The impacts of turbulence, mixing, and stratification on phytoplankton blooms: unraveling causation from observations

Andrew J. Lucas
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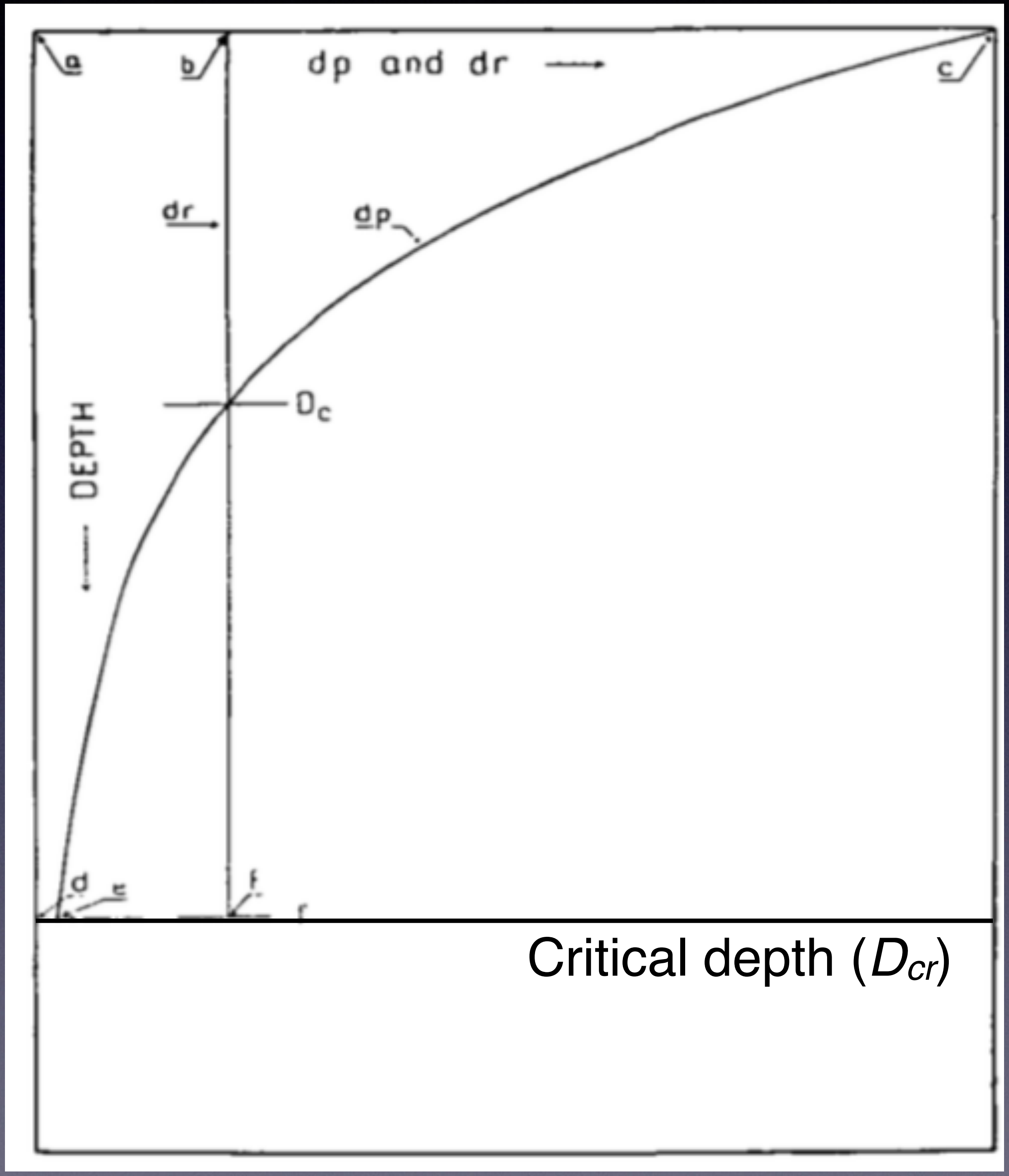
Outline:

- Sverdrup's 1-dimensional model of bloom formation.
- Examining Sverdrup's assumptions and modern formulations of schematic bloom models.
- The era of turbulence is upon us: prolonged *in situ* microstructure measurements.
- An example of prolonged turbulence observations in the upper ocean.
- A plea for more (kinds and quantity of) data.

1-D models of phytoplankton blooms: Sverdrup Critical Depth hypothesis



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H.U. Sverdrup, *Journal du Conseil,* 1953

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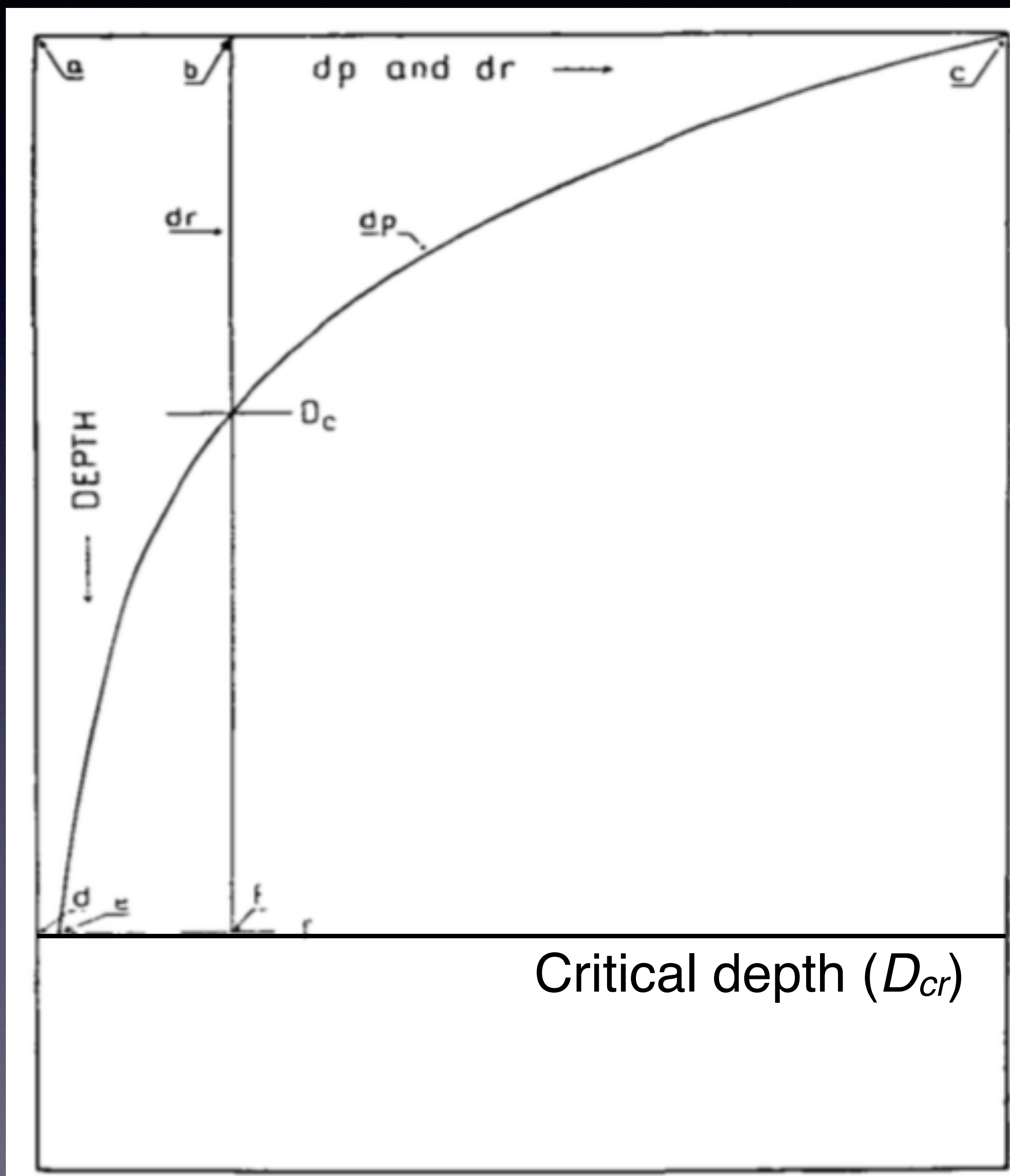

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Depth at which vertically integrated biomass accumulation equals respiration losses

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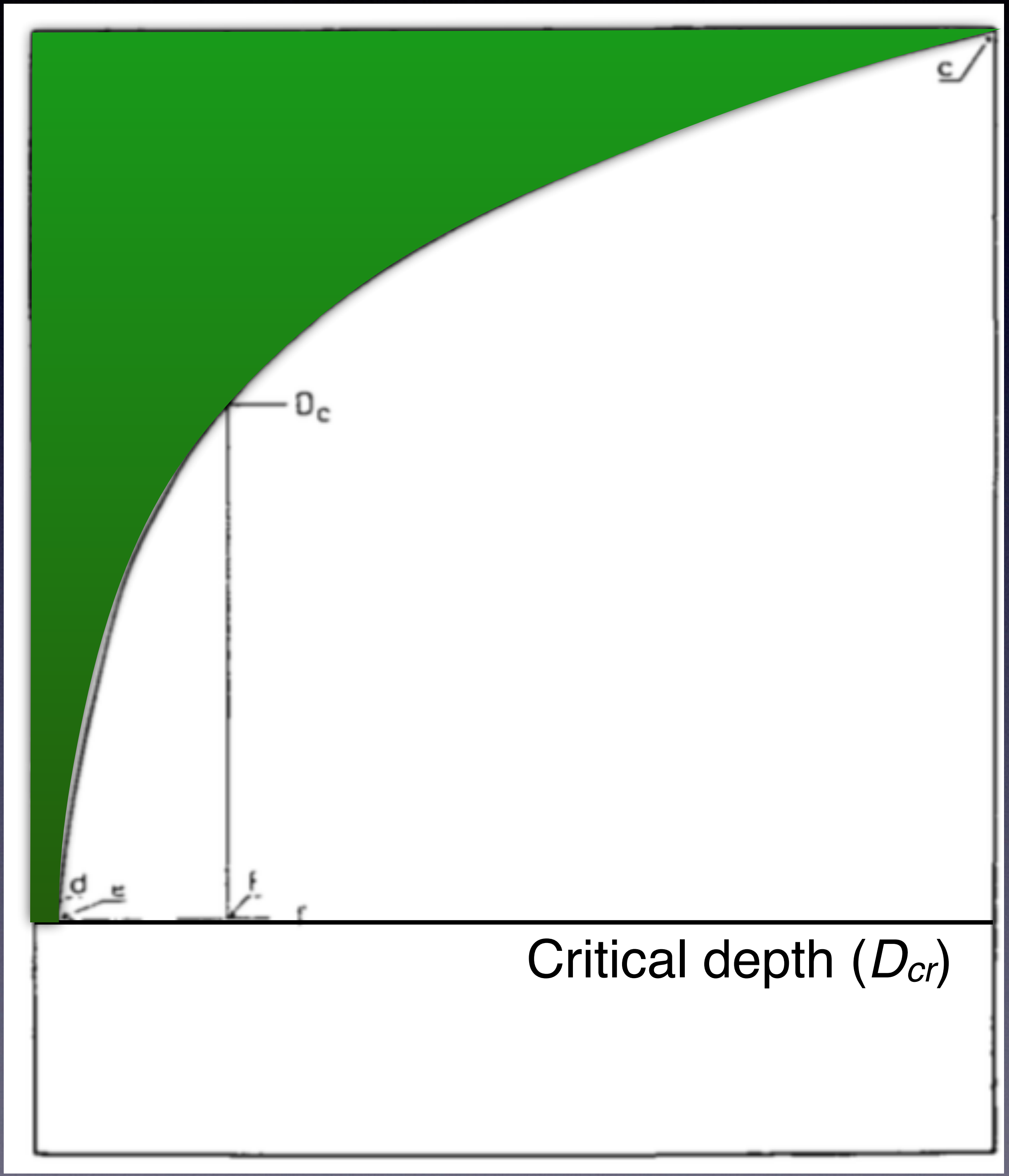

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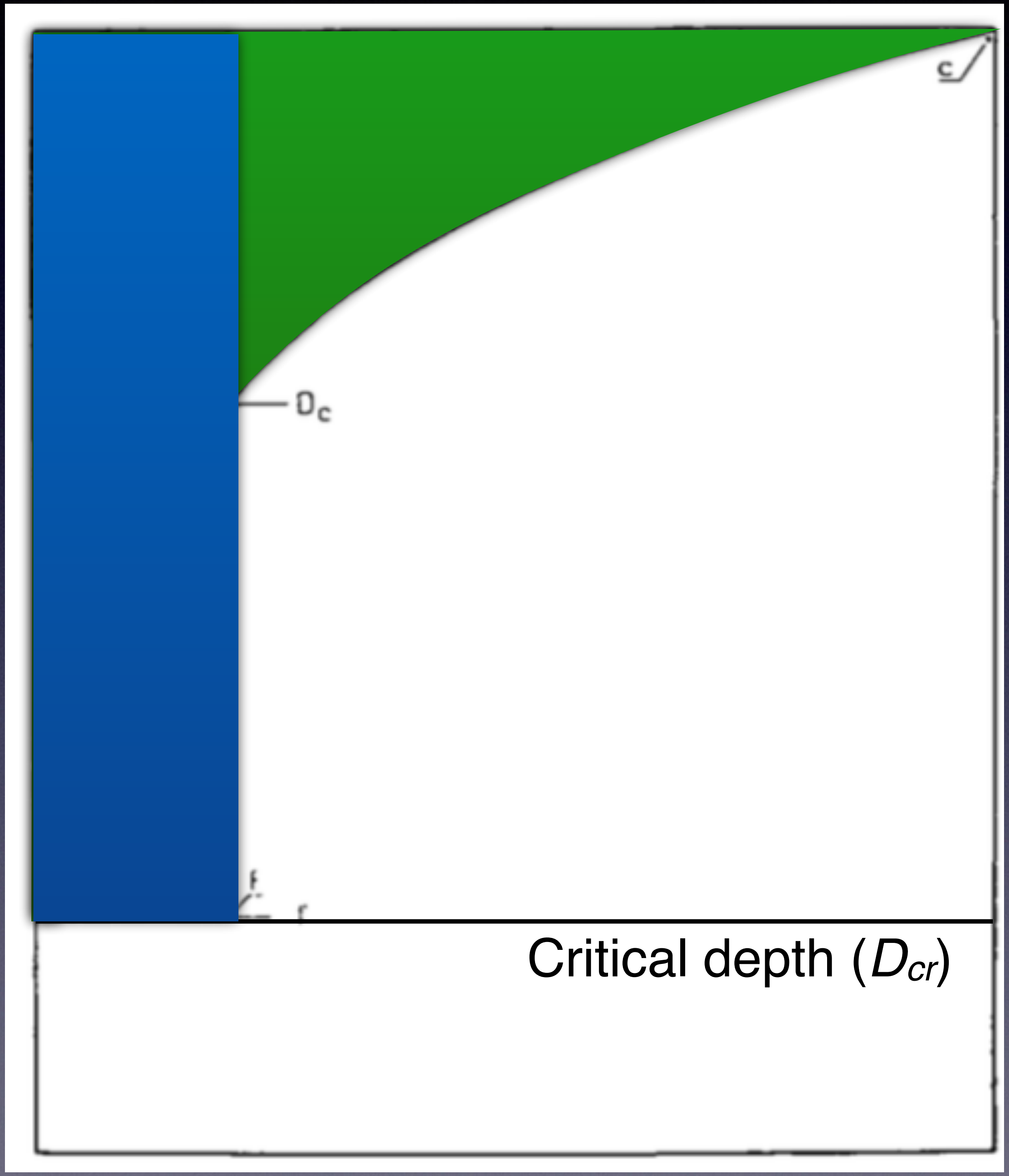

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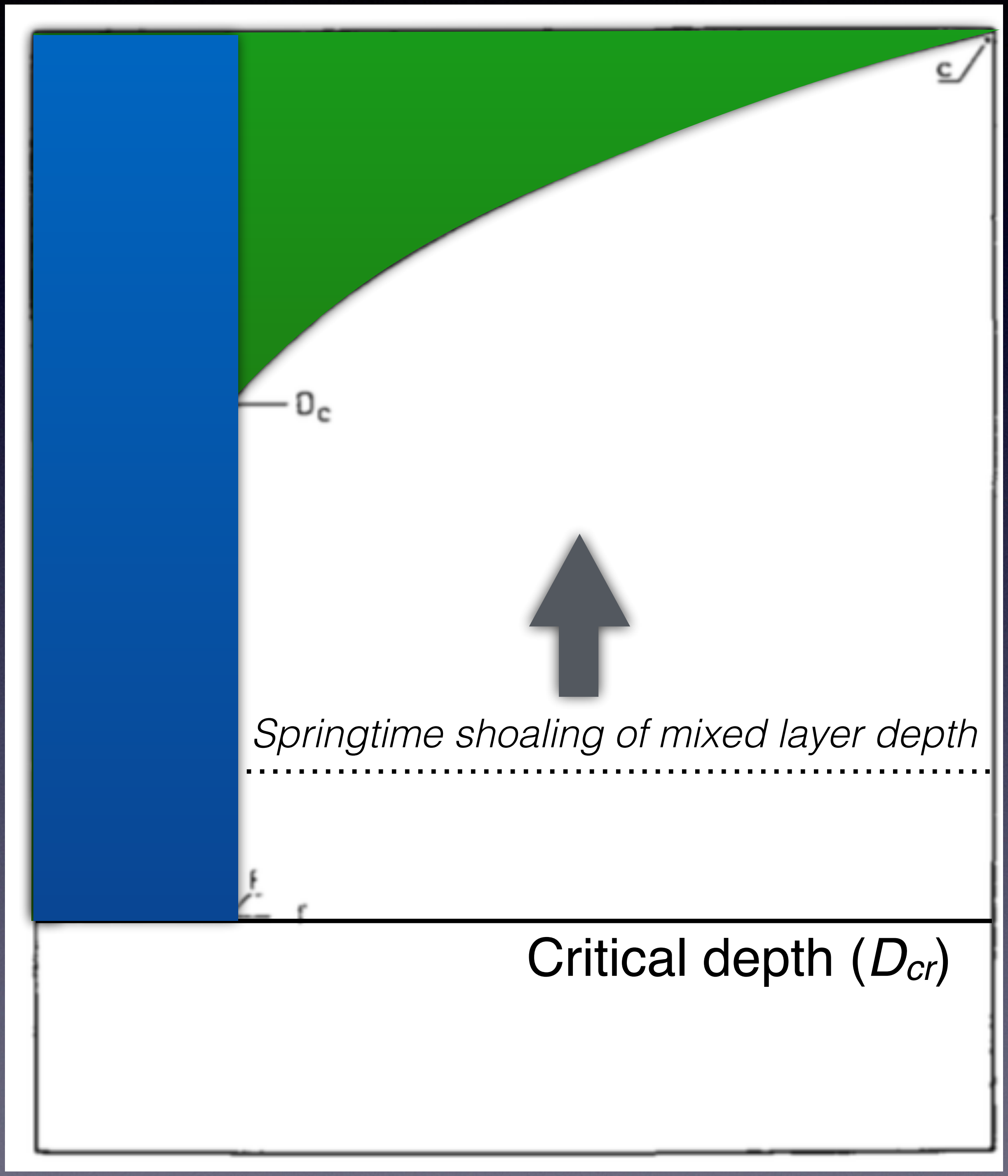

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Sverdrup: "Vernal bloom" is initiated when the *mixed layer depth* is shallower than the critical depth.

1-D models of phytoplankton blooms: Sverdrup's analytical model for for the critical depth

Assumptions:

1) There is a mixed layer.

2) Layer is actively mixing such that plankton all receive mean irradiance.

3) No nutrient limitation.

4+5) Extinction coefficient *k* is constant, fraction of surf. irradiance penetrating below the upper few meters is constant (α = 0.2).

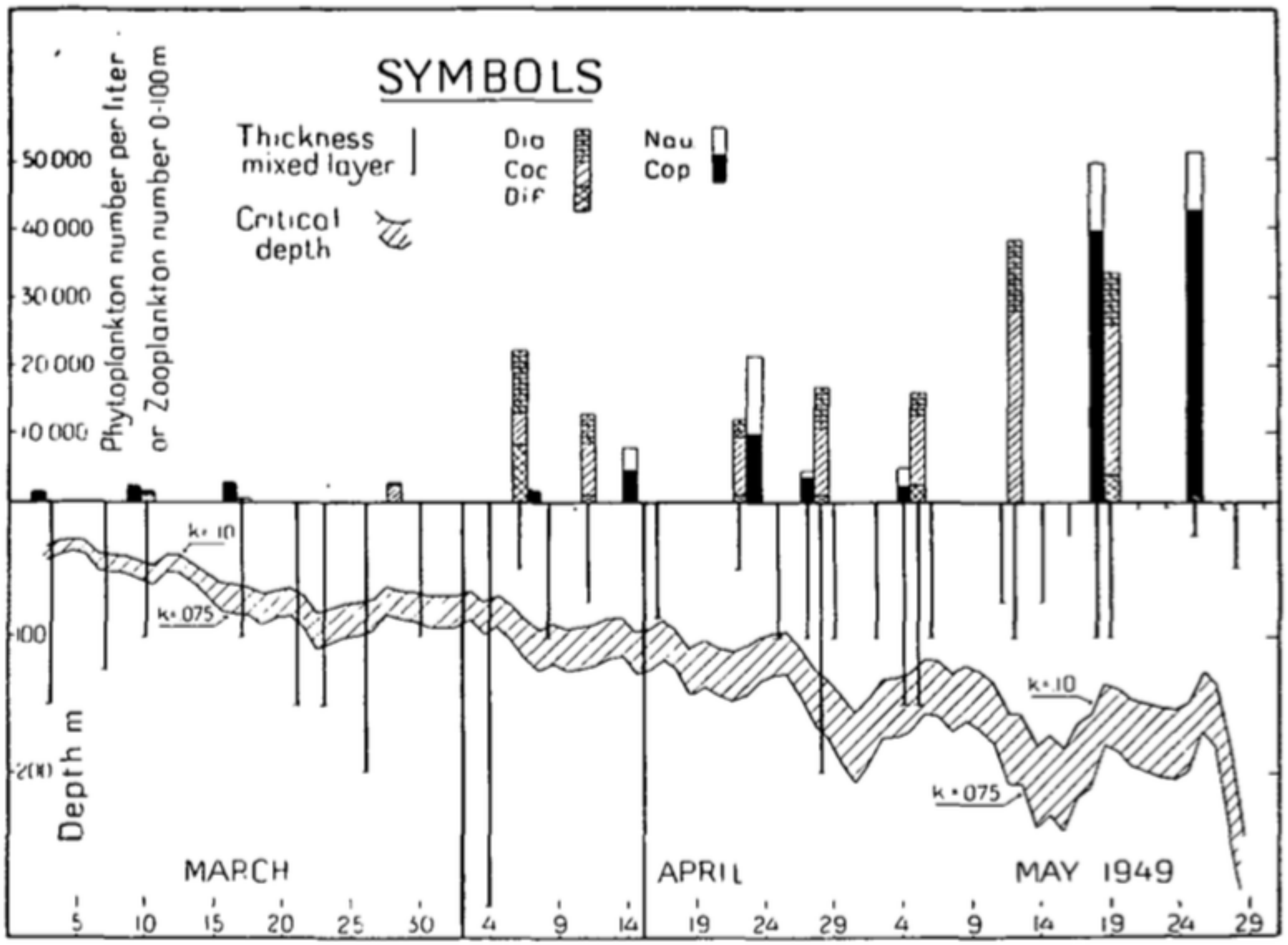
6) Production is proportional to irradiance.

7) Loss rate is uniform with depth.

1-D models of phytoplankton blooms: The Figure that Launched 1,050 Studies

(according to Web of Science)

Helen of Troy approves



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Weather Ship "M" measurements

Mixed layer depth
Cloud cover

Phytoplankton counts
Zooplankton counts

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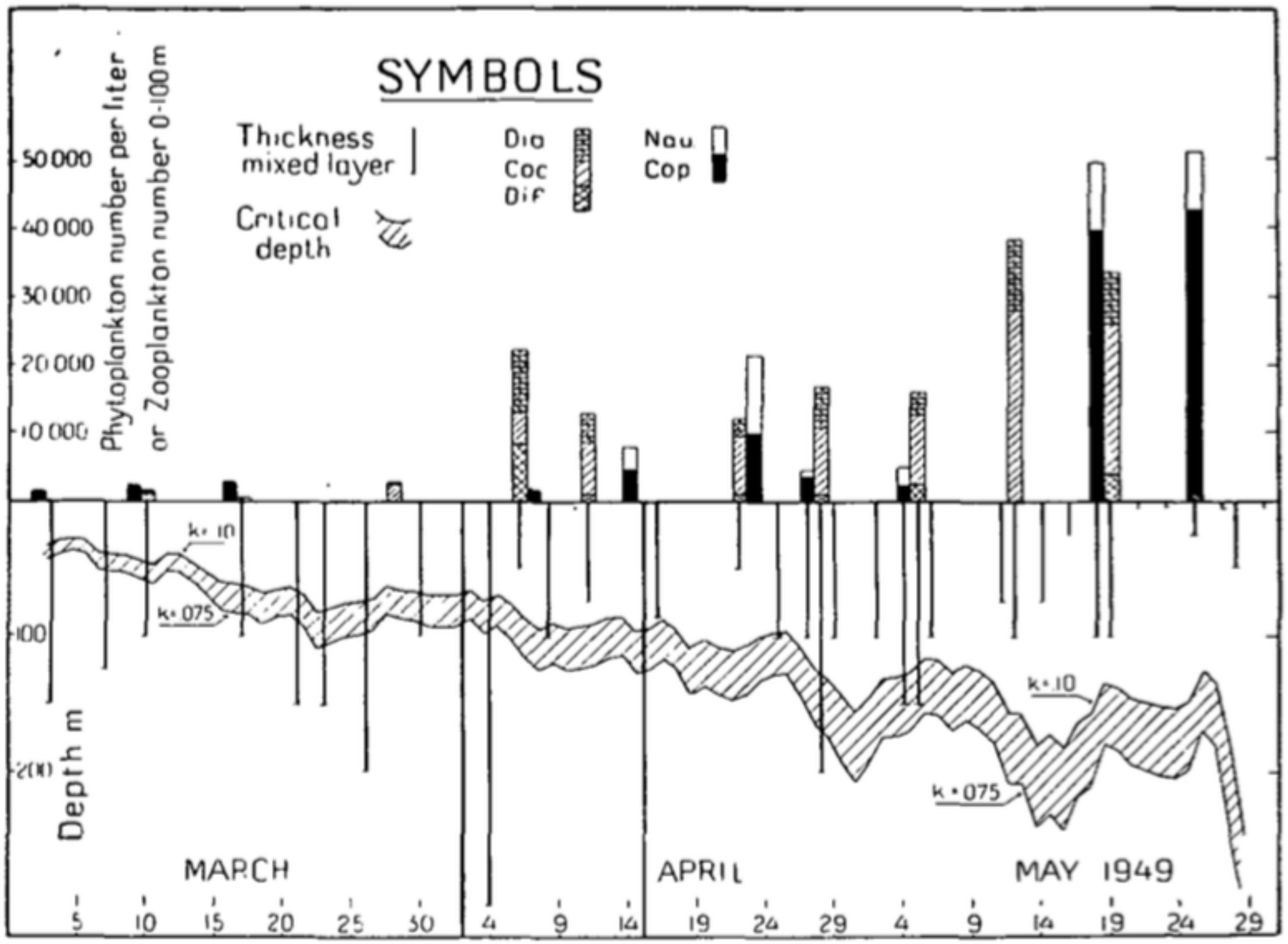

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Increase in critical depth of ~150 m in three months

MLD on April 15: 200-400m,
MLD on April 16: 75-100m.

