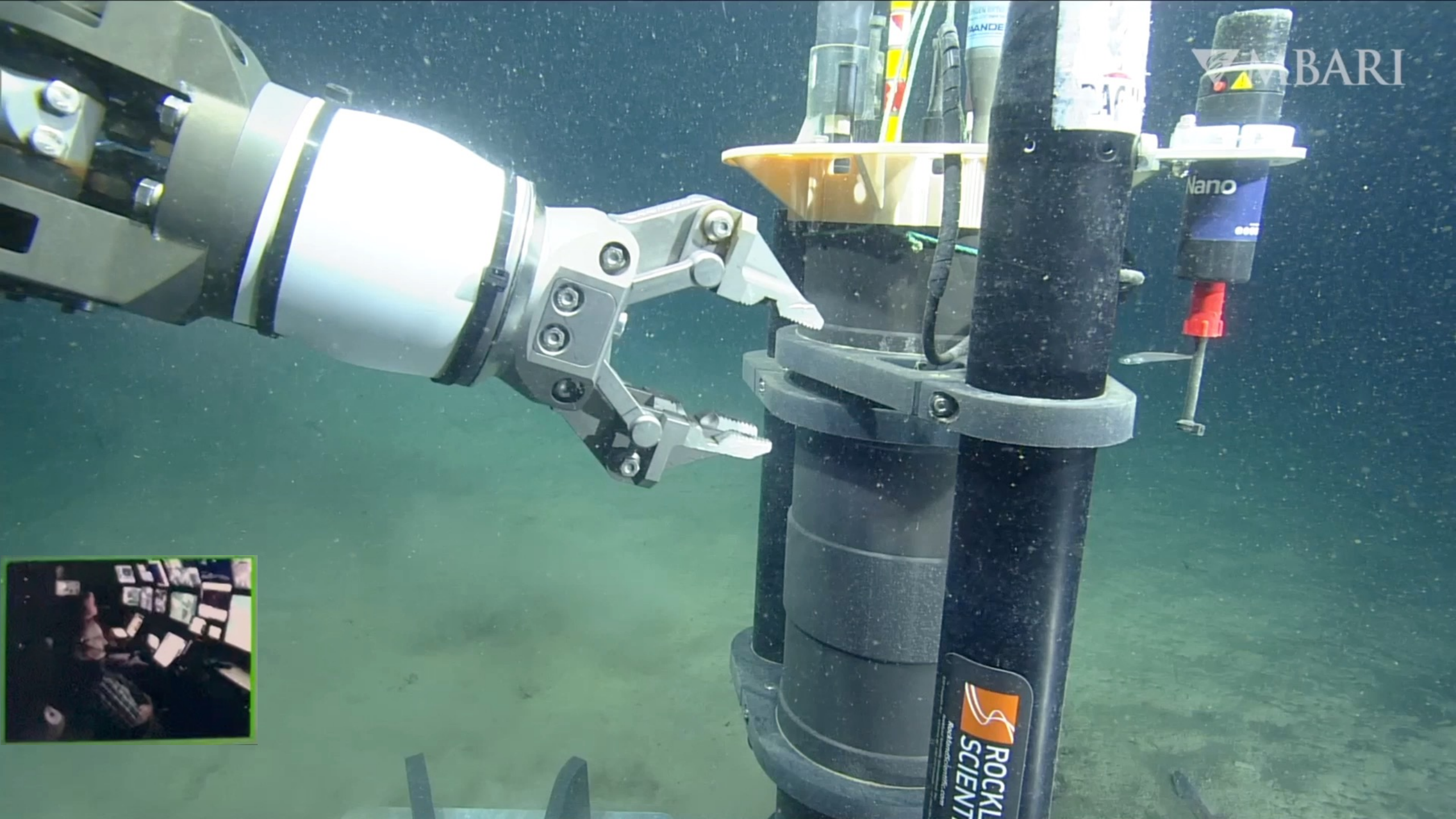


10/08
1st at-sea
Deployment



12/2021



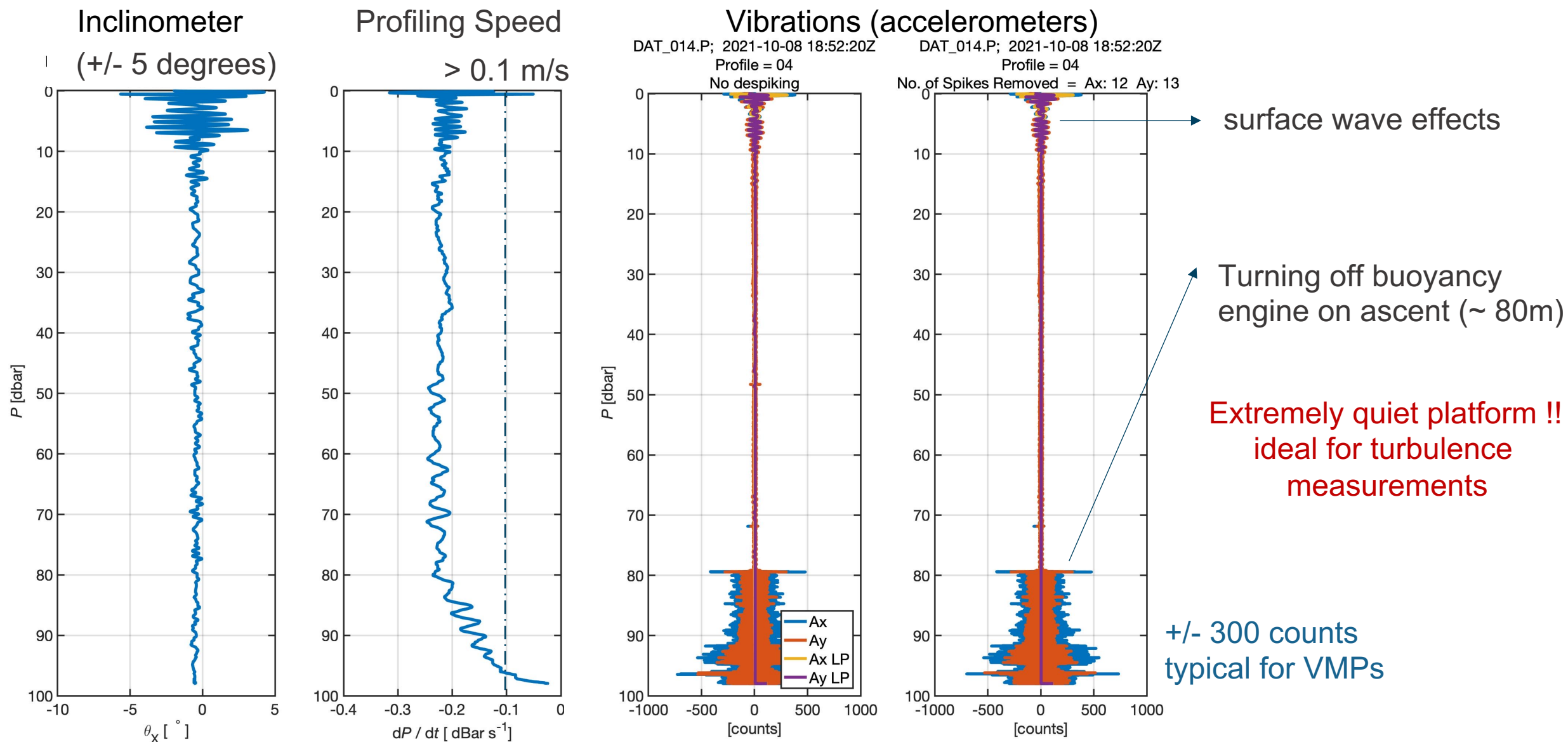


BARI

Nano

ROCK
SCIENT

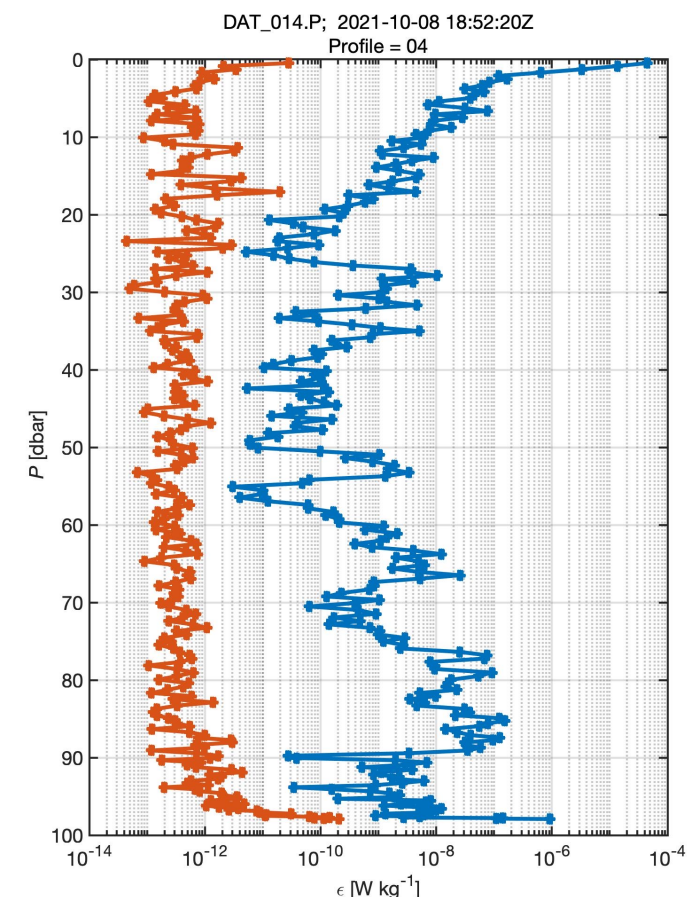
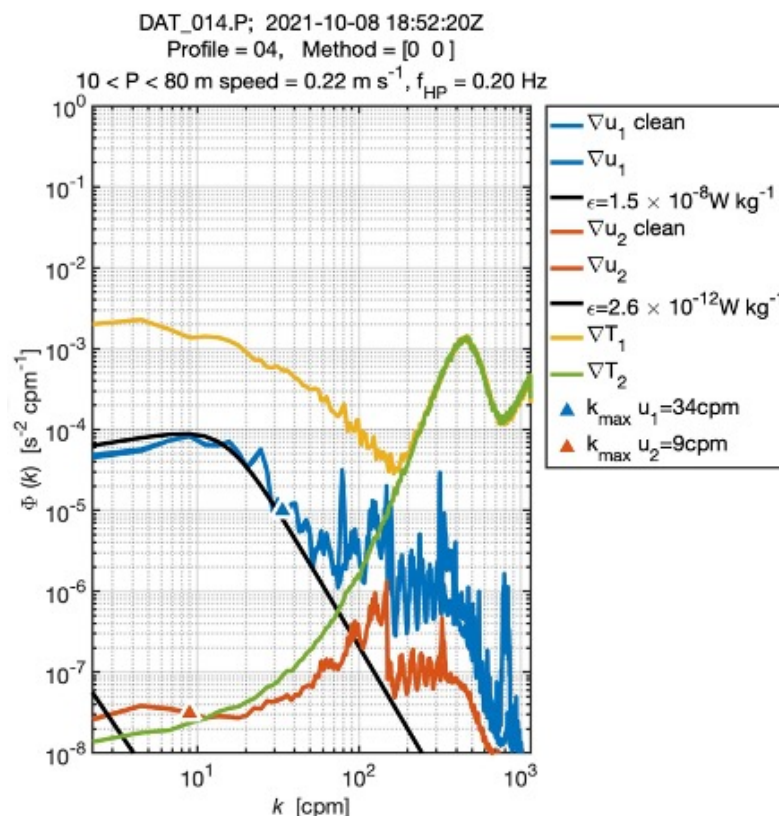
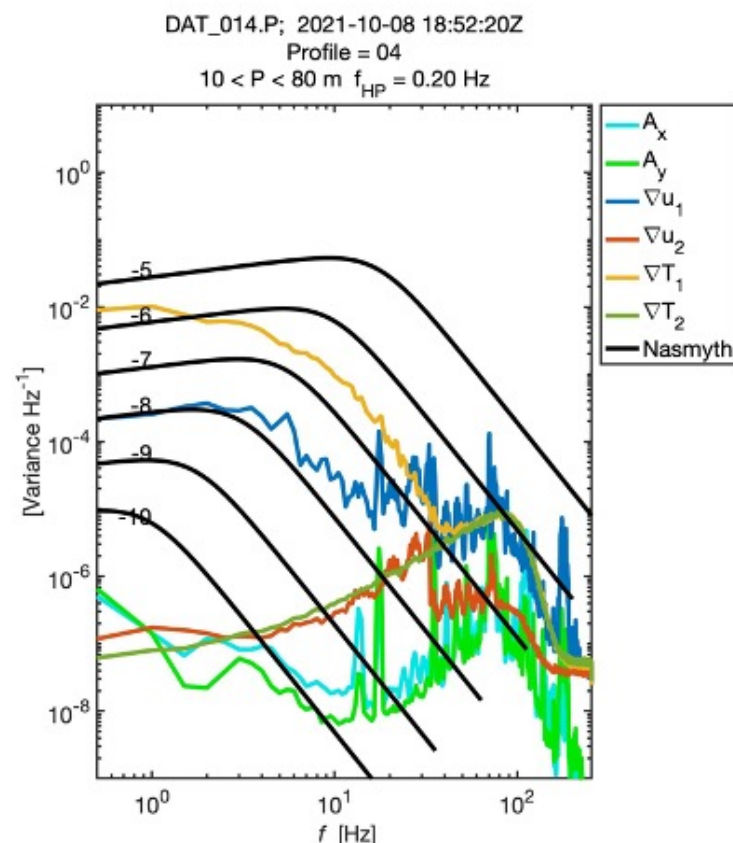
CPF- MR: First at-sea Deployment on Oct 08, in the south Monterey Bay



CPF- MR: Turbulence Intensity through the water column

Vertical Current Shear spectra between 10-80m

Vertical profile of ϵ
(a.k.a mixing rates!)

