# Sub~~(Intra)~~-seasonal variability in driving physical and biogeochemical dynamics in the Southern Ocean



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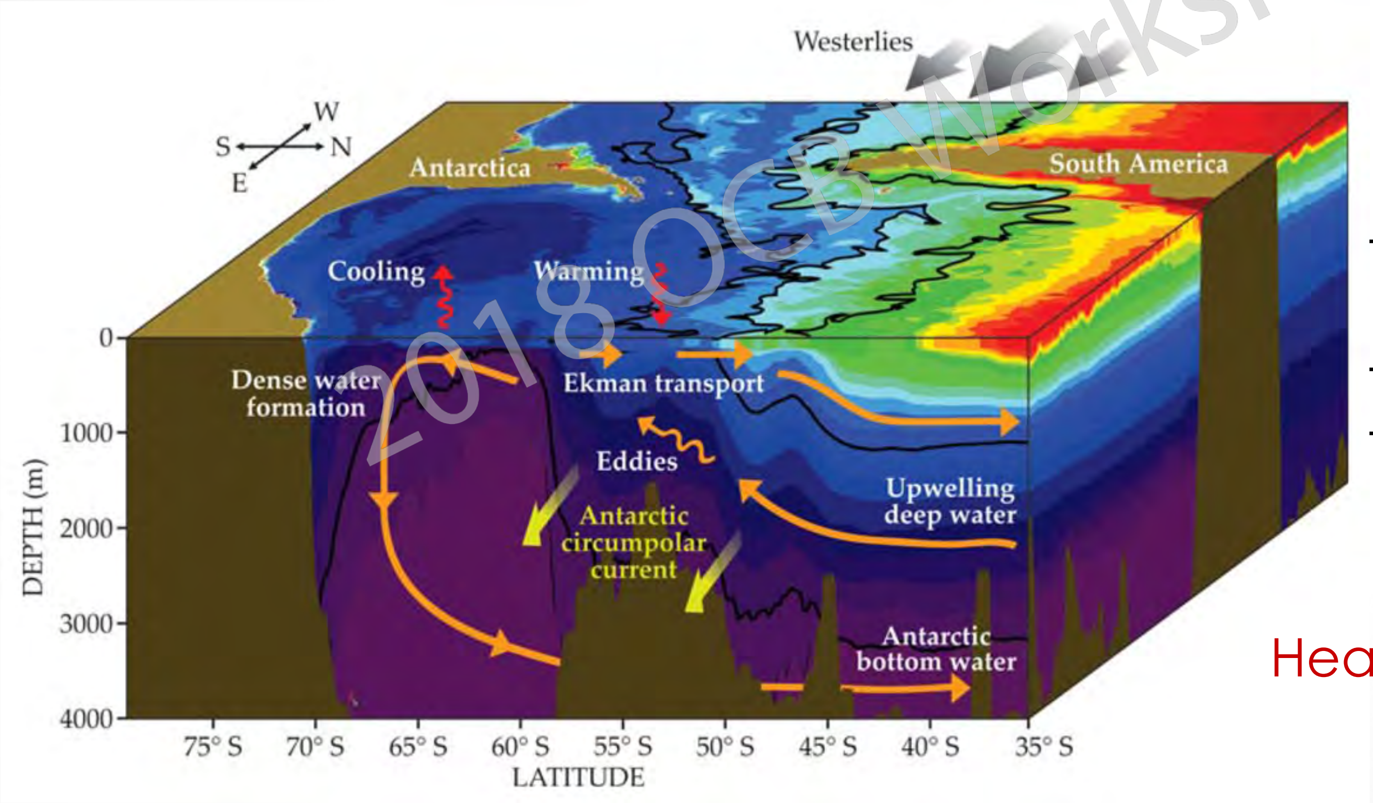
*OCB Workshop 2018, Woods Hole, MA*

# Southern Ocean Circulation and Biogeochemistry

Strong westerly winds




+ Circulation

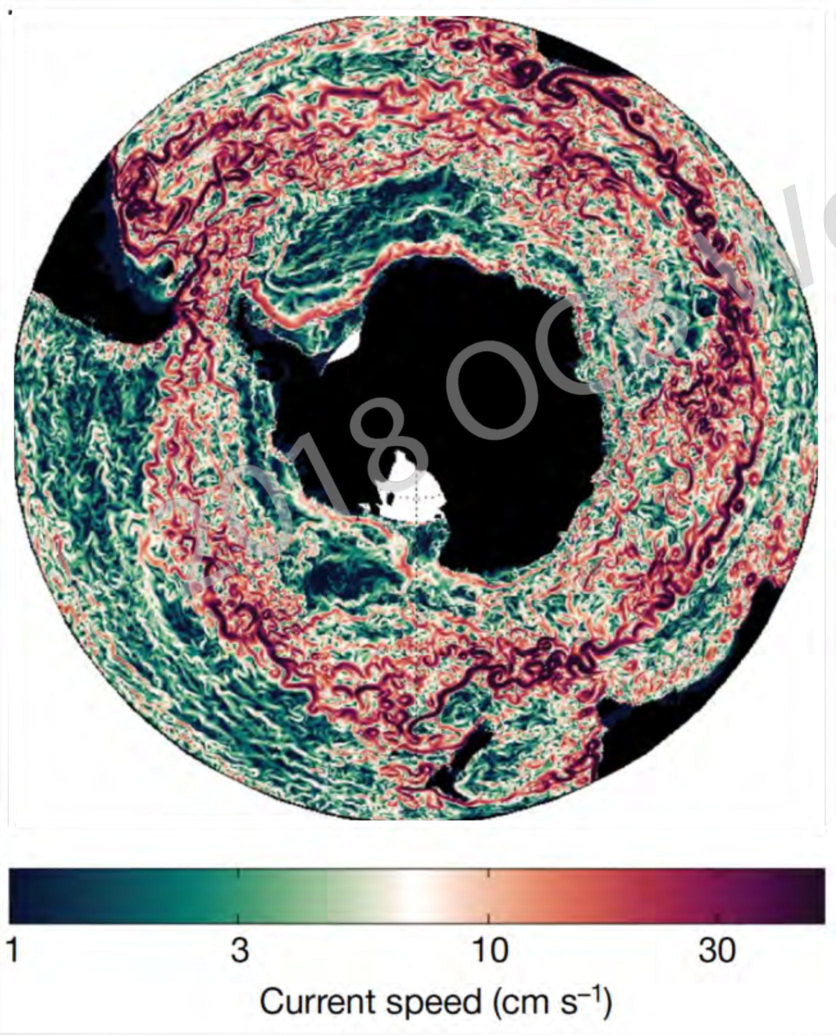
+ Solubility pump
+ Biological pump

Heat and carbon uptake



- *Morrison et al. (2015)*

# Southern Ocean Circulation and Biogeochemistry






Highly dynamic region

+ Synoptic-storm activity
+ Weak stratification
+ Vigorous eddy field
+ Flow strongly influenced by topography

*Rintoul (2018)*

# Sources of Subseasonal Variability:

1. Atmospheric weather:
   externally forced

2. Oceanic weather:
   internally forced

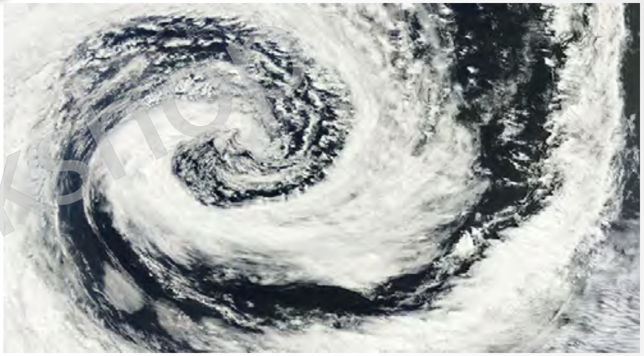
3. Ocean-atmosphere weather interactions

# Synoptic Storms

2 - 10 days

500 – 1000 km

# Sources of Subseasonal Variability:



1. Atmospheric weather:
   externally forced

2. Oceanic weather:
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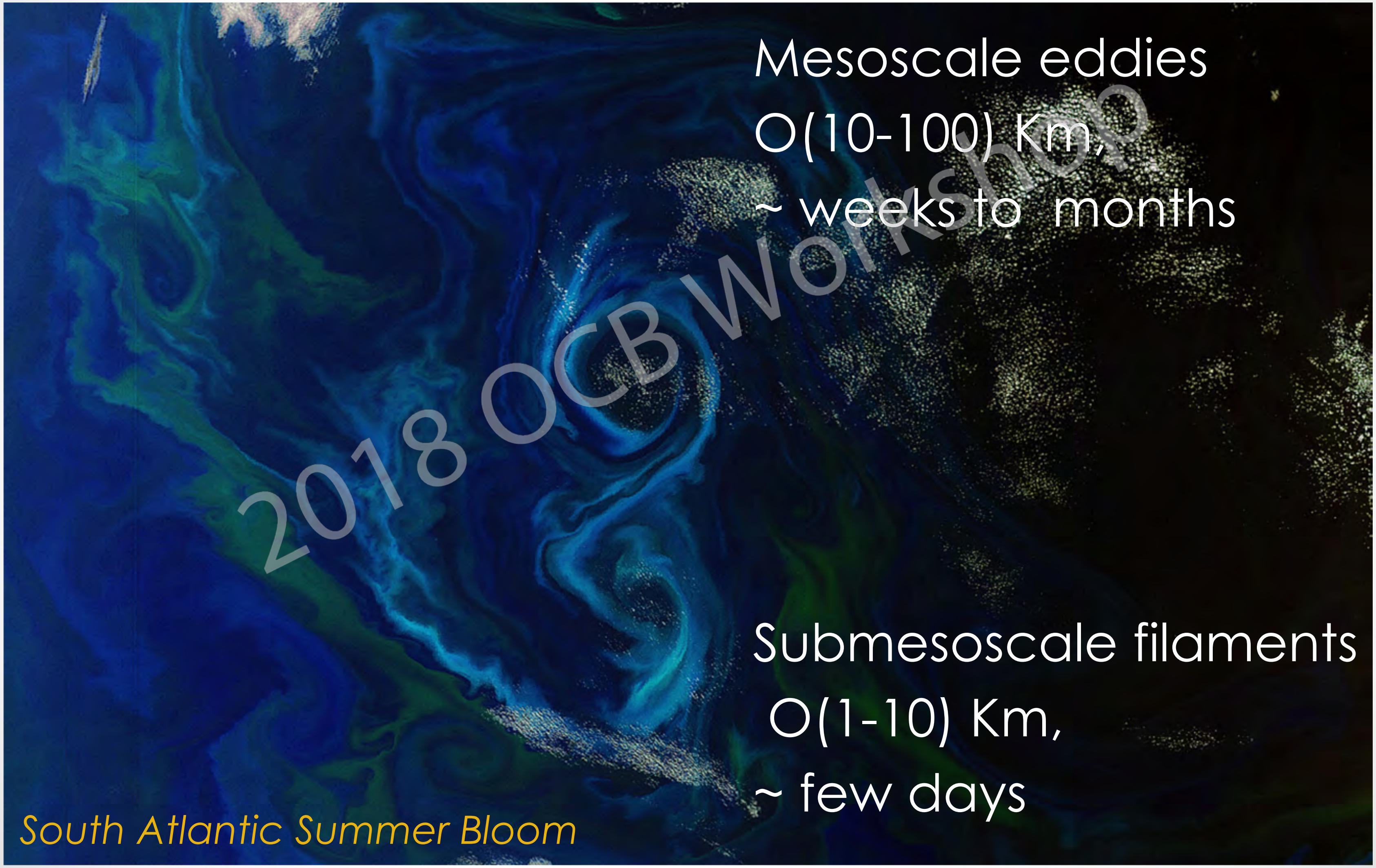
# Oceanic Weather





Envisat's MERIS Ocean Color (300 m), ESA

# Oceanic Weather

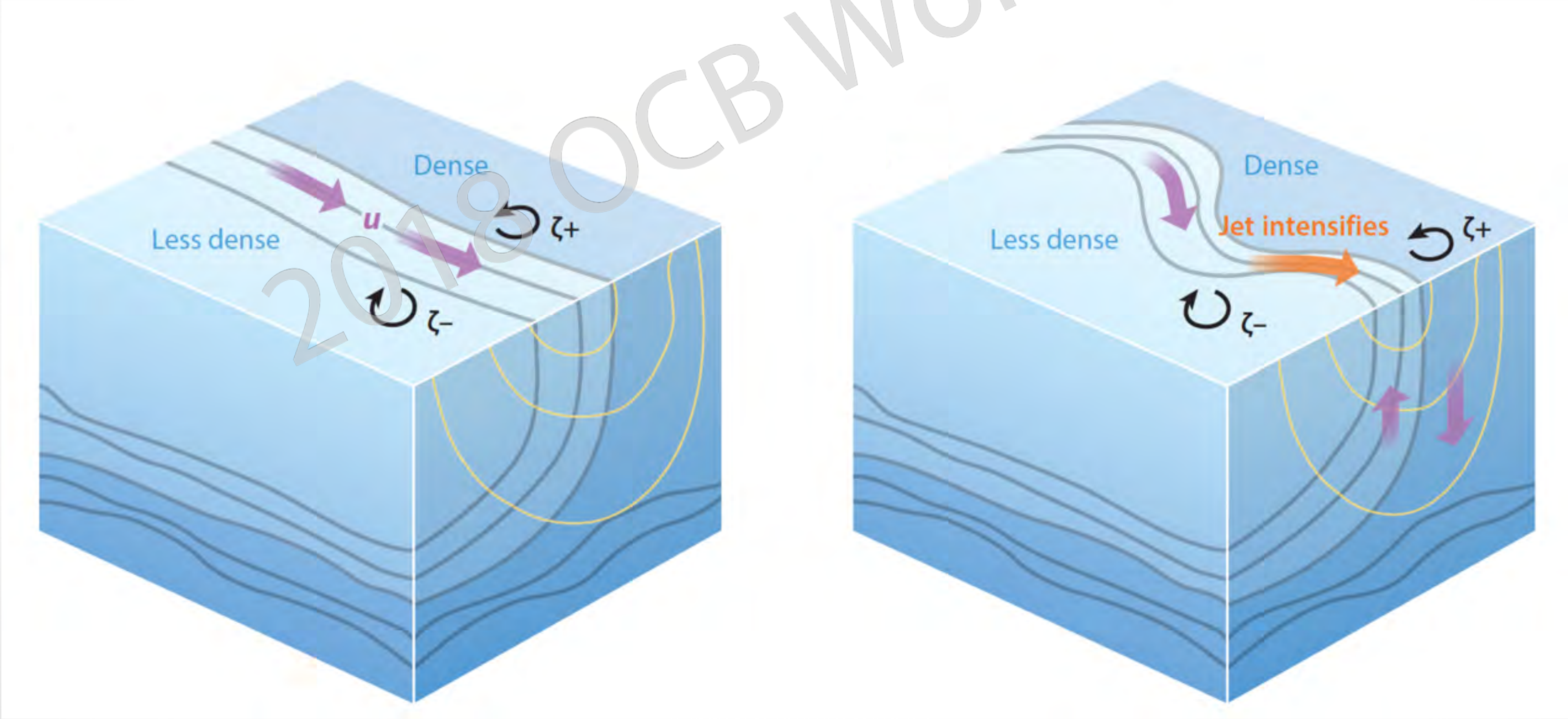
- Mesoscale:

O(10-100km), ~weeks to months
Flow largely horizontal,
w ~ O(1-10 m $d^{-1}$)

- Submesoscale:

O(1-10) Km, ~ few days
Large vertical velocities
w ~ O(10-100 m $d^{-1}$)