First elevated phytoplankton measurement <1 week after measurement of 300m deep mixed layer.

Zooplankton response lagged relative to phyto. response.

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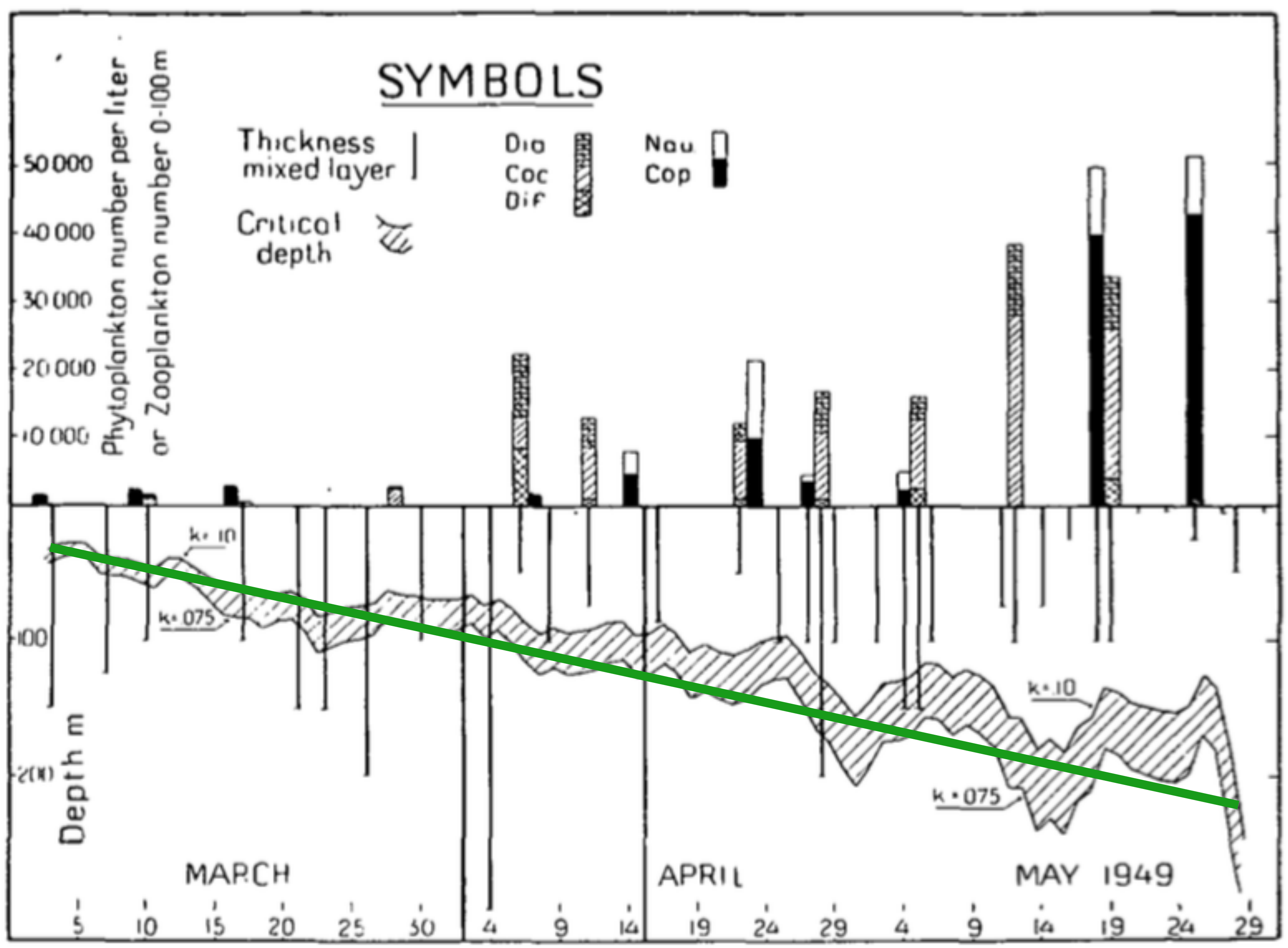

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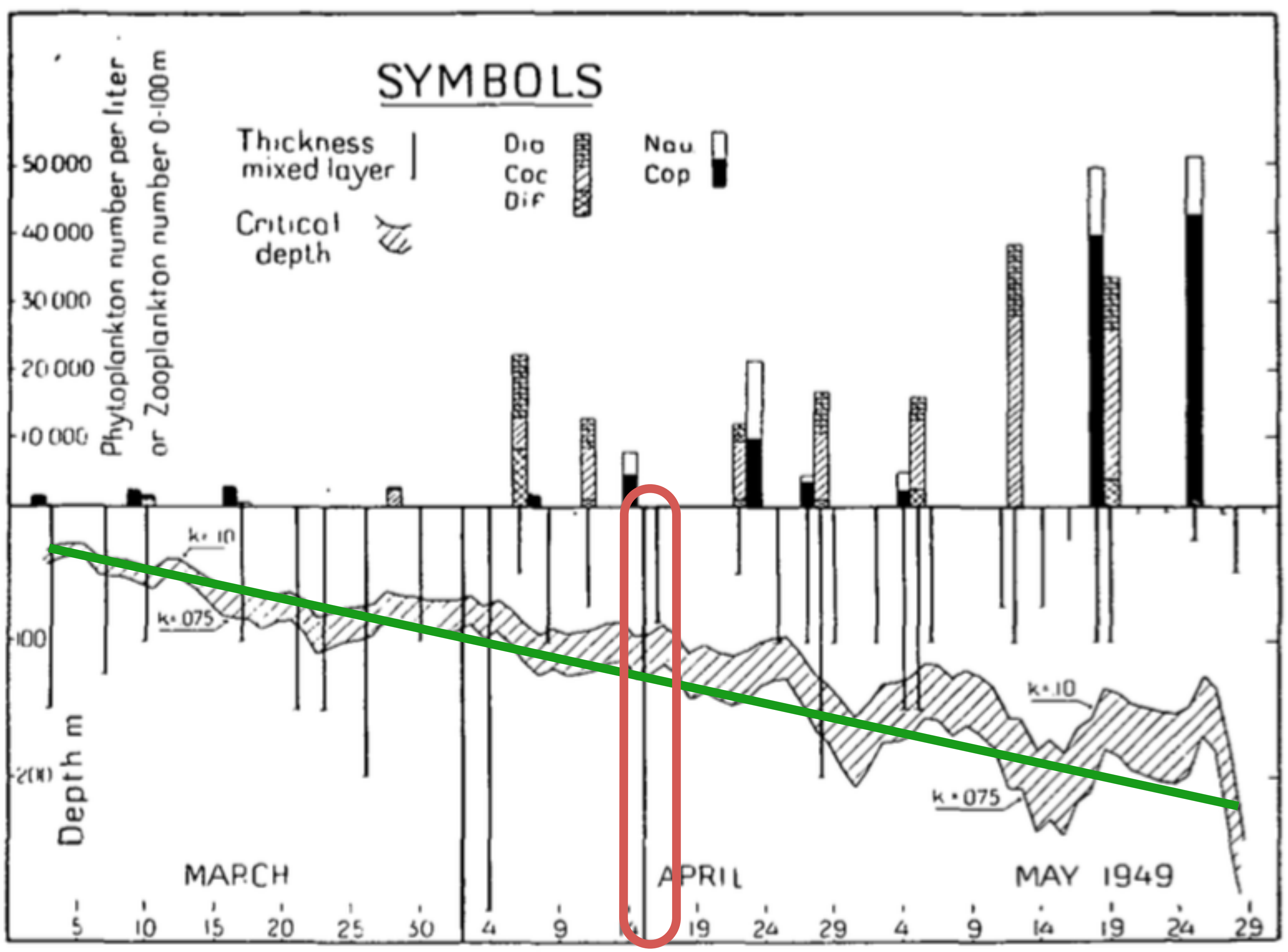

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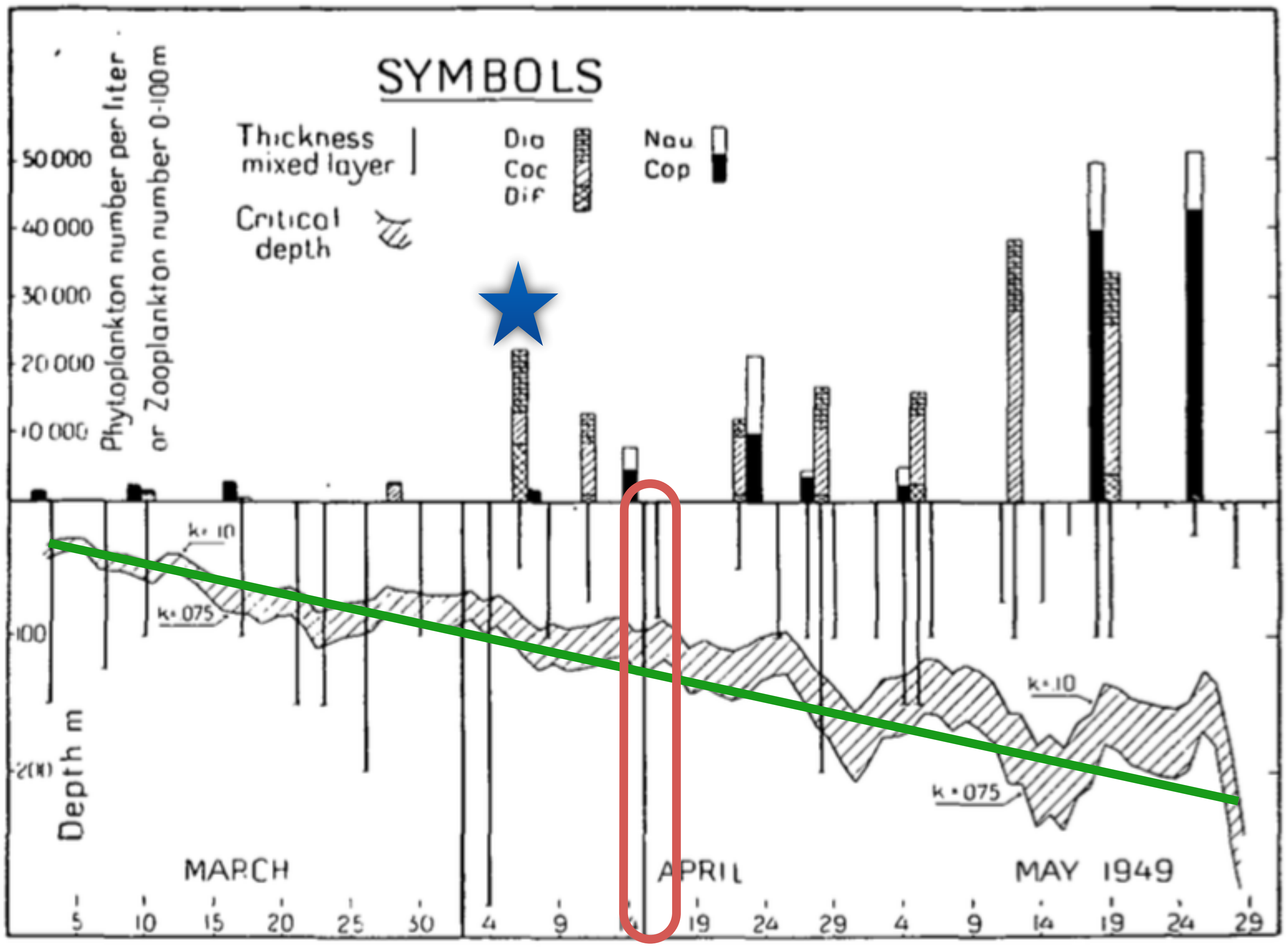

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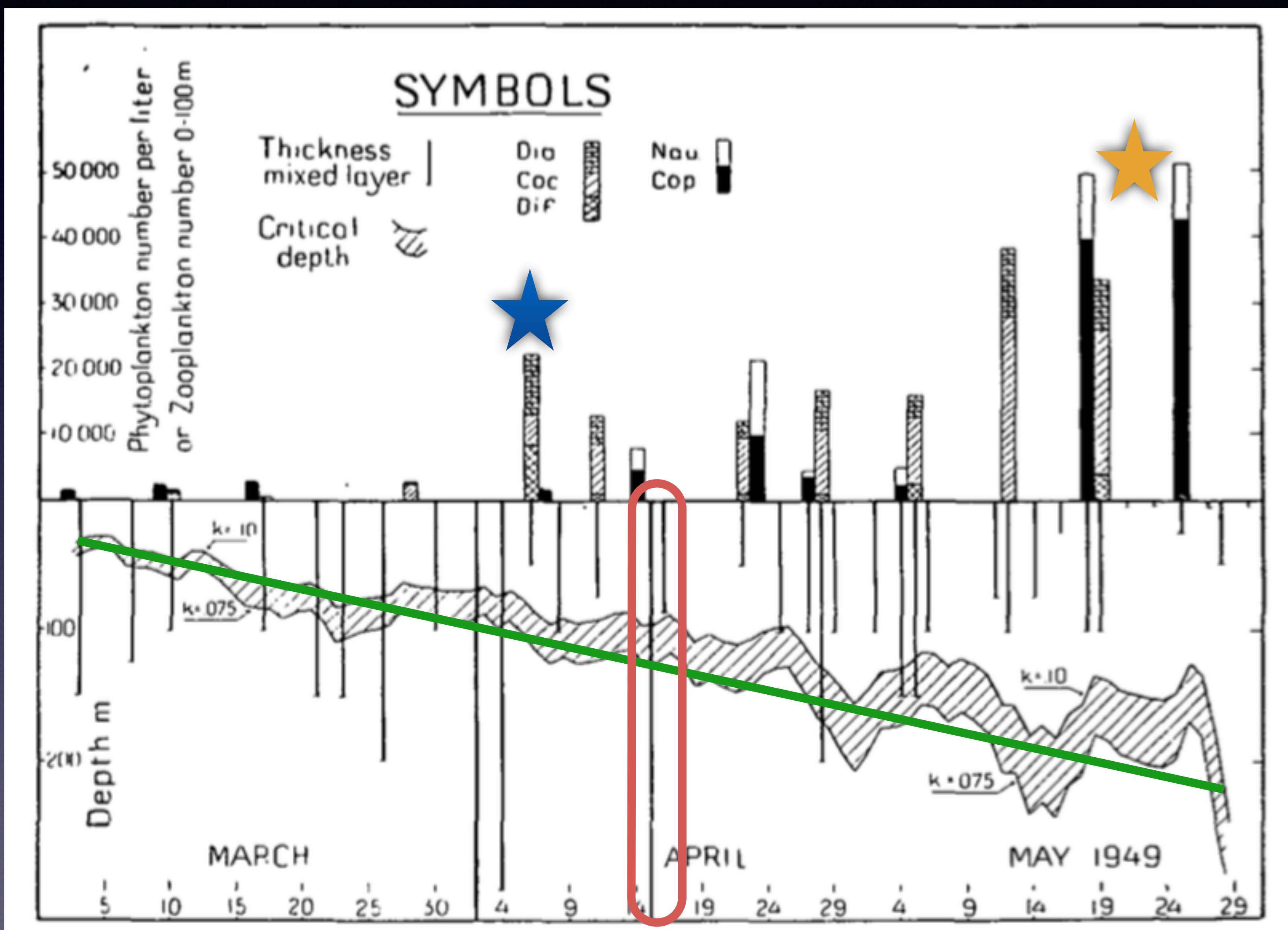

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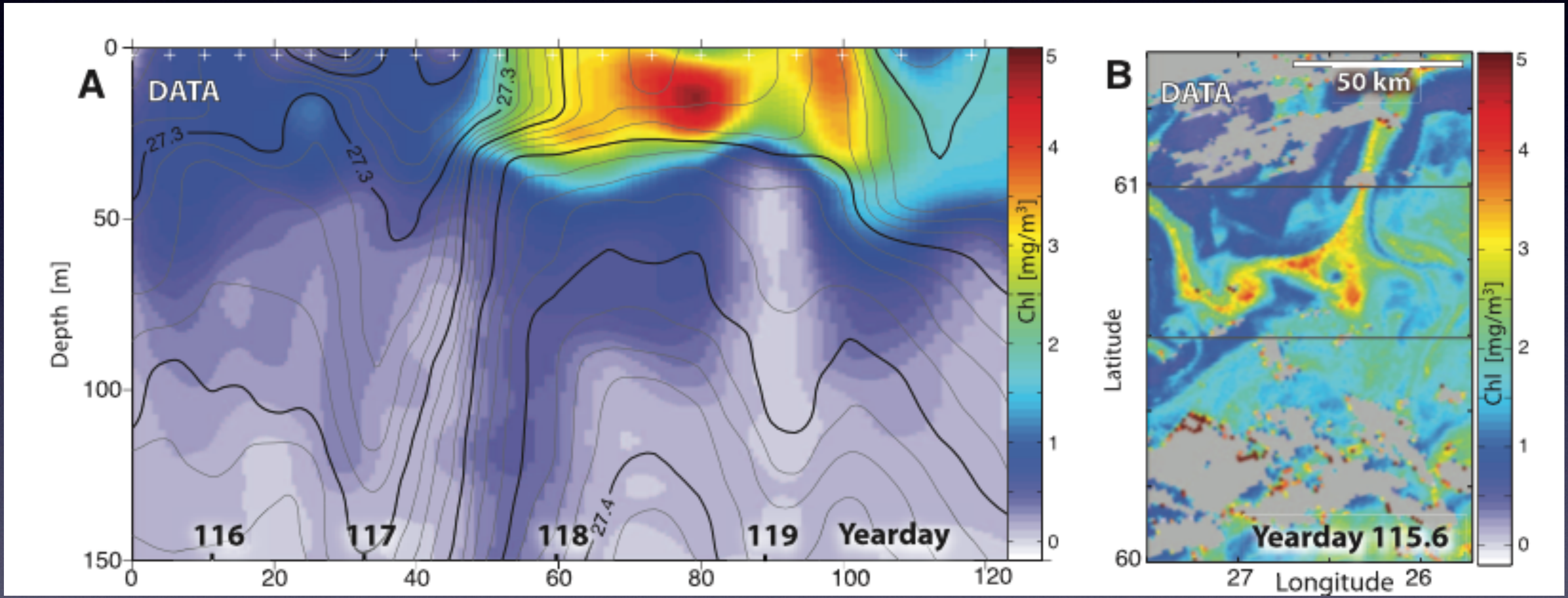
Modern perspectives of the North Atlantic Spring Bloom initiation



Mahadevan et al. (2012) *Science 337: 54-58*

Modern perspectives of the North Atlantic Spring Bloom initiation

- One-dimensional (the cessation of convective mixing; Taylor and Ferrari 2011) and 3-dimensional (slumping of horizontal gradients, Mahadevan et al. 2012) processes lead to re-stratification.

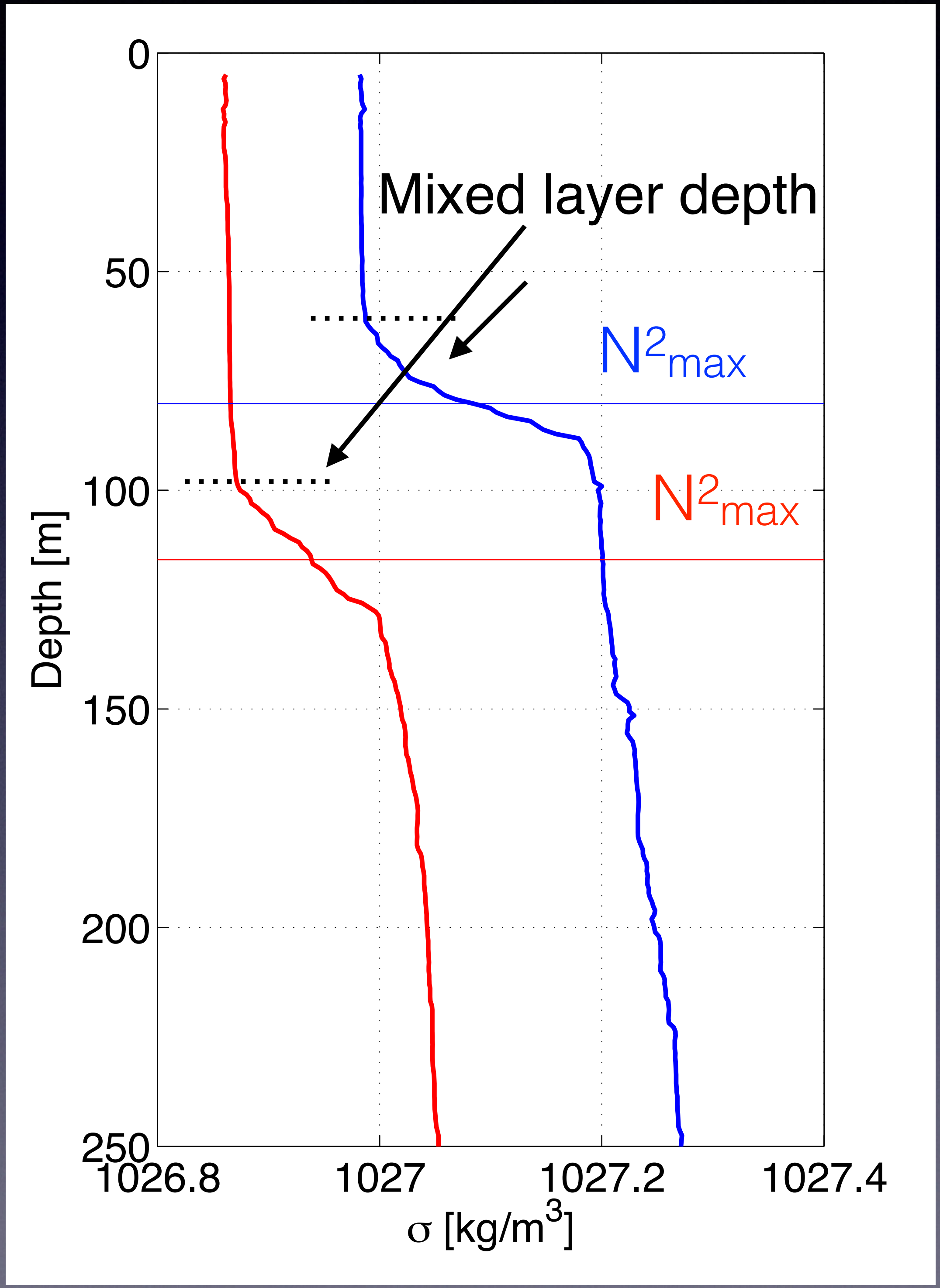
- NAB phytoplankton *accumulations* are normally associated with stratification, but *accumulation rates n*eed not be (e.g. Behrenfeld and Boss 2014).

- Lively debate in the literature based on satellite data, sparse autonomous sampling, and a handful of process studies, few of which measure turbulent fluxes or predator/prey interactions.

What have we learned from recent, prolonged in situ measurements of turbulence?

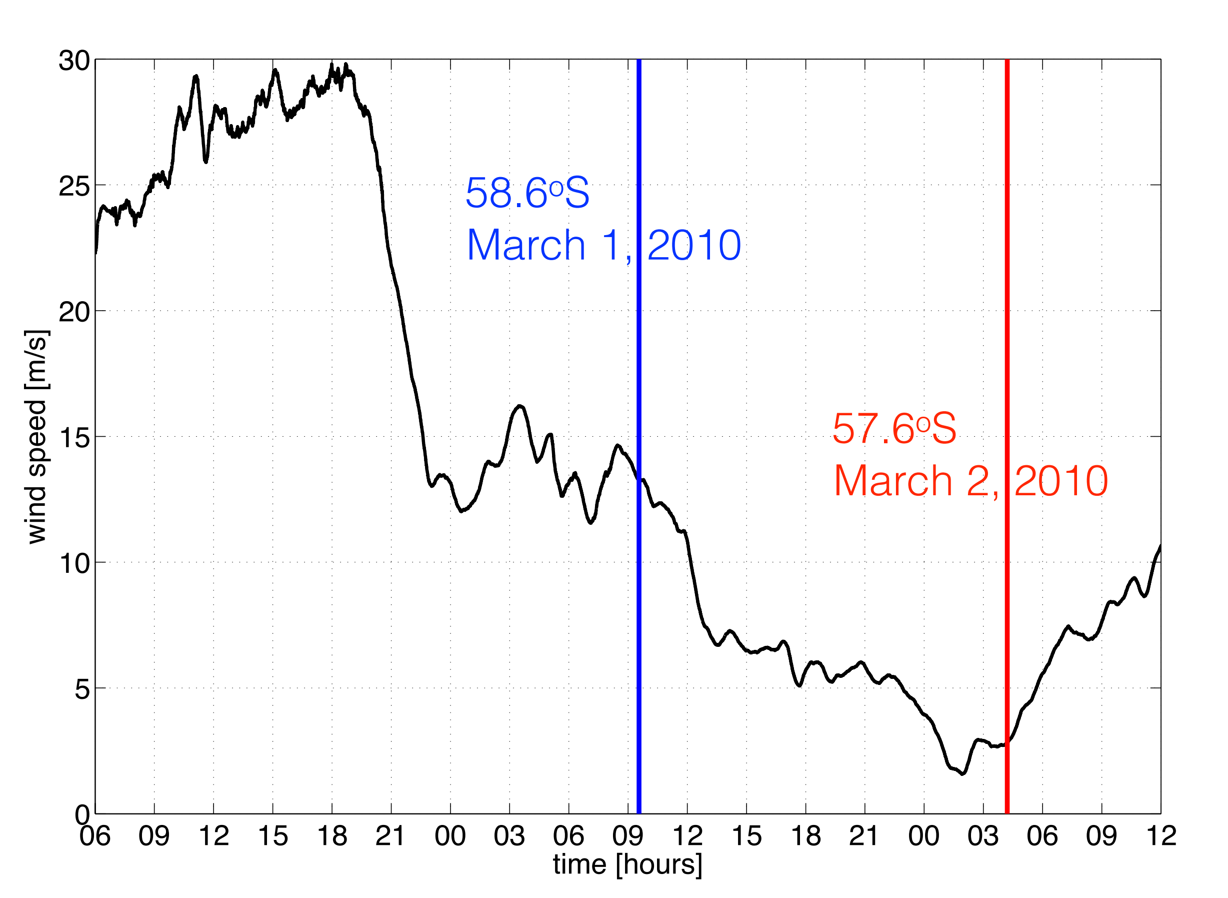
A few thoughts about stratified turbulence and blooms

Southern Ocean mixed layer



Very strong wind forcing, 75-100 m deep mixed layer. What is the distribution of turbulence?