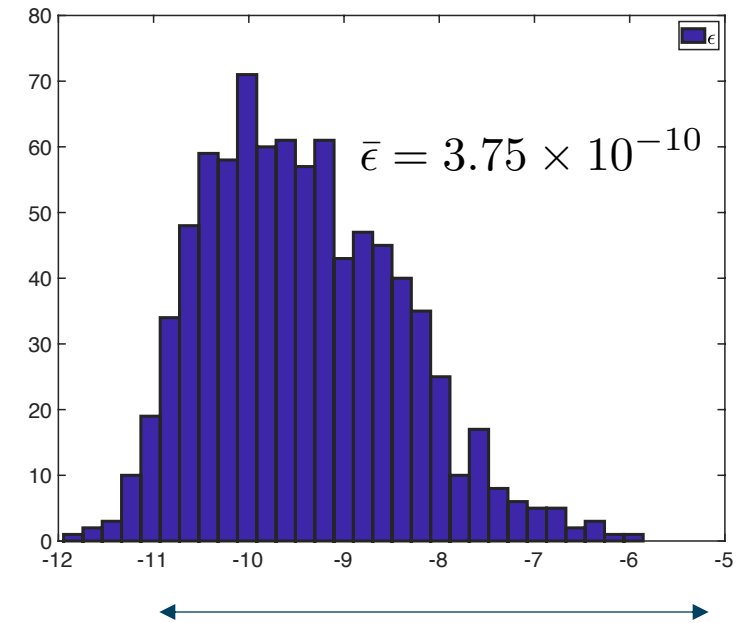
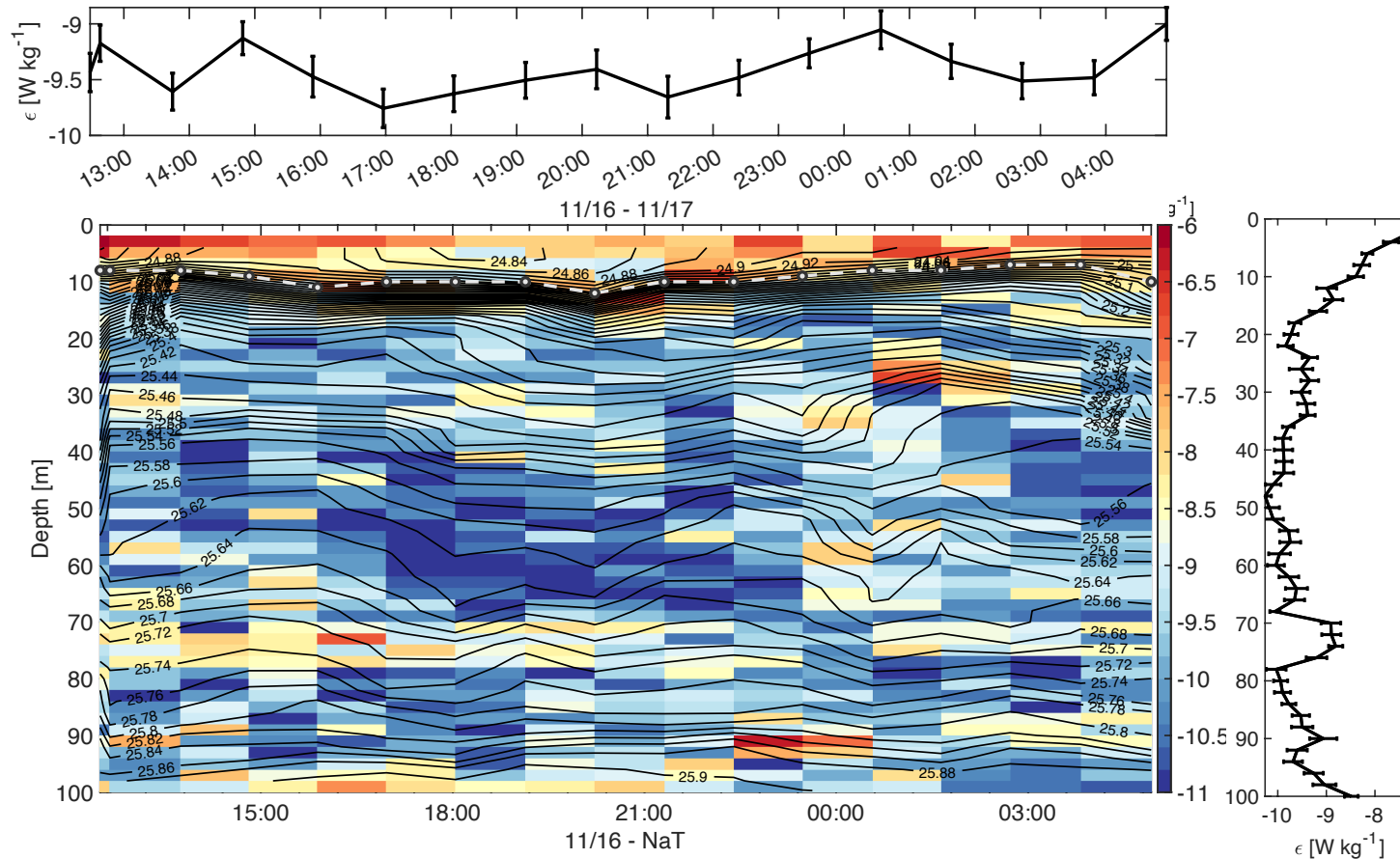


Frequency space → Wavenumber space

W: platform velocity

Turbulence Intensity

ϵ dissipation rate
(from microstructure shear obs)



Low compared to:

$\bar{\epsilon} = 1.1 \times 10^{-6}$ Kunze et al. 2002

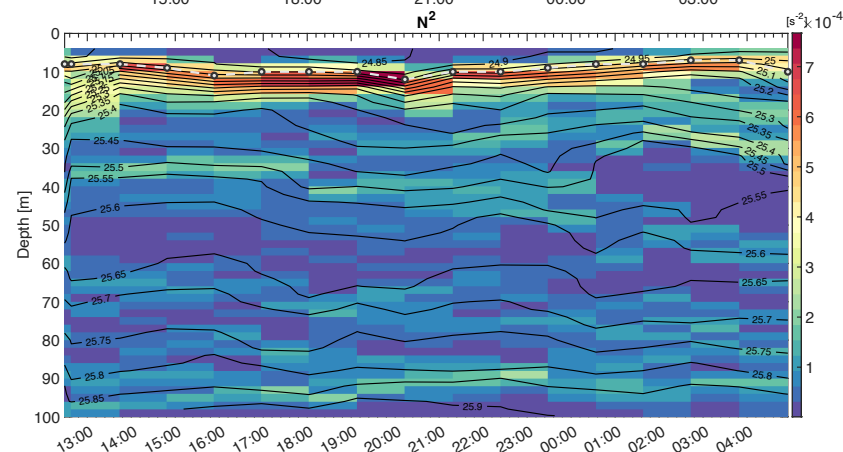
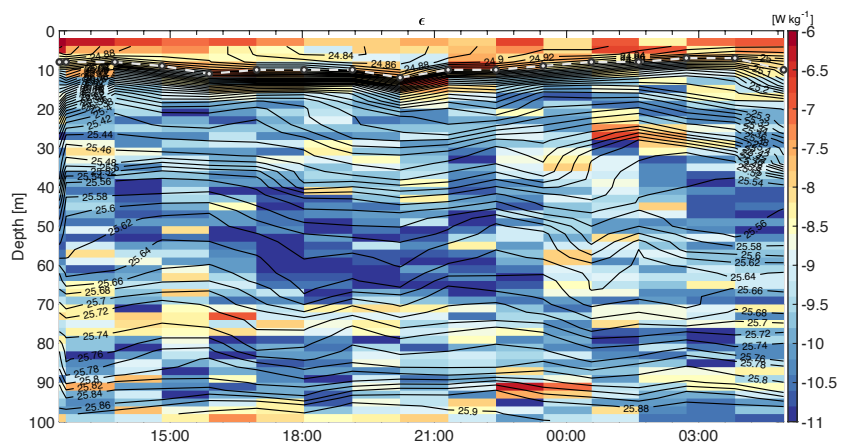
$\bar{\epsilon} = 7.4 - 55.8 \times 10^{-9}$ Carter et al. 2005

$\bar{\epsilon} = 4 \times 10^{-8}$ Kunze et al. 2012

Lueck & Osborn, (1985)

Eddy Diffusivity coefficient, K_z

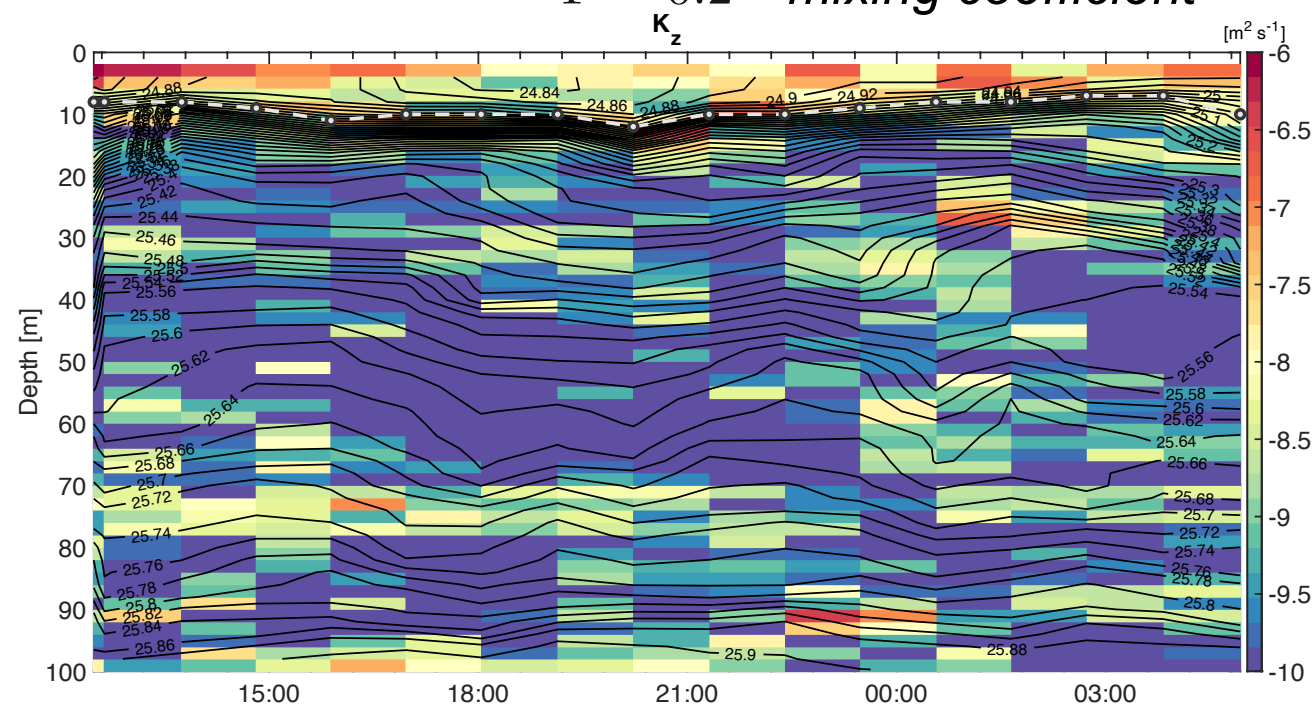
ϵ dissipation rate of TKE
(from microstructure shear obs)



$$\bar{N}^2 \sim \frac{\partial \rho}{\partial z} \text{ stratification}$$

$$K_z = \frac{\Gamma}{N^2} \epsilon \quad [m^2 s^{-1}] \quad \text{Osborn (1980)}$$