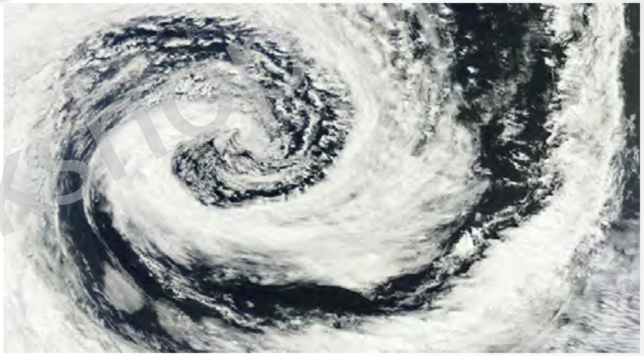




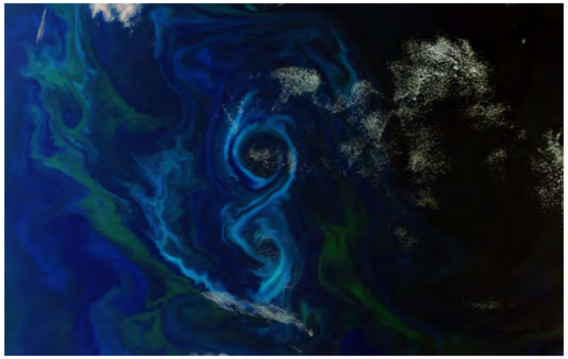

*Mahadevan (2016)*

# Sources of Subseasonal Variability:

1. Atmospheric weather: externally forced

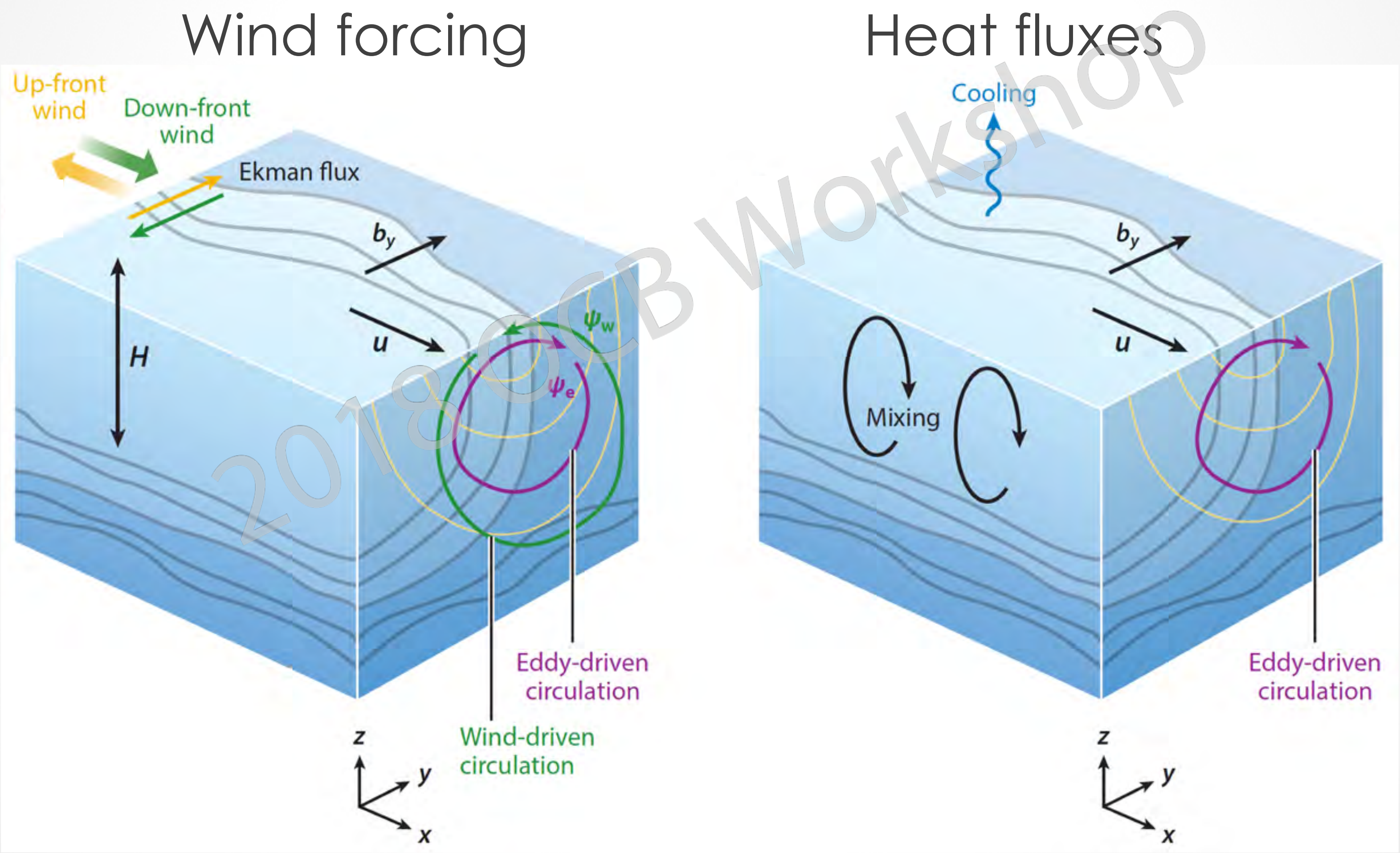


2. Oceanic weather: internally forced



3. Ocean-atmosphere weather interactions

# Ocean-Atmosphere Weather Interactions






*Mahadevan (2016)*

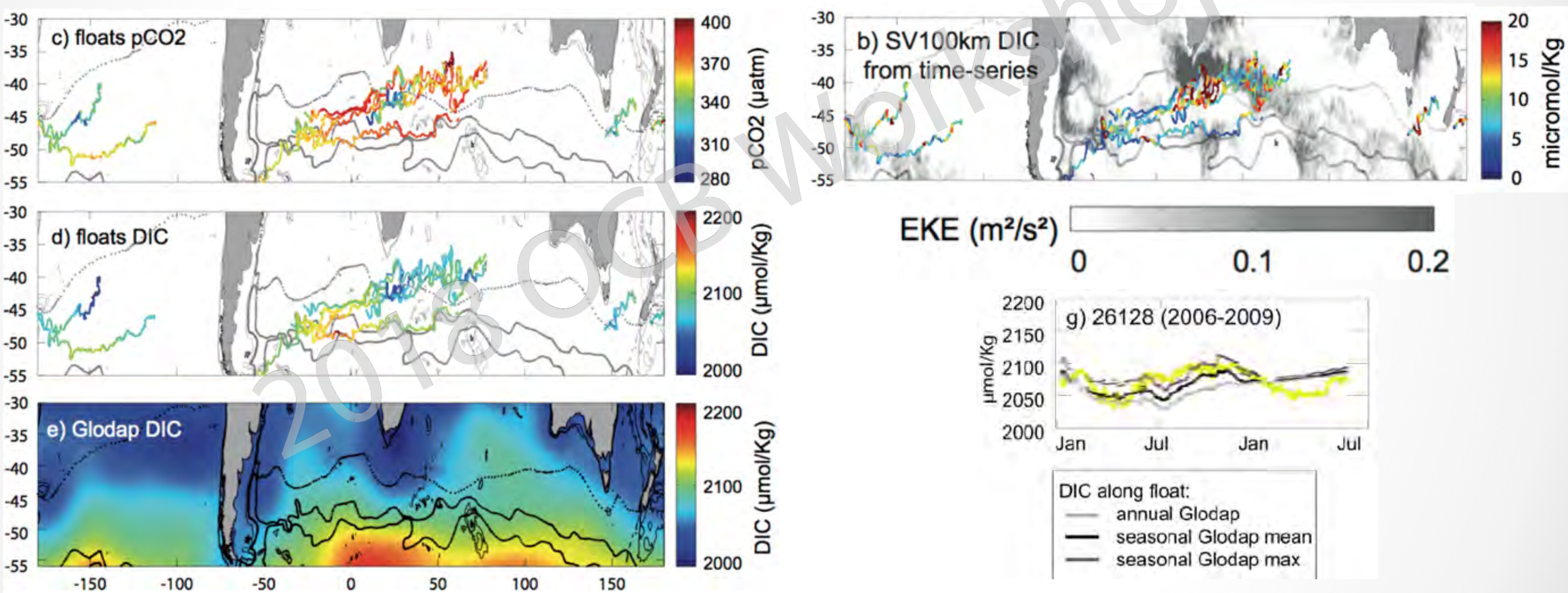
# Why do we care?

- ✓ Interesting phenomena *per se*…
- ✓ Weather timescales (~days) resonate with the life cycle of phytoplankton
- ✓ Weather perturbations (short/small time/space scales) can influence climate (longer/larger scales)

# Small-scale Impacts on the Carbon System

- CARIOCA drifters (hourly, 1-3km)

Small-scale Variability:





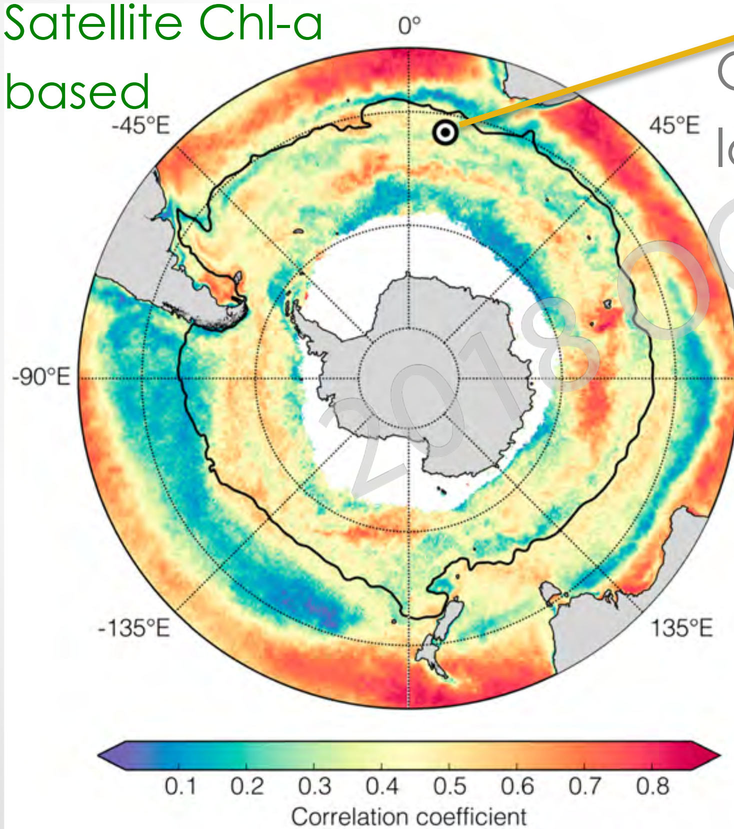

Small spatial-scale structures (~100 km) are a non-negligible source of variability for DIC, with amplitudes of about a third of the variations associated with the seasonality

*Resplandy et al. (2014)*

# Subseasonal Impacts on the Carbon System

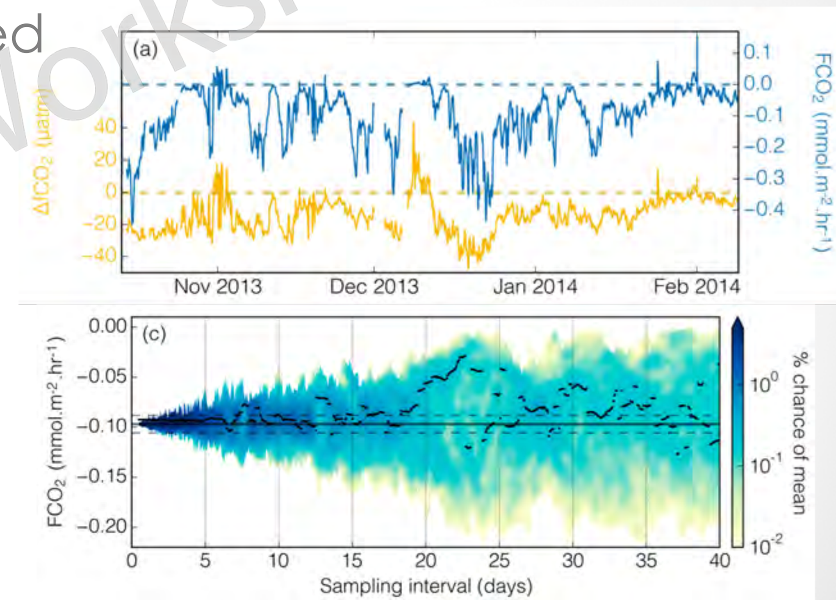
Seasonal cycle reproducibility:

Satellite Chl-a based




Quasi-fixed location

SO Seasonal Cycle (SOSCEx II) Glider Experiment (1h, 1km)




Uncertainties in seasonal mean CO2 fluxes may arise from undersampled/unresolved dynamics

*Thomalla et al. (2011), Monteiro et al. (2015)*

# Atmospheric Weather

# Stormy Seas


very deep mixed-layer depths (MLD) and gloomy conditions

# Phytoplankton Blooms

The mixed layer controls:

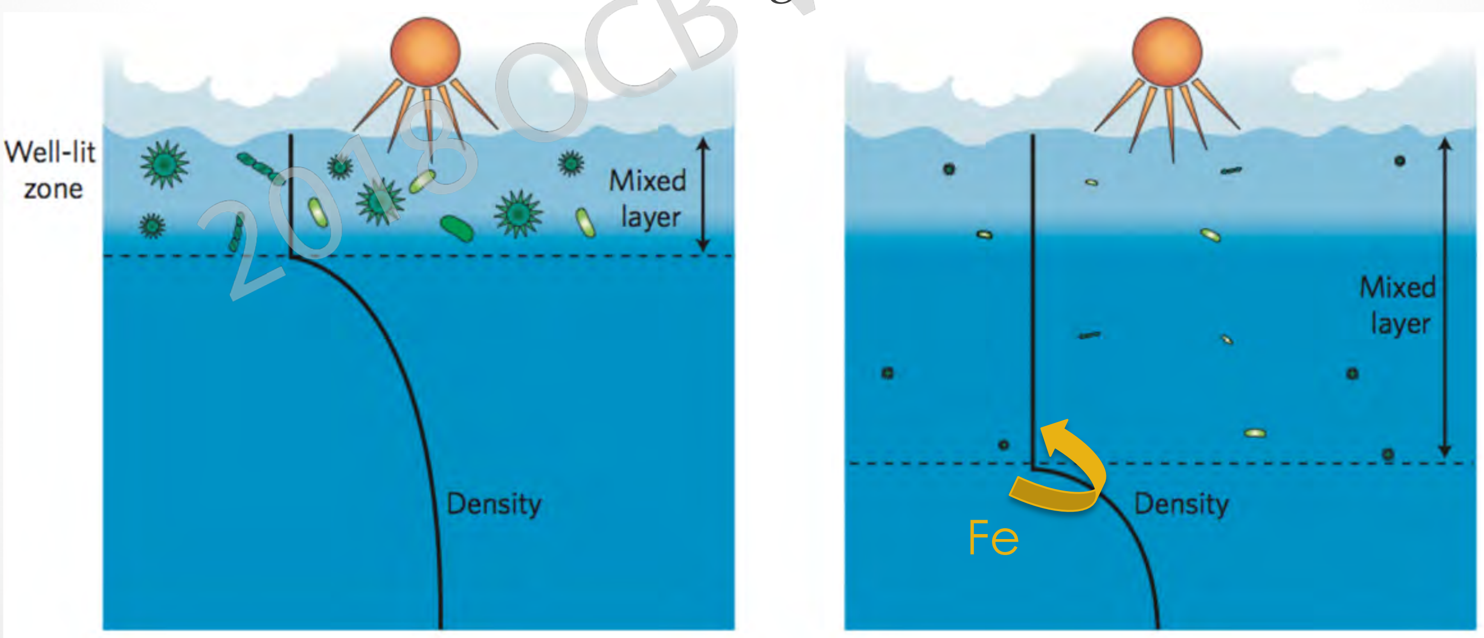
+ exposure to light
+ nutrient supply
+ grazing pressure
+ …