Wind speed (m/s)



DIMES data courtesy of
Lou St. Laurent
and Sophia Merrifield, WHOI

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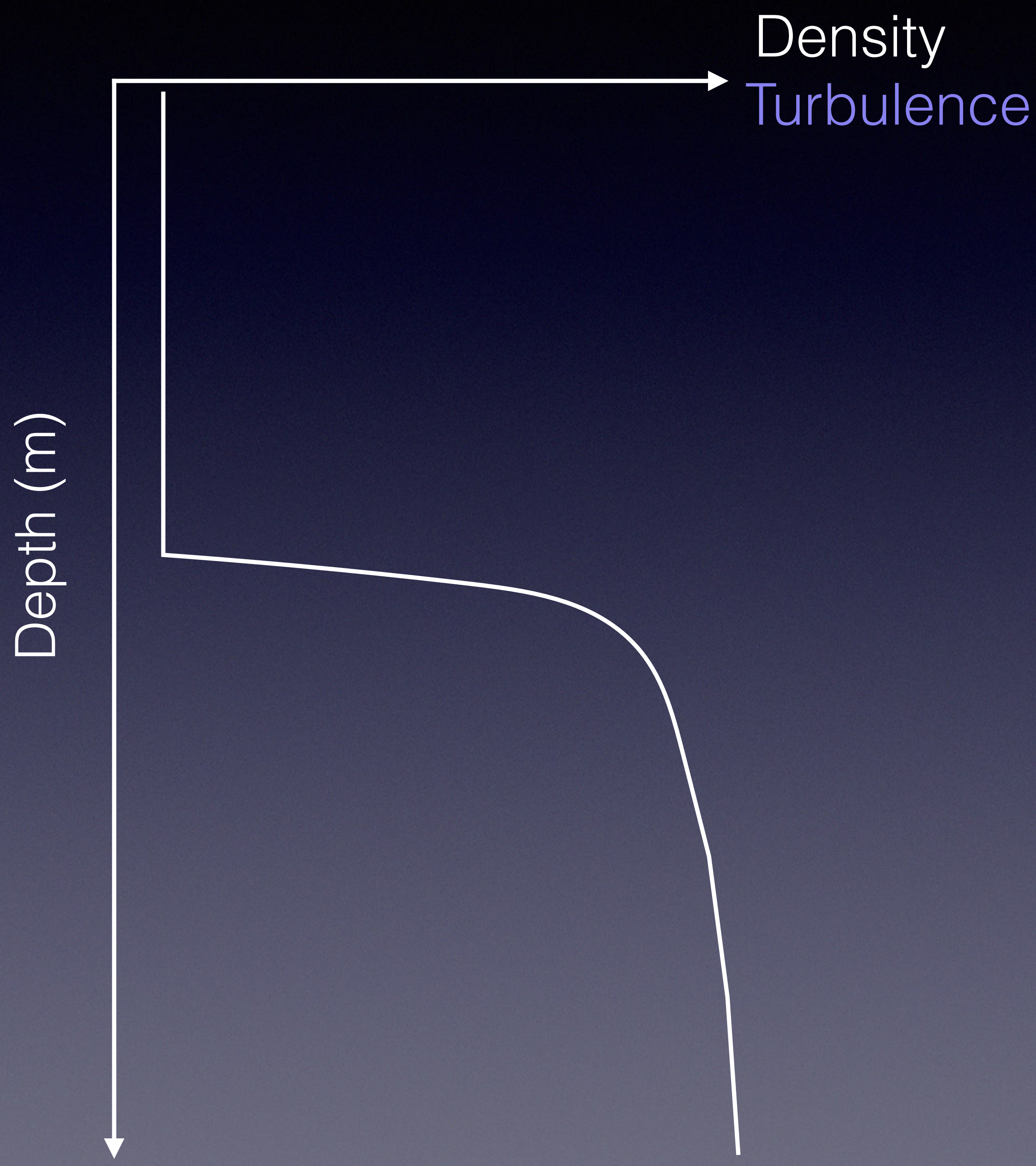

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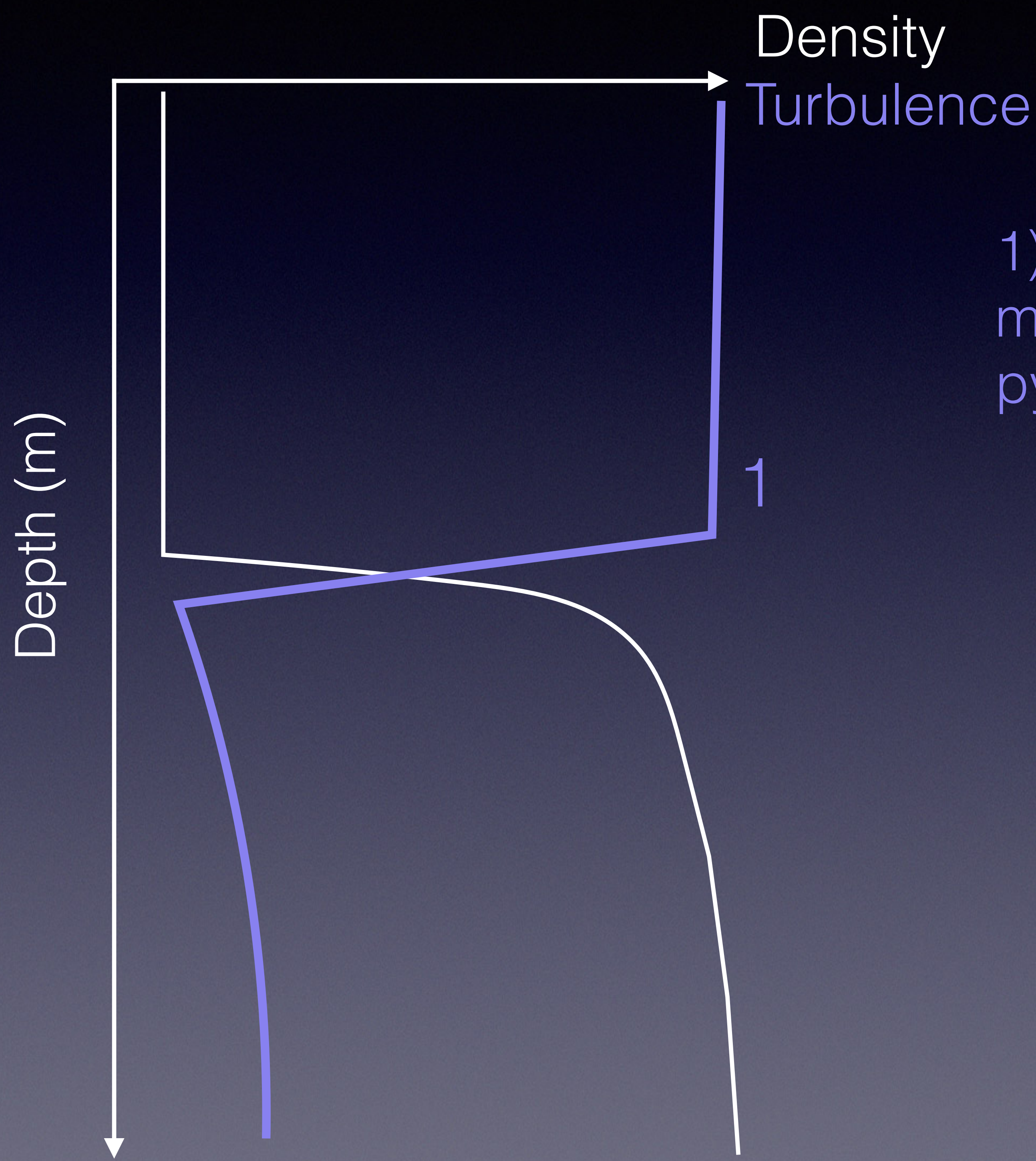
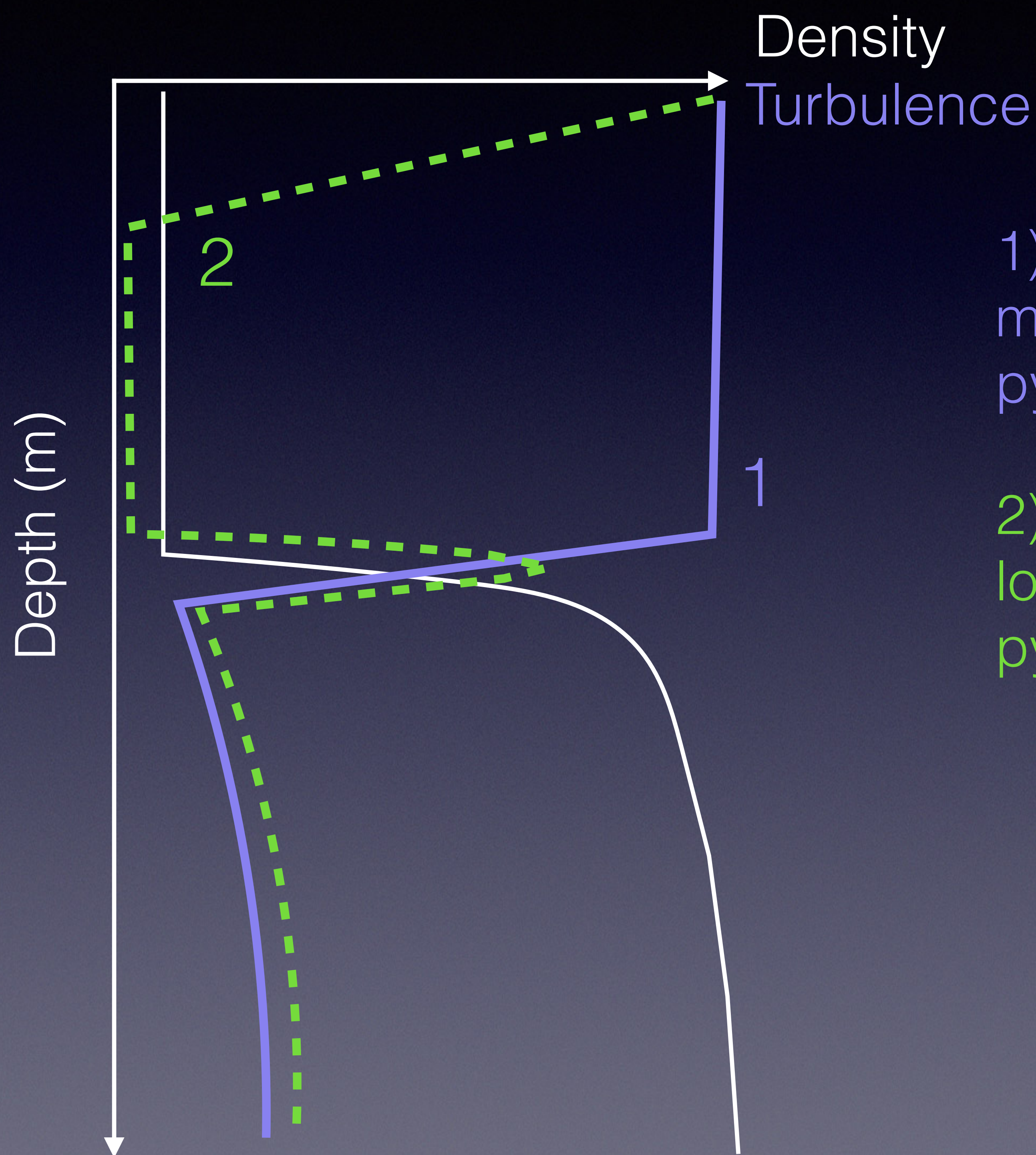


1) Turbulence roughly even throughout mixed layer, drops abruptly at the pycnocline.

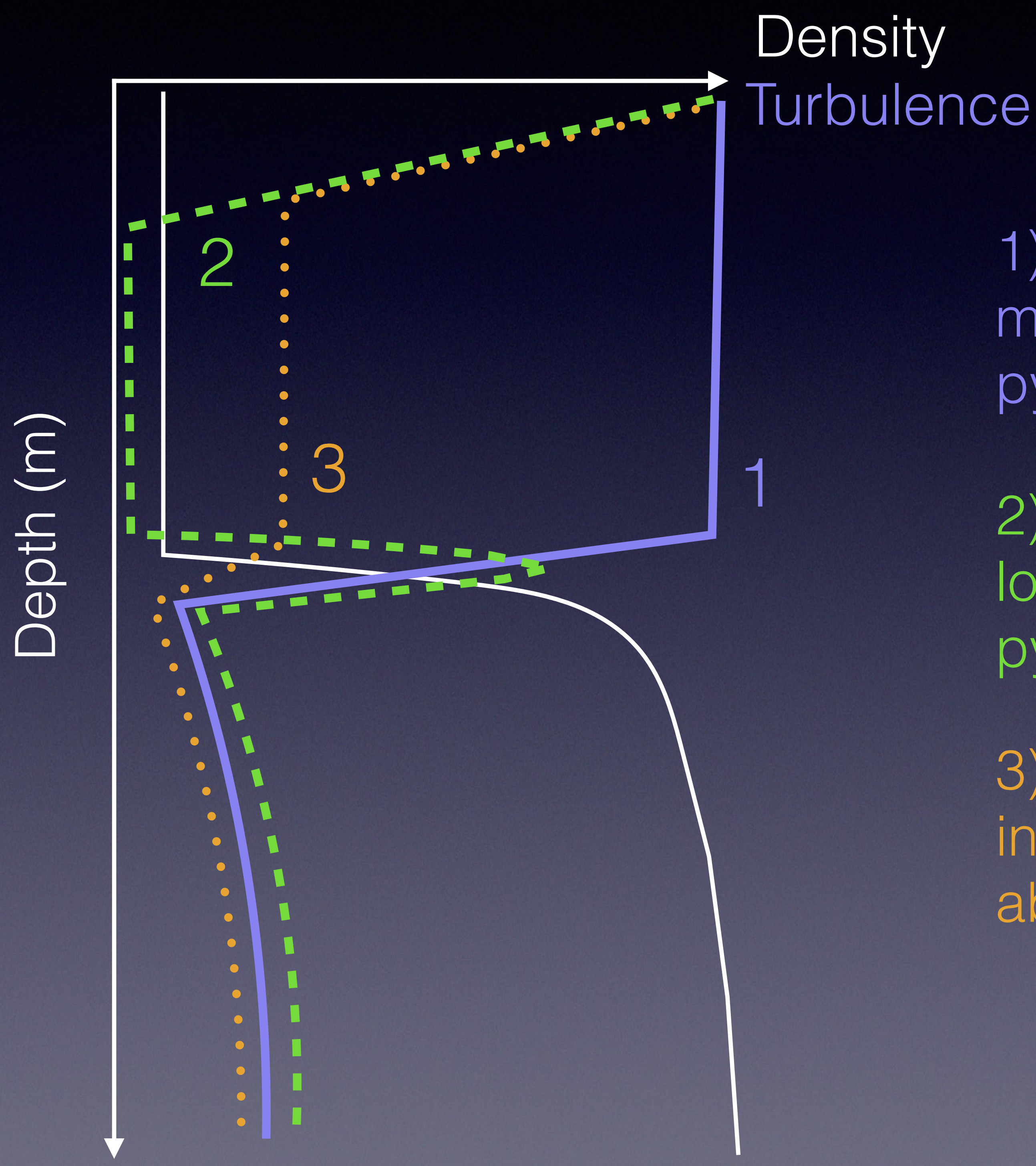
Very strong wind forcing, 75-100 m deep mixed layer. What is the distribution of turbulence?



1) Turbulence roughly even throughout mixed layer, drops abruptly at the pycnocline.

2) Turbulence decays in depth to some low value within ML, increases at pycnocline.

Very strong wind forcing, 75-100 m deep mixed layer. What is the distribution of turbulence?



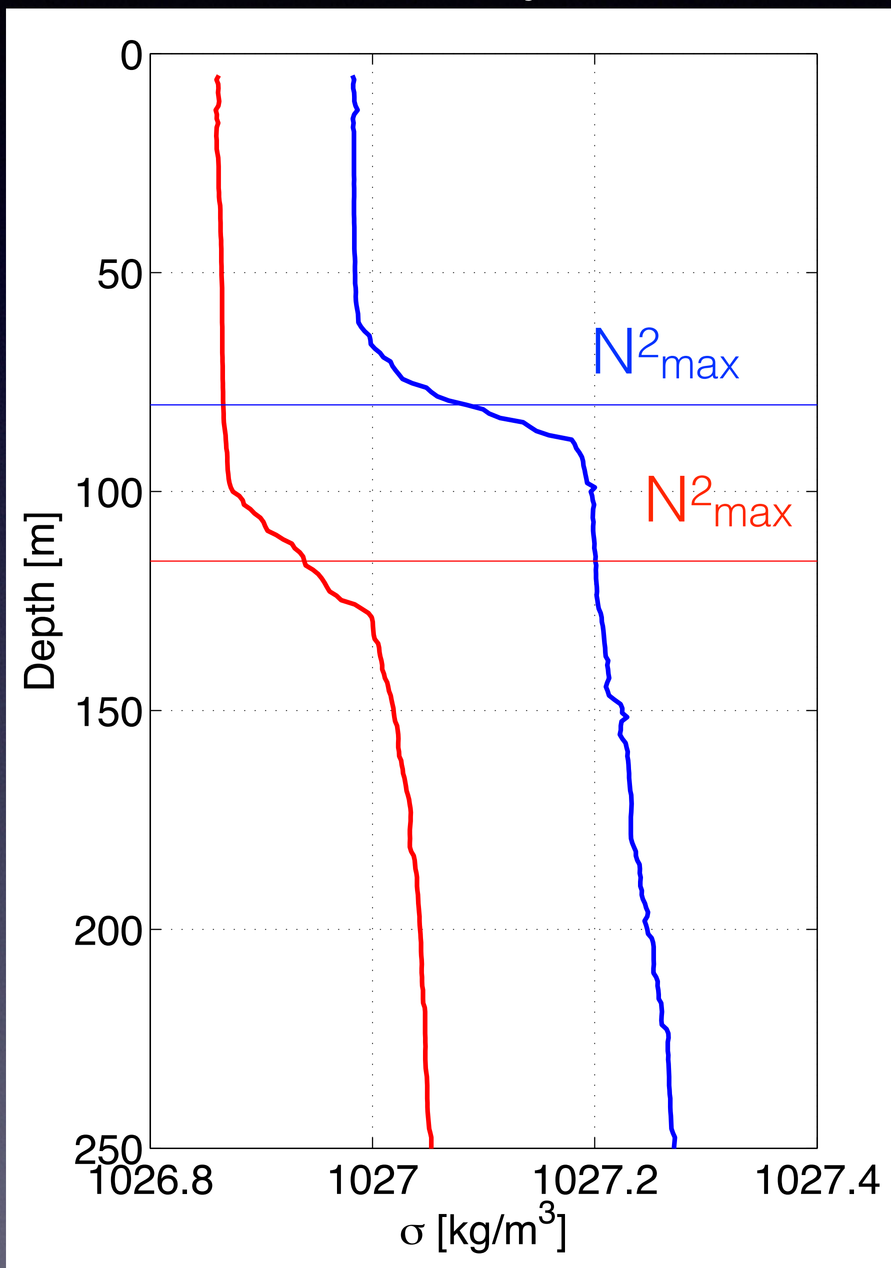
1) Turbulence roughly even throughout mixed layer, drops abruptly at the pycnocline.

2) Turbulence decays in depth to some low value within ML, increases at pycnocline.

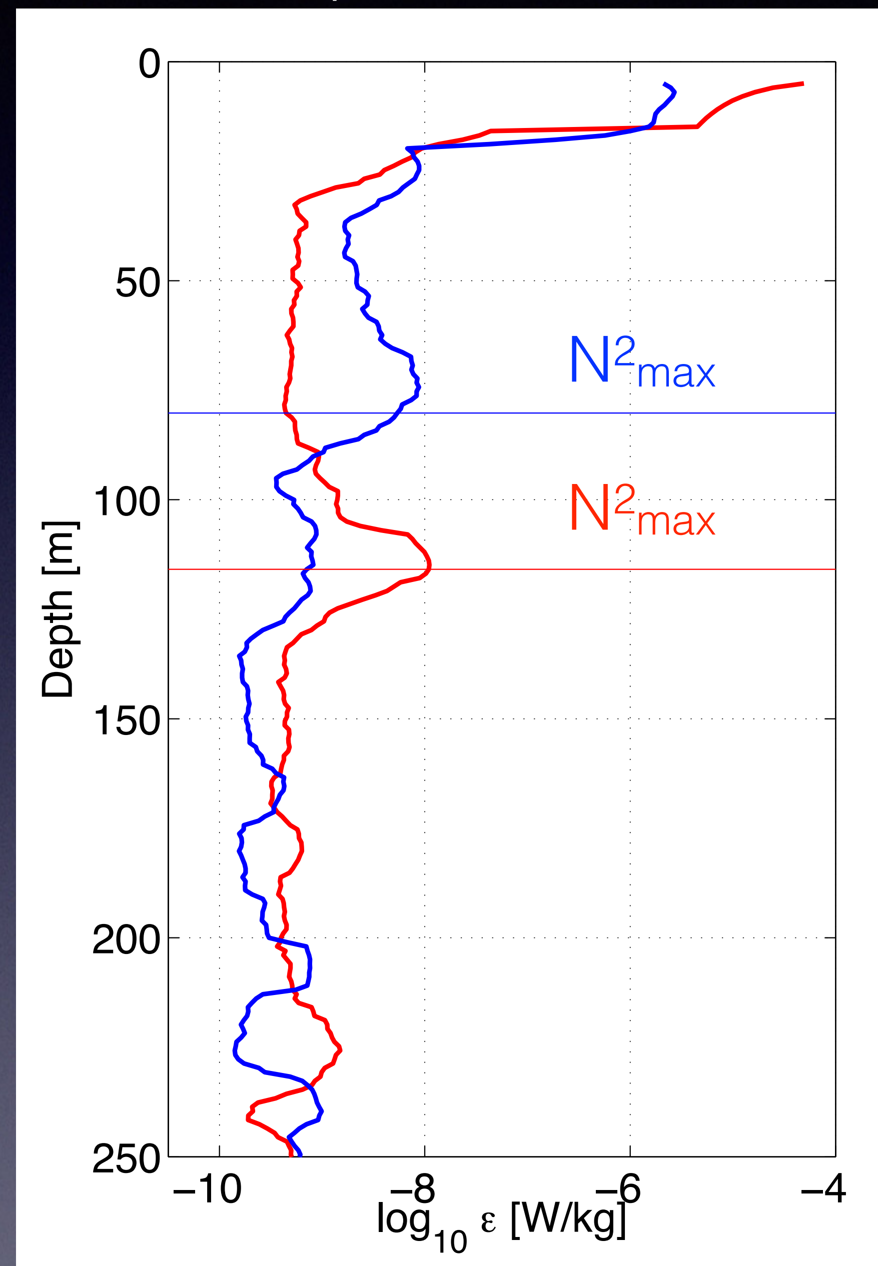
3) Turbulence decays in depth to some intermediate value within ML, drops abruptly at the pycnocline.

A few thoughts about stratified turbulence and blooms

Density



Dissipation of TKE



DIMES data courtesy of Lou St. Laurent and Sophia Merrifield, WHOI

Rapid drop with depth

Low levels in mixed layer below near-surface

Elevated turbulence at the pycnocline

A few thoughts about mixing and the NAB

- Deep mixed layers (>100m) in mid/high latitudes are formed by convection.
- After cessation of convection, interior ML is remanent i.e. ‘mixed’ but not ‘mixing.’
- Thus, homogenous distribution of mixing/phytoplankton is exception rather than the rule after the cessation of convection.
- Small lateral/vertical/temporal scales. Rare turbulent events might have outsize importance to bloom initiation.

Sampling strategies for measuring turbulence *in situ*

Modern

DIMES data courtesy of
Lou St. Laurent
and Sophia Merrifield, WHOI

Really modern

Wave-powered
vertical profiler (SIO)
Lucas/Pinkel
chi J. Moum/J. Nash, OSU

Seaglider (APL/UW)
Craig Lee and Luc Rainville

Slocum turbulence glider
Lou St. Laurent (WHOI)

Sampling strategies for measuring turbulence plus biological variability *in situ*

Pinkel et al. 2011 JTECH

Wirewalker profiler

1) Wave-powered profiling (wave down, buoyancy up).

2) Fast profiling relative to floats and gliders.

3) Flexible payload (CTD, currents, optics, DO, turbulences, nitrate).