$\Gamma = 0.2$ mixing coefficient



$$\bar{K}_z \leq 15 \times 10^{-4}$$

$$\bar{K}_z = 1.0 \times 10^{-2}$$

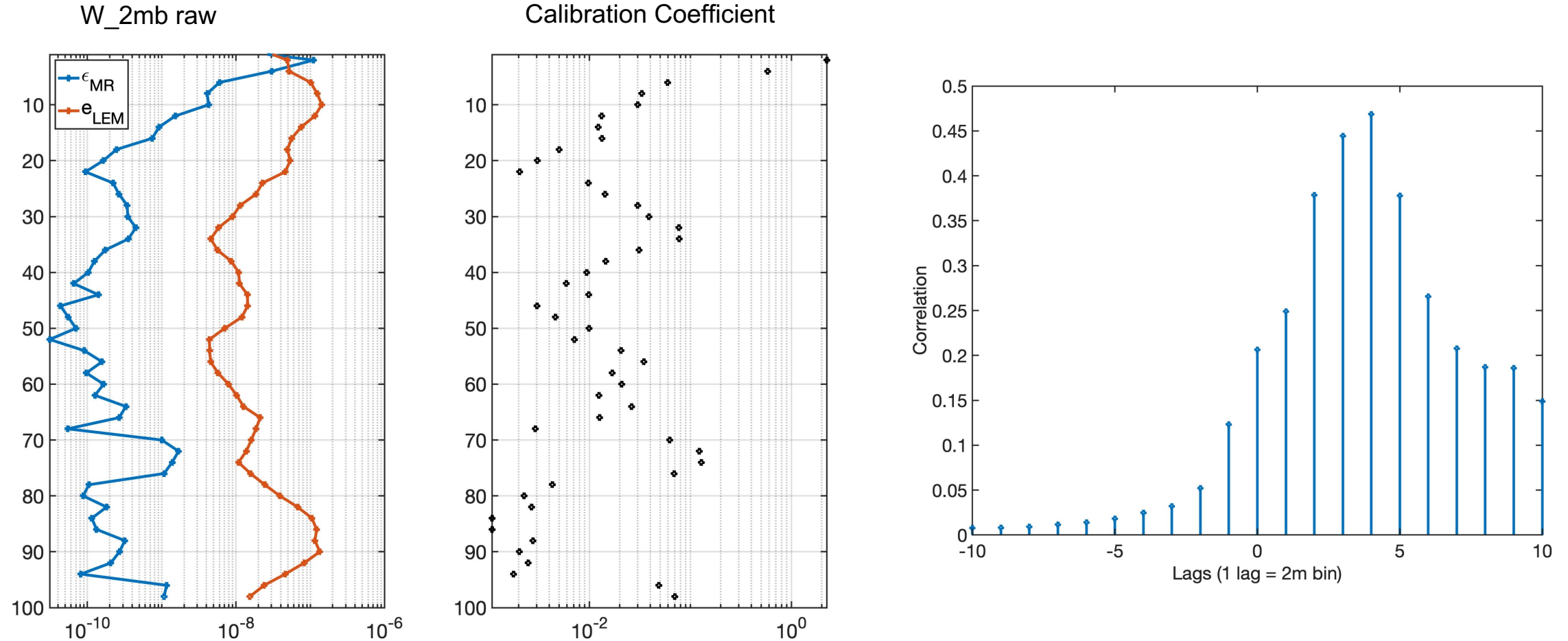
$$\bar{K}_z = 6.1 - 37.8 \times 10^{-5}$$

Lueck & Osborn, 1985

Kunze et al. 2002

Carter et al. 2005

Turbulence Intensity Estimates from CPF's ascent rates (LEM)



Preliminary Results: Float ascent rate tends to overestimate dissipation rates

Main Take Aways

- ✓ Spatio-temporal variability in Apex float's ascent rates within the mixed layer suggest an oceanic signal potentially related to turbulence
- ✓ Both mean and standard deviation in ascent rates correlate with high winds and deep mixed layers.
- ✓ The LEM looks promising for estimates of vertical mixing rates, albeit for a narrow band of turbulence scales
- ✓ CPF+MR deployments could provide a calibration coefficient for the LEM



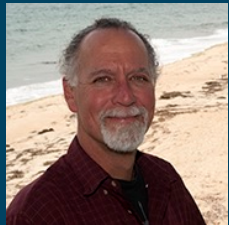
Gene Massion



Joseph Warren



Jared Figurski



Paul Coenen



Eric Martin



Tom O'Reilly



the David & Lucile Packard
FOUNDATION

Thank you!

Questions?

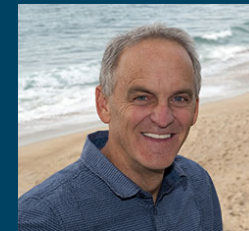
www.mbari.org



Tanya Maurer



Josh Plant



Brett Hobson
& LRAUV Team



Ken Johnson



Yui Takeshita

Future Research Perspectives

Vertical velocities from glider's CTD data and steady flight model

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- ✓ Rudnick et al. (2013) for a Spray glider

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↓

water vertical velocity

$$w_{ctd} = \frac{dp}{dt}$$

↓

Low freq ~ flight

High freq ~ water motion

w_{steady} vertical velocity that the glider would have if going through still water

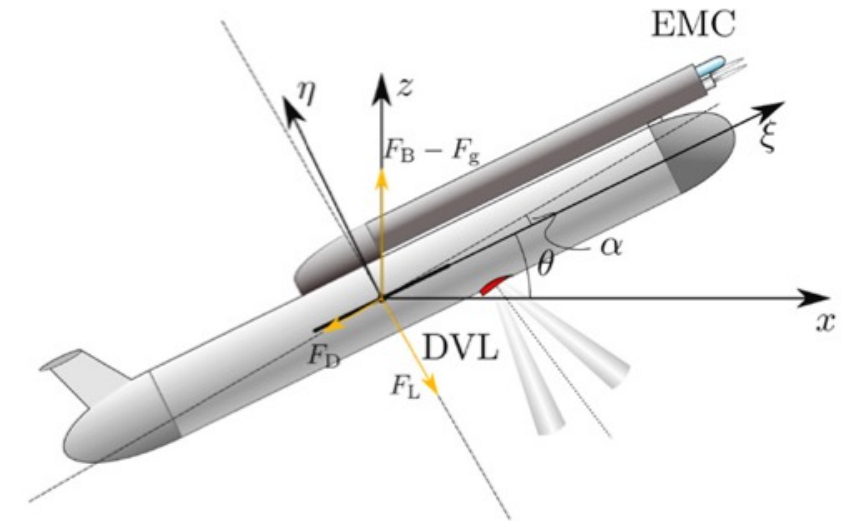
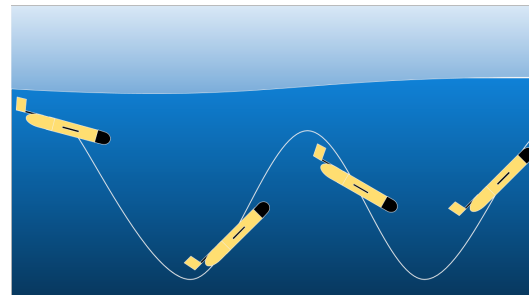


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Dissipation rate estimates from w

Large Eddy Method (LEM):

$$\varepsilon \sim \frac{(q')^2}{\tau} \sim \frac{(q')^3}{l} \cdot \left[\frac{m^2}{s^3} \right] \quad K \sim q'l, \left[\frac{m^2}{s} \right]$$

q' velocity scale of the largest (energy-containing) eddies

τ time it takes to overturn once

l their length scale

For stratified flow, $l \sim L_{Oz} = \sqrt{\frac{\epsilon}{N^3}}$ (Ozmidov Scale)

$$e = c_\epsilon N (q')^2$$

c_ϵ calibration coefficient (determined from MR casts)

N buoyancy frequency/stratification

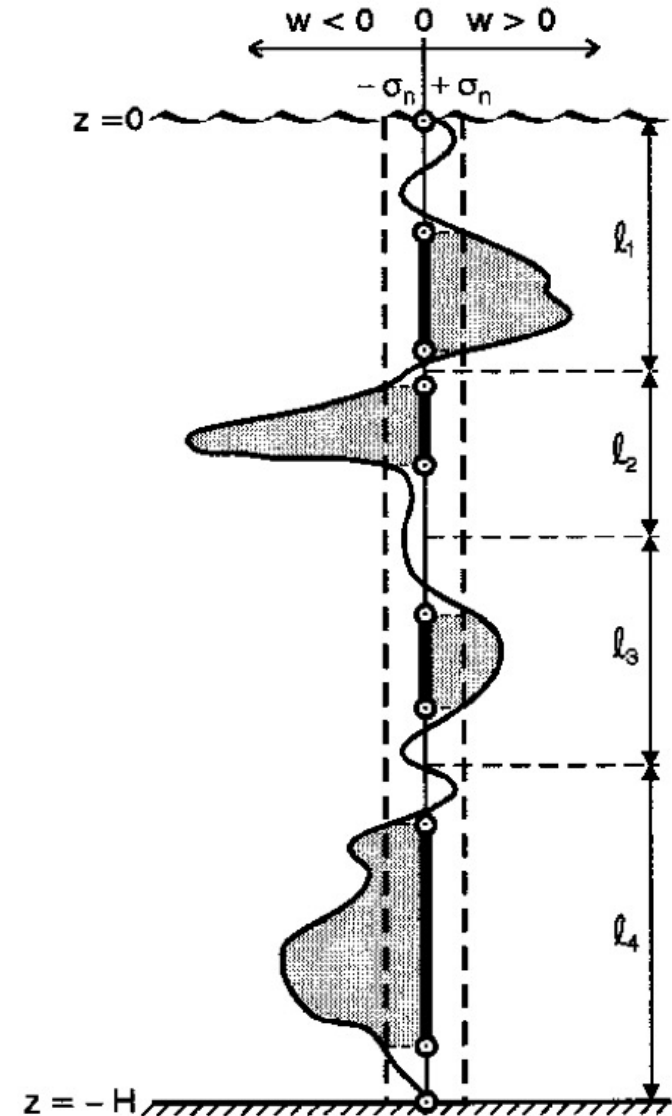
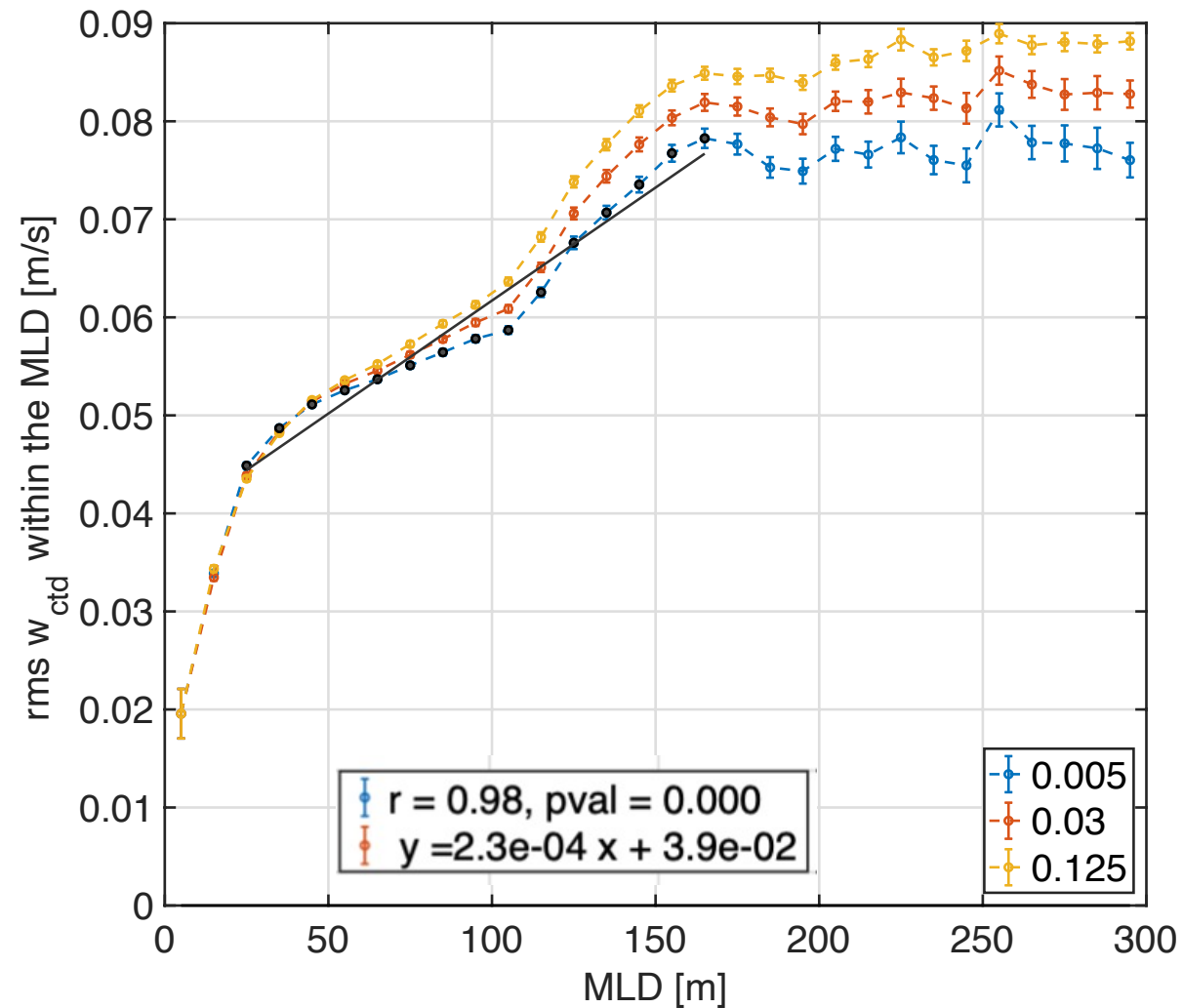


FIG. 6. Schematic of the zero crossing algorithm used for local determination of a (vertical) length scale associated with the large eddies of the turbulent velocity field. For discussion see text, section 3.