Net growth rates:

$$r = \mu - g - s - p - f$$

- $\mu$: phyto specific growth
- $g$: grazing
- $s$: sinking
- $p$: parasitism
- $f$: physical flushing

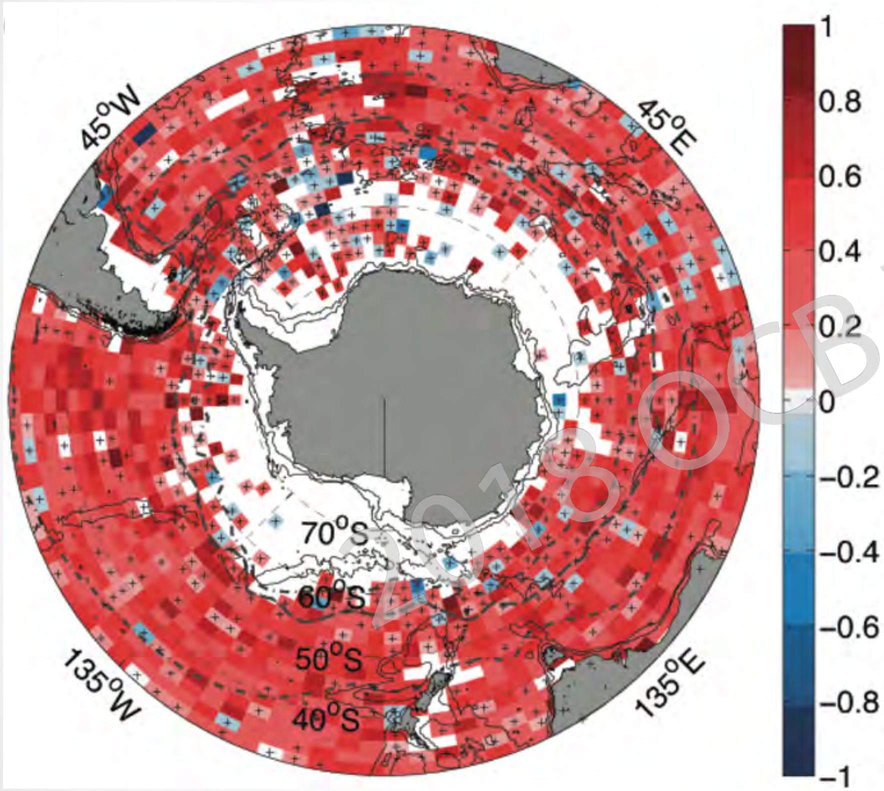




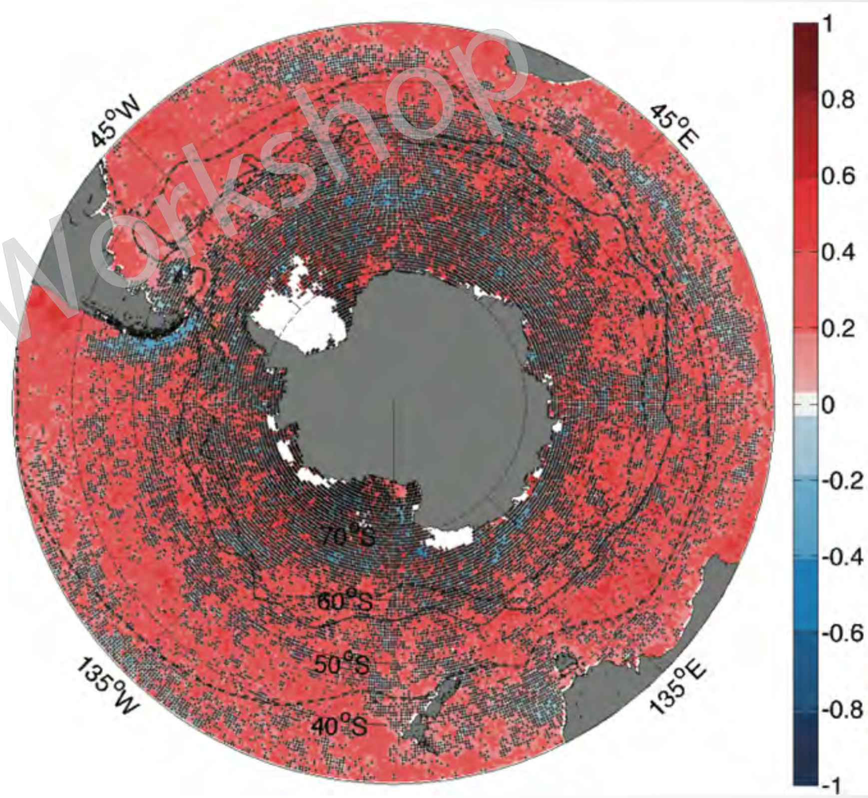

*Gille (2010)*

# Chl-a response to high winds

Wind speed vs MLD




Wind speed vs Chl-a





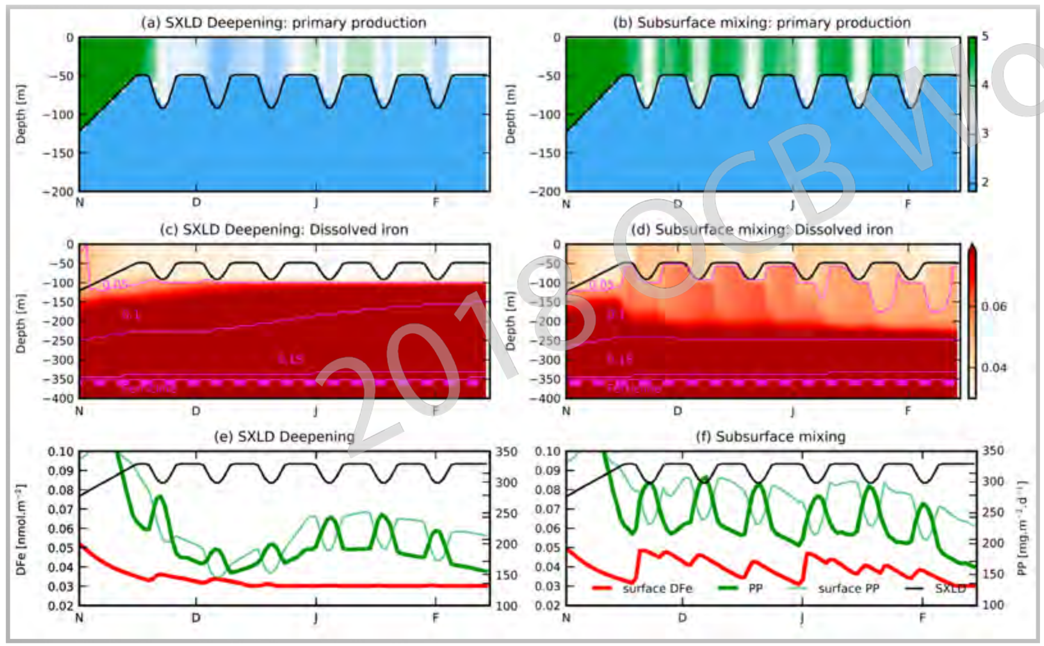

High winds deepen the mixed layer and enhance satellite Chl-a

- *Carranza and Gille (2015), JGR*

# Storm-driven mixing enhances summer primary production

Entrainment (MLD deepening)

Subsurface mixing




1. Entrainment of Fe impacting growth rates?

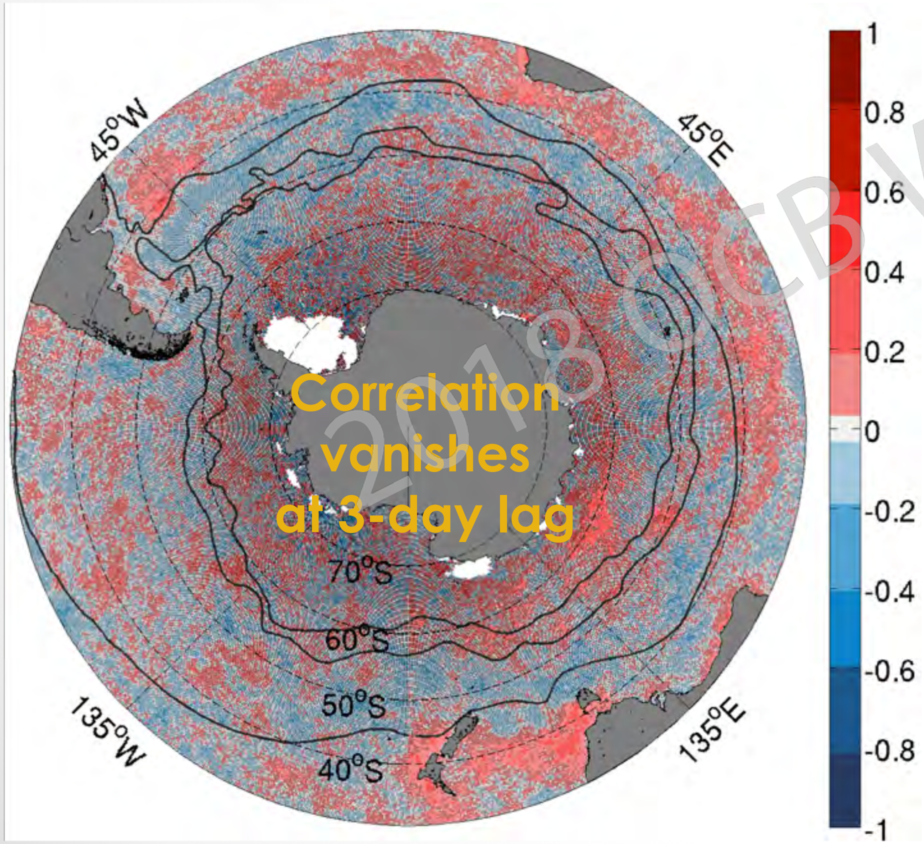
Storm-driven mixing enhances summer primary production (by 60%)

- *Nicholson et al (2016)*

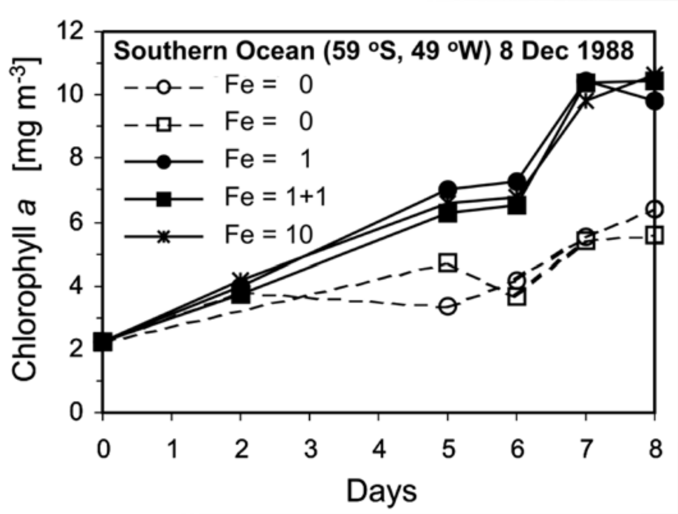
# Chl-a response to high winds

## High winds enhance satellite Chl-a through the summer

Chl-a vs wind speed, 3-day lag




1. Entrainment of Fe impacting growth rates?

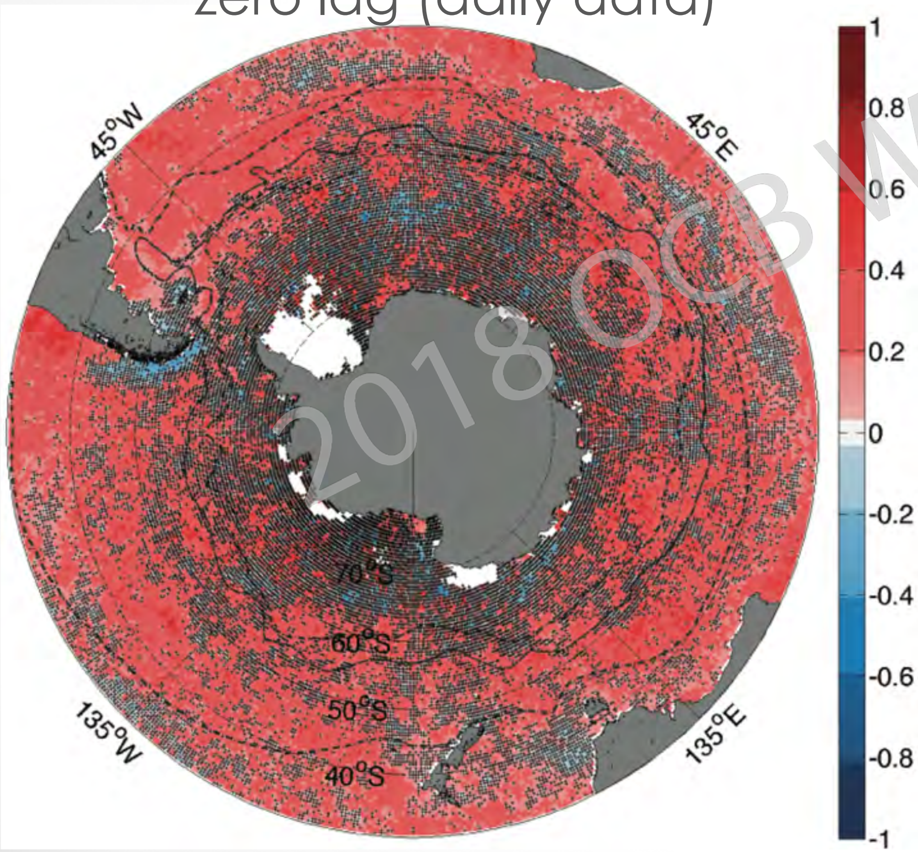



de Baar et al. (2015)

# Chl-a response to high winds

## High winds enhance satellite Chl-a through the summer

Chl-a vs wind speed, zero lag (daily data)