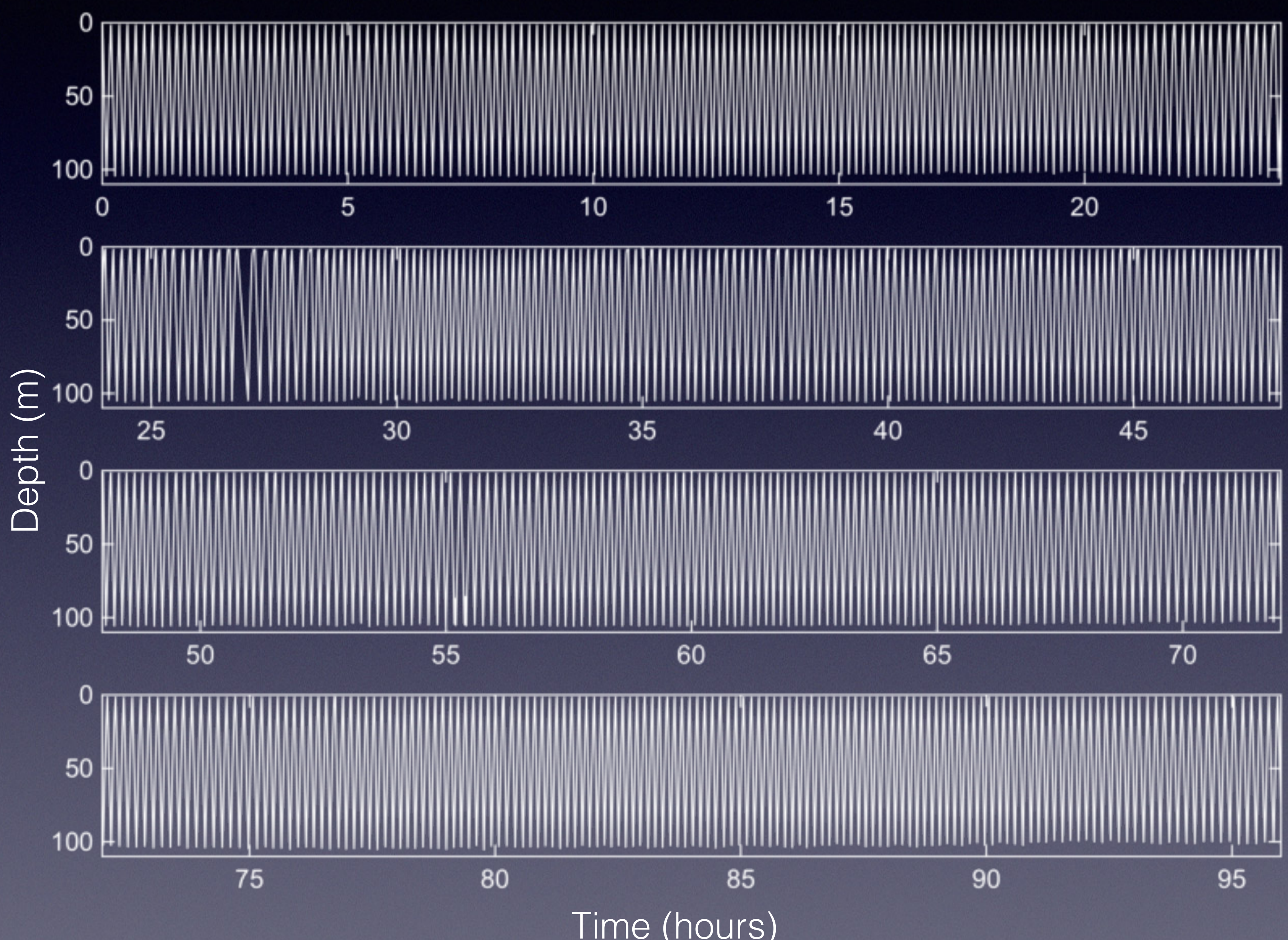
4) Over a decade of use around the world (>400K profiles and over 18,000 km of profiled distance).

5) Export to the community (12 units delivered to colleagues).

Sampling strategies for measuring turbulence plus biological variability *in situ*

Pinkel et al. 2011 JTECH

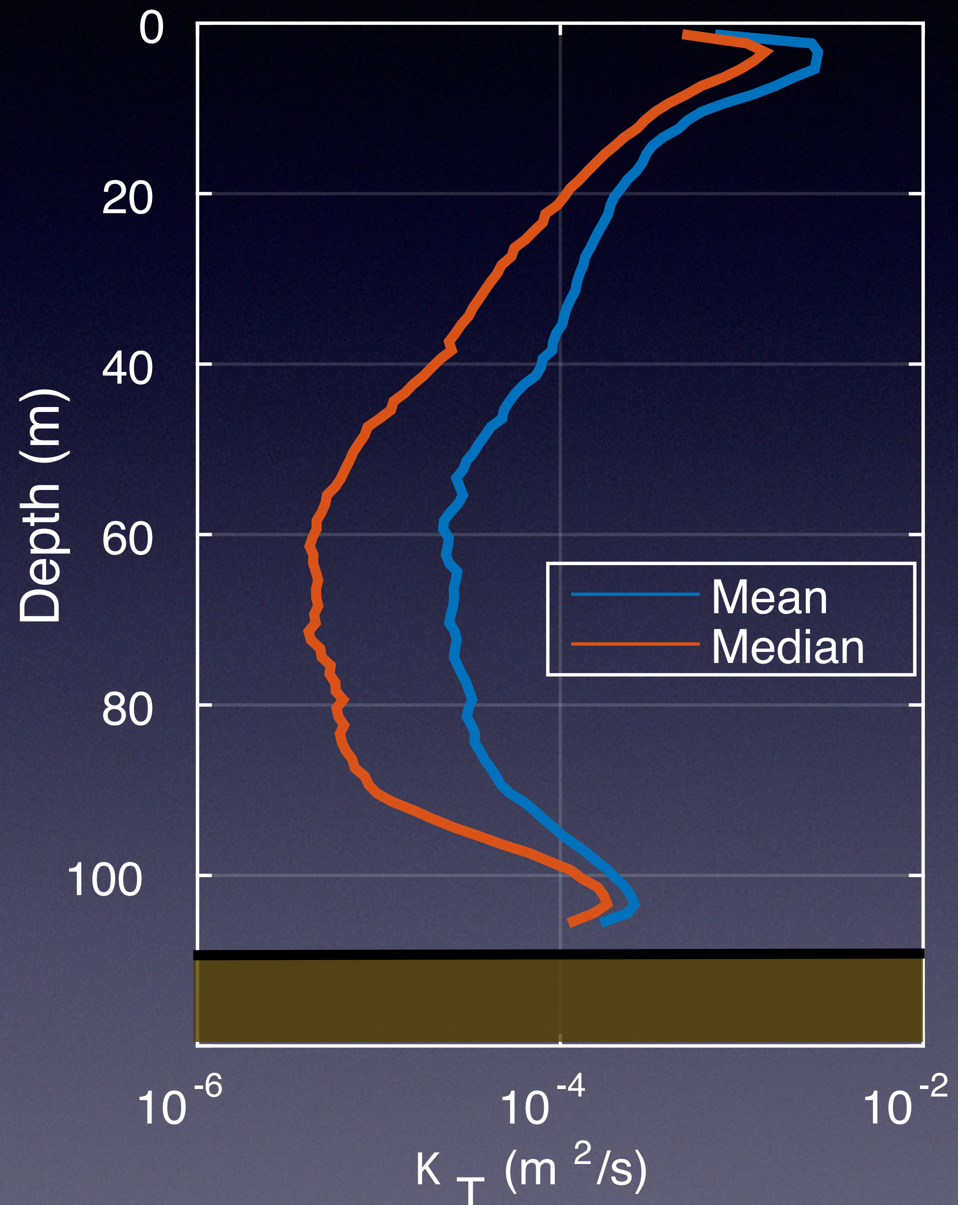
Wirewalker wave-powered profiler



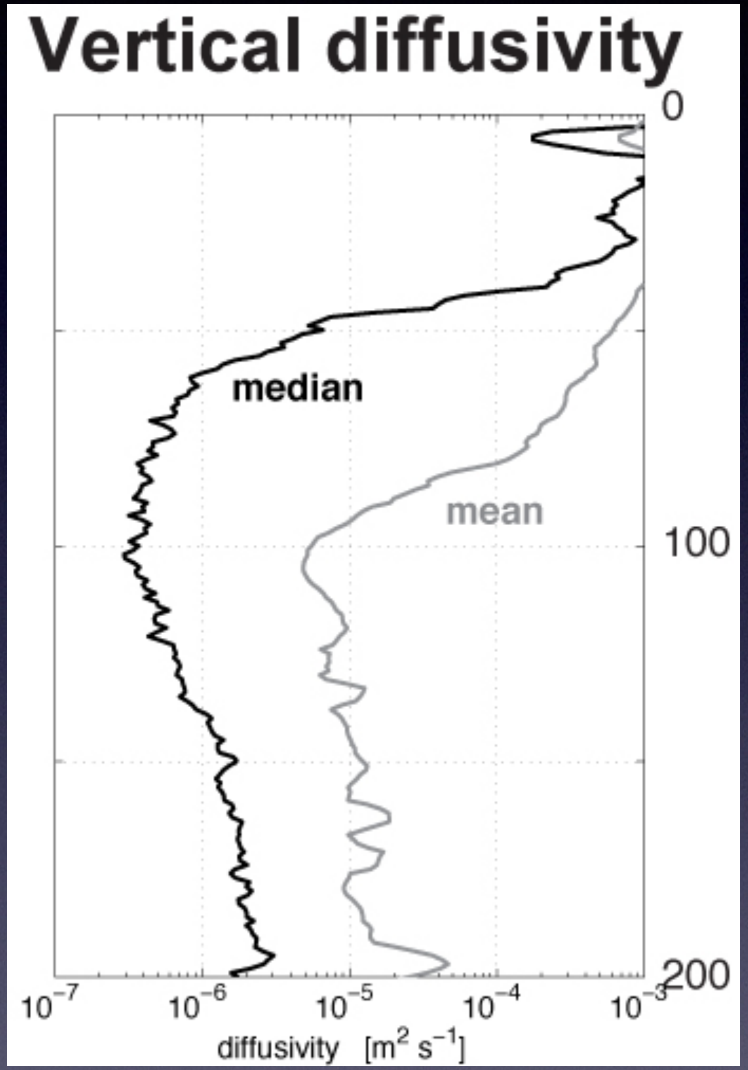
524 profiles to 100m in 4 days (profile ~10 min)

Insights from prolonged in situ turbulence measurements

Mixing on the Tasman shelf (16d continuous record)



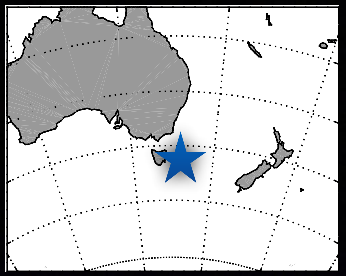
North Atlantic Seaglider sections

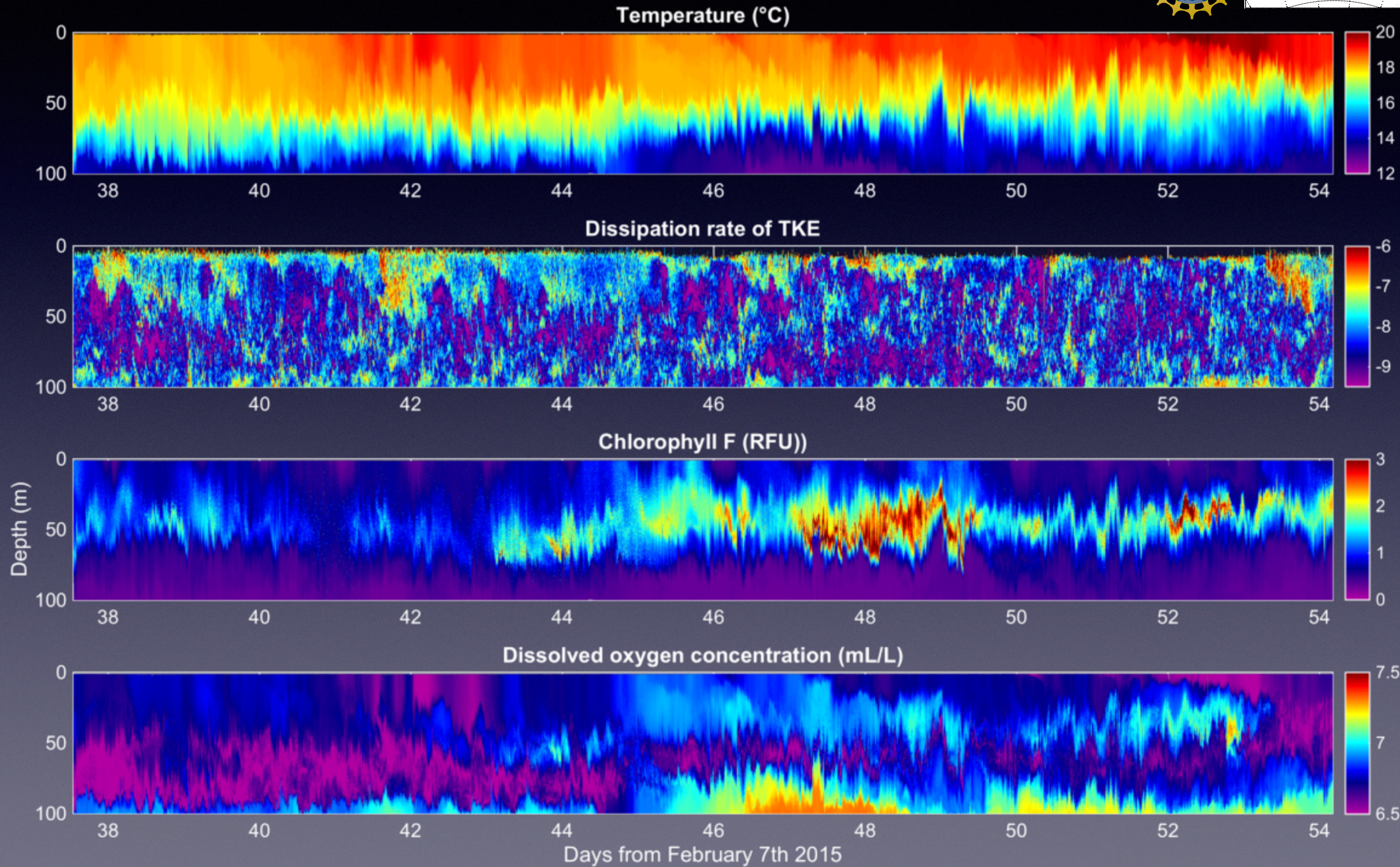


Craig Lee and Luc Rainville
APL/UW

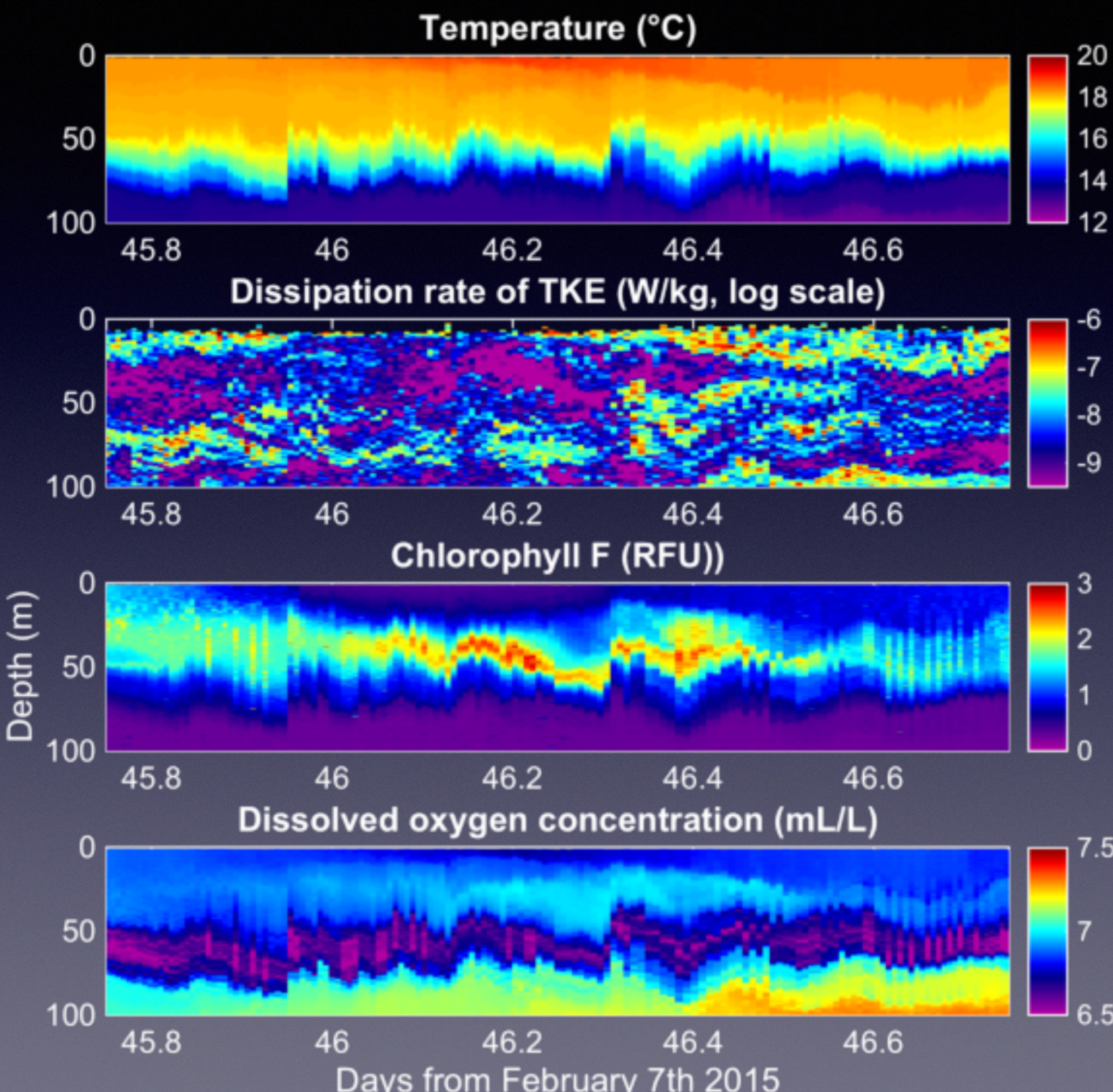
Turbulence is: unsteady, log-normally distributed, positively skewed (many small values, few large ones).

Observations of turbulence during a subsurface bloom in a nitrate-limited system: the Tasman Shelf





High-frequency internal waves and subsurface blooms



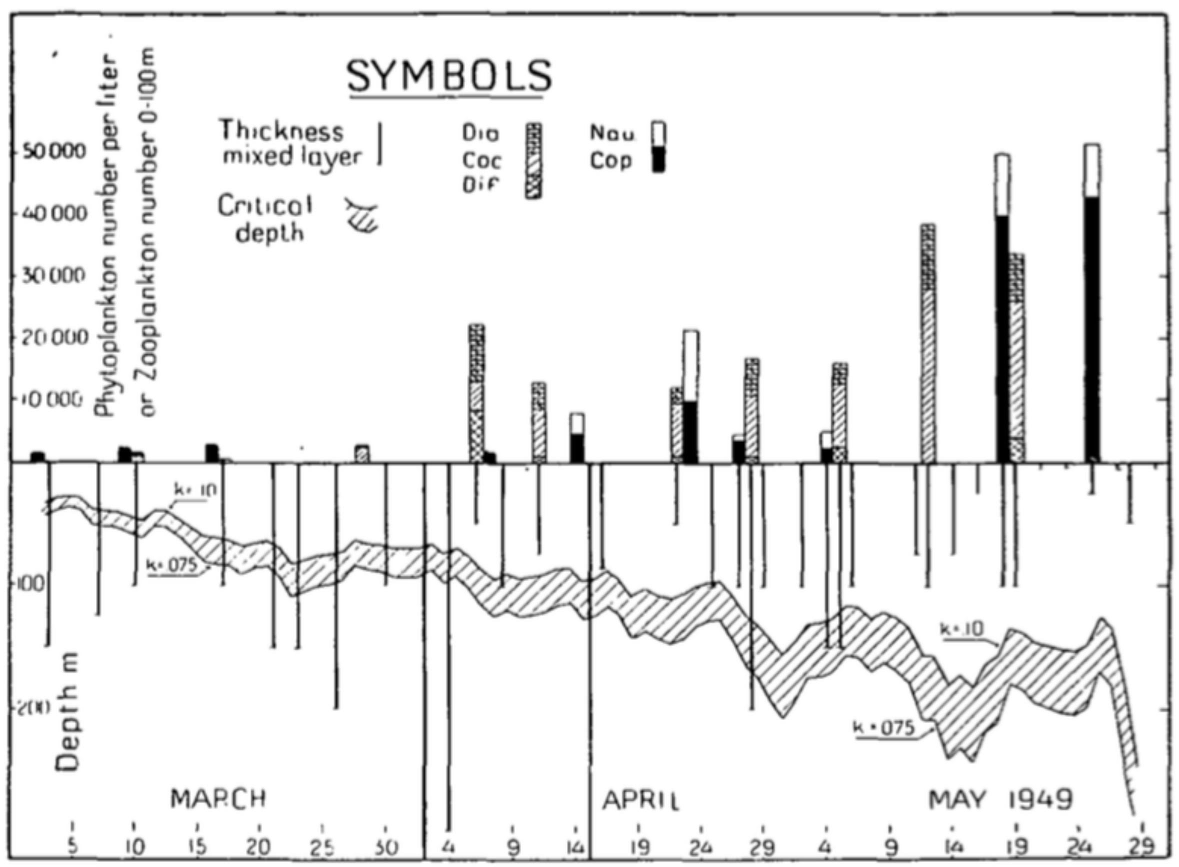
Timescales of variability in phytoplankton energetics (and zooplankton response) overlap the internal wave band.

Very few *concurrent* observations of turbulence, biological, and physical variability in this band.

Testing hypotheses that relate physical forcing and bloom formation require observing the relevant spectrum of physical dynamics (particularly statistics of turbulent fluxes).

A plea for more (quantity and kinds of) data

Back to Weather Ship "M"



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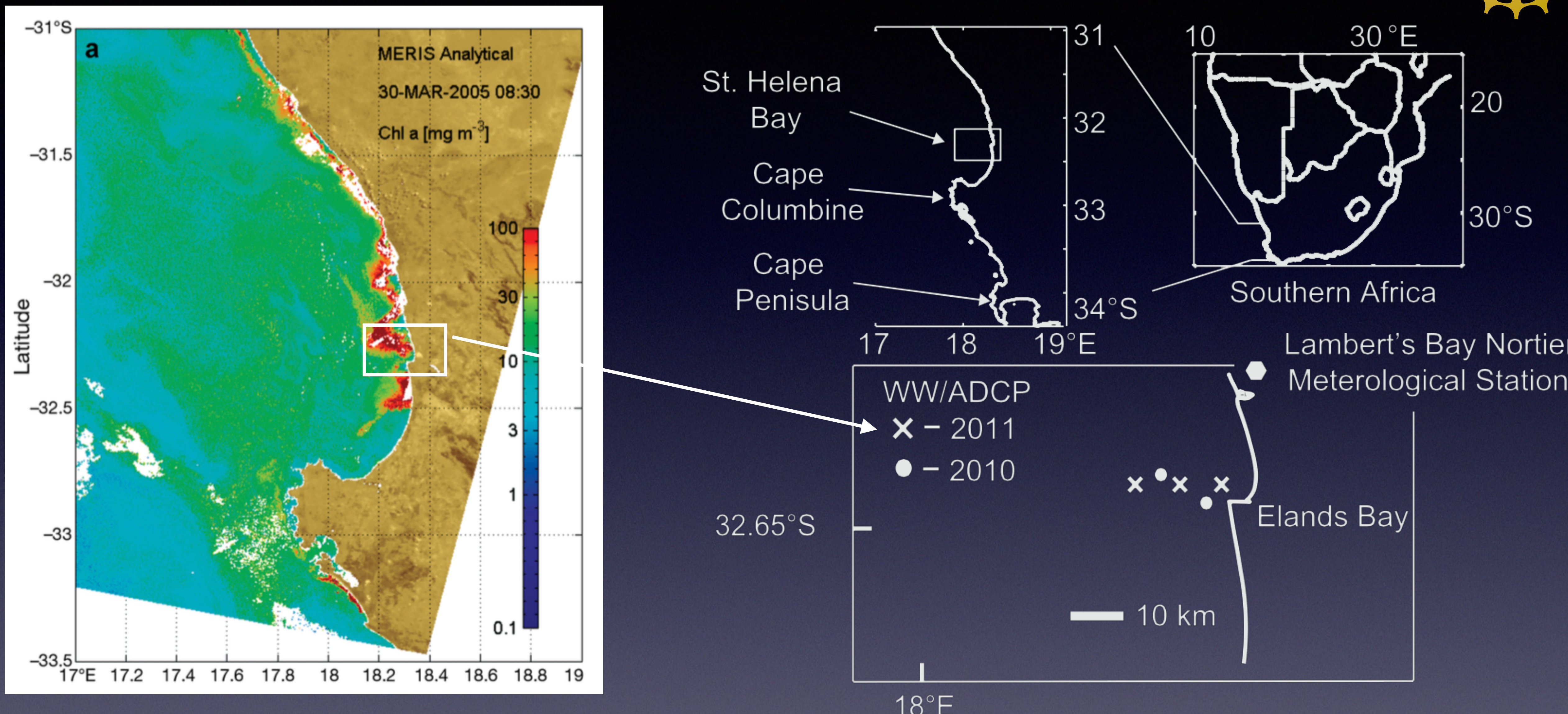
- Small spatial scales of gradients in MLD, turbulent layer depth, properly assessing gradients in the mixed layer.
- In situ time-series observations* of *fluxes, irradiance,* and *anything biological that isn't just fluorescence* are direly needed.
- Density gradients are often associated with strong current shear and mixing.
- High-frequency variability probably matters to both predator/prey interactions and productivity/ community structure of phytoplankton during blooms.

**a relevant time-scale of observation >> than doubling time, loss rate*

Take home: this is a tractable problem. Still, 60 years after Sverdrup, depends on gathering concurrent, high-frequency, in situ obs. of physical, chemical, and biological variability.

Thank you OCB!

Embedded dynamics: high frequency modulation of blooms due to low-frequency forcing

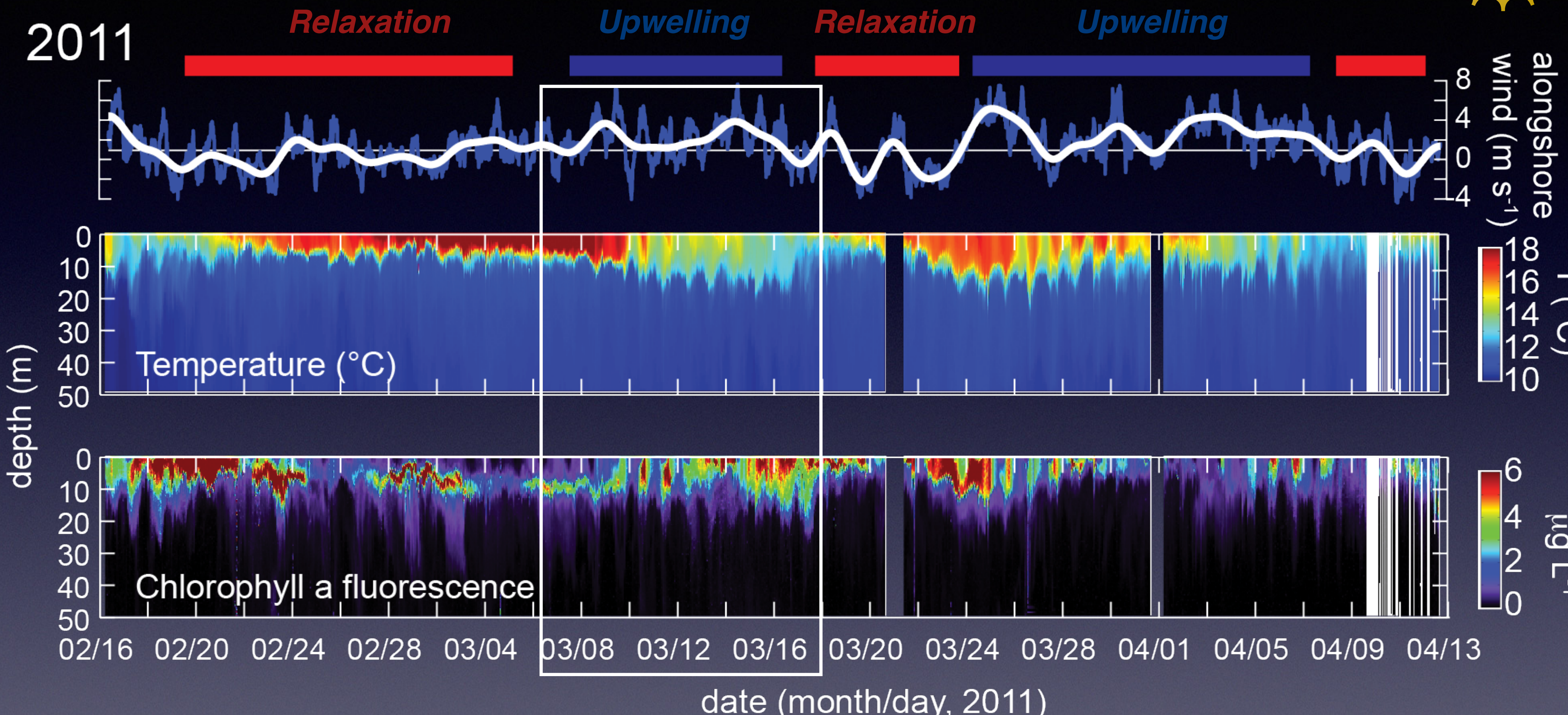


- CTD, Chla F, currents, dissolved oxygen. Wind from nearby station. Biological and biogeochemical measurements made by DAFF, South Africa.