Is w variance larger for deeper mixed layers?

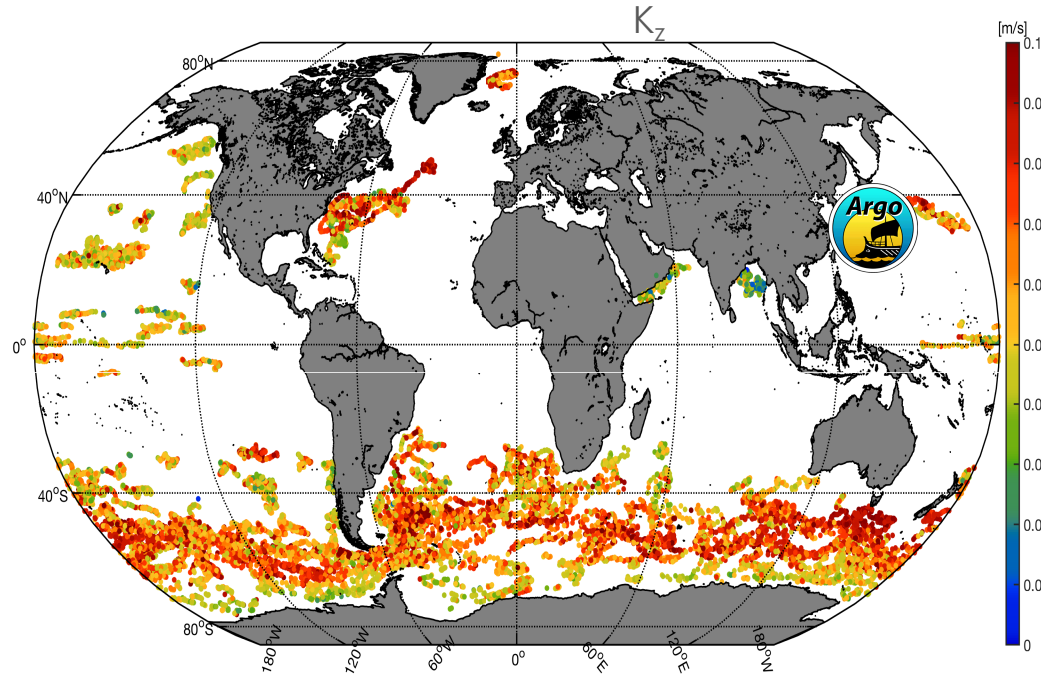


Theme 1. Scalability of vertical mixing rates for the global Argo array

GLOBAL OBSERVATIONS of mixed-layer mixing

Validation of vertical
mixing rates

- ✓ Expand analysis to
the entire Argo fleet
- ✓ Modelling work
(KPP or LES)

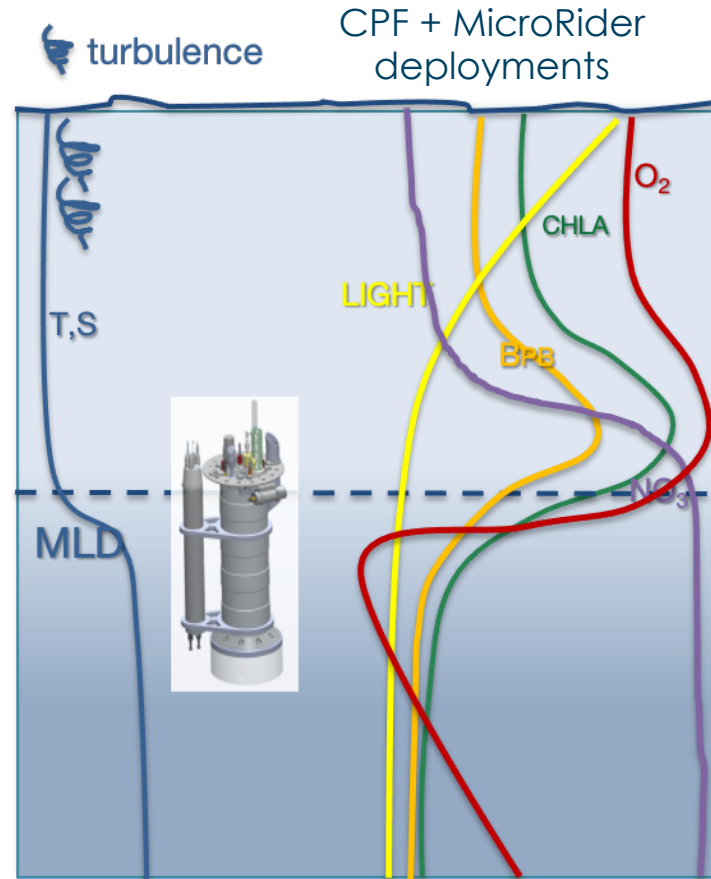


Global patterns and
variability in surface mixing

Turbulent fluxes of
heat and BGC
properties

Ultimate inform CLIMATE MODEL development
(e.g. surface ocean mixing schemes and
BGC parameterizations)

Theme 2. Collect/validate Turbulence obs/estimates in the Monterey Bay



- ✓ Capture seasonality in a broad range of turbulence regimes

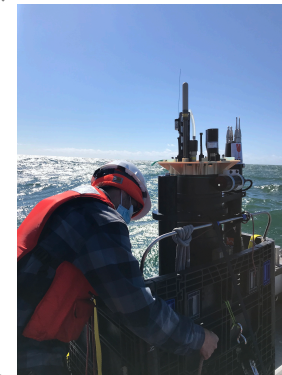
- ✓ Expose students to:

Turbulence Sensors



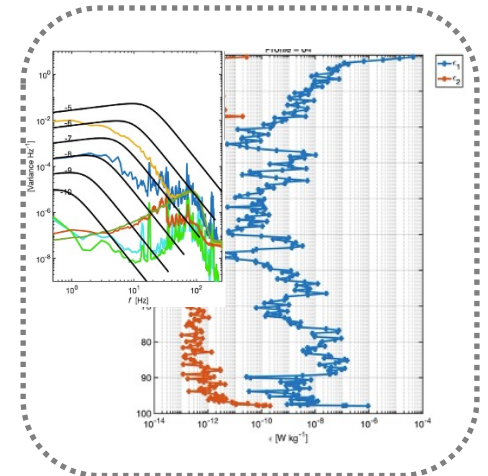
+

Field Work



+

Advanced Data Analysis Techniques



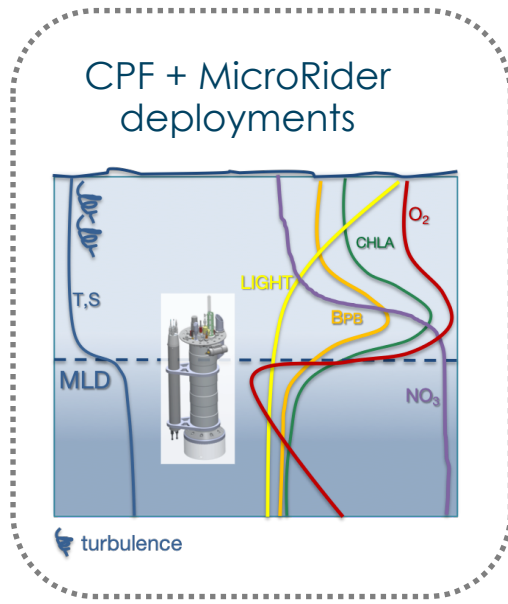
Coastal Research Themes:

- ✓ Canyon upwelling and mixing induced by breaking of the internal tides
- ✓ Importance for nutrient delivery and biological production

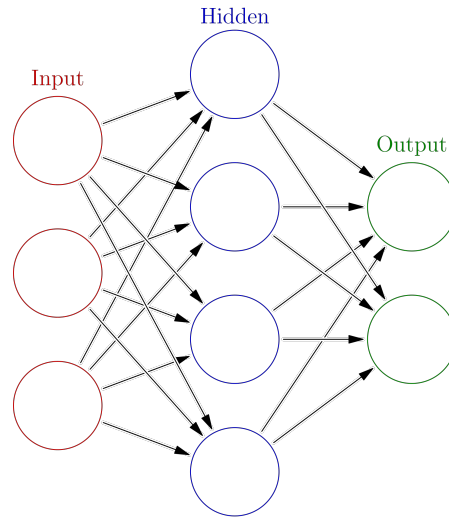
Theme 3.

Improved Parameterizations using Machine Learning Techniques

Observations



Machine Learning Methods



✓ Test relationships between variables

✓ BGC parameter estimation

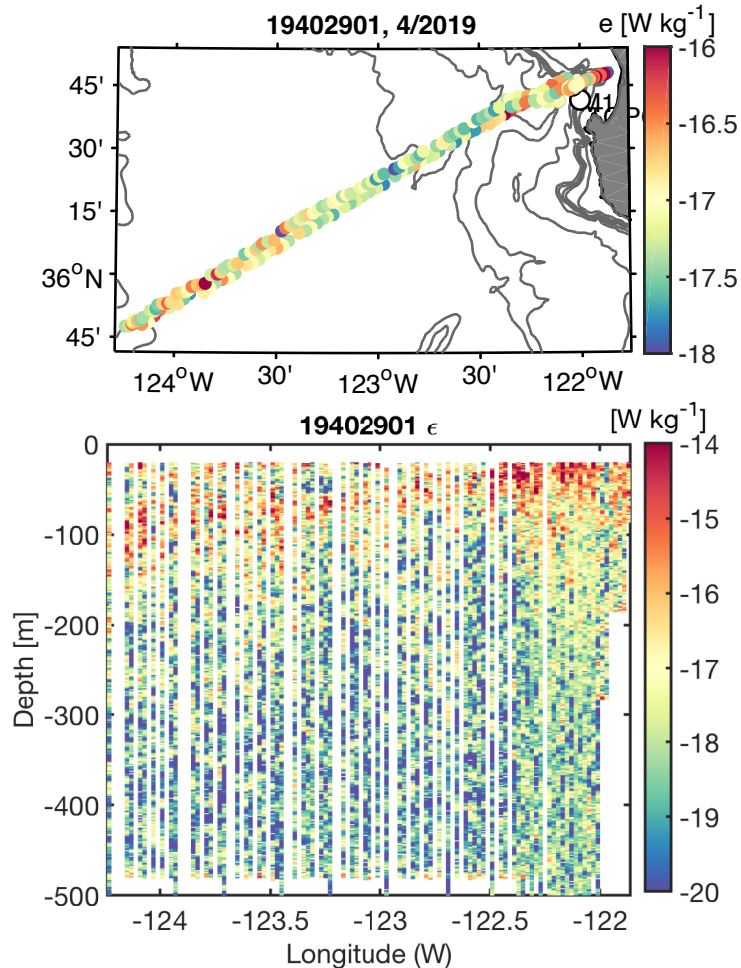
✓ New functional forms

Reduce biases in CLIMATE MODELS and improve CLIMATE PROJECTIONS

Better Predictions for the Coastal Oceans

Improve mechanistic understanding and representation of unresolved processes

Theme 2. Glider Surveys in Monterey Bay: Calibrate Vertical Mixing Rates from the LEM with VMP cast

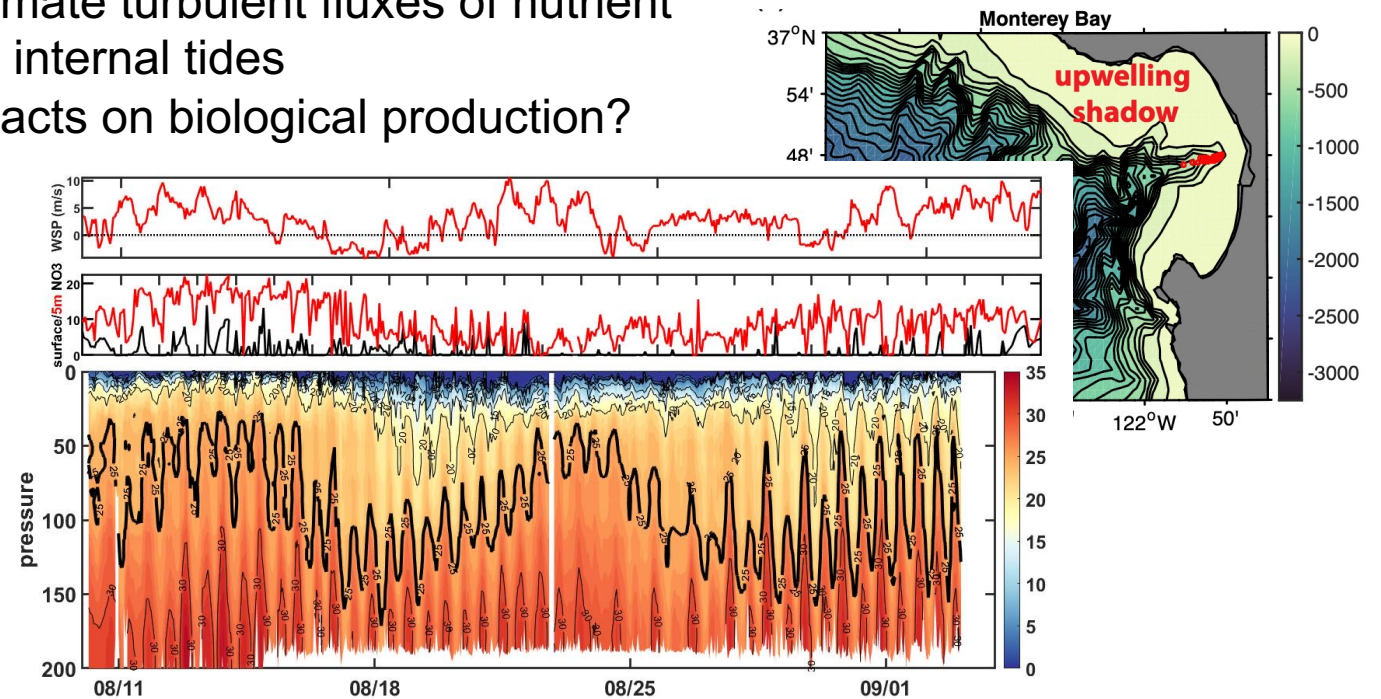


Planned activities/analysis to get a calibration coeff:

- ✓ VMP casts from an upcoming cruise in June
- ✓ Bottom mounted ADCPs (Astrid Leitner's project)

Estimate turbulent fluxes of nutrient
and internal tides

Impacts on biological production?