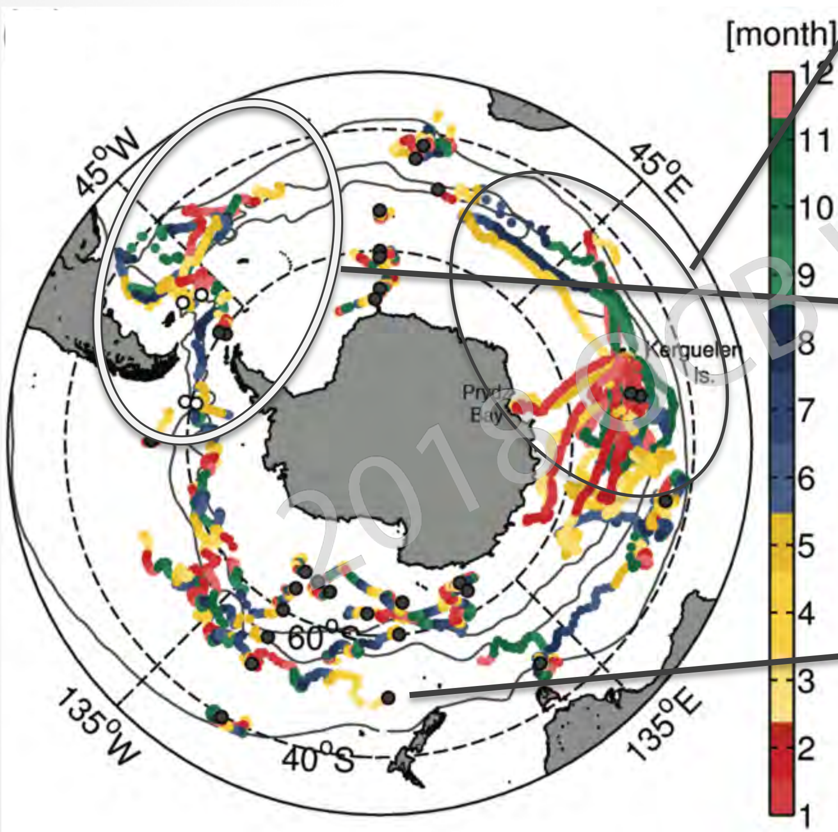

1. Entrainment of Fe impacting growth rates?

2. Entrainment of Chl-a from a deep Chl-a maximum?

1. Reduced grazing pressure on phytoplankton due to dilution effects?

# New Tools: Bio-optical profiles

Chl-a profiles locations



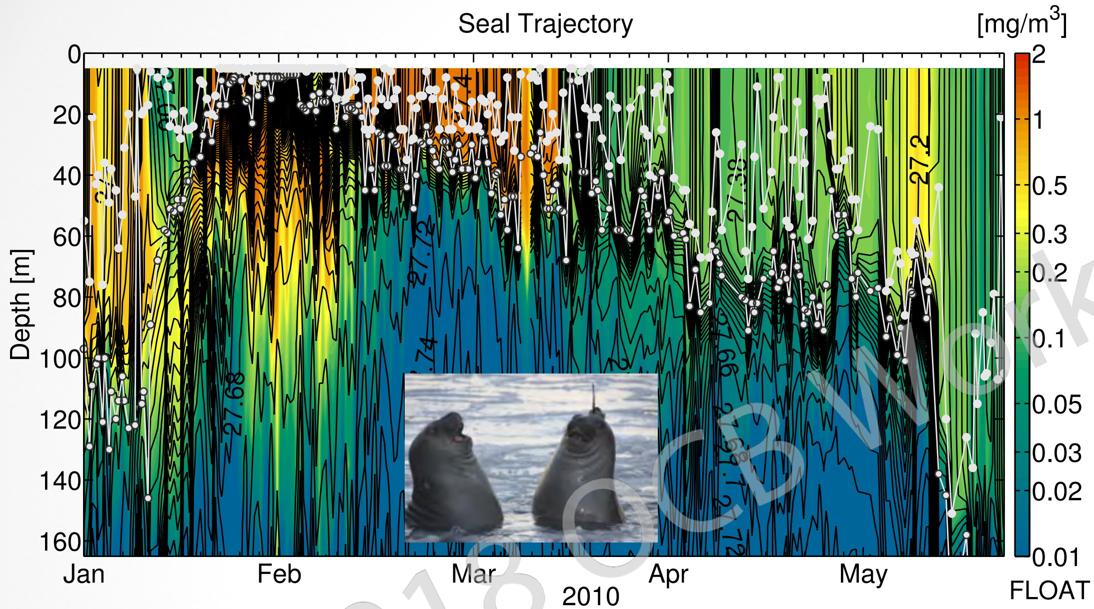

~ 6300 fluorescence
> 3000 nighttime profiles

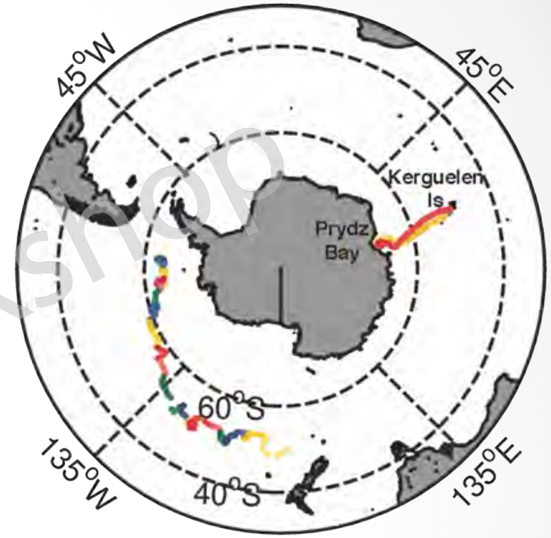
Seals (Guinet et al. 2013):
- Chl-a fluorescence
- twice daily
- 10 m vertical resolution
- up to 200 m depth

EM-APEX floats (DIMES):
- Chl-a and Bpb profiles
- 5-10 days
- ~ 2.5 m vertical resolution
- 200 m, 500 m

BGC Argo floats (SOCCOM):
- Chl-a and Bpb profiles
- 5-7 days
- variable resolution: 2m, 5m, and 10m
- greater depths

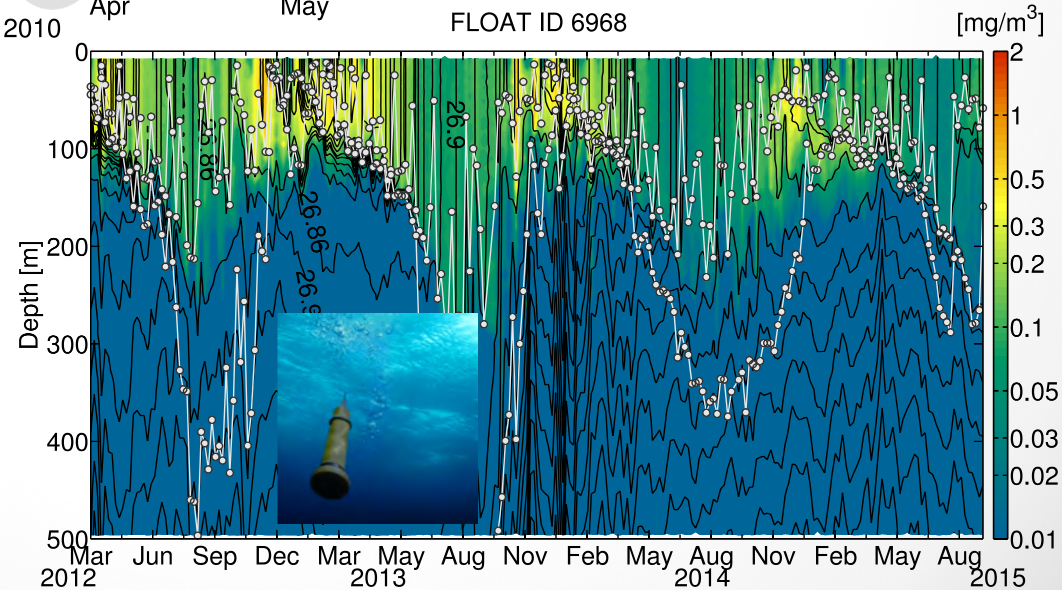
# Chl-a vertical structure




1) Chl-a fluorescence variability

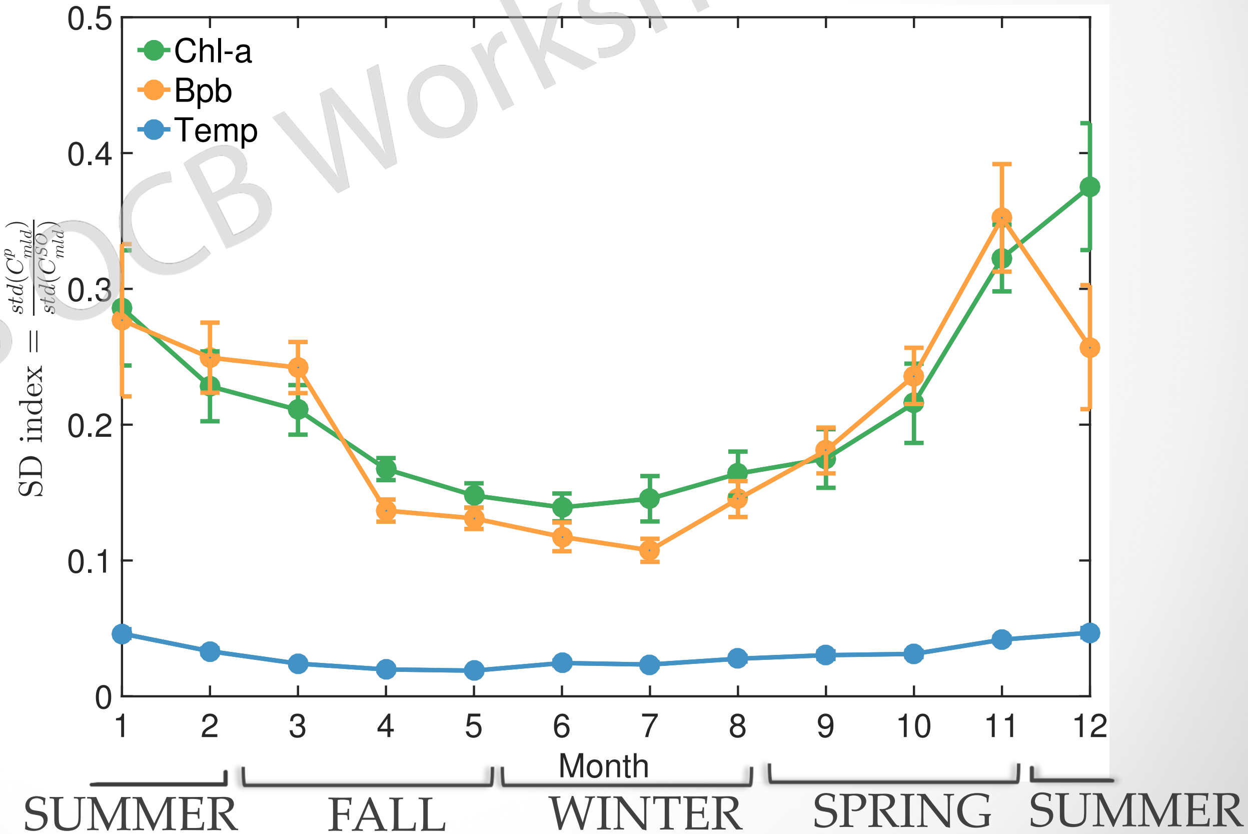
2) Presence of Deep Chl-a Maxima (DFM)



# Chl-a and Bpb unevenness within mixed layer: seasonal variability

Unlike temperature, Chl-a fluorescence and Particle Backscatter show consistently large variance within the mixed layer in all seasons

Standard Deviation Index (SDI):
compares variability within the mixed layer
with spatial variability across SO mixed layers






*Carranza et al. (2018), in revision for JGR Oceans*

# Bio-optical profile fits

**σ** : potential density (rescaled)

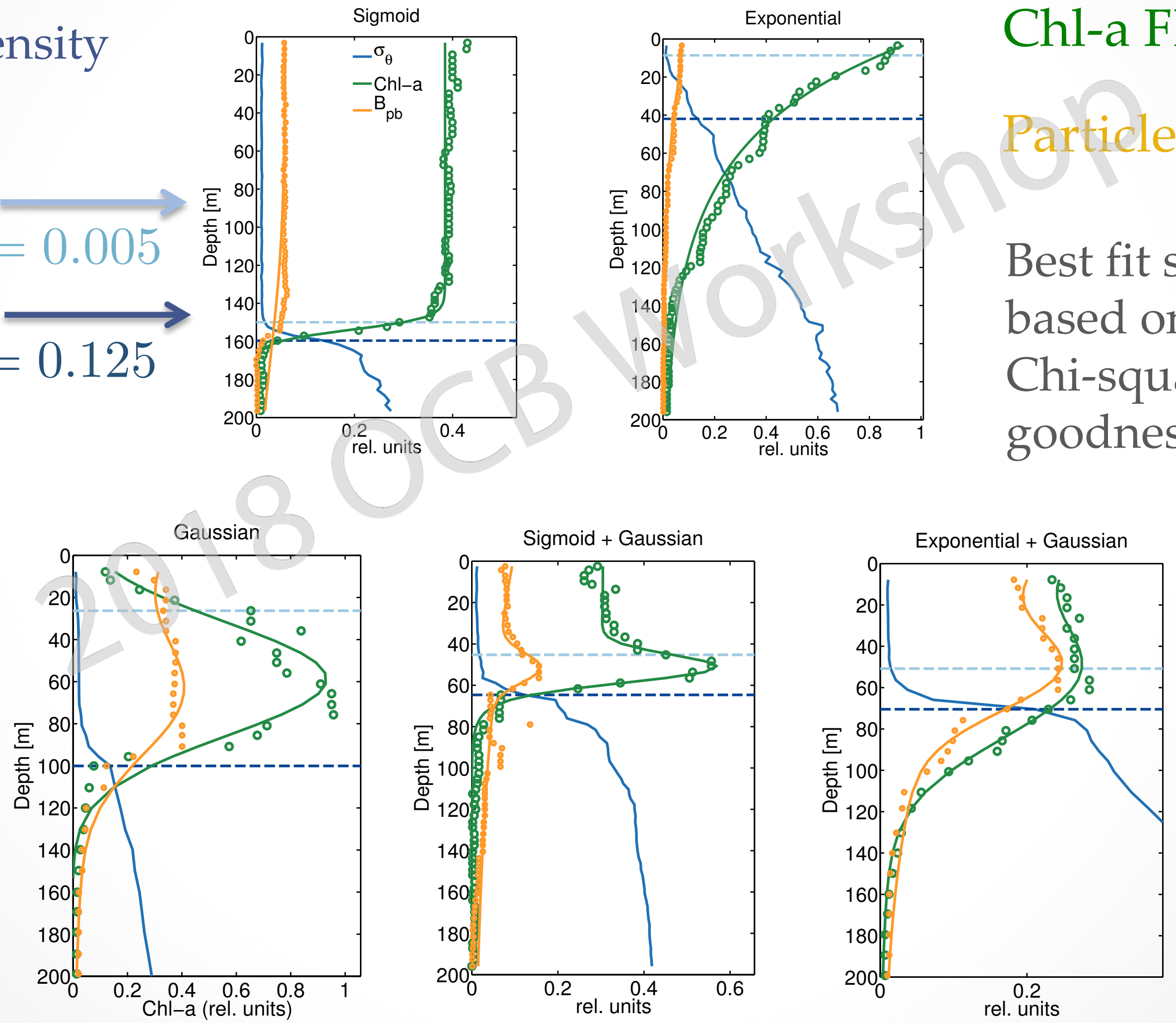
MLD $\Delta\sigma = 0.005$

**MLD** $\Delta\sigma = 0.125$

Chl-a Fluorescence

Particle Backscattering

Best fit selected based on a Chi-square goodness of fit test



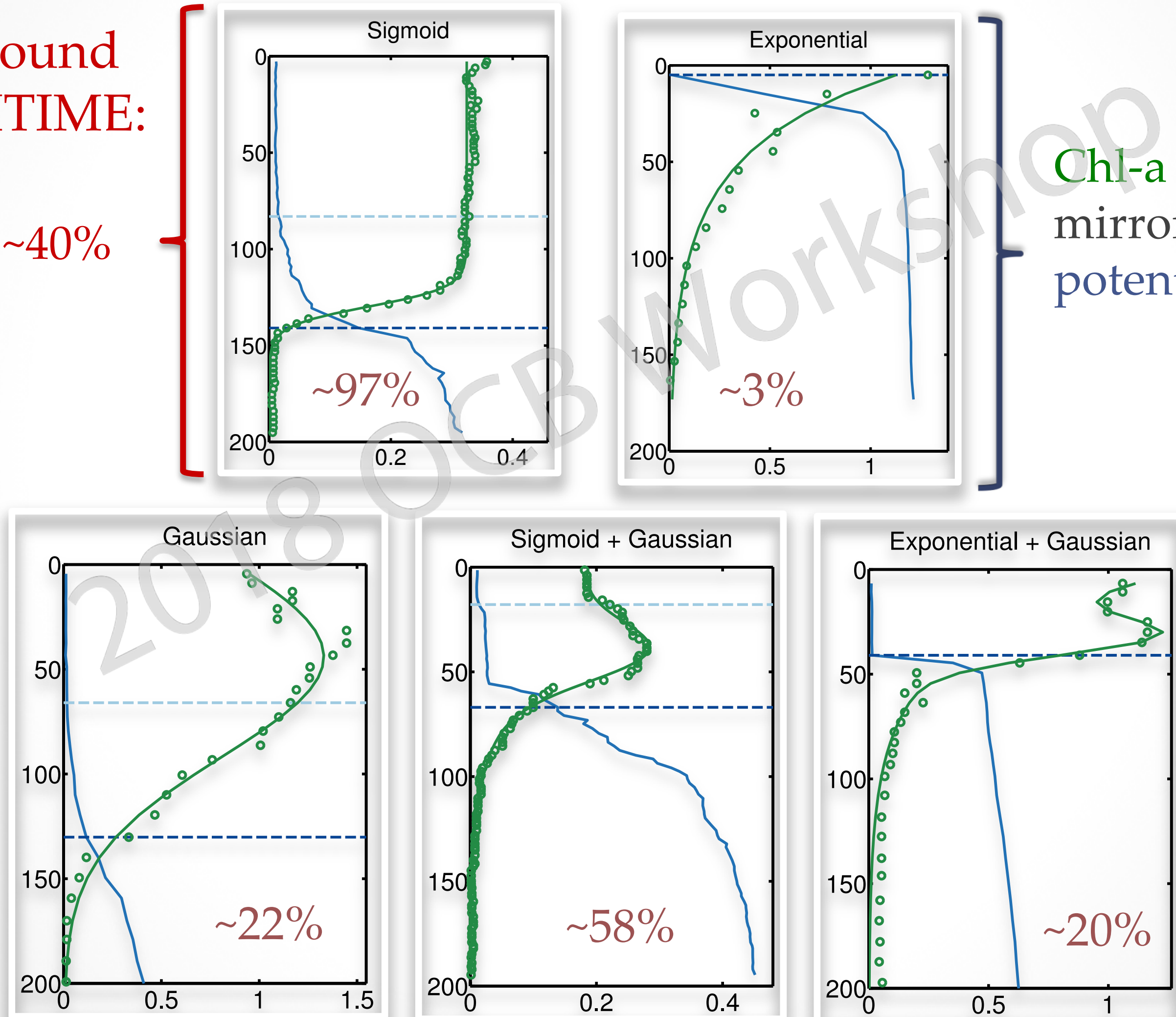



*Carranza et al. (2018), in revision for JGR Oceans*

# Gaussian vs non-Gaussian

Year-round NIGHTIME:

~40%




~60%

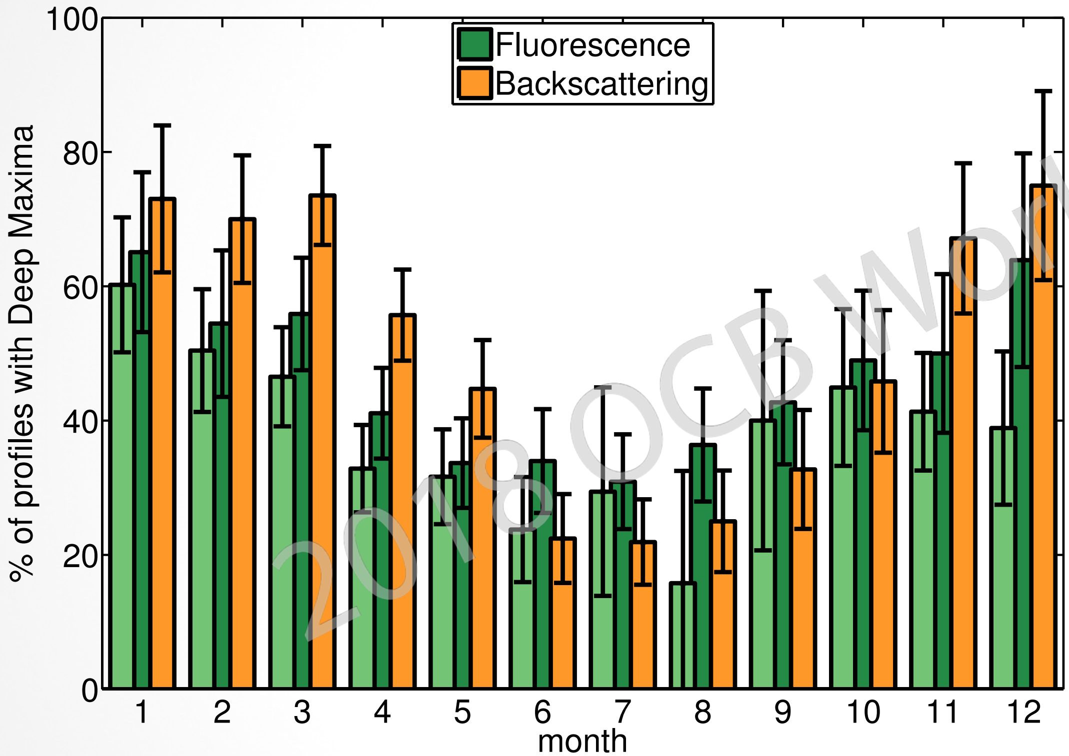
Chl-a fluorescence mirroring potential density

Chl-a shows Gaussian structure



*Carranza et al. (2018), in revision for JGR Oceans*

# Occurrence of Deep Maxima (DM)




Nighttime DFM

from Gaussian fits with a prominent peak

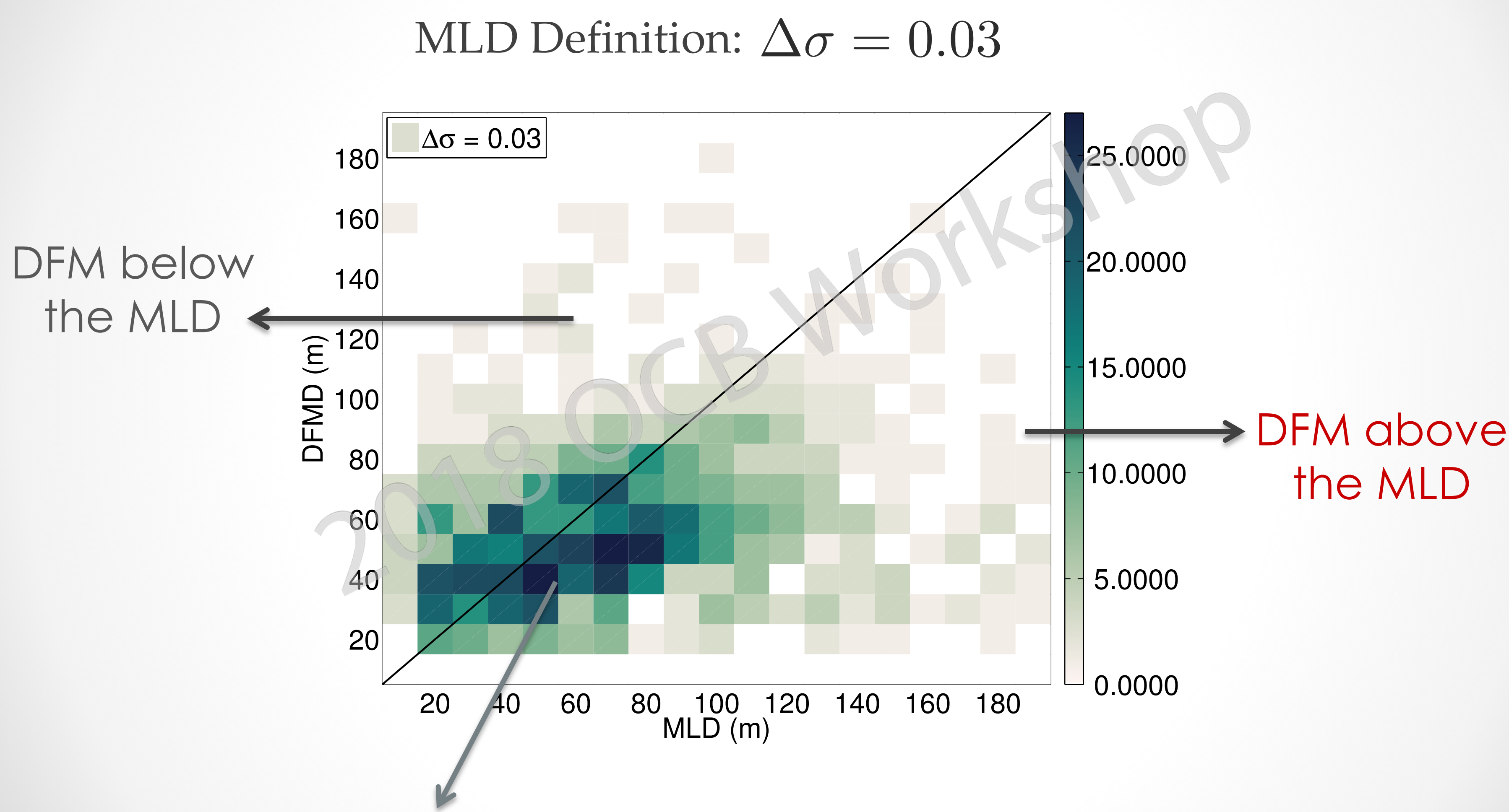
deeper than 20 m and at least twice as large as the noise level (0.04 mg $m^{-3}$)

Peak prominence ~0.1-0.7 mg $m^{-3}$

Nighttime DM are more frequent in summer, but may occur in all seasons and are generally well-correlated with maxima in particle backscattering

*Carranza et al. (2018), in revision for JGR Oceans*

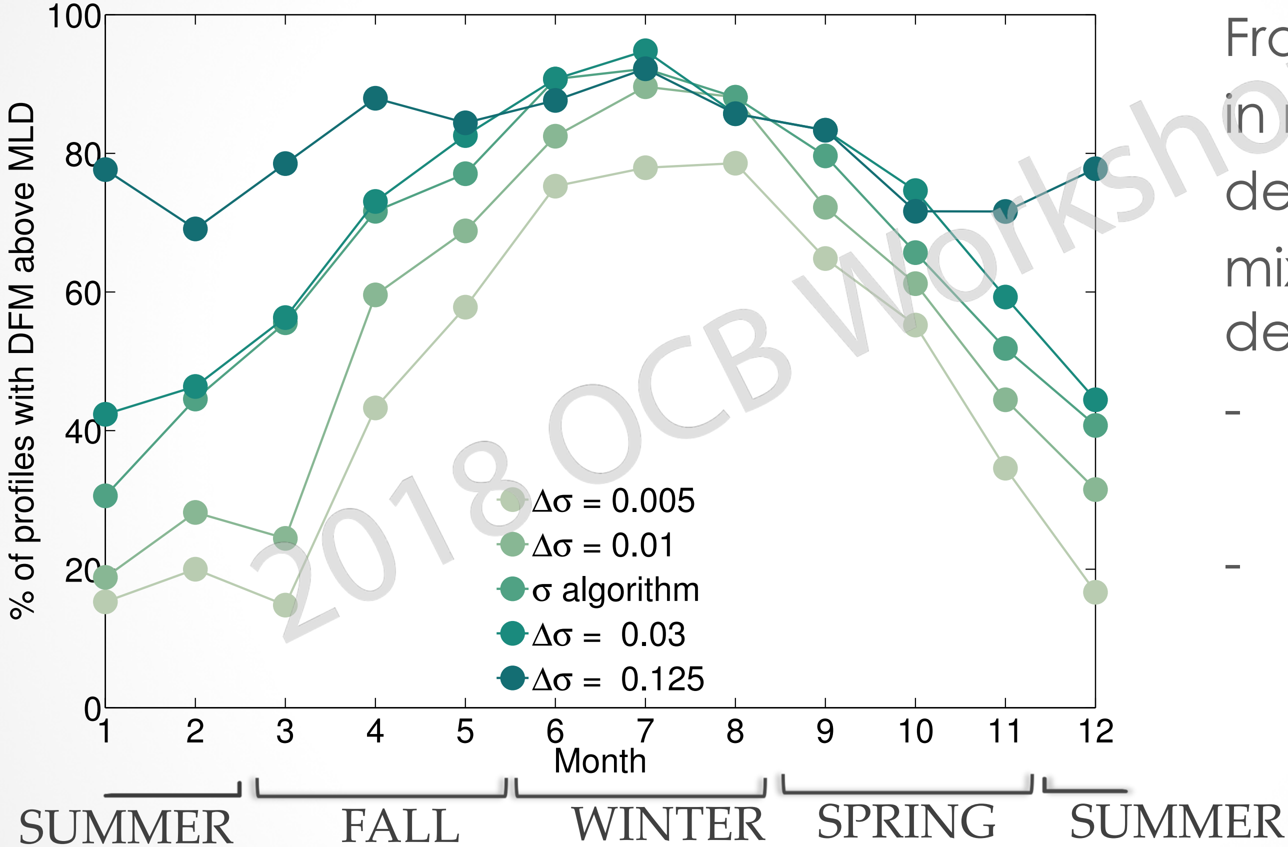
# DFMD vs Mixed-layer Depth (MLD)




DFM are more often found close to the MLD

*Carranza et al. (2018), in revision for JGR Oceans*

# DFM above the MLD: Sensitivity to MLD definition






Fraction of DFM in mixed layer depends on mixed layer definition:

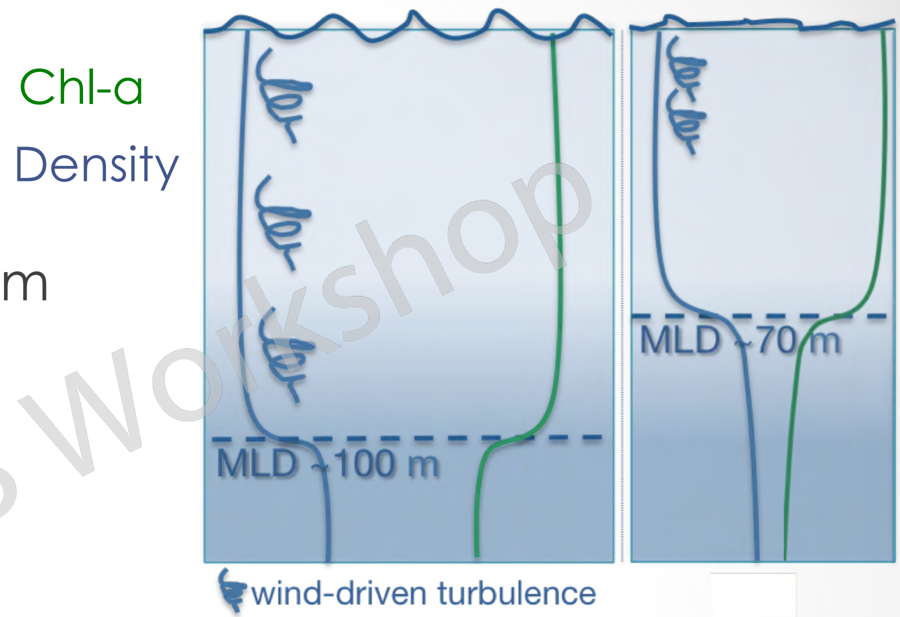
- $\Delta\sigma = 0.005$ (mixing layer)
- $\Delta\sigma = 0.03$ (canonical)

At least ~ 20% of profiles with DFM show subsurface maxima above! the MLD

*Carranza et al. (2018), in revision for JGR Oceans*

# Mixed layers vs Mixing Layers

- The mixing layer
  (i.e. actively turbulent)
  is fundamentally different from
  the mixed layer
  (i.e. homogenous in density
  from a past mixing event)






- Light decreases exponentially with depth and turbulence stirs phytoplankton through the light gradient

- The trade-off between timescales of mixing and photo-adaptation determine whether gradients in Chl-a fluorescence can form within a hydrographic mixed layer:

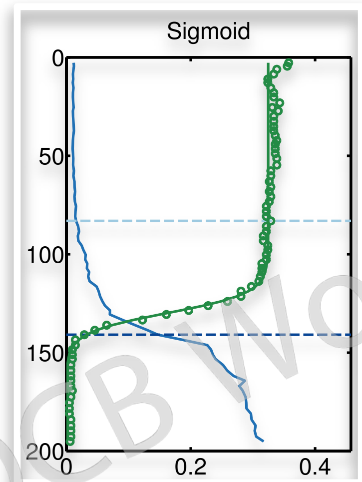
  $\tau_{bio} > \tau_{mix}$ → Uniform Chl-a

  $\tau_{bio} < \tau_{mix}$ → Vertical gradients in Chl-a can exist

# Homogeneous vs Heterogeneous

WINTER (JJA):