- 2 Year total: 5 WW moorings, ~100K profiles, >4000 km profiled distance. >200 profiles per inertial period.

Lucas et al. DSR II 2014

Embedded dynamics: high frequency modulation of low-frequency forcing



- Oscillating period of upwelling and relaxation.
- Elevated levels of primary productivity associated with wind-forcing.
- Strong diurnal variability in all measured properties.

Lucas et al. DSR II 2014

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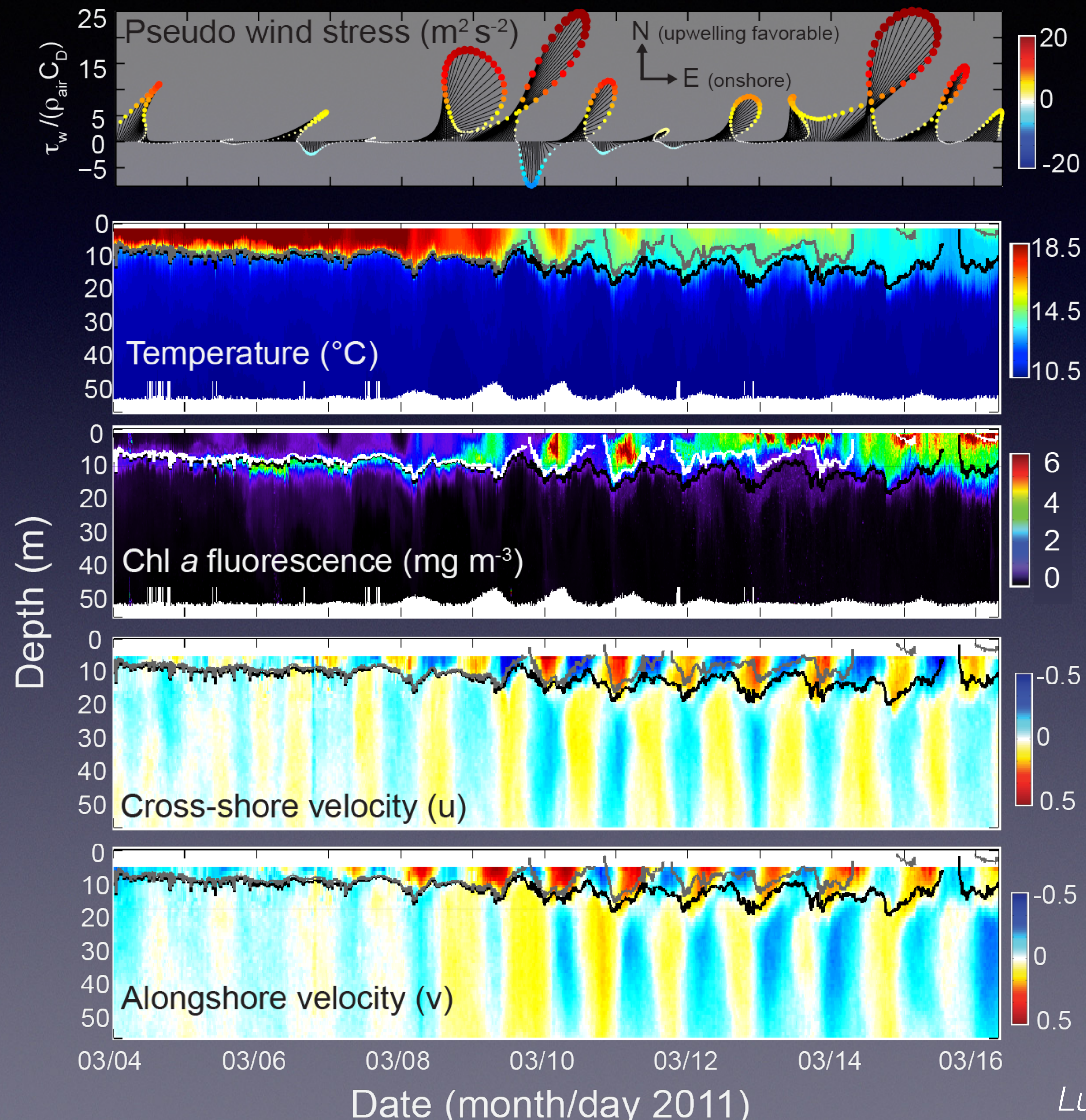

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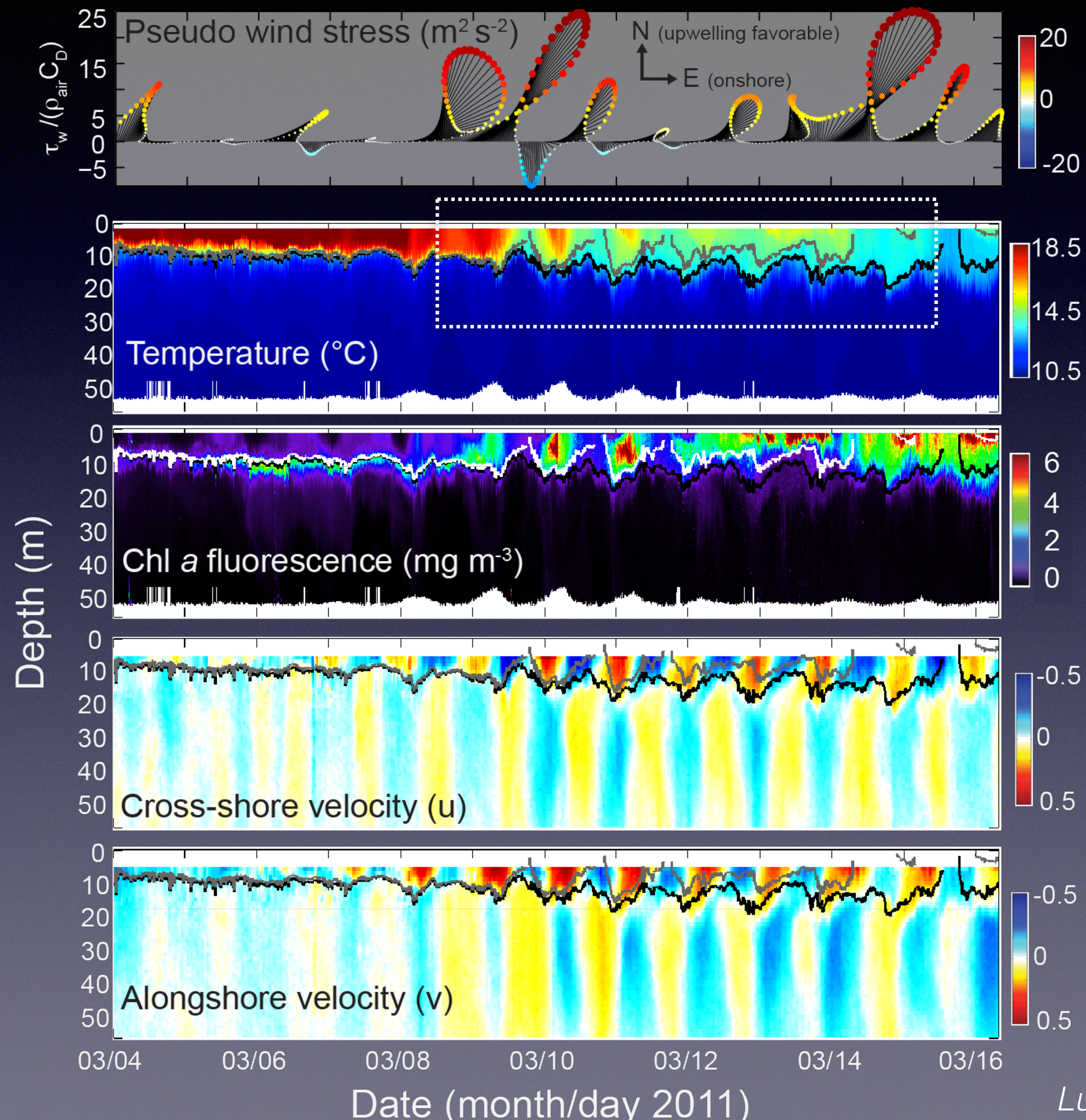

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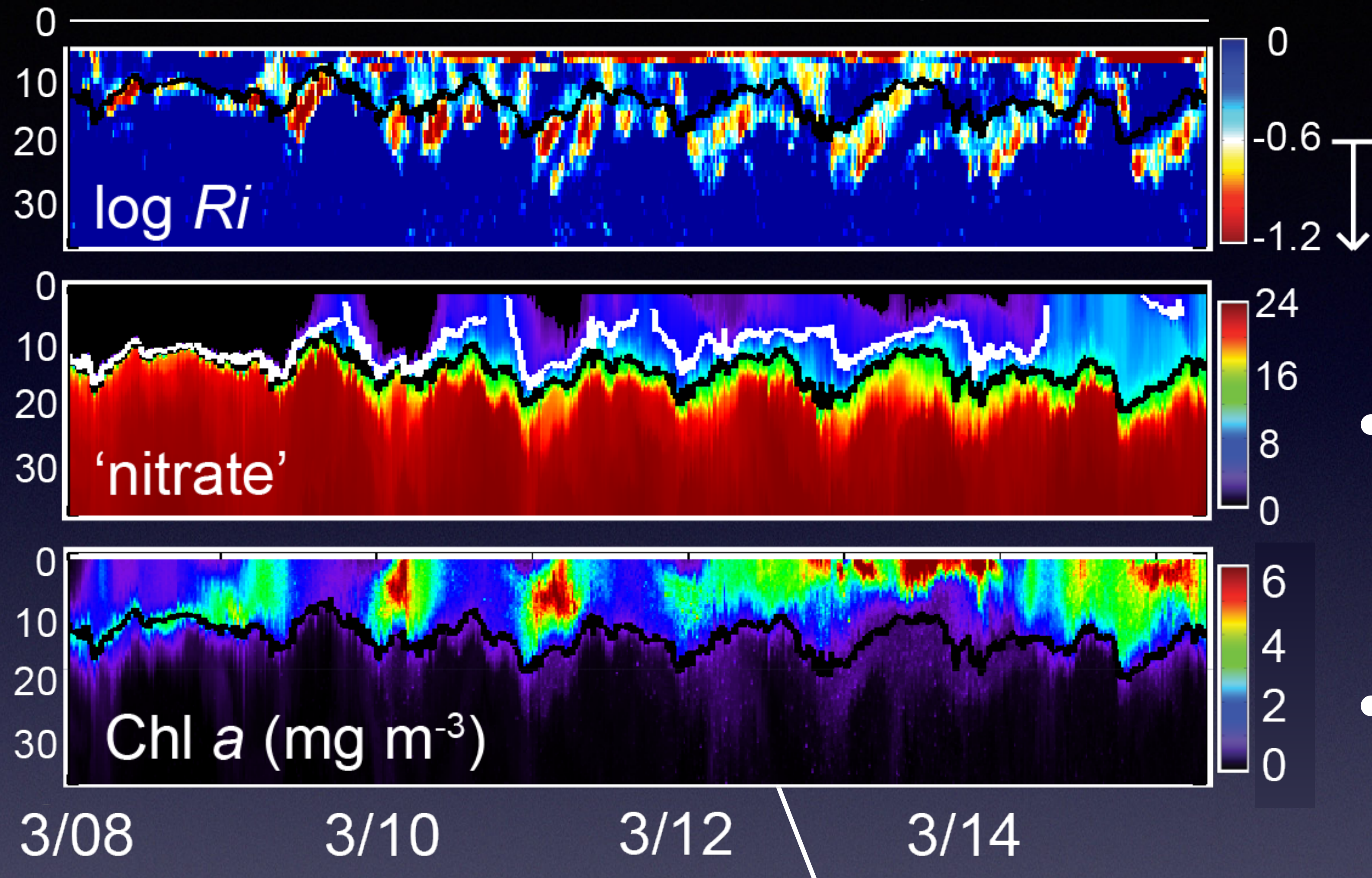
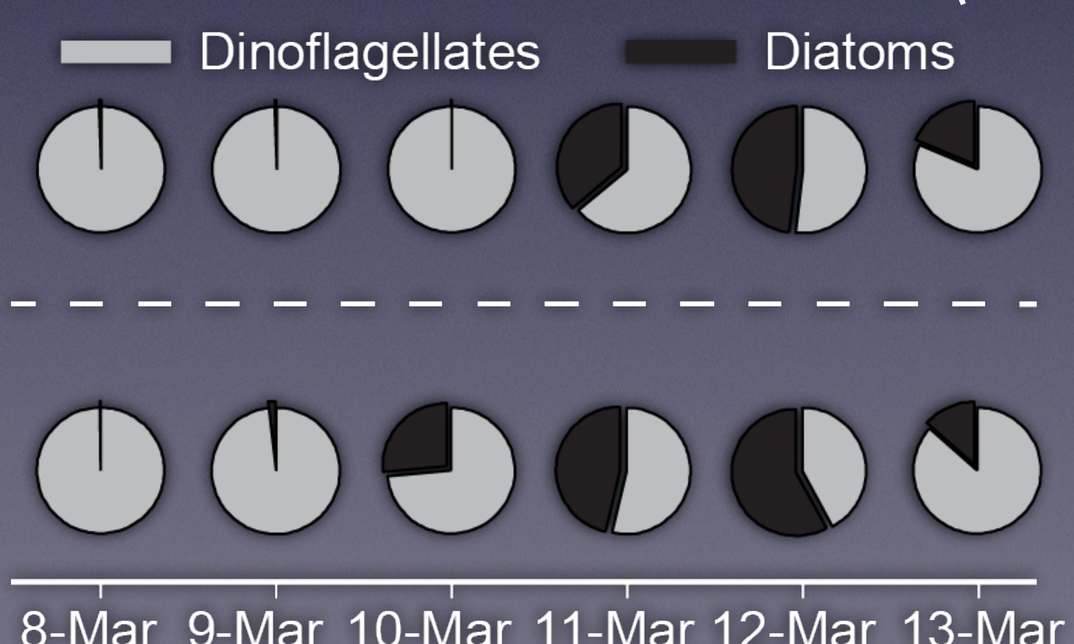
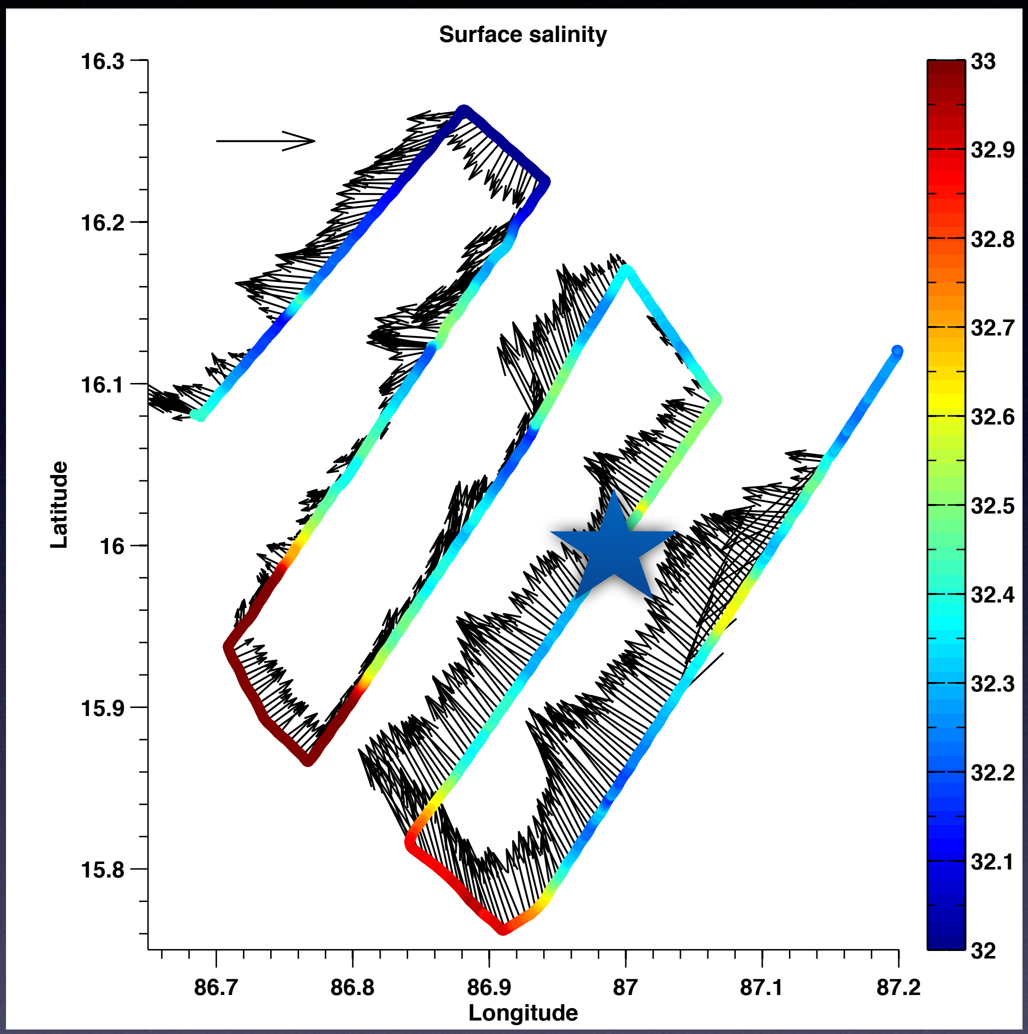


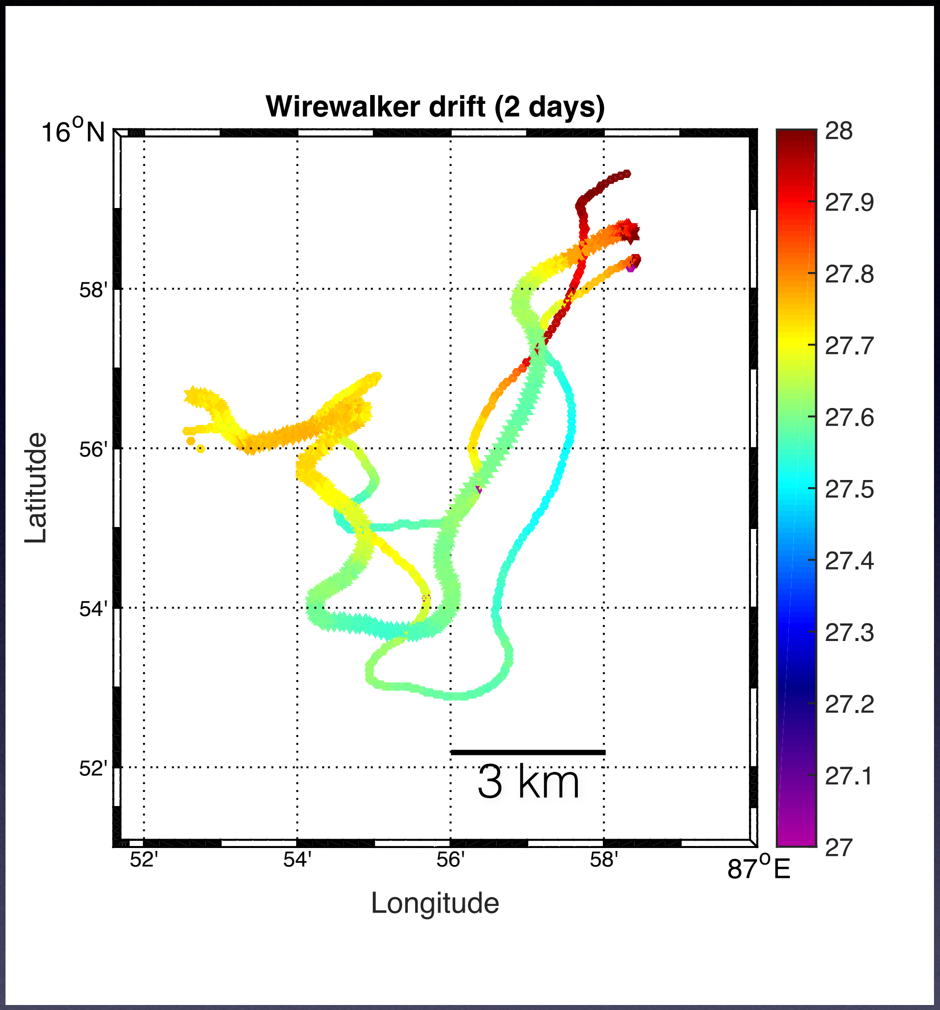


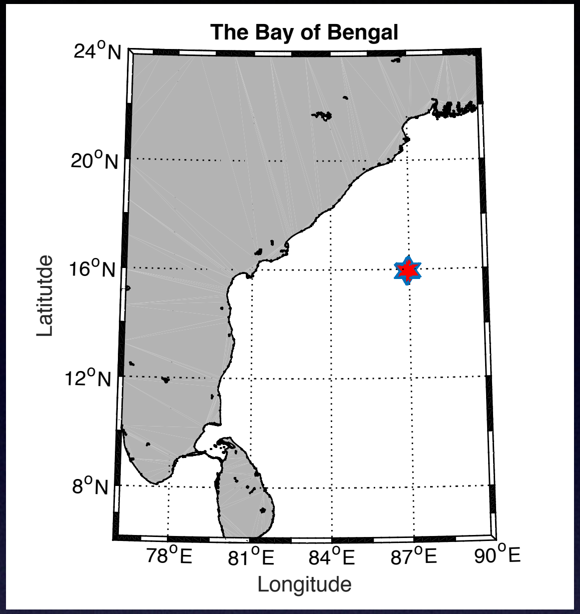
- Transition from a dinoflagellate-dominated community to an important fraction of diatoms.
- Onset of transition coincides with inertial outcropping of the pycnocline, increased mixing.
- Total chl a and total abundance increase rapidly.

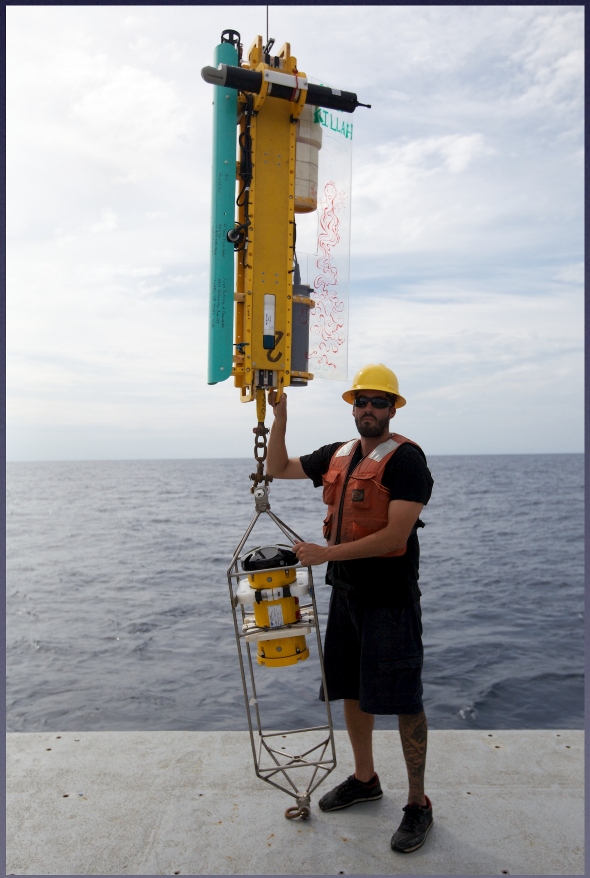
Lucas et al. DSR II 2014

Submesoscale variability in the open ocean: fronts, filaments, and phytoplankton









Wirewalker Profiling vehicle
(Ocean Physics Group, SIO)

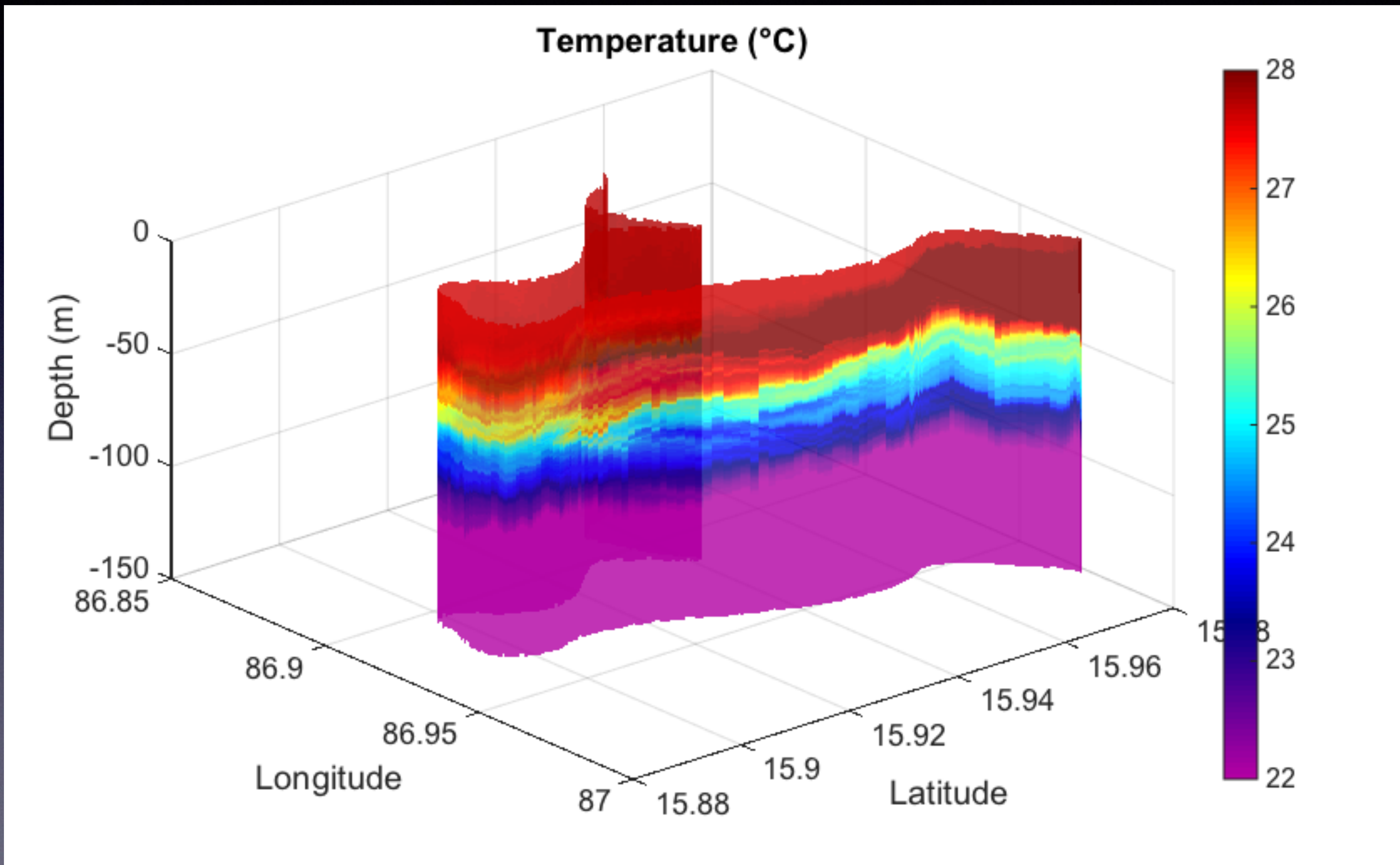
An array of wave-powered profiling vehicles, positioned across a submesoscale front.