Extra Slides

Dissipation rate estimates from glider's CTD data

Large Eddy Method (LEM):

$$\varepsilon \sim \frac{(q')^2}{\tau} \sim \frac{(q')^3}{l}.$$

q' velocity scale of the largest eddies

τ time it takes to overturn once

l their length scale

For stratified flow, $l \sim L_{Oz} = N^{1/2} \epsilon^{3/2}$
(Ozmidov Scale)

$$e = c_\epsilon N (q')^2$$

c_ϵ calibration coefficient

N buoyancy frequency

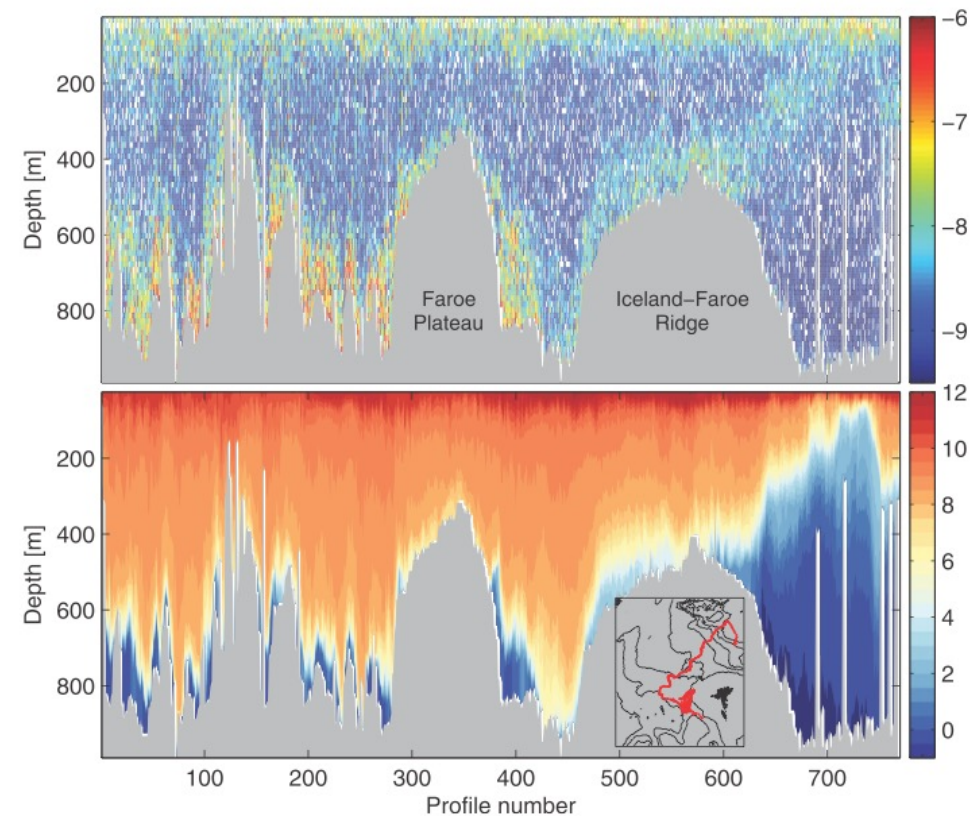
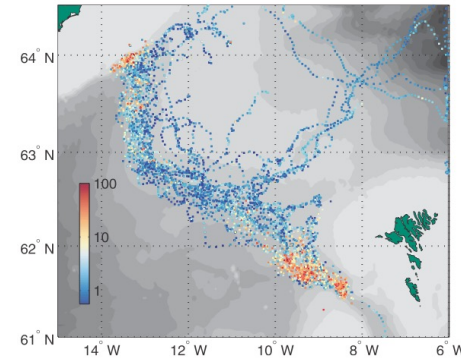


FIG. 9. (top) Depth vs profile number section of dissipation, $\log_{10}(e)$ [W kg^{-1}], from the entire sg005 deployment for which where each dive and climb is counted as a profile, and (bottom) corresponding temperature section ($^{\circ}\text{C}$). Inset map shows the dive locations in red; the FBC dives may be seen in more detail in Fig. 2.

Following Beaird et al. 2012

Annual Cycle of Turbulence Intensity (North Atlantic)

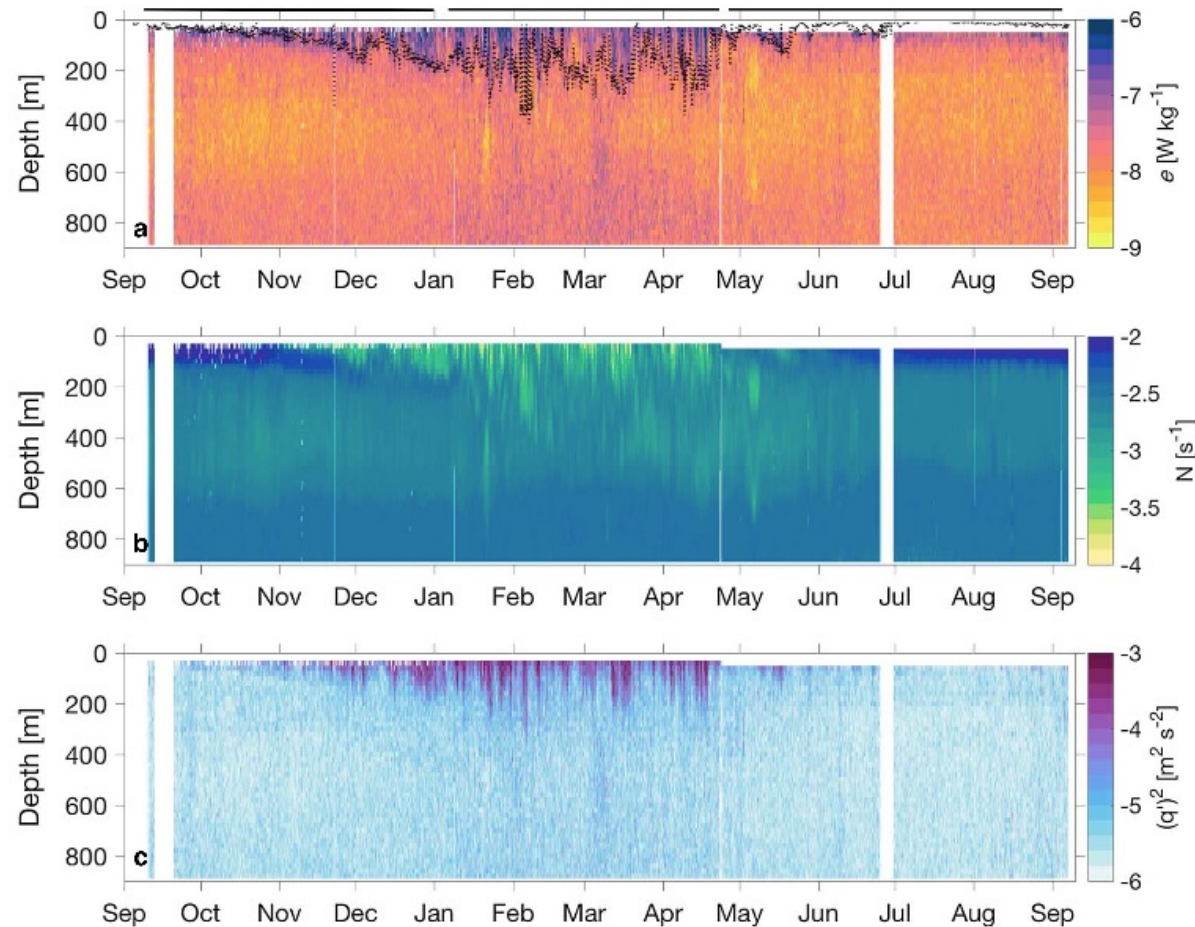
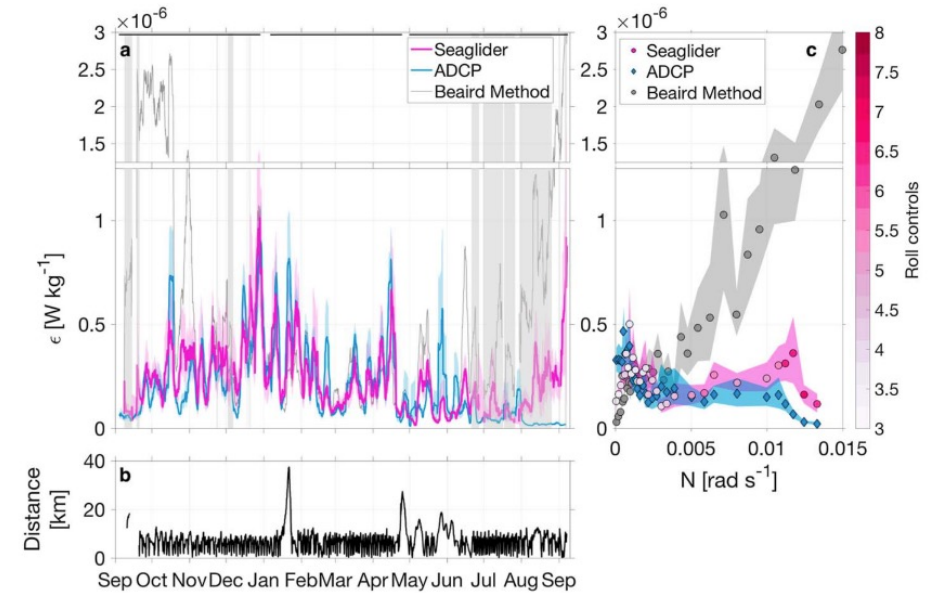


Figure 2. Time series of (a) Seaglider-based dissipation rate e , (b) N and (c) $(q')^2$ from equation (1). Each variable is calculated in 20-m vertical bins from the surface to 900 m. The black line represents the mixed layer depth determined as the depth at which density exceeds the density at 10 m by 0.03 kg/m^3 . The horizontal black bars indicate each individual glider deployment.