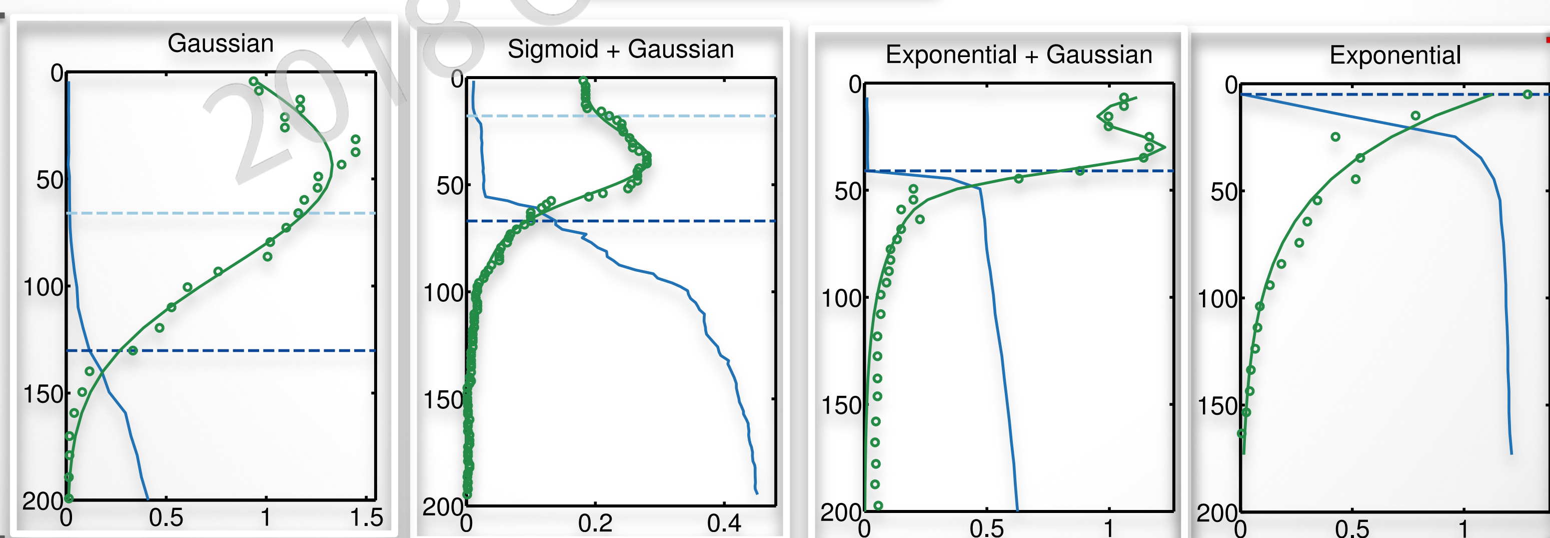
~49%




SUMMER (DJF):

~29%

~51%




~71%



- *Carranza et al. (2018), in revision for JGR Oceans*

# Biological and Mixing Timescales

- ✓ The existence of gradients and variance in Chl-a fluorescence and Bpb within mixed layers homogeneous in density suggest that the biological timescales of photo-adaptation to light (i.e. growth/photo-acclimation) are shorter than mixing timescales:

$$\tau_{bio} < \tau_{mix}$$

$$\tau_{photacclimation} < \tau_{growth}$$

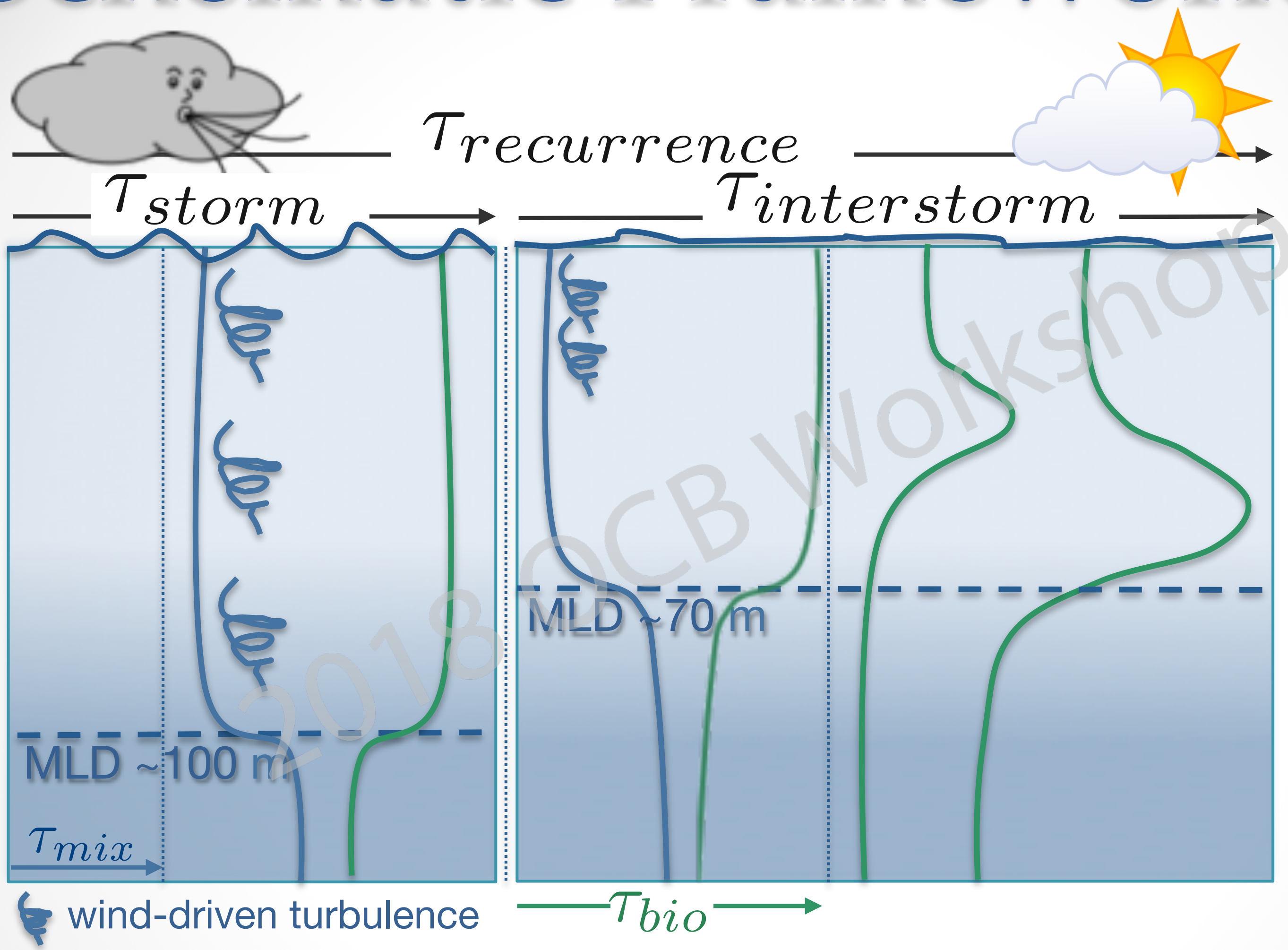
(~ few hours) ( >3-4 days)

?

Synoptic Storms (2-10 days)

Oceanic submesoscale (~few days)
Or mesoscale (weeks)

# Schematic Framework

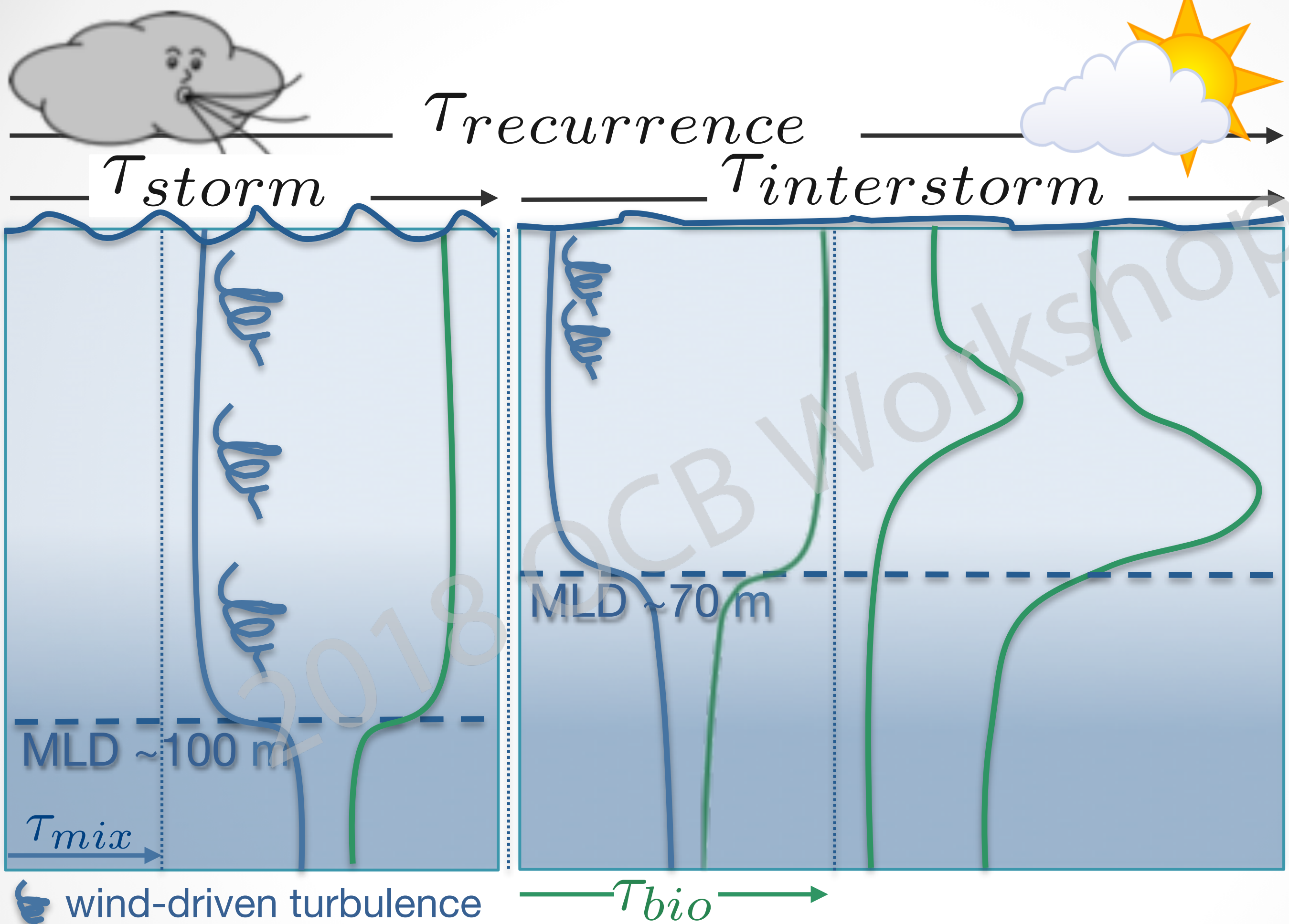



Phytoplankton grow where mixing is minimal?

Storm events deepen and homogenize the mixed layer

When storm ends density remains mixed and top of mixed layer might cotinue mixing

# Can we constrain $\tau_{bio}$ ?




Satellite (CCMP) winds

+

Profile structure statistics from floats

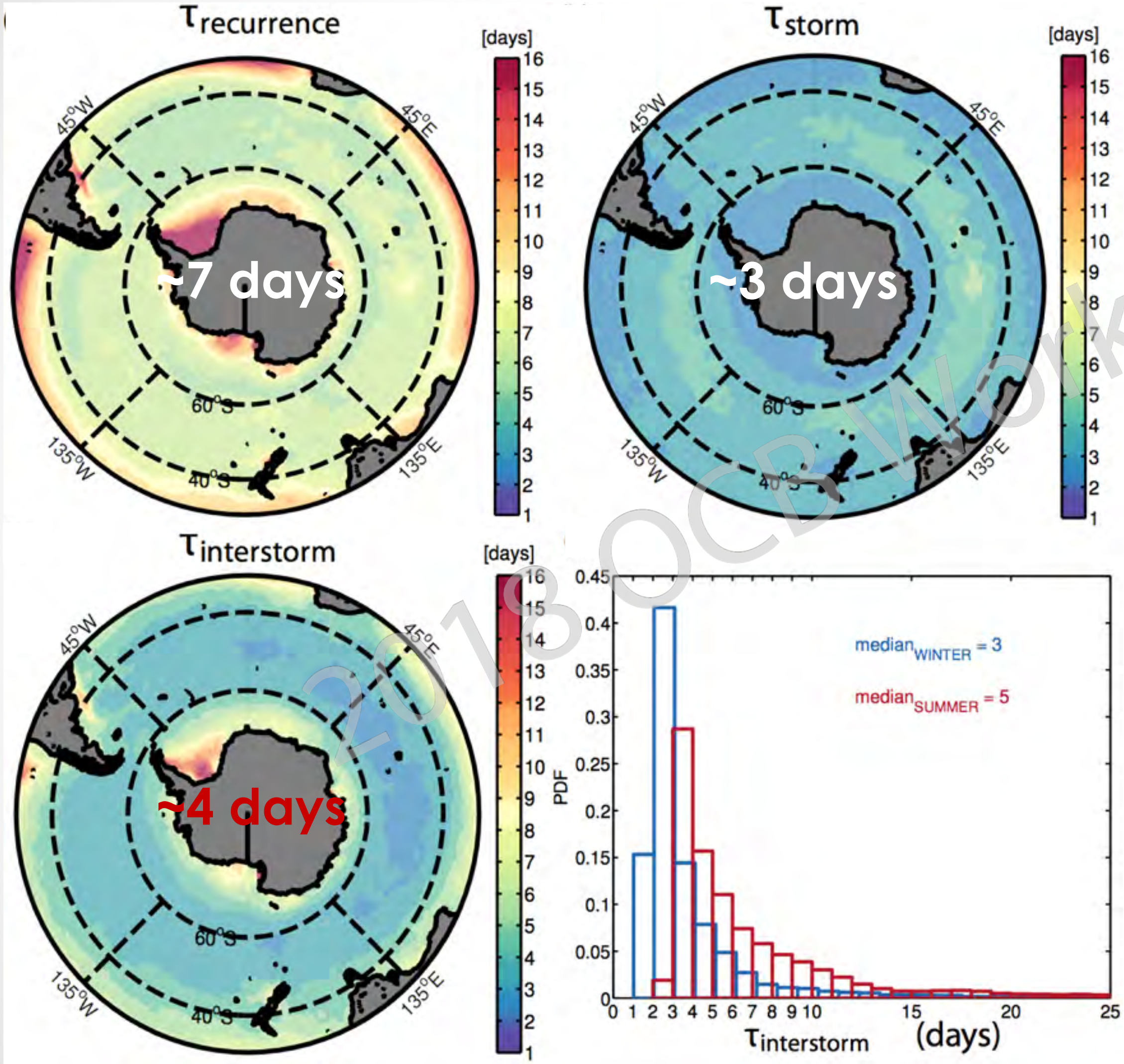
biological timescale of restratification

$\tau_{mix} < 1$ day (i.e. time it takes to homogenize a gradient)

?

$$f_{homogeneous} \sim \frac{\tau_{storm} - \tau_{mix} + \tau_{bio}}{\tau_{recurrence}}$$