Optical instrumentation, DO, density, currents, turbulence.

Profiles repeat rates <10min

(Lucas et al. 2014 *Eos;* From mixing to monsoons. Ongoing ONR Air-Sea Interactions DRI)

Submesoscale variability in the open ocean: fronts, filaments, and phytoplankton



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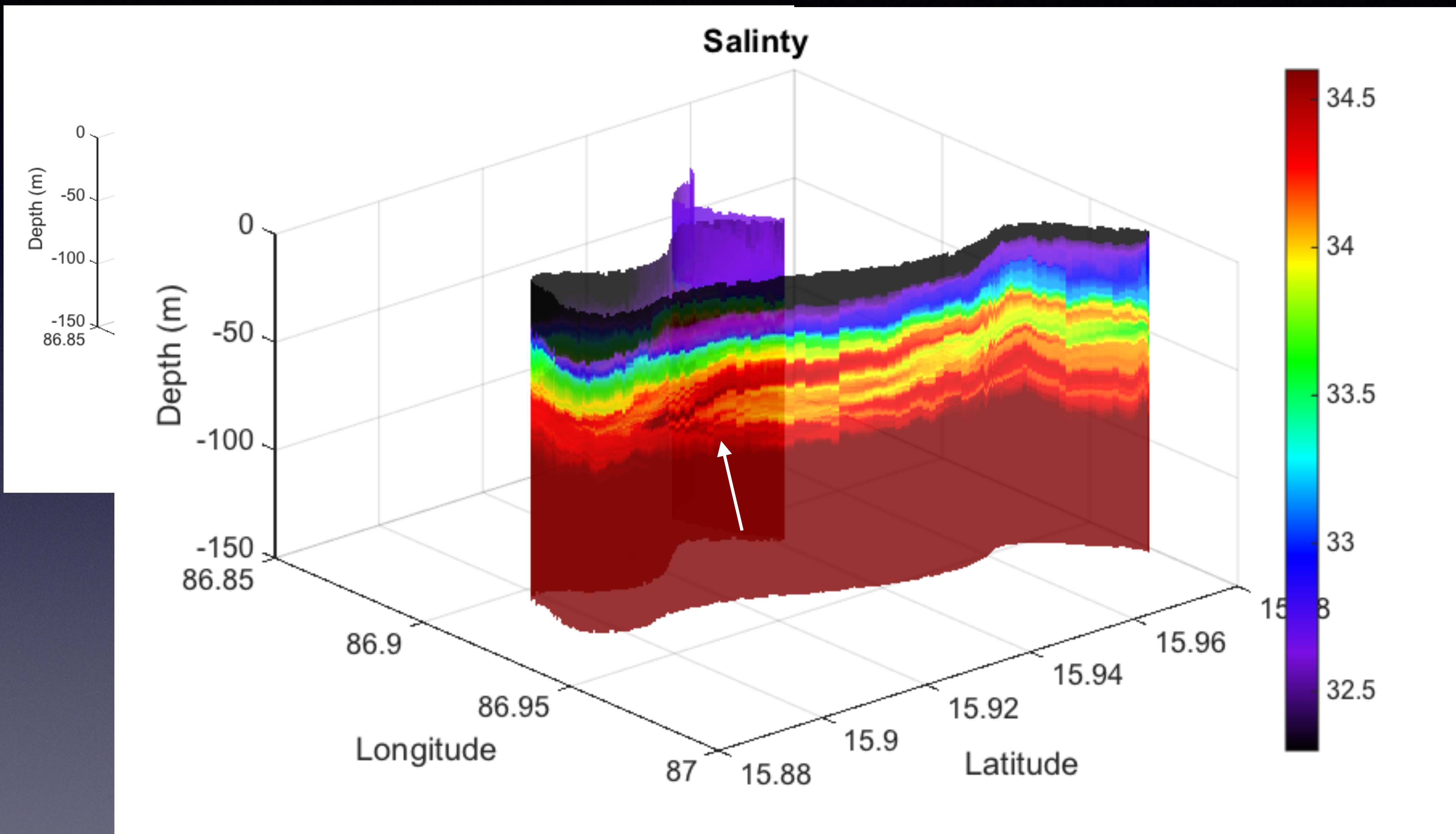

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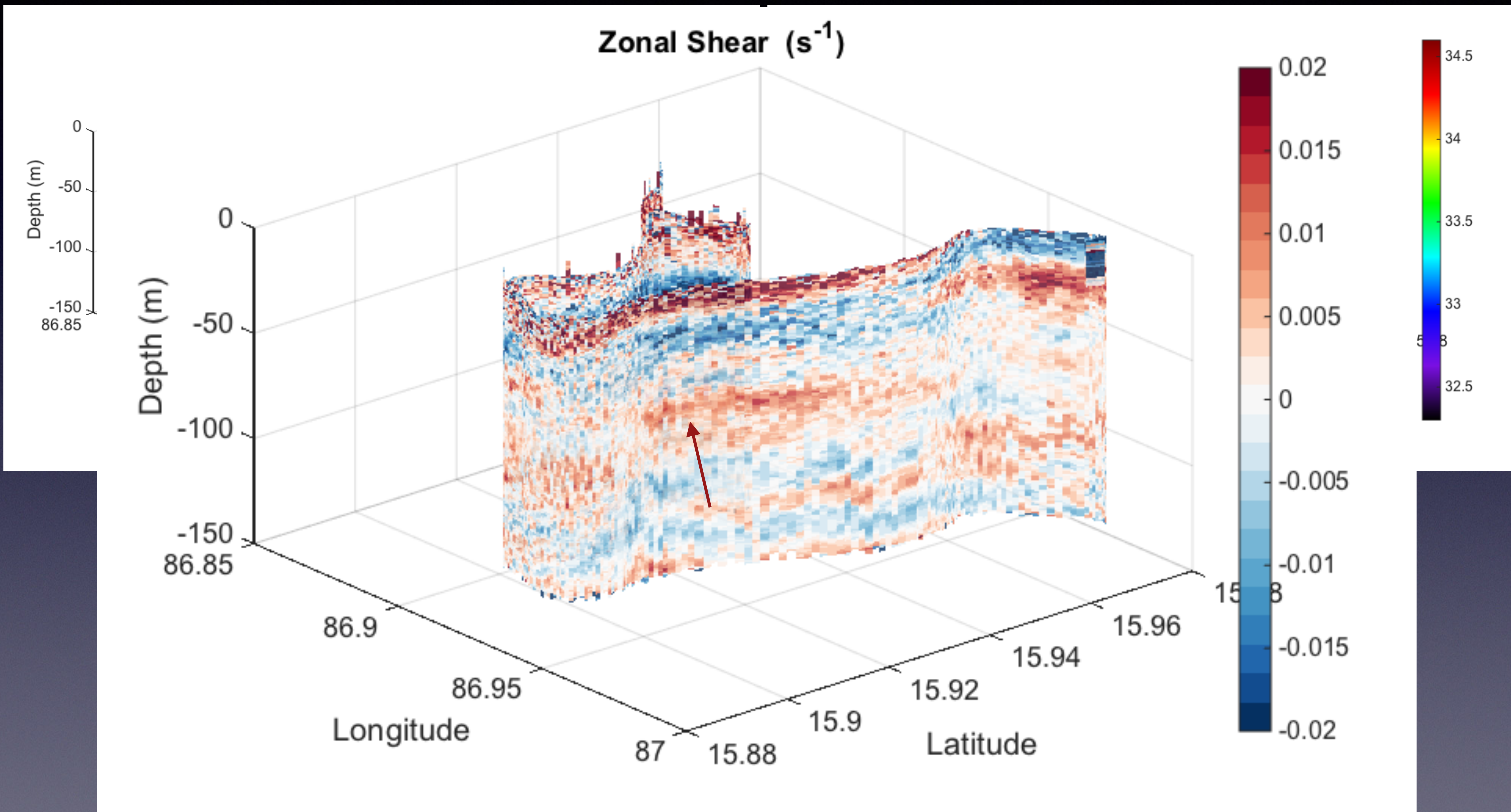
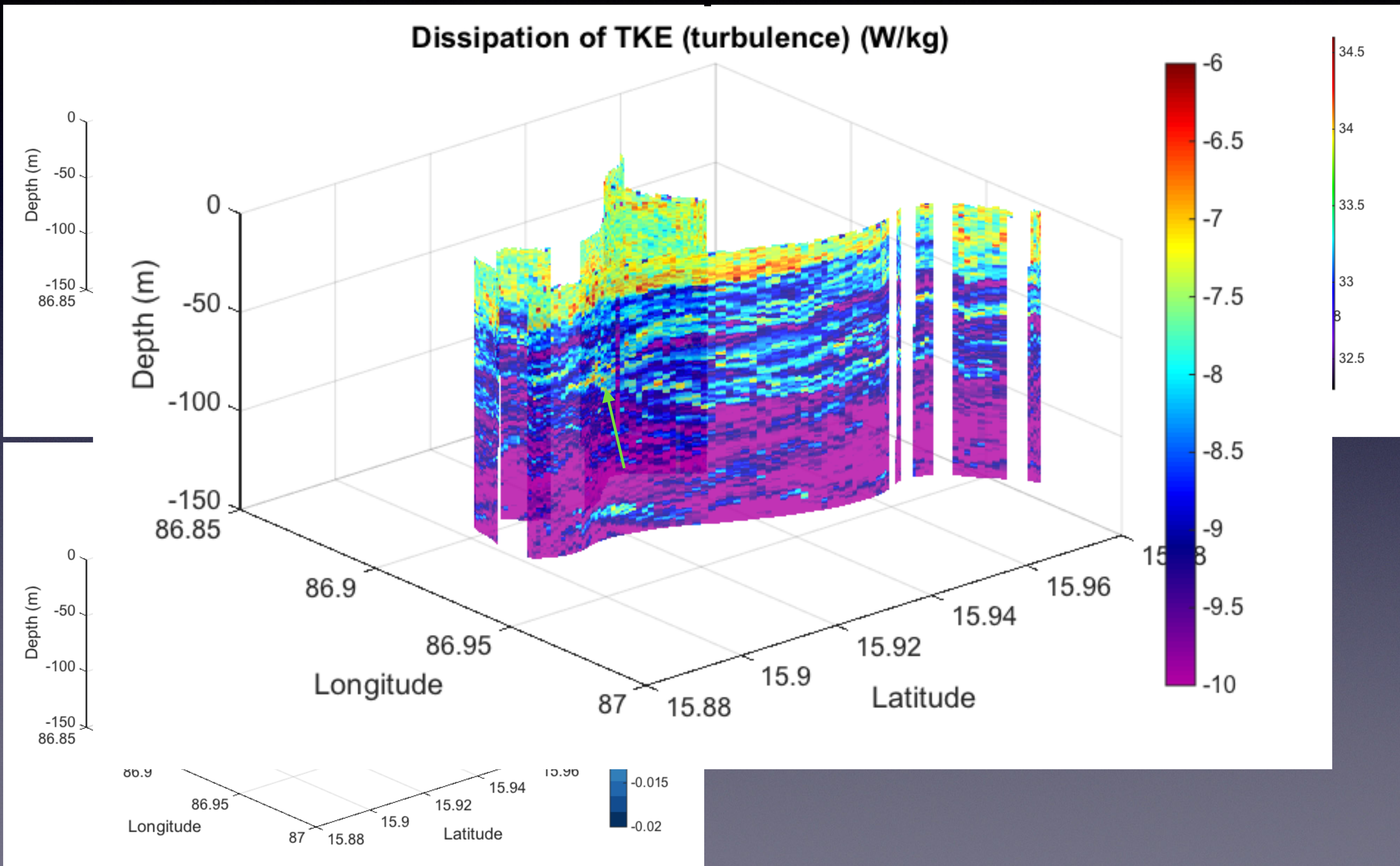


Submesoscale variability in the open ocean: fronts, filaments, and phytoplankton



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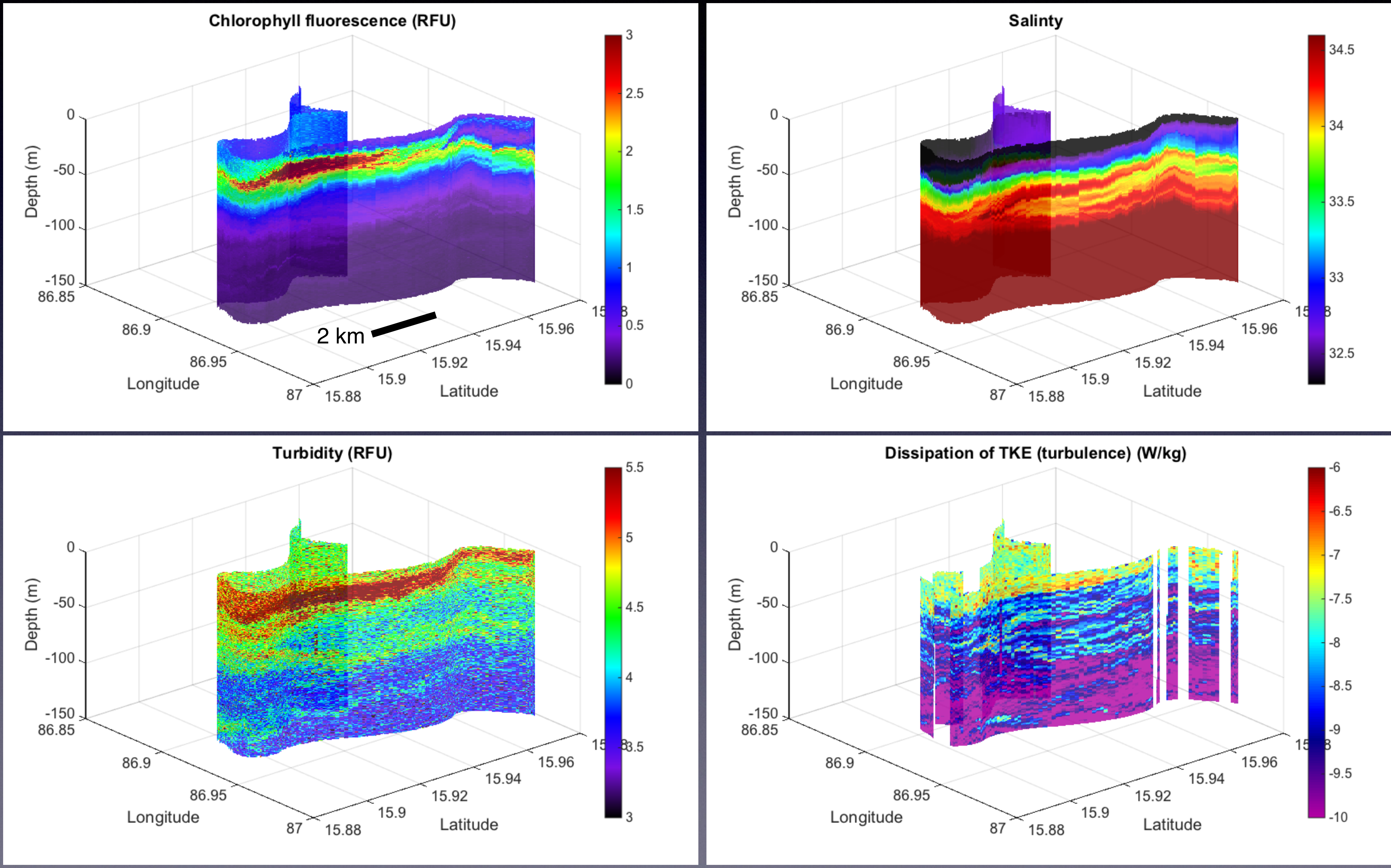
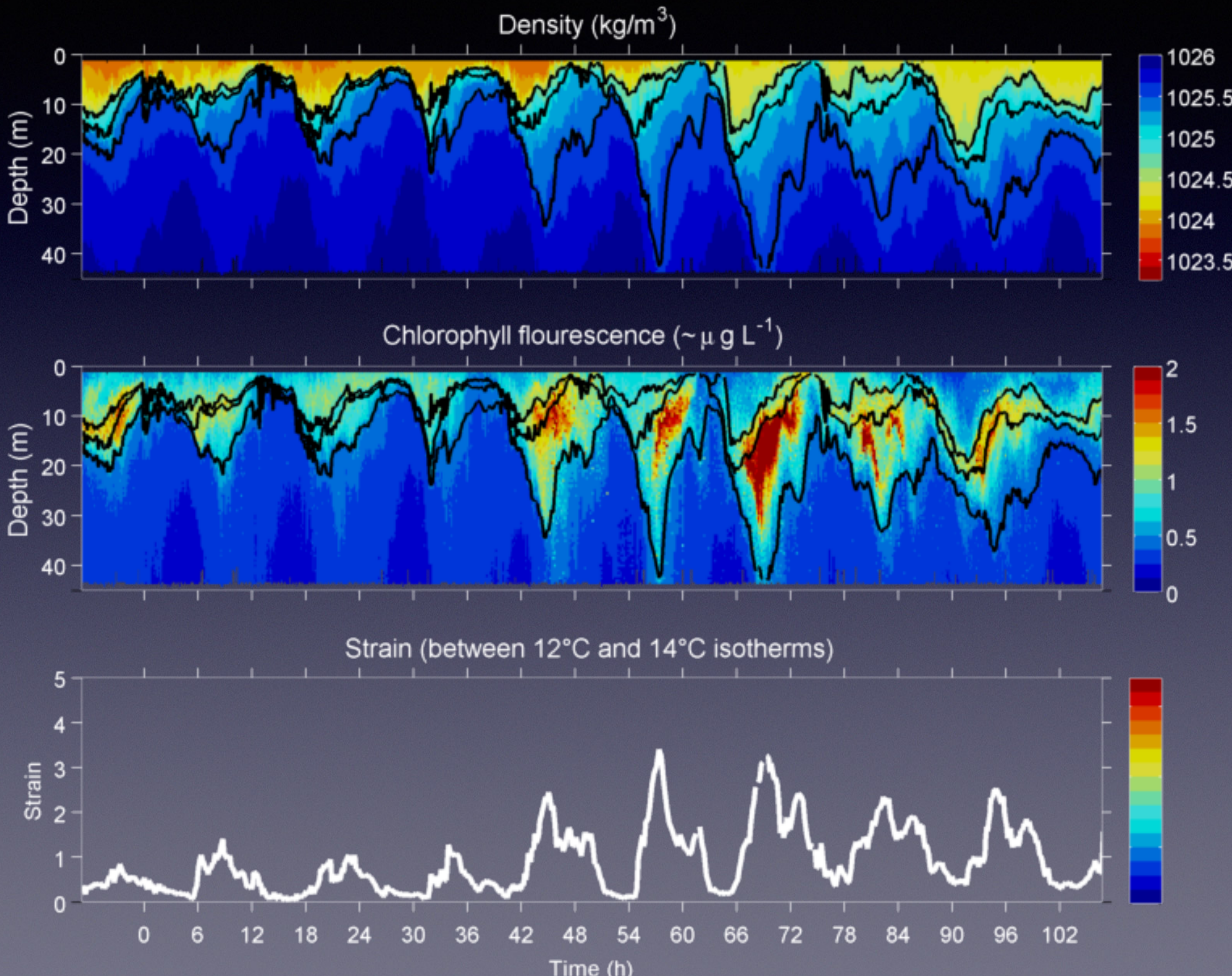


Vignette 3

SIO Ecology Seminar Series. Dec. 3, 2014

The internal surf: biological variability in the context of breaking internal waves (Lucas, Pinkel, MacKinnon, Nash, Shroyer, Fine, in prep).



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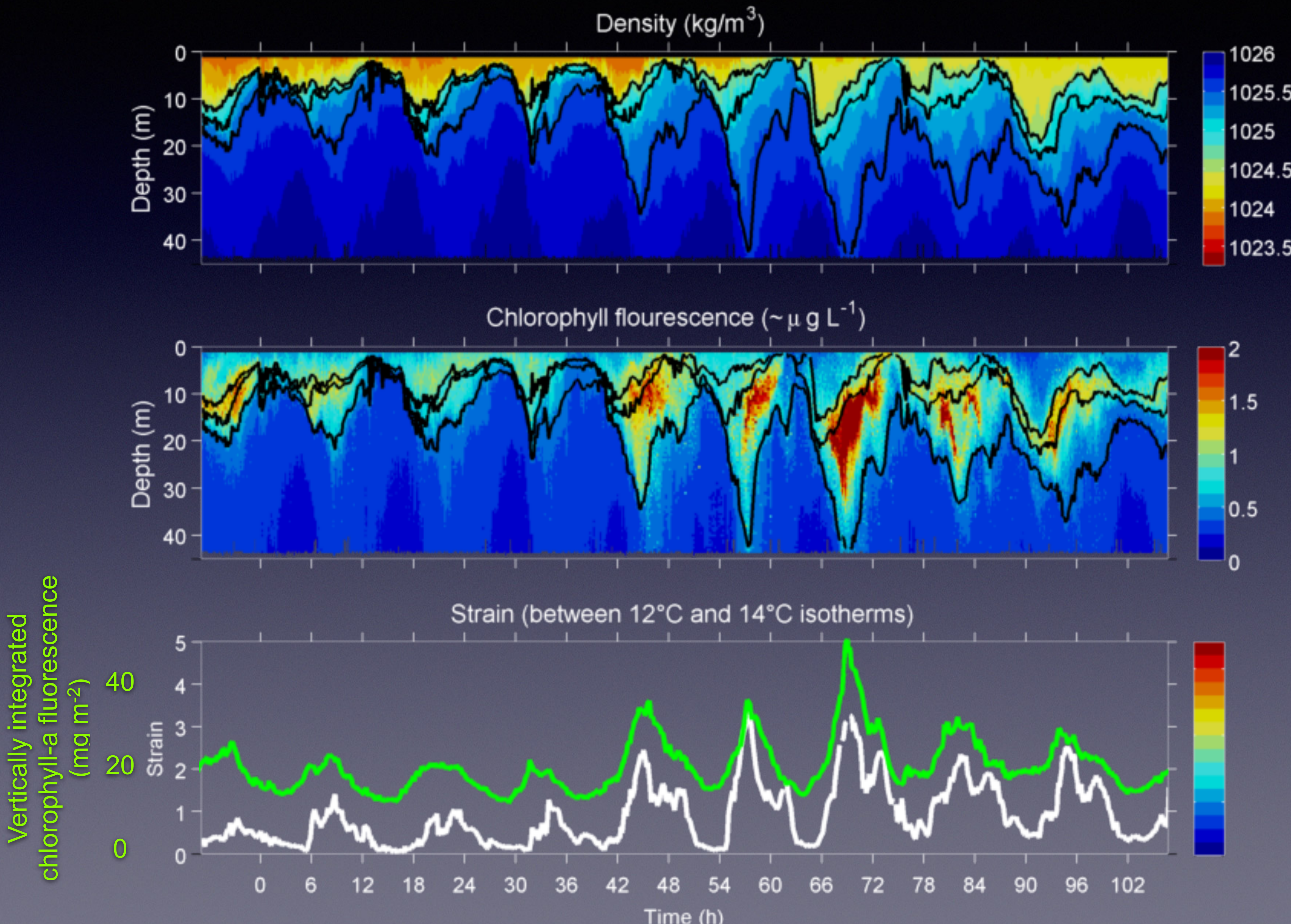