Large Eddy Method (LEM)
for high stratification conditions



Comparison of e against 600 kHz ADCP:

$$C_e = 1.96 \pm 0.2$$

$$W_{\text{noise}} = 1 \text{ mm/s}$$

Vertical Velocities and TKE Dissipation Rates from EM-APEX floats

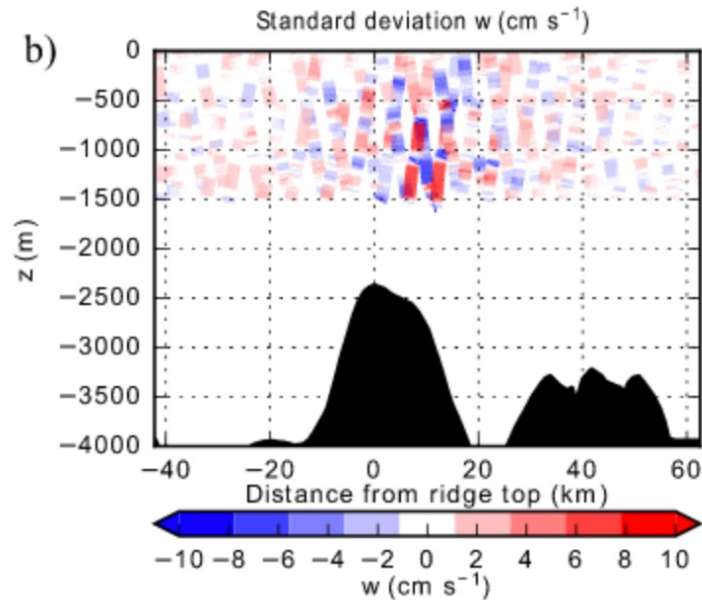


FIG. 6. (a) Mean horizontal velocity vector below 100m within the boxed region in Fig. 1. Arrow color denotes the standard deviation of vertical velocity measured below 100-m depth. Depth is contoured in 500-m increments. (b) A vertical section of vertical velocity from the same region. The observations from both floats

$$w_{\text{noise}} = 1 \text{ mm/s}$$

Large Eddy Method (LEM):

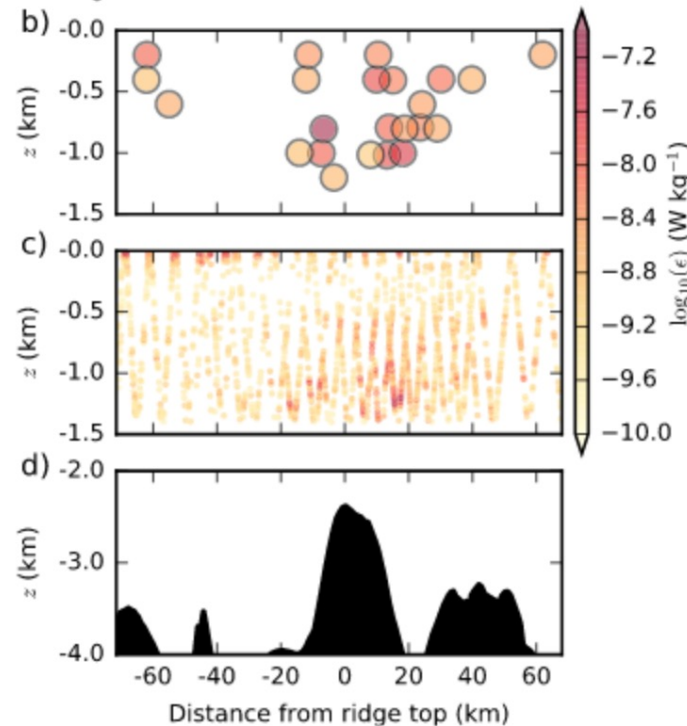


FIG. 12. (a) Depth-integrated TKED rate. (b) Thorpe-scale-derived estimate of the TKED rate on a logarithmic scale; the large circles denote 200-m bin averages. (c) LEM-derived TKED rate calculated on a 20-m sliding window. (d) Bathymetry. Measurements smaller than the noise threshold of the LEM, $c(w_{\text{noise}})^2 N$, where the noise velocity, $w_{\text{noise}} = 1 \text{ mm s}^{-1}$, has not been plotted. Similarly, portions of the water column where overturns are not detected have no associated Thorpe estimate.

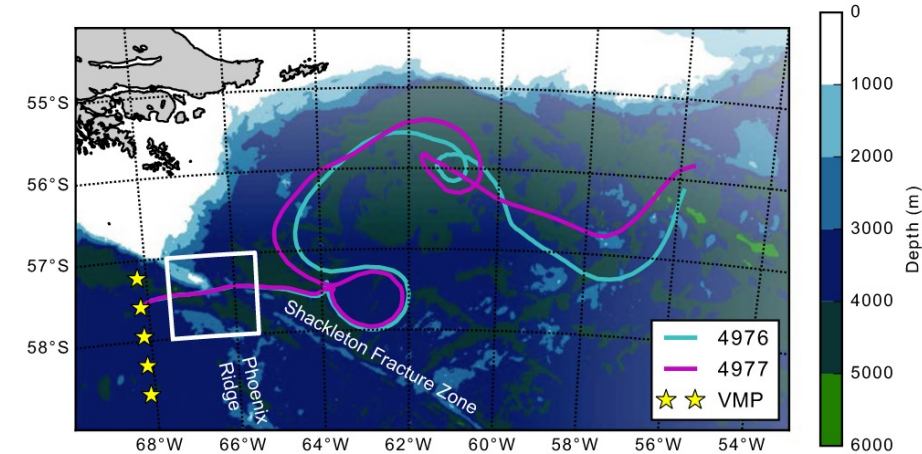


FIG. 1. Map of the northern Scotia Sea with float trajectories and vertical microstructure profiler stations (VMP) used in calibrating the float-derived dissipation rates. Lee-wave measurements were obtained within the boxed region, which is expanded in Fig. 6.

Comparison of ϵ against VMP casts:

$$C_e = 0.146$$

$$C_e = 0.123$$

(overall statistics)

Large Eddy Method (LEM) requirements

$$e = c_{\epsilon} N (q')^2$$

Eddy Length Scale, l :

- Thorpe Length (L_T , from high resolution density profiles, Thorpe 1977)
- Zero-crossing of a w' profile (Gargett, 1999)
- Ozmidov Length (L_{Oz} , largest turbulent eddy that is unaffected by stratification)
- $L_T \sim L_{Oz}$ even in the weakly stratified mixed layer (Dillon, 1982)

Vertical Velocity Scale, q' :

- removing any platform induced motion from w_{ctd}
- removing non-dissipative w signals (upwelling, internal waves, surface waves, etc)

Calibration Coefficient:

- From estimates of e , against a direct measurement of epsilon
- will take up differences between measurements of l and L_{Oz} , choices made in the high-pass filtering of w , or varying N , etc.

Scaling Arguments for rms w in the surface layer

$$w^* = \langle w^2 \rangle^{1/2}$$

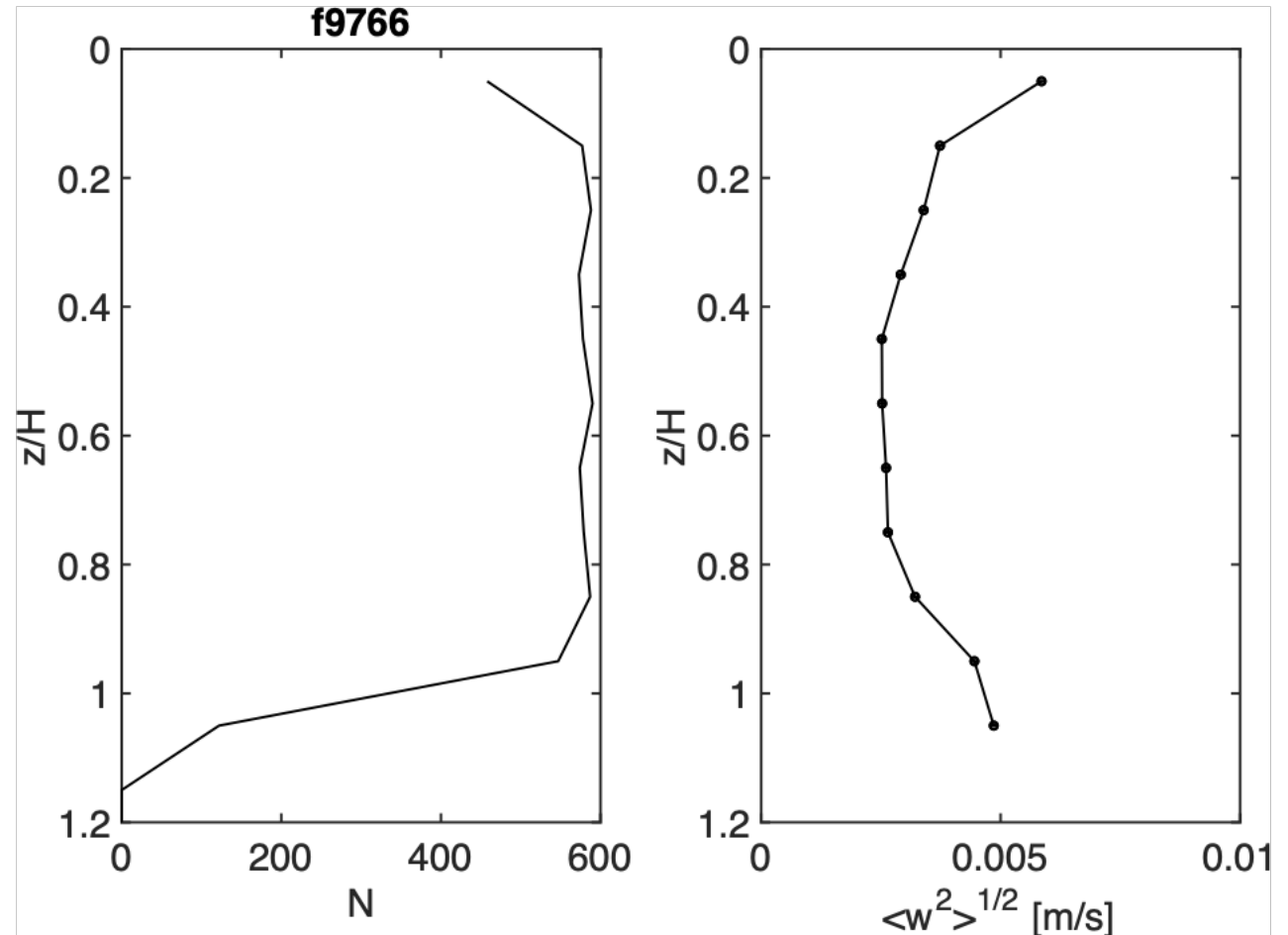
Wind-driven mechanical mixing

$$w^* \sim u_*$$

$$u_* = \sqrt{\frac{\tau}{\rho}} \quad : \text{friction velocity}$$

$$\sigma_w^2 = A(z) u_*^2$$

$$\overline{\sigma_w^2} = \overline{A} u_*^2$$



Scaling Arguments for rms w in the surface layer

$$w^* = \langle w^2 \rangle^{1/2}$$

Wind-driven mechanical mixing

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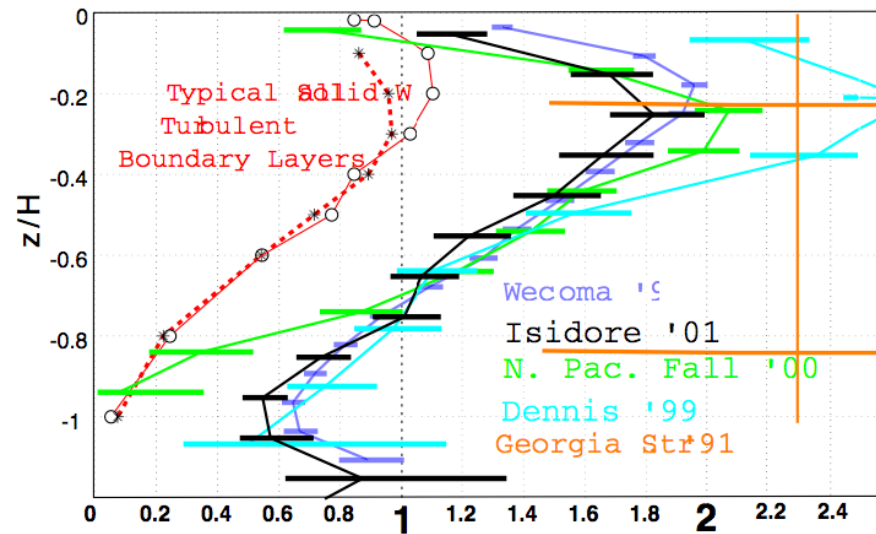


Figure 5. Scaled vertical velocity as in Fig. 4, but for all five data sets.