# Storm-mixing Timescales




One storm arrival every week, that will last ~ 3 days

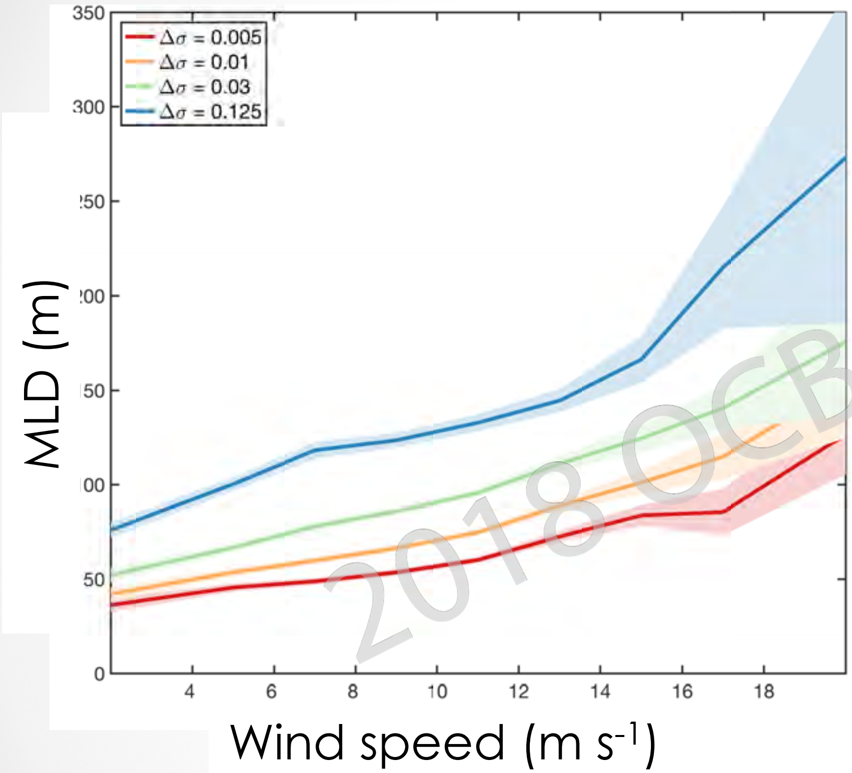
Storm:
wind speeds >10 m $s^{-1}$

Exhibit seasonality:

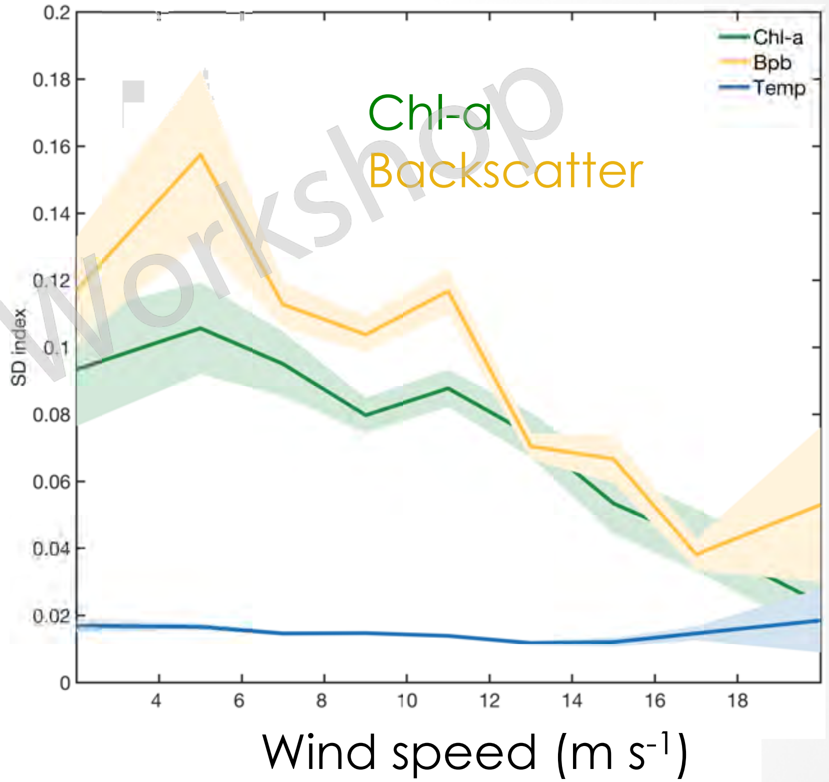
slightly less frequent storms in summer, lasting ~ 1 day shorter, allowing for longer periods of quiescence (~ 5 days)

Storm timescales imply biology restratifies in less than 1-3 days

# Wind-profile matchups

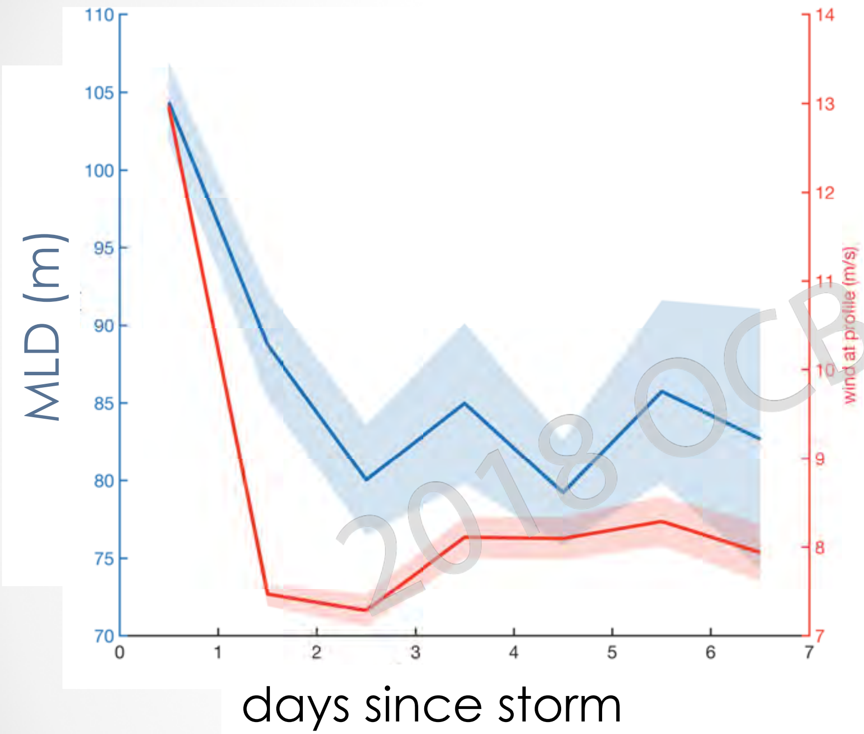


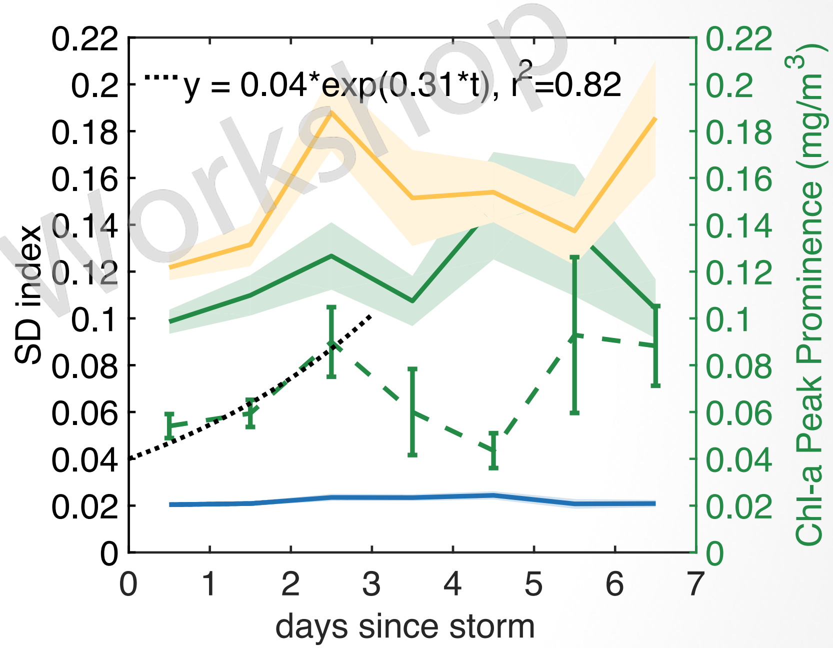

MLD increases as winds get stronger




Bio-optics get homogenized within the mixed layer

# Wind-profile matchups: What happens after a storm?





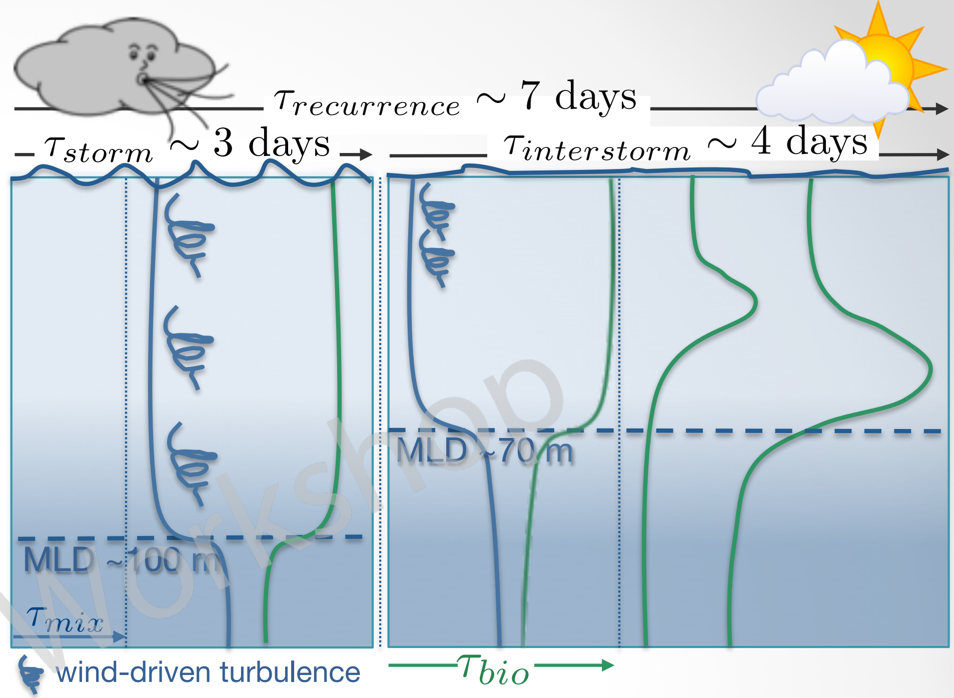

MLD shoals within 1-2 days

Mixed layer bio-optical variance and peak prominence increase

$$\mu = 0.31 \text{ day}^{-1}$$

Biological restratification timescales of < 3 days

# Implications

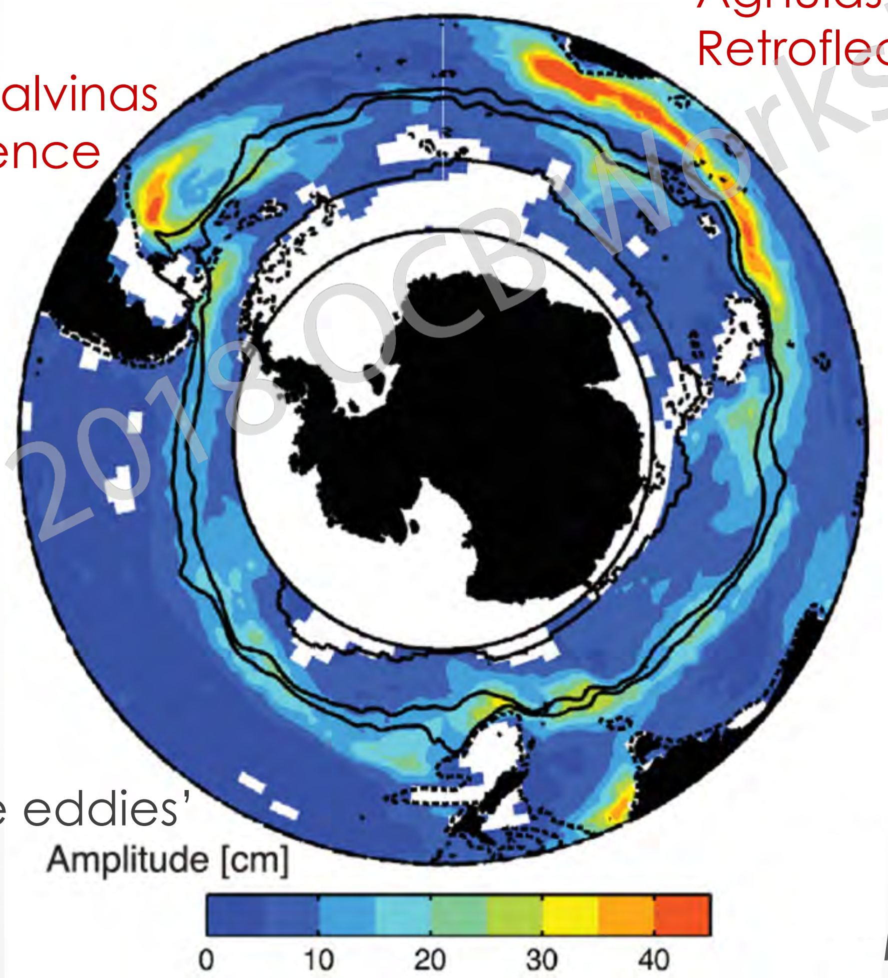



- ✓ Hydrographic mixed layers are not mixed in bio-optical properties
- ✓ Biological timescales for growth might be shorter than previously thought, i.e. SO's phytoplankton is well adapted to cold temperatures, low light and Fe conditions
- ✓ Seasonality/Asymmetry in storm-mixing timescales suggests atmospheric weather can have a net effect on annual means and longer-term biogeochemical properties