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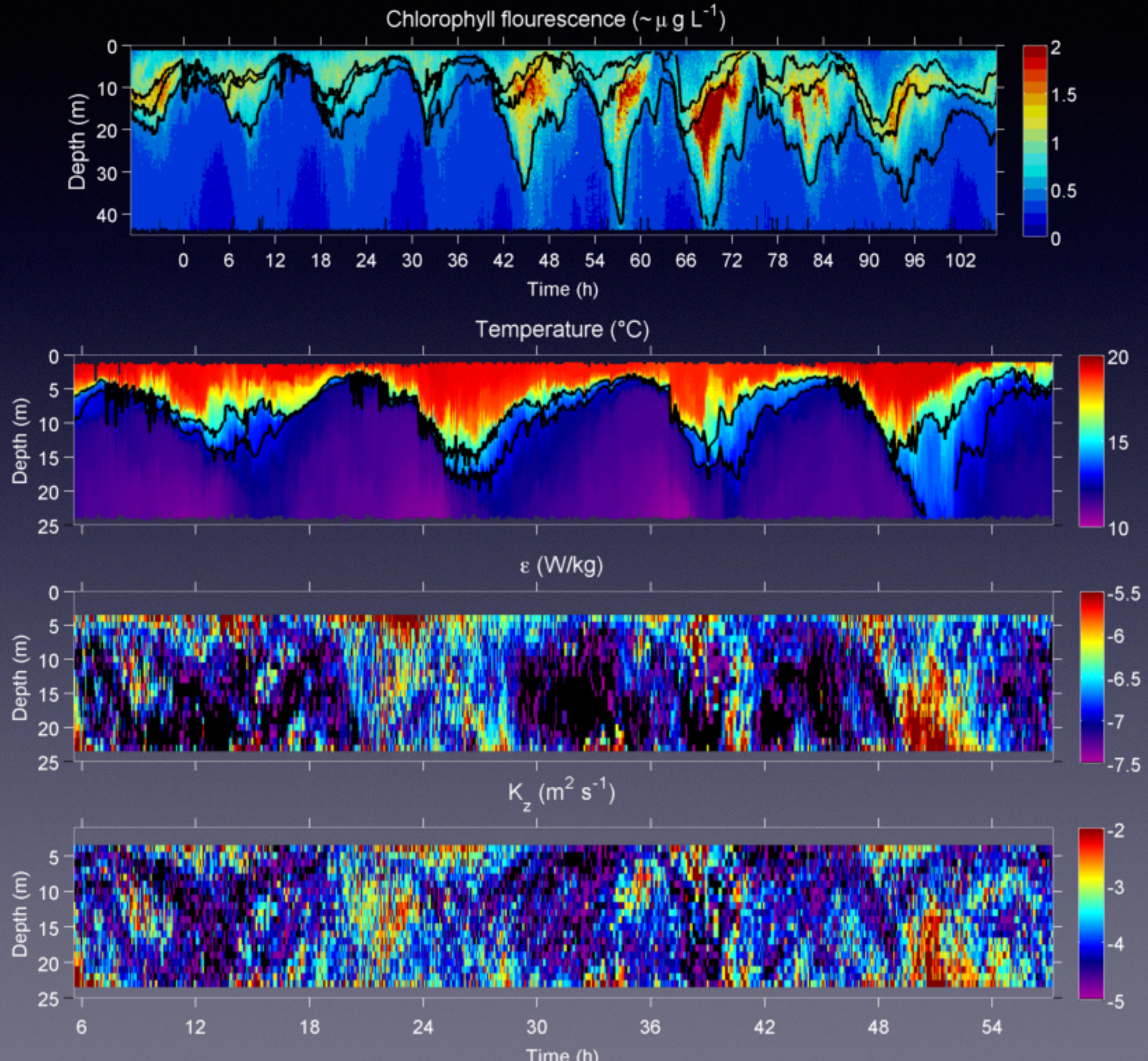

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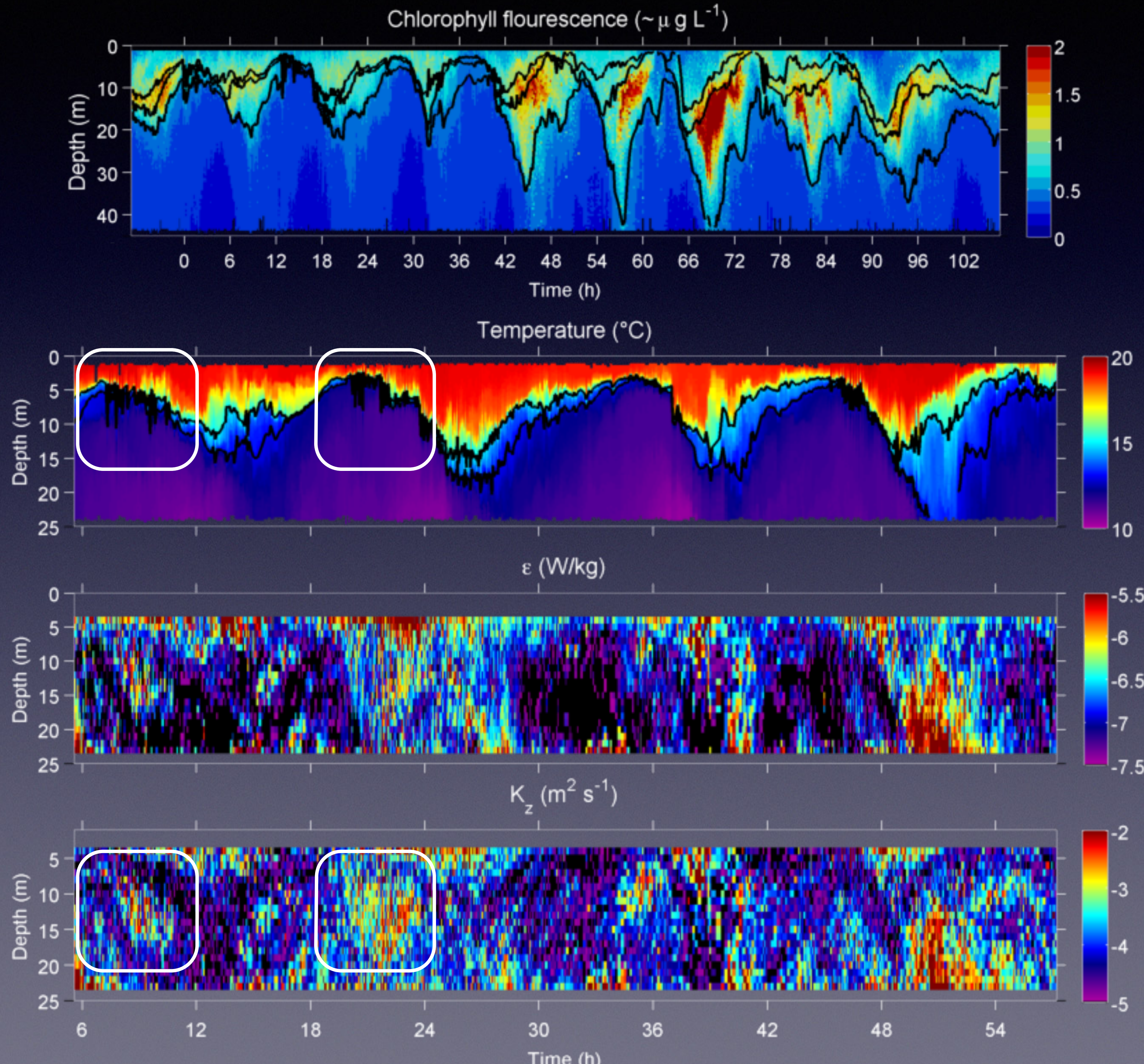

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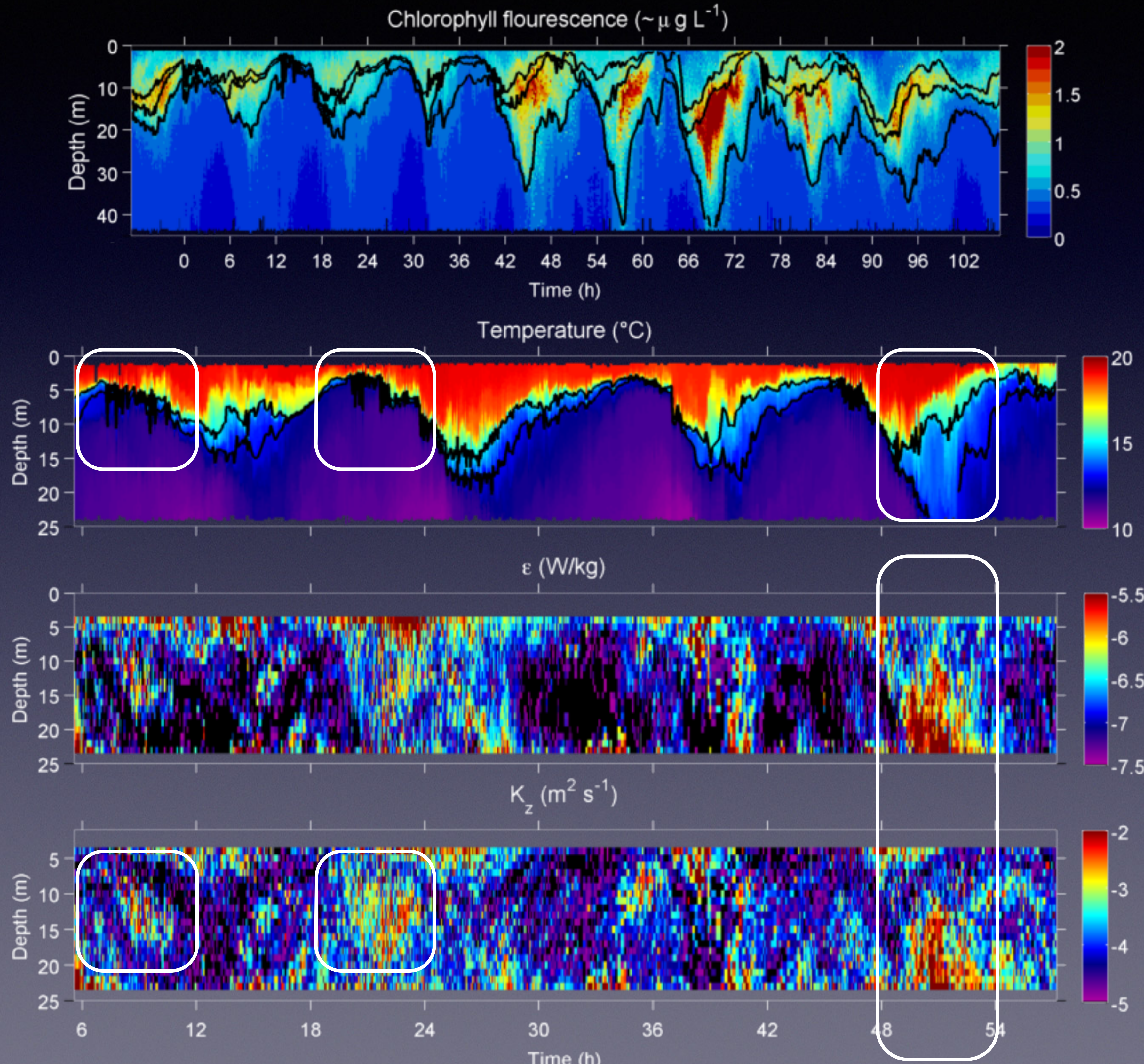


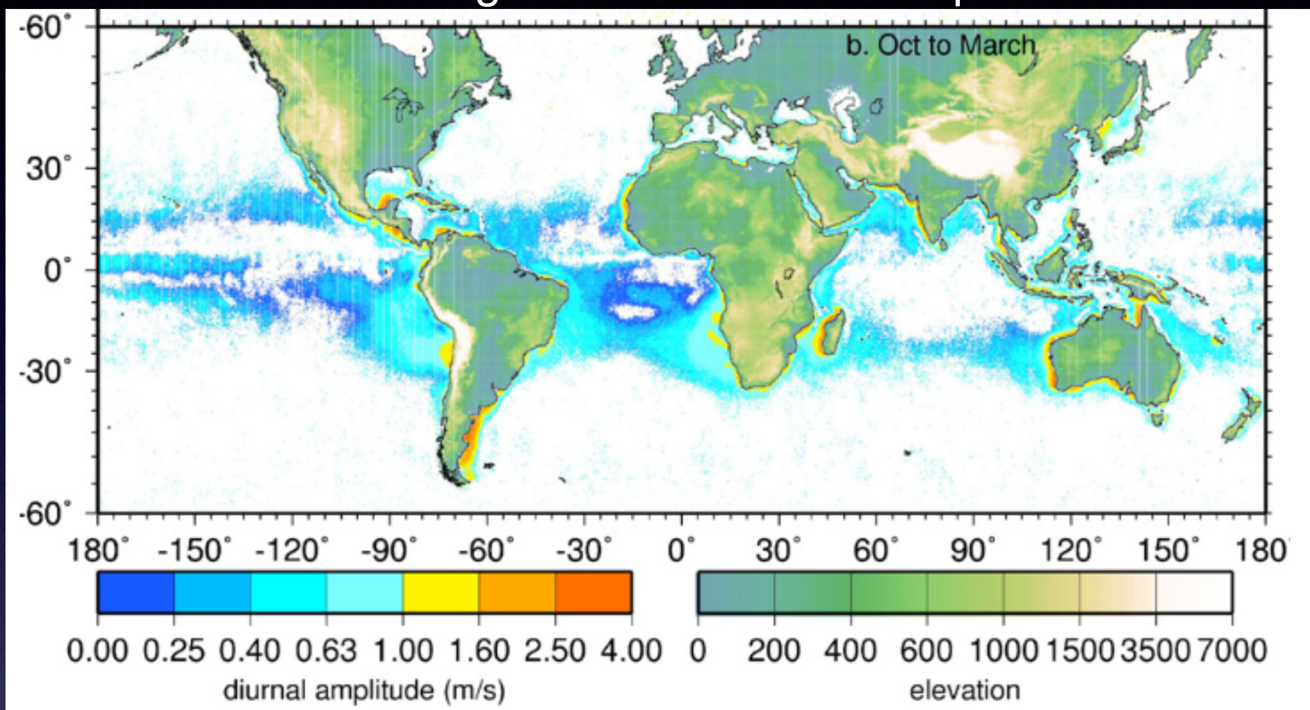
What (else) do we need to measure?

- Mixed layer depth evolution in a frame of reference relative to mixed layer.
- Evolution of MLD characteristics (physical, biological, chemical) in a reference frame relative to mixed layer.
    - CTD, DO, optics, irradiance, turbulence, currents or shear.
- Mesoscale is small, inertial period is short, demands rapid measurements.
- Robust quenching estimates. Robust parameterizations.

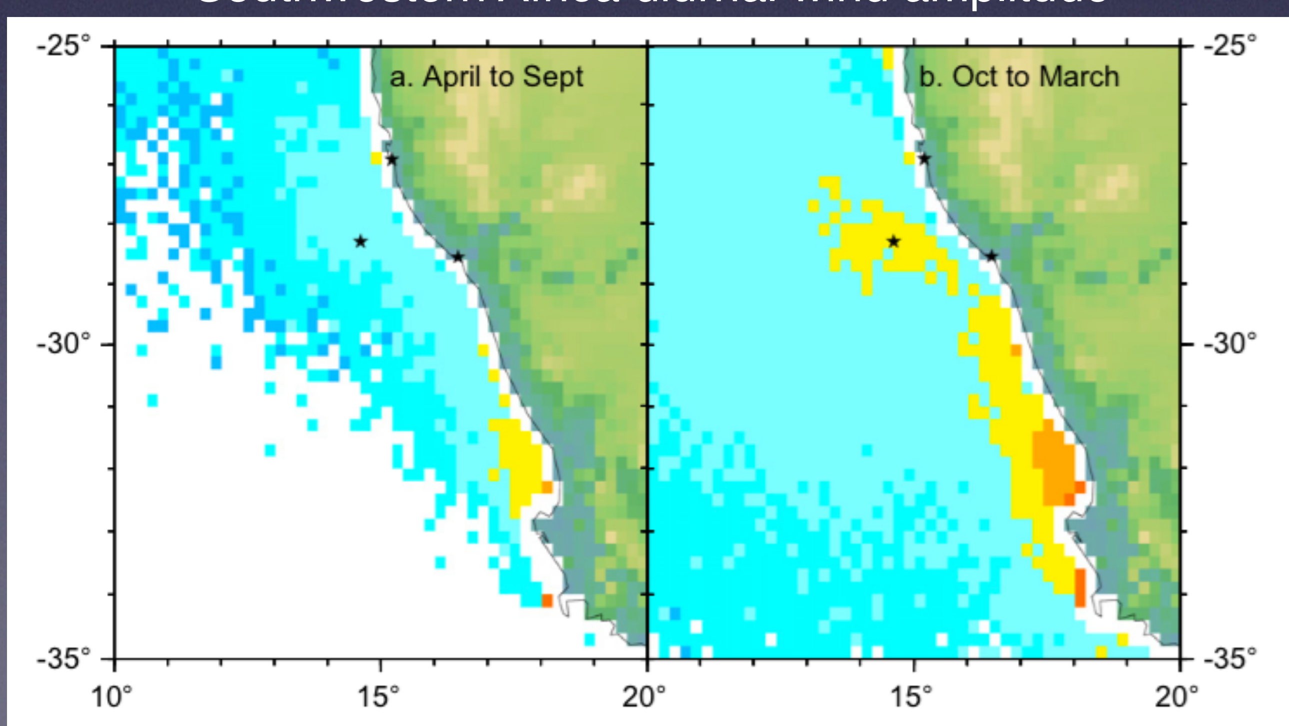
Process studies and long term

The influence of near-inertial waves on the biological response to coastal upwelling (Lucas et al. 2014 DSRII)

Patterns of global diurnal wind amplitude



Southwestern Africa diurnal wind amplitude



Hyder et al. 2011. CSR 31: 1526-1591

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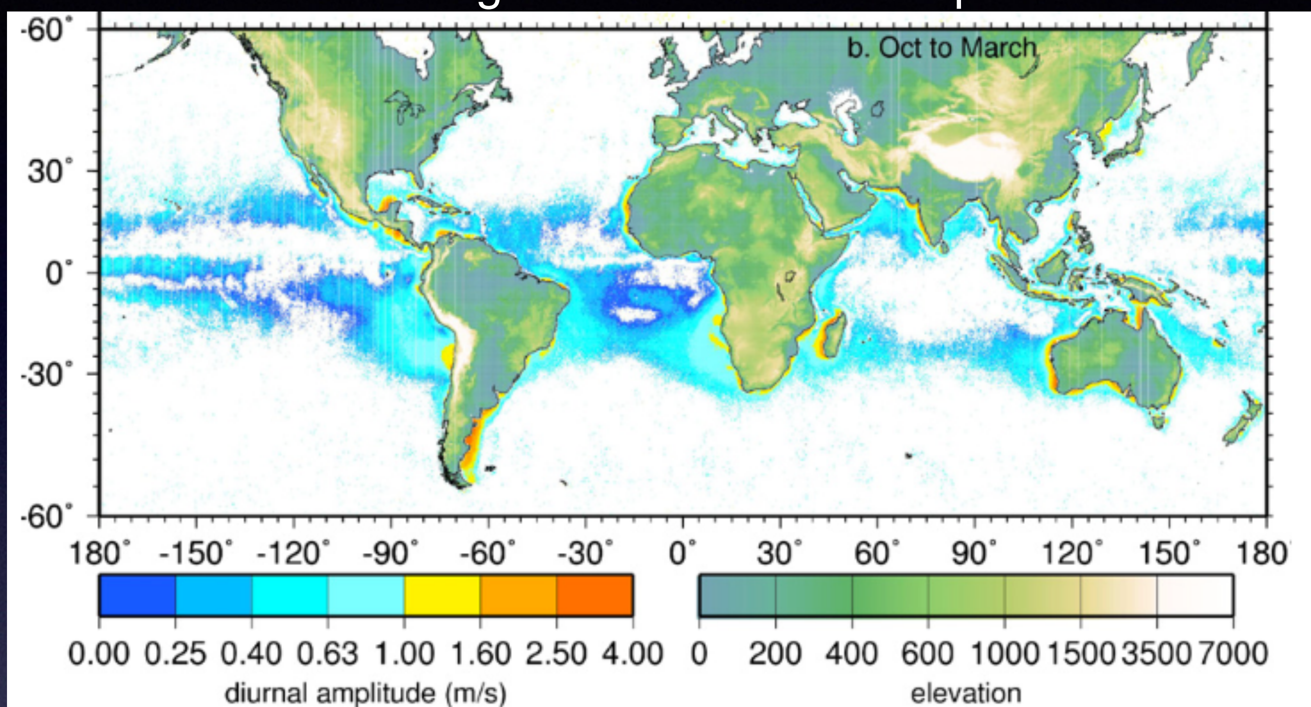
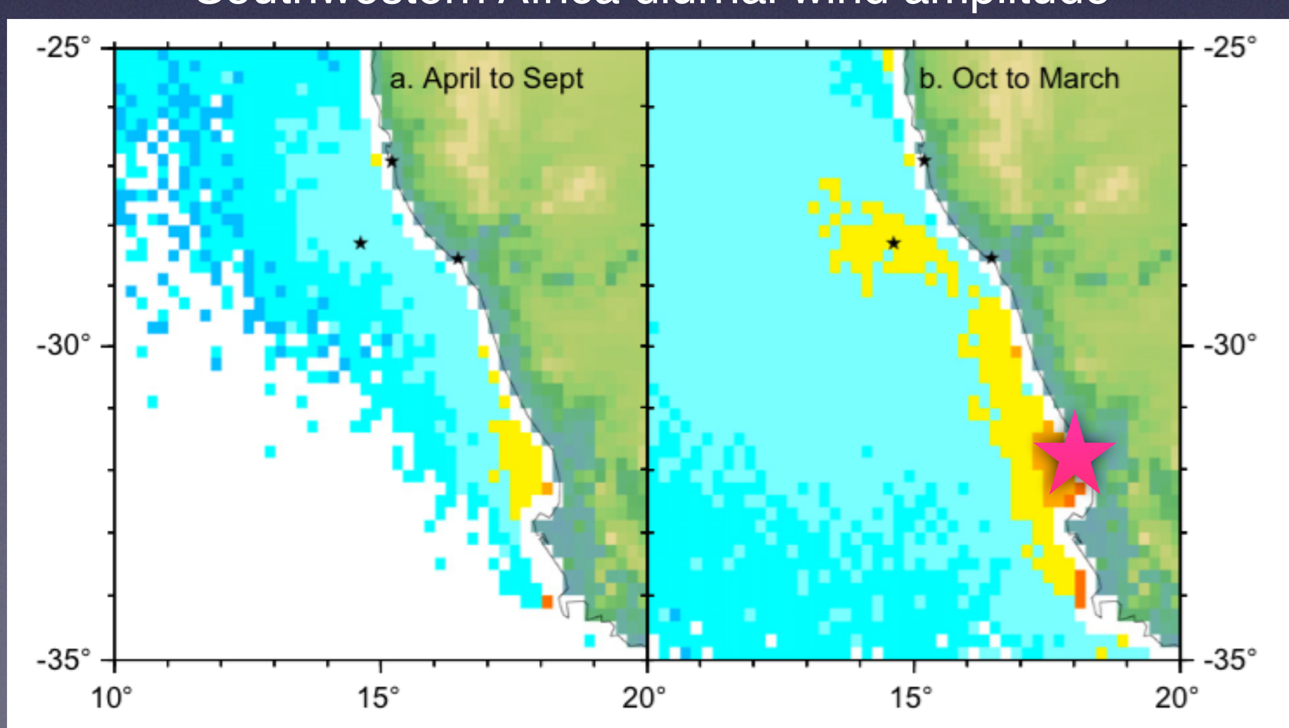


Southwestern Africa diurnal wind amplitude



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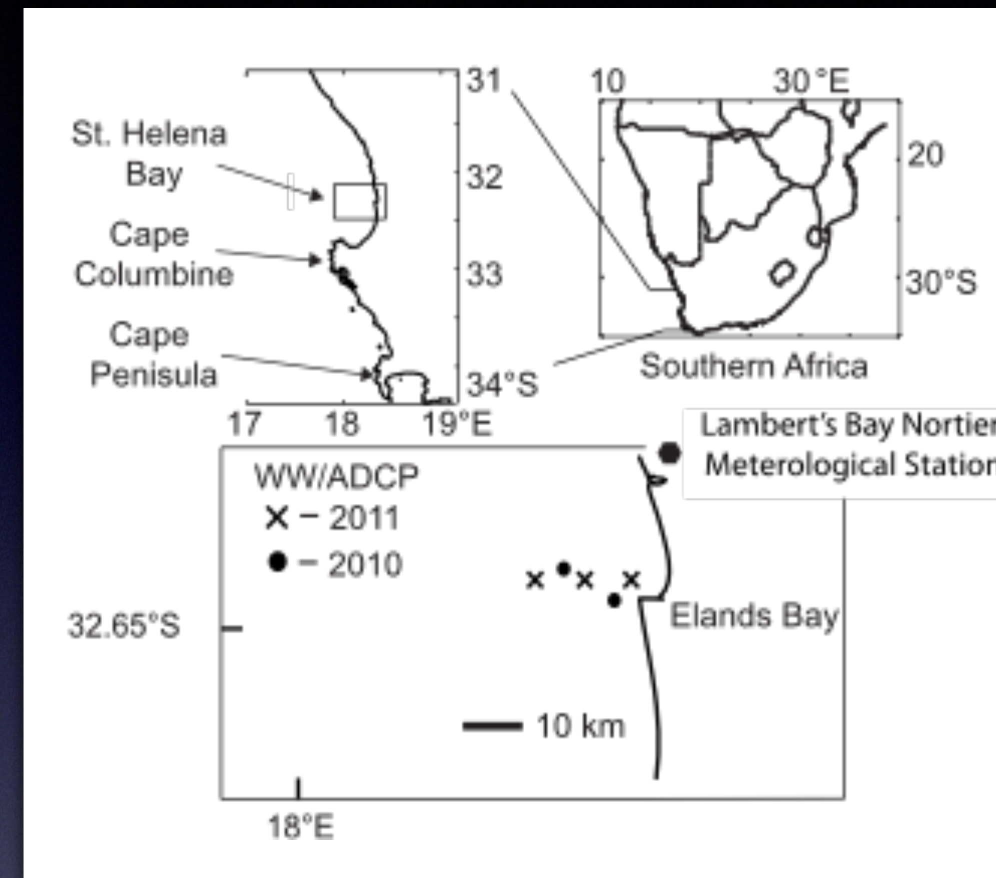
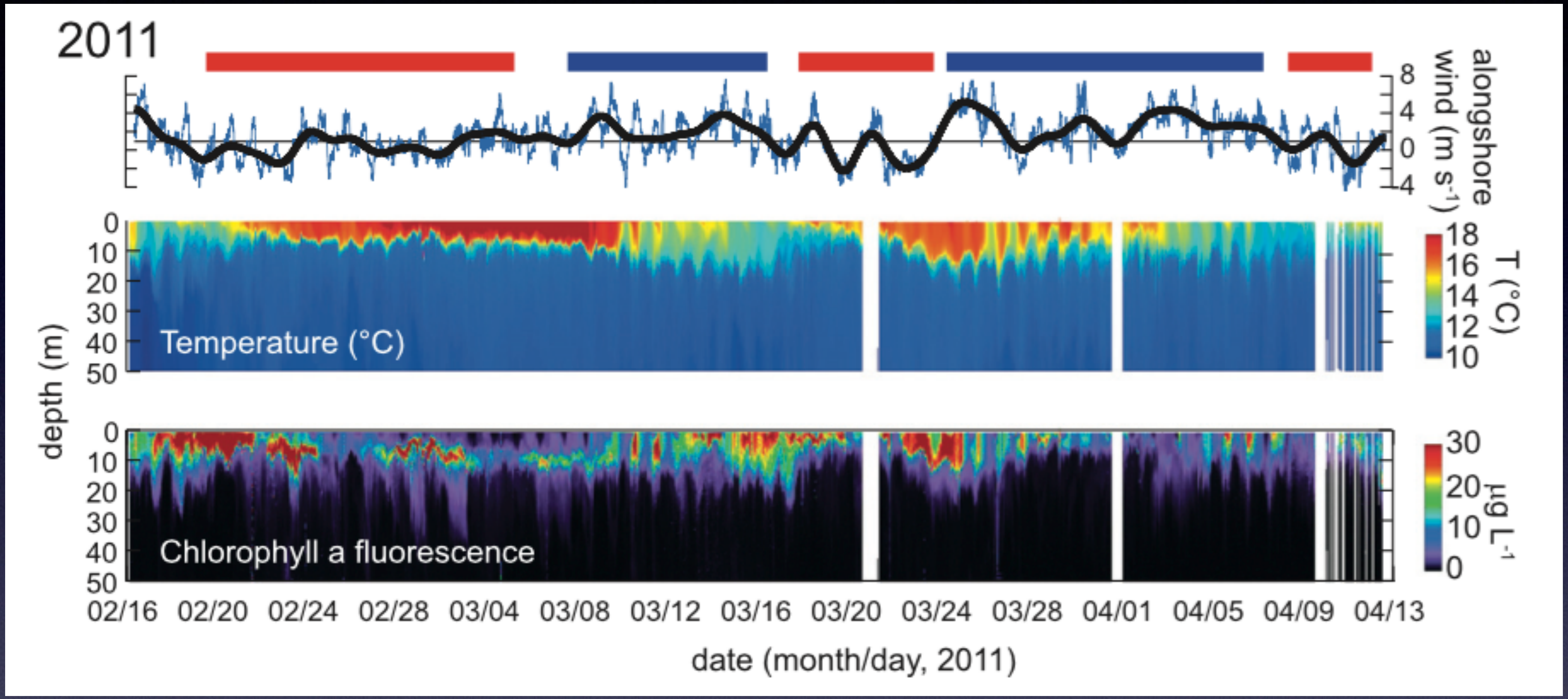


We deployed an array of Wirewalker (SIO) profiling moorings and current meters.