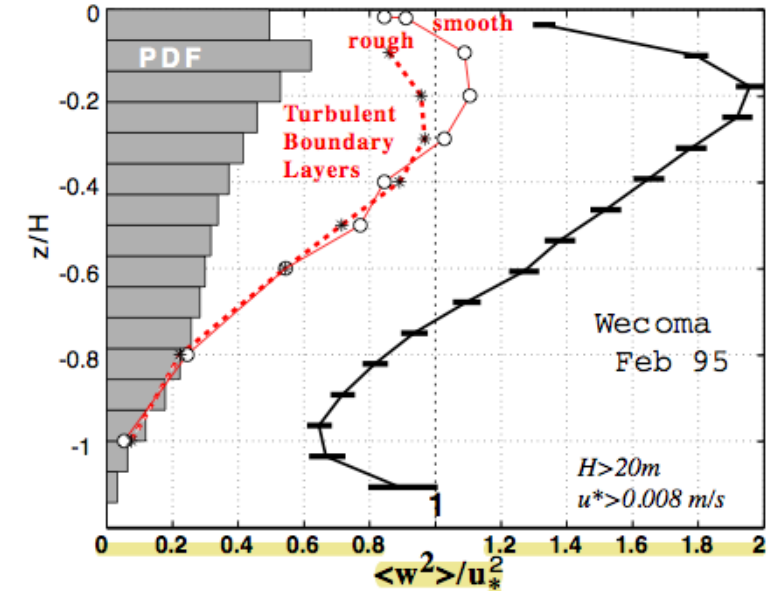
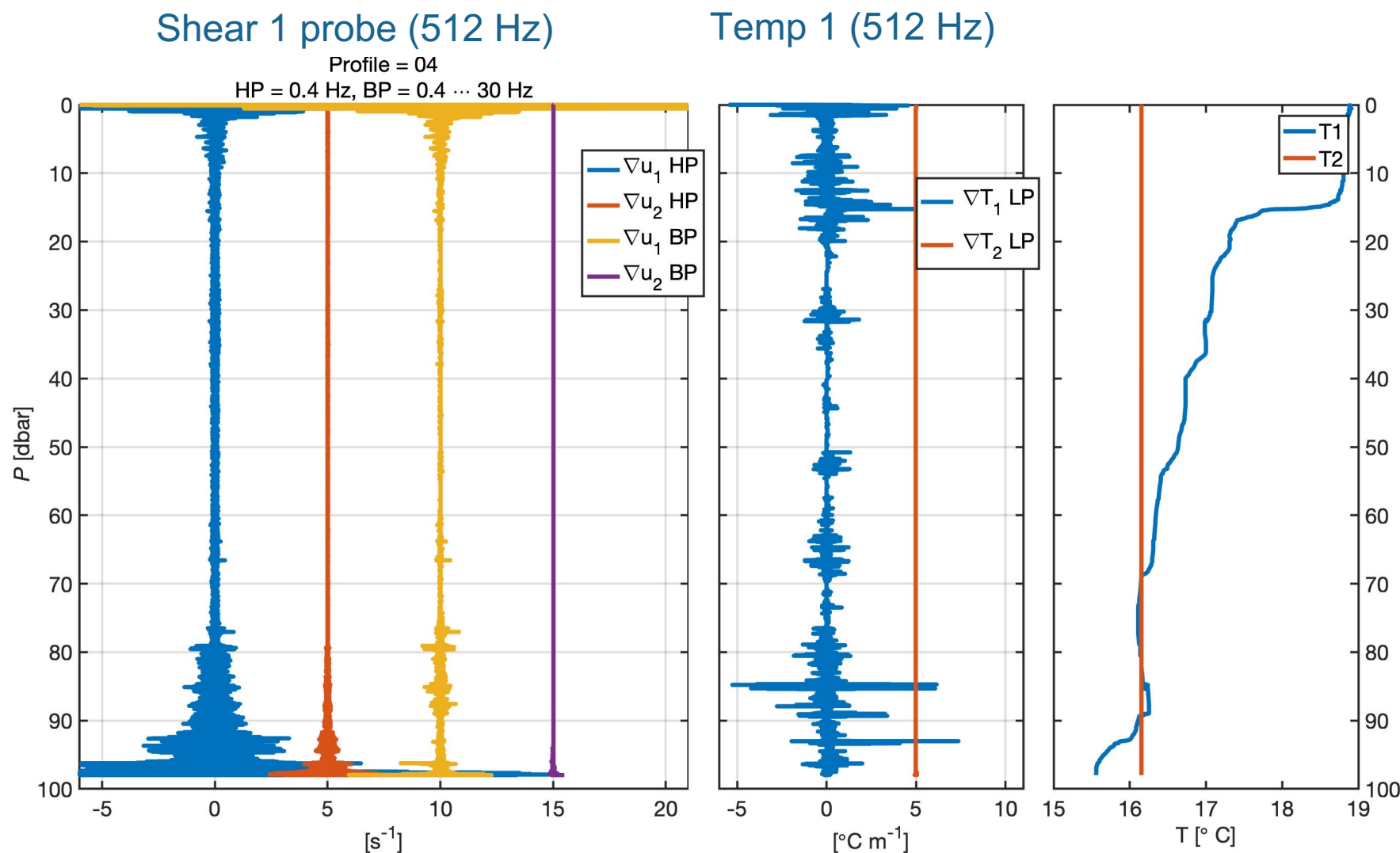


Figure 4. Scaled vertical kinetic energy $A(z) = \sigma_w^2/u_*^2$ as a function of scaled depth z/H (curve). Error bars are 95% confidence limits. Circles (o) represent σ_w^2/u_*^2 for a smooth wall zero-pressure-gradient turbulent boundary layer; stars (*) represent the same for a rough wall boundary layer (Hinze, 1975). Bars indicate probability distribution of float data on an arbitrary scale.

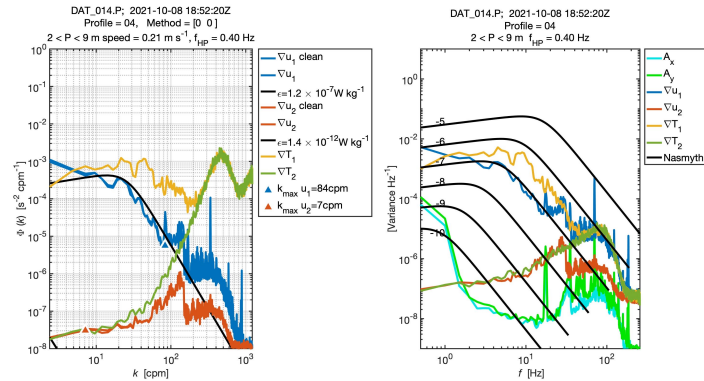
CPF- MR: First at-sea Deployment on Oct 08, in the south Monterey Bay



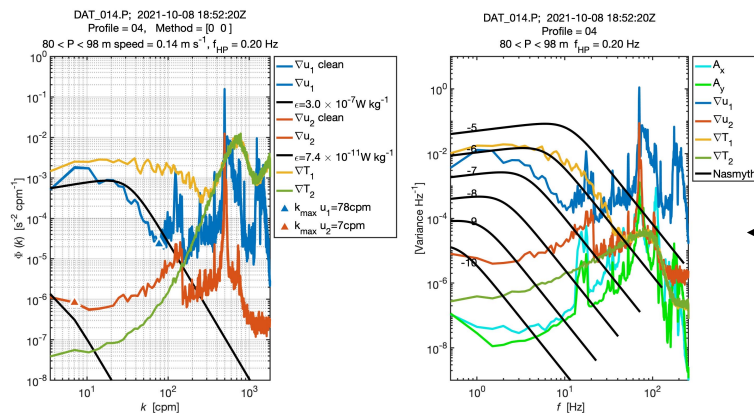
measure cm-scale
variations of
horizontal currents (u,v)
and temperature with depth

we can infer turbulent
mixing rates!

Surface, buoyancy control OFF

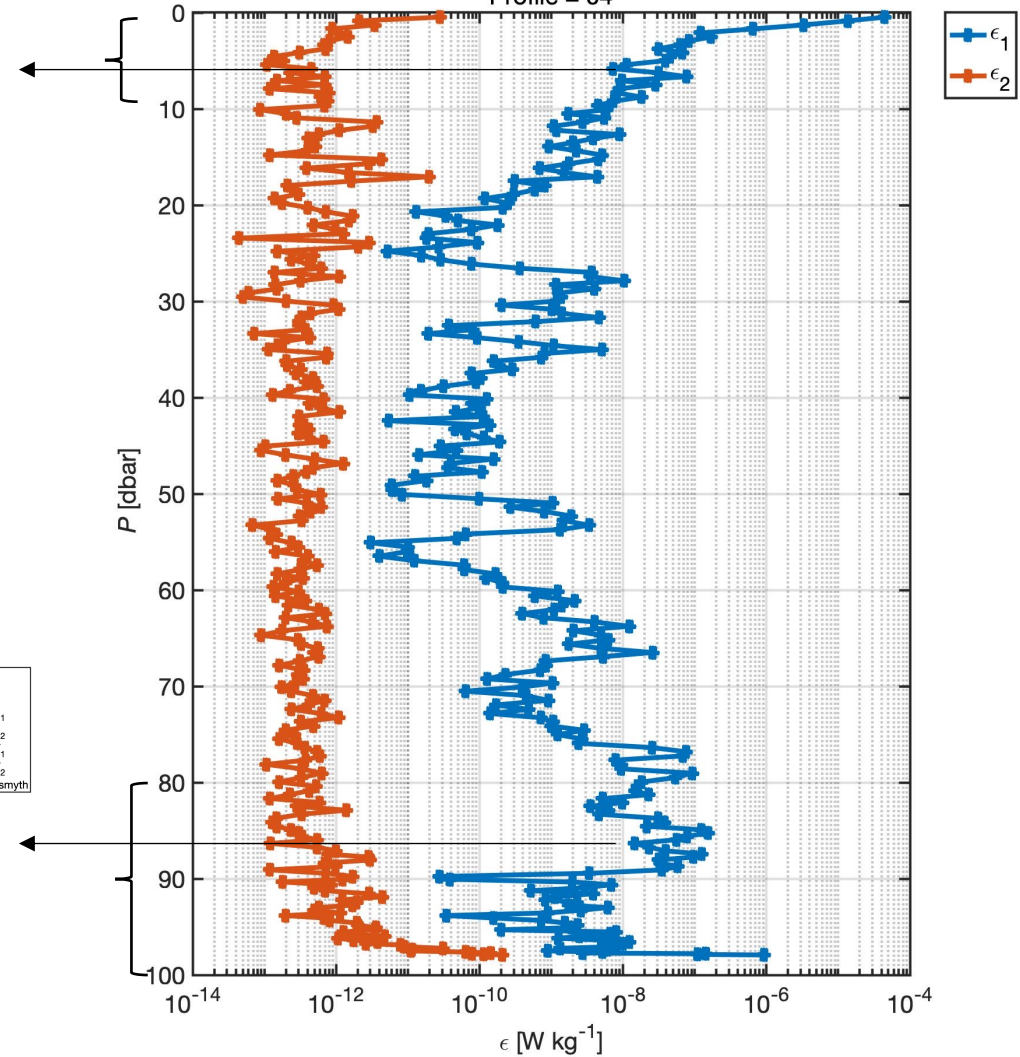


Bottom, buoyancy control ON

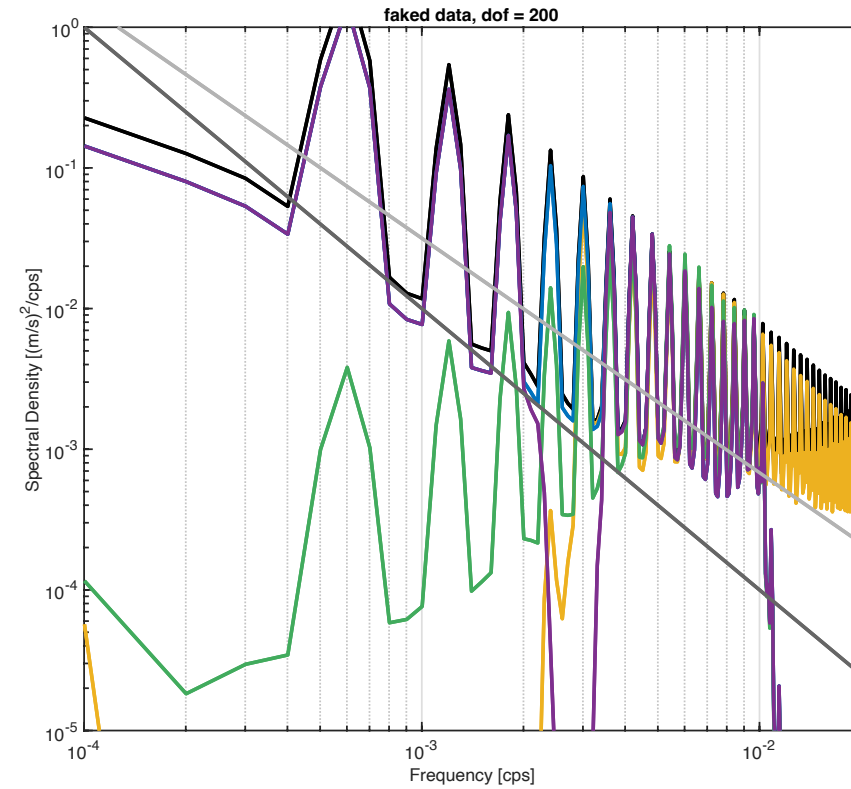
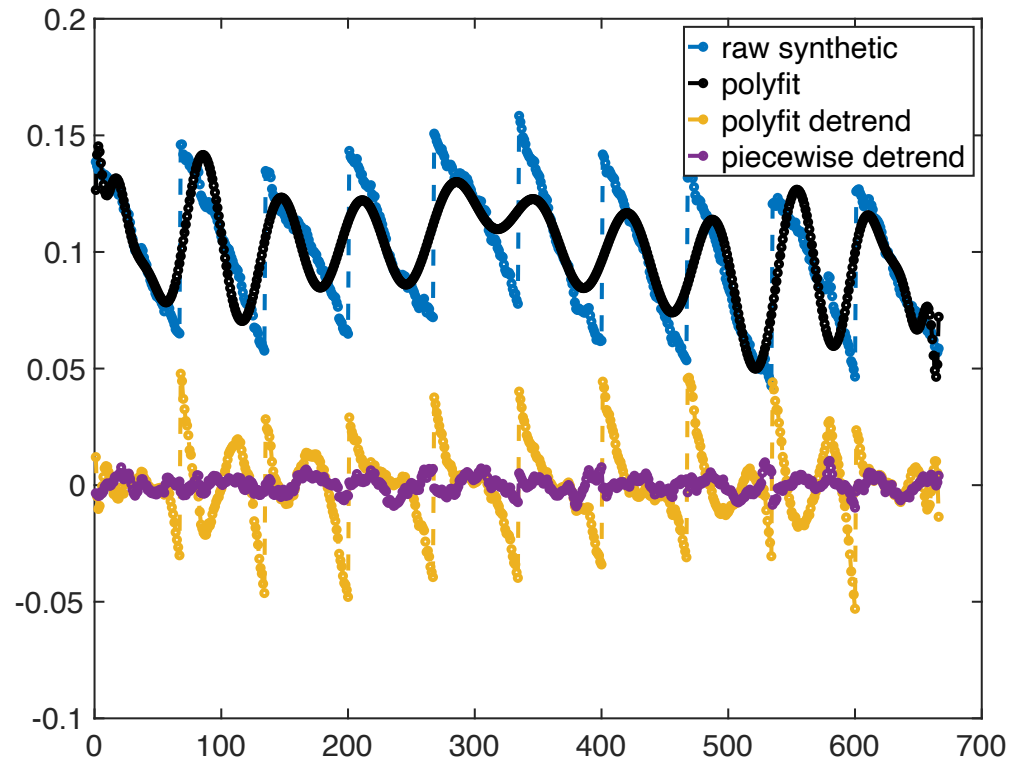