Q: Coastal upwelling at the critical latitude: physical mechanisms and biological effects? (NSF International Postdoctoral Fellowship)

The influence of near-inertial waves on the biological response to coastal upwelling (Lucas et al. 2014 DSRII)

~2 months of Wirewalker profiles, 50m mooring



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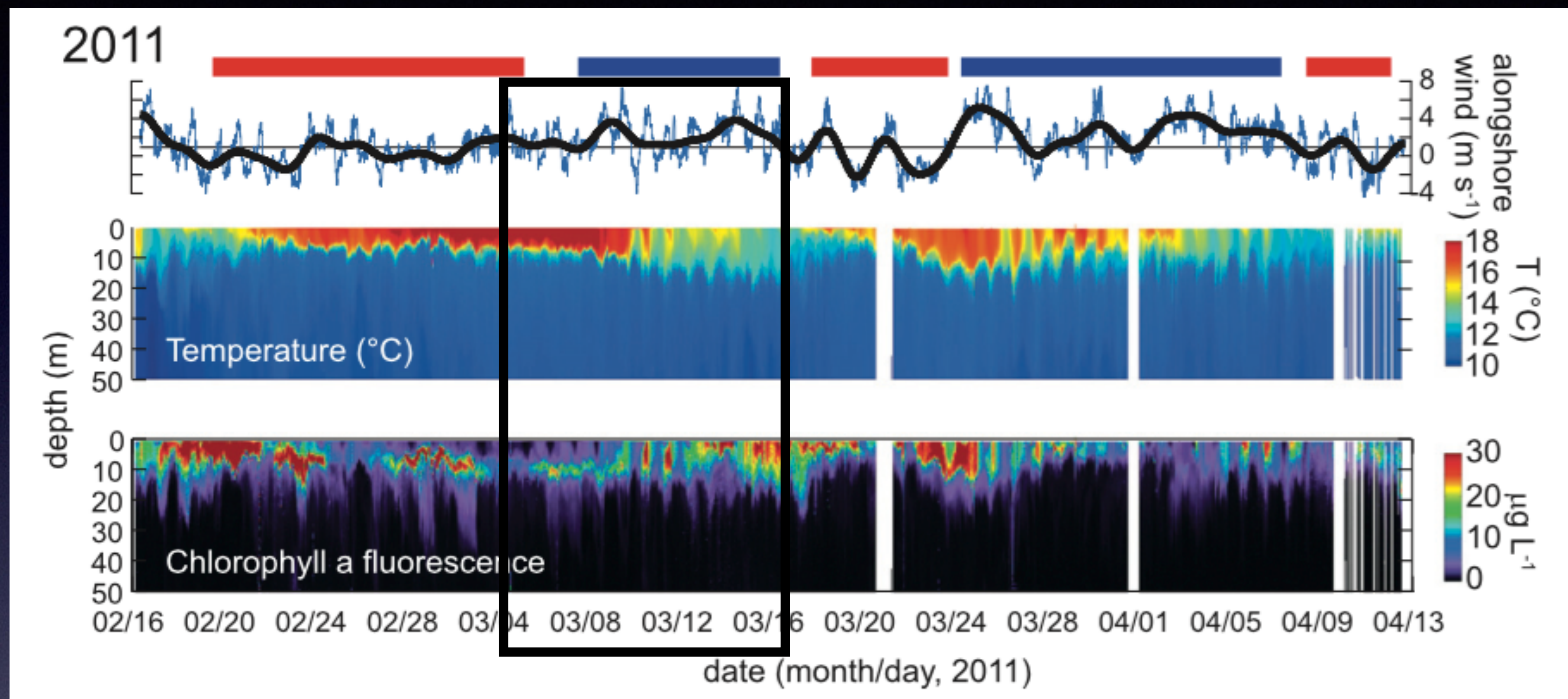

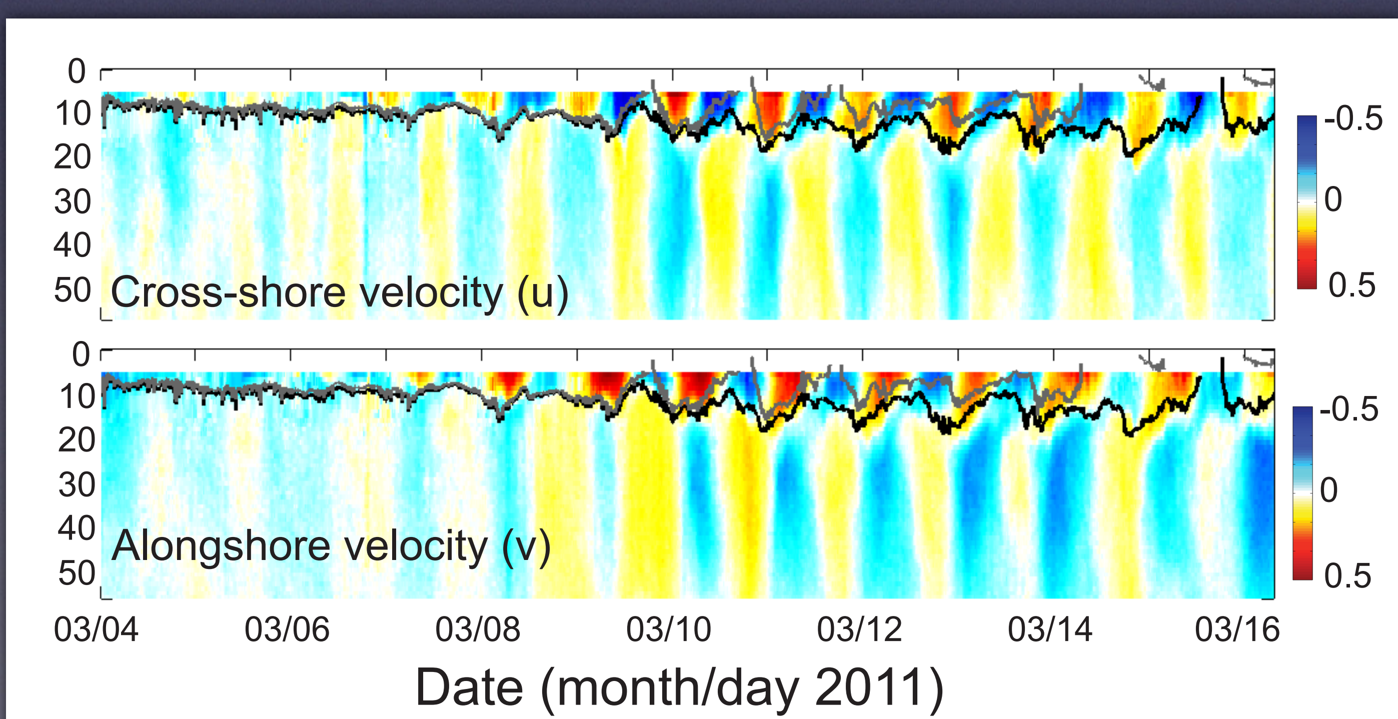

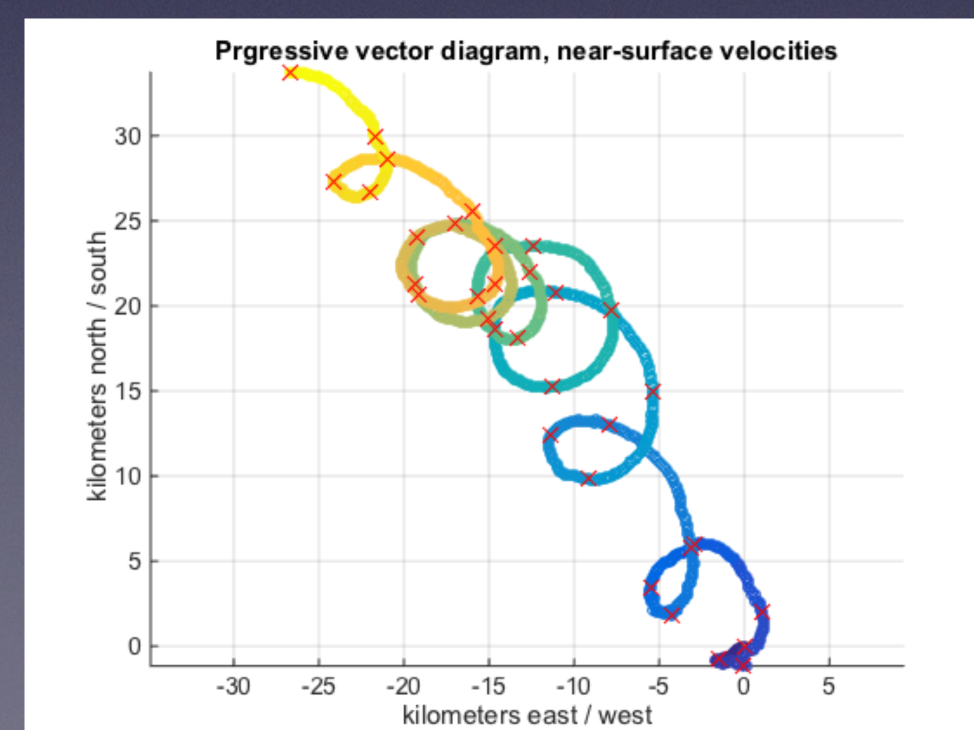

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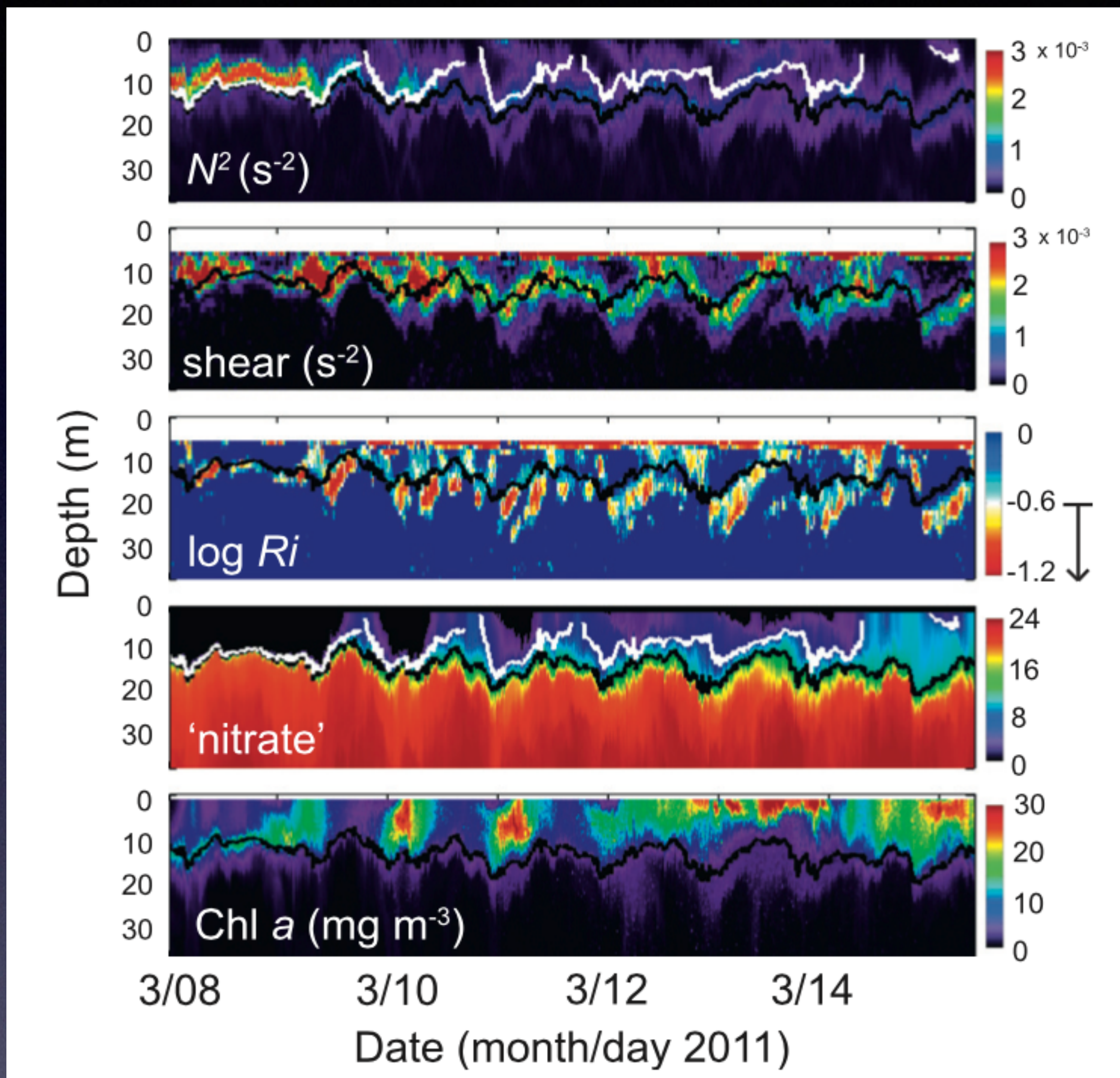
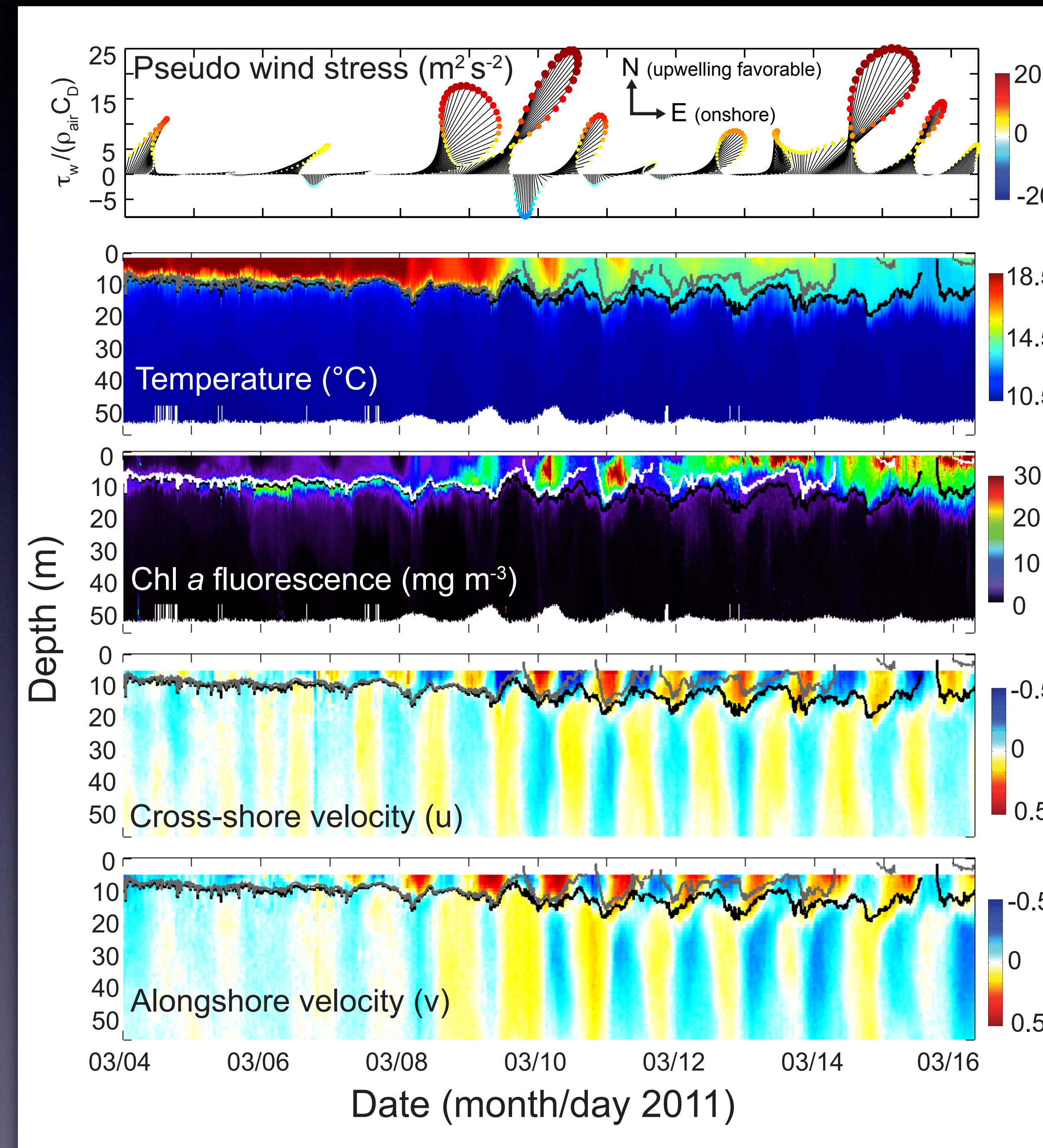


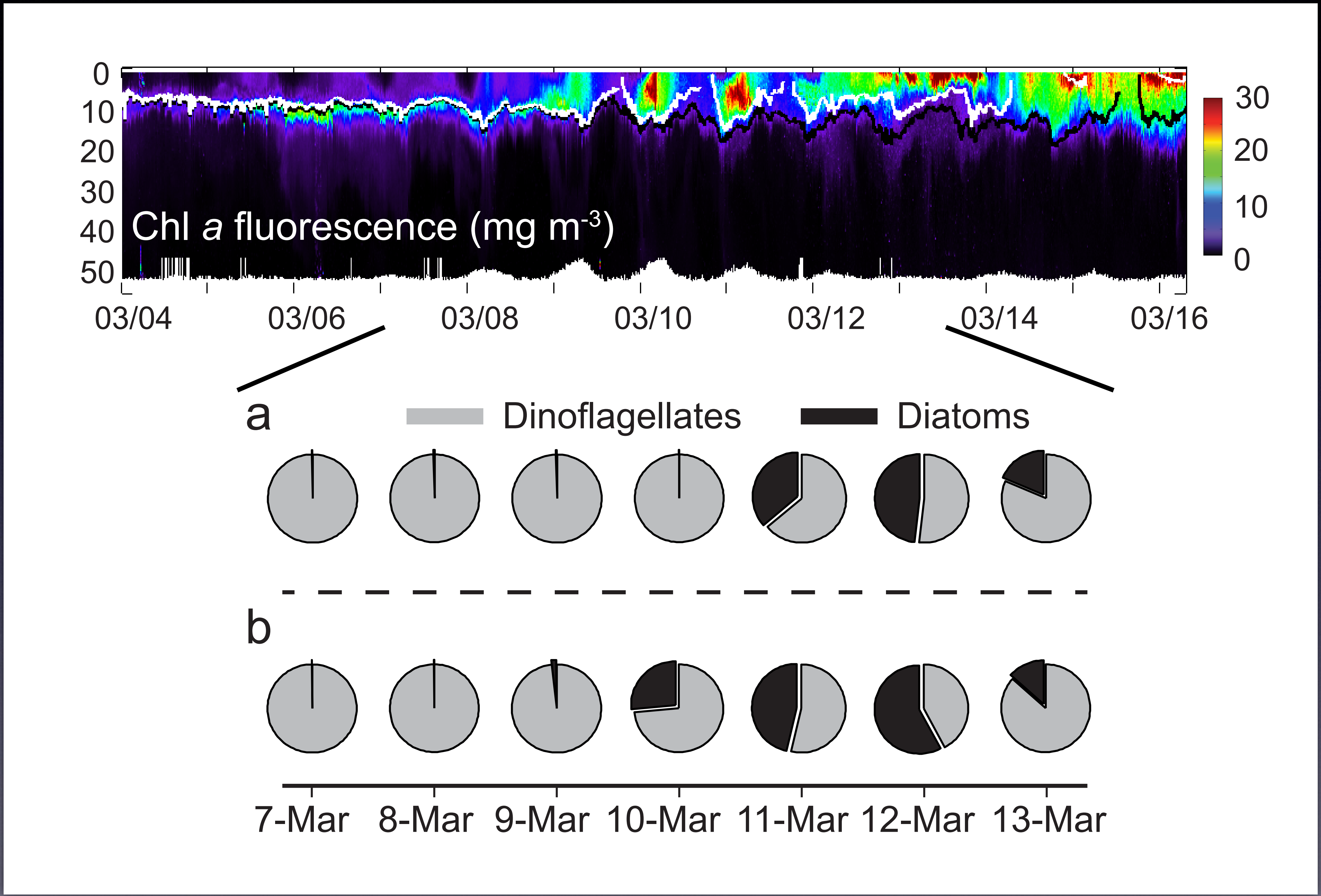


- Clear signature of inertial shear-driven diapycnal mixing.
- Rapidly weakening stratification
- 'Nitrate' mixed upwards, heat mixed downwards.
- "Connecting" upwelling pulses.

Vignette 1

SIO Ecology Seminar Series. Dec. 3, 2014

The influence of near-inertial waves on the biological response to coastal upwelling (Lucas et al. 2014 DSRII)



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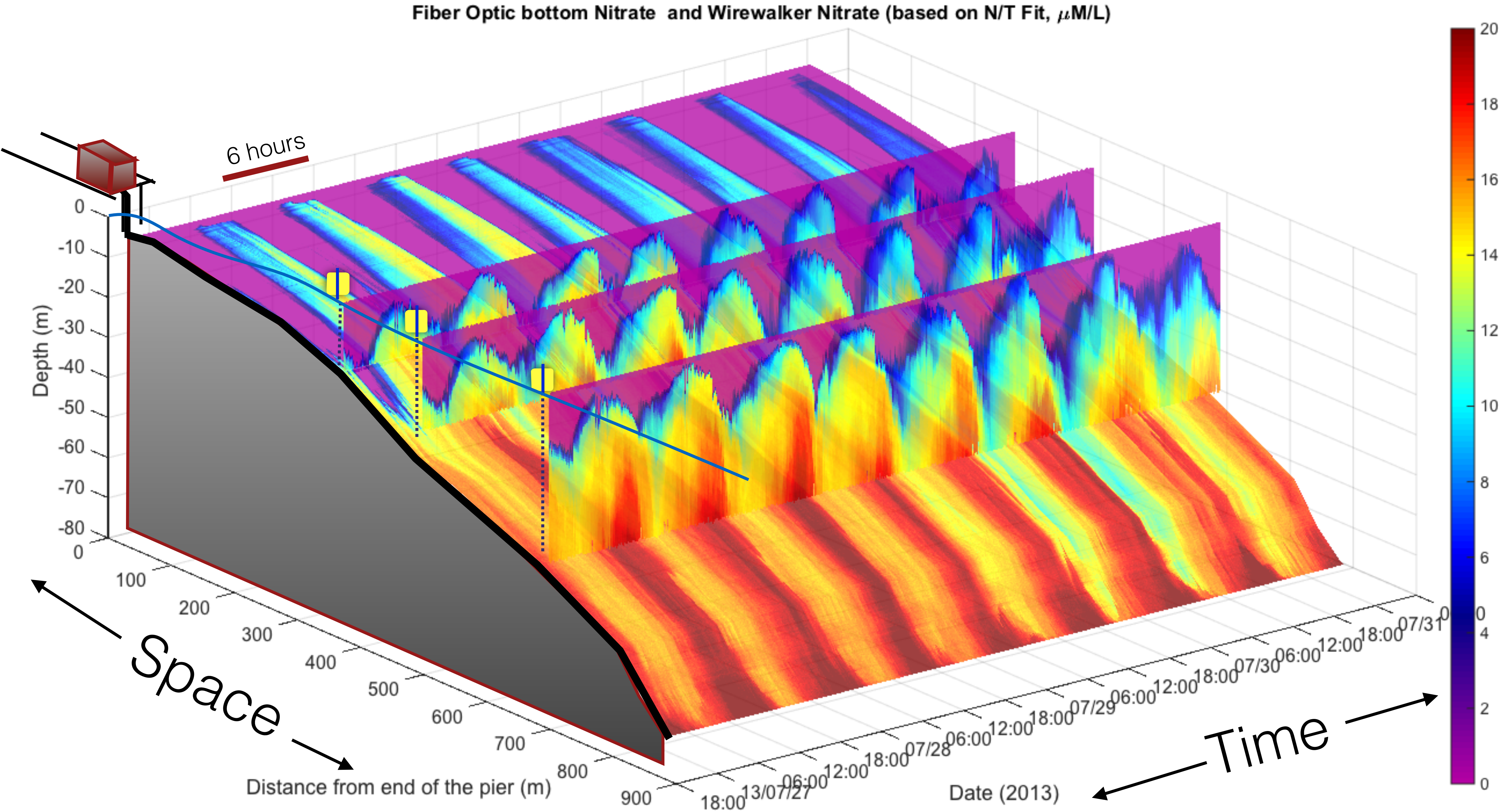

Submesoscale variability in the open ocean: fronts, filaments, and phytoplankton (Lucas et al. 2014 *Eos;* Ongoing ONR Air-Sea Interactions DRI)