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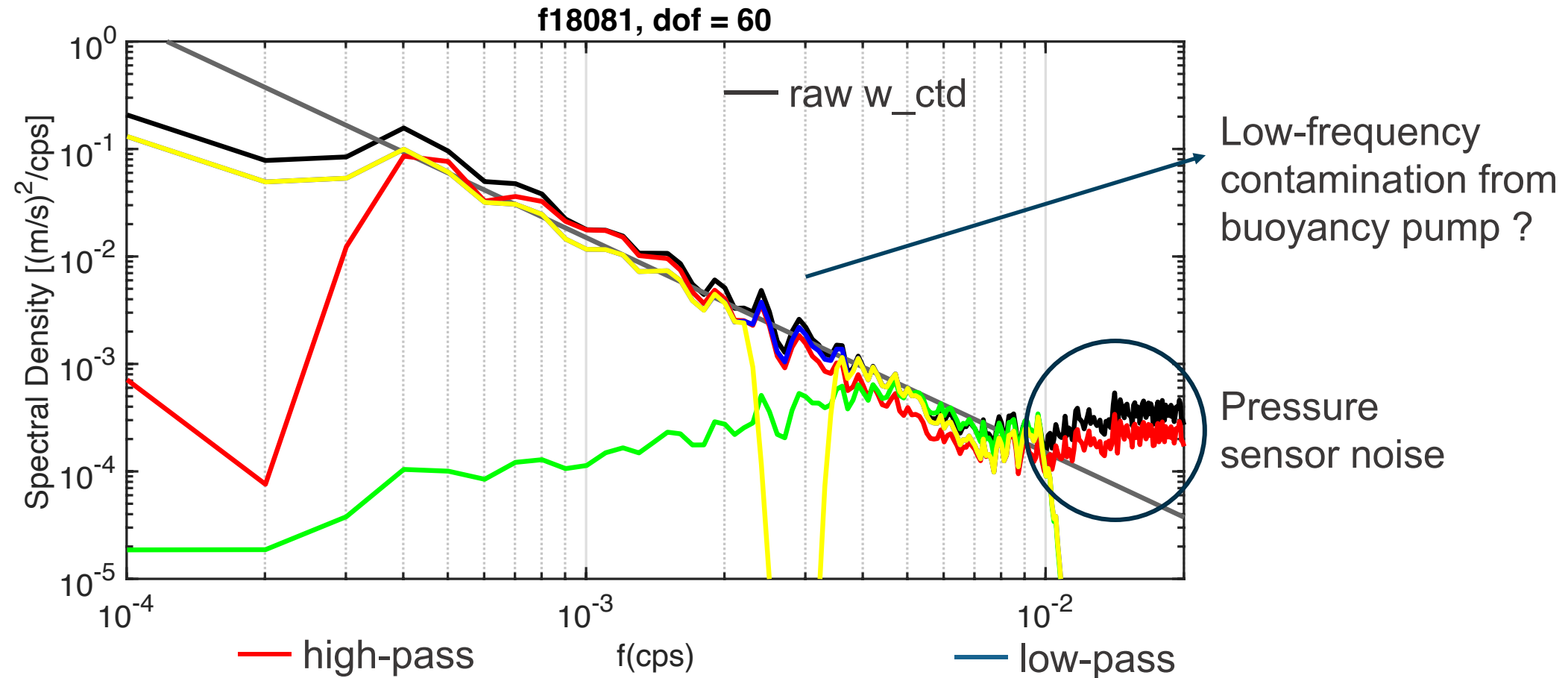
Profile = 04



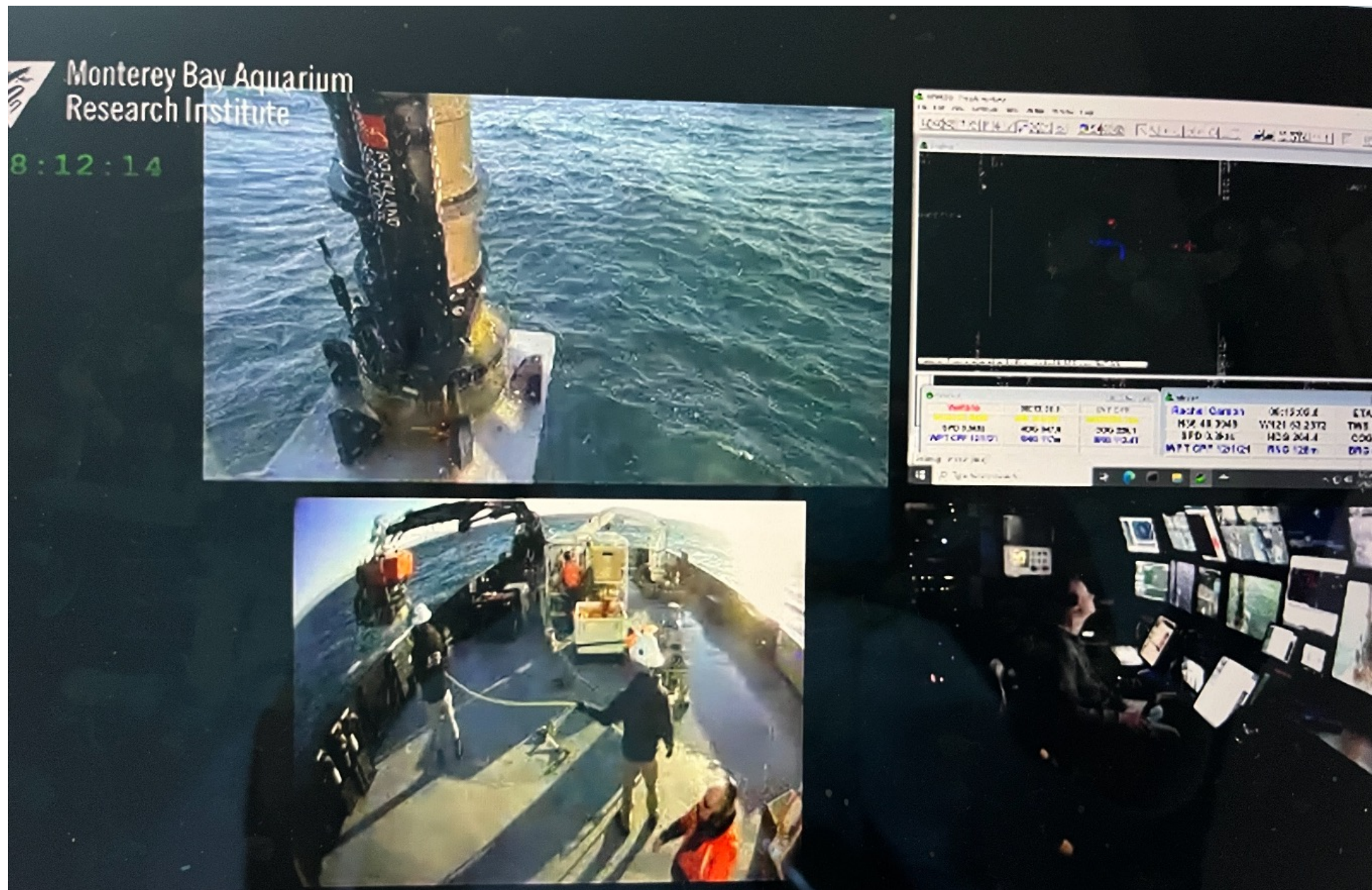
Can we filter out these effects to recover w ?



Can we filter out these effects to recover w ?







Monterey Bay

Moss Landing

Nov 18

EstimatedPosition_20211119 CPF_UnderTime_1213
SBD0_1204 CPF_StartTime_1207

Nov 16

CPF003-P0
CPF-150m CPF003-P2
CPF003-P0
CPF003-P19 CPF003-P5
CPF003-P16

Topo 1

Nov 12

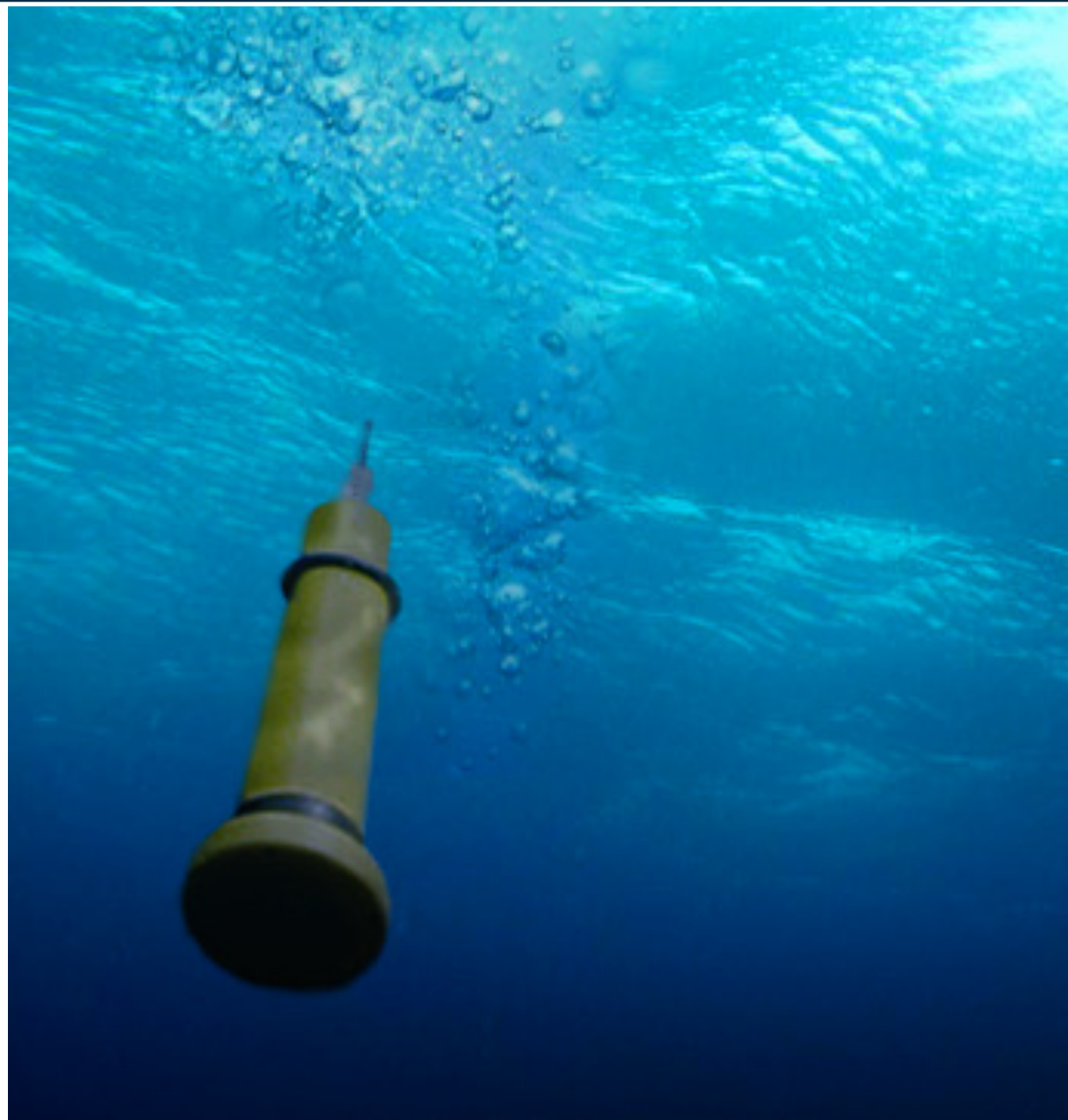
CPF003-P1 CPF003-P0
CPF003-P0
CPF003-P9 CPF003-P7
CPF003-P8
CPF003-P10 CPF003-P12
CPF003-P11
CPF003-P13
CPF003-P15
CPF003-P19

Marina

Seaside

Image © 2021 TerraMetrics
Data CSUMB SFML, CA OPC
Data MBARI

Google E



Observations of Turbulence