# Oceanic Weather

# Hotspots for Eddy Activity

- Downstream of topographic features

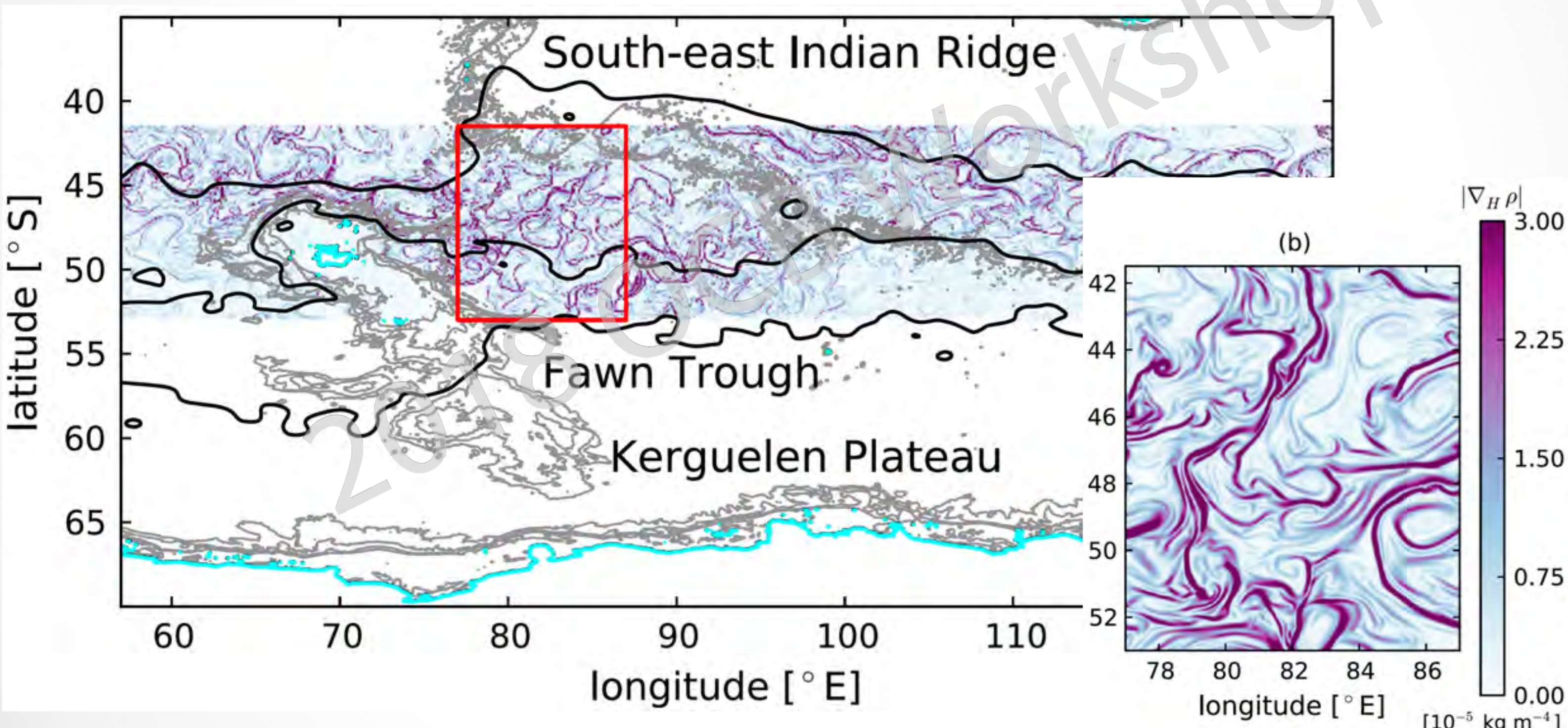





*Frenger et al. (2015)*

# Submesoscale patchiness linked to topography

Kerguelen Plateau



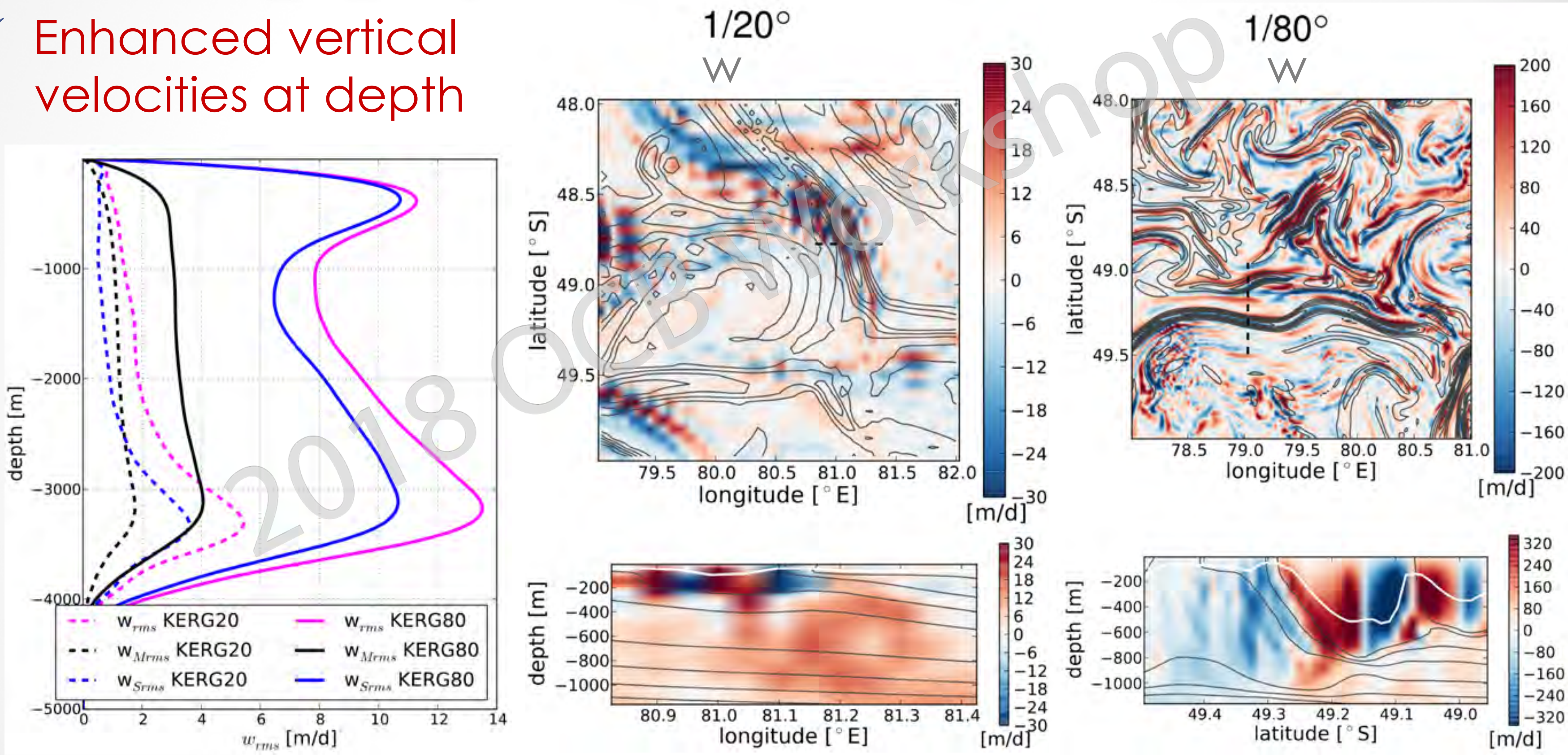

1/20° horizontal resolution (mesoscale-resolving)

1/80° horizontal resolution (submesoscale-resolving)

*Rosso et al. (2015), Rosso et al. (2016)*

# Submesoscale Impacts on Fe supply

- ✓ Enhanced vertical velocities at depth





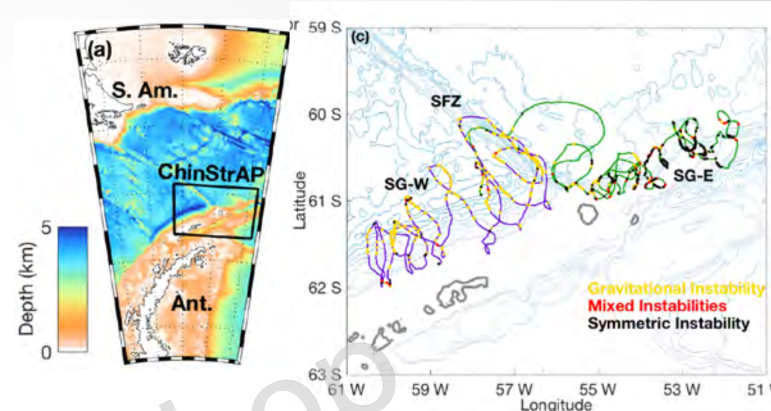

Iron fluxes are enhanced by a factor of 2 by the sub-mesoscales, though differences in mean [Fe] are small

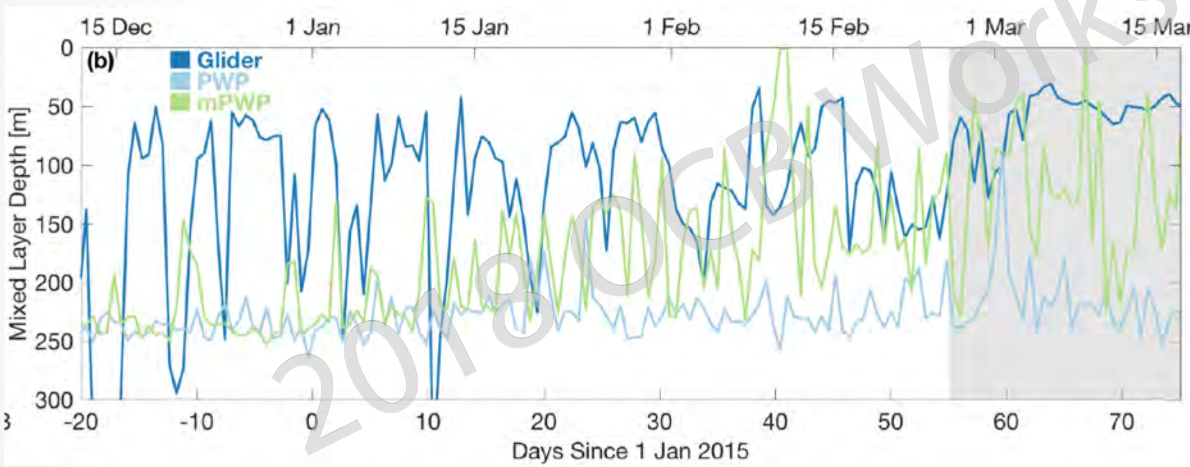
*Rosso et al. (2015), Rosso et al. (2016)*

# Submesoscale Observations…

Southern Drake Passage (ChinStrAP)

Glider observations (1-3km, hr) crossing fronts




evidence for intermittent episodes of a highly active submesoscale field during summer months

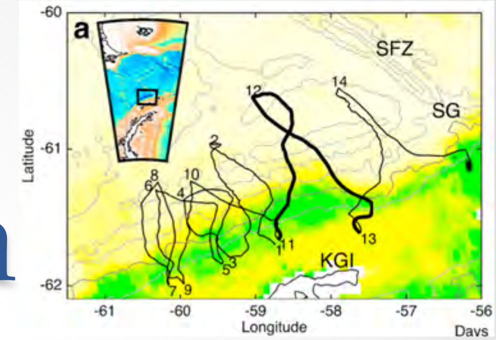
PWP: 1-D bulk mixed layer model

mPWP: PWP + parameterized submesoscale

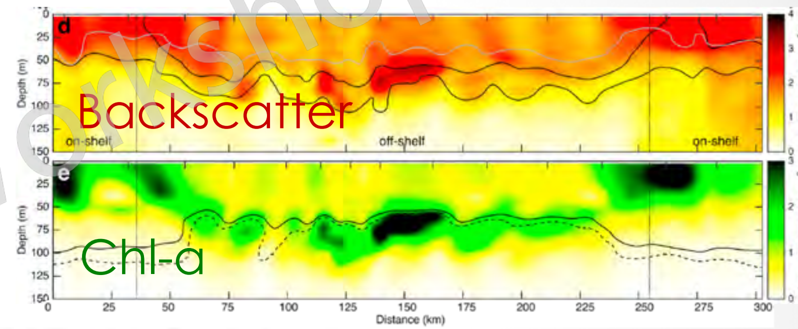
Ekman buoyancy flux and BCI are at least as important as the surface wind and buoyancy forcing in setting mixed layer variability in the Southern Ocean

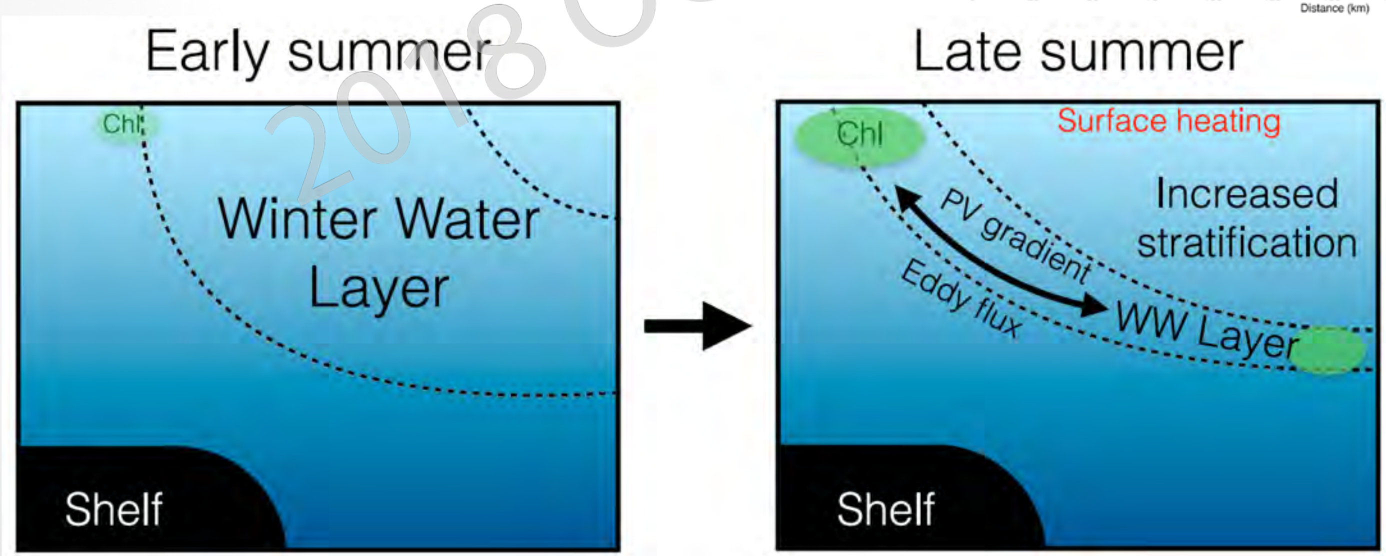
*Viglione et al. (2018)*

# Submesoscale Impacts on Subduction of Chl-a




Evidence of submesoscale-driven subduction of Chl-a.. contributing to the formation of deep Chl-a maxima inn summer



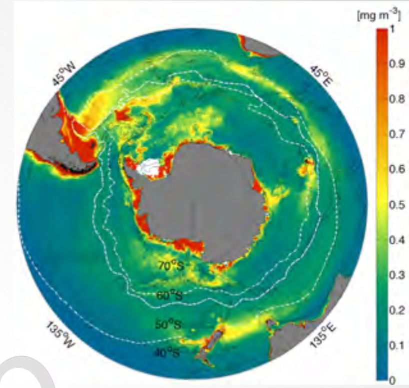





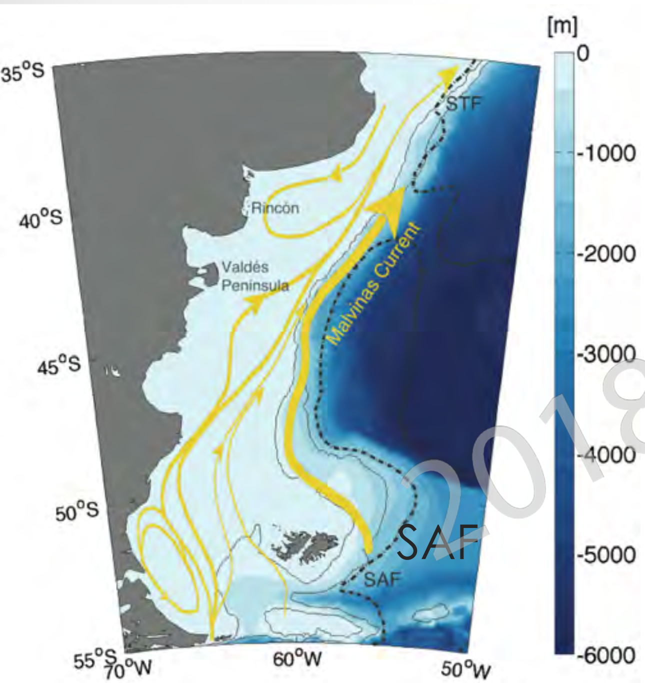

*Erickson et al. (2016)*

# Wind modulation of upwelling at a SBF

Shelf-break Front (SBF)

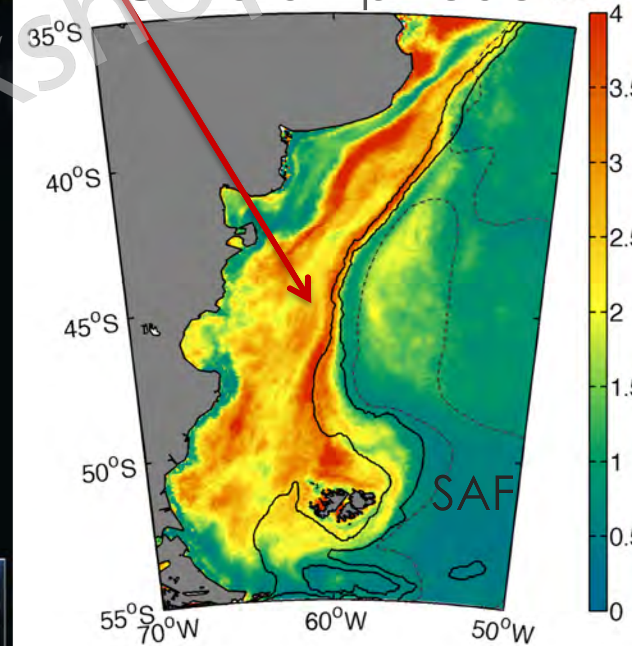



Patagonian Shelf




Wind-driven currents
and
and high tidal energy


Chl-a amplitude [mg/m³]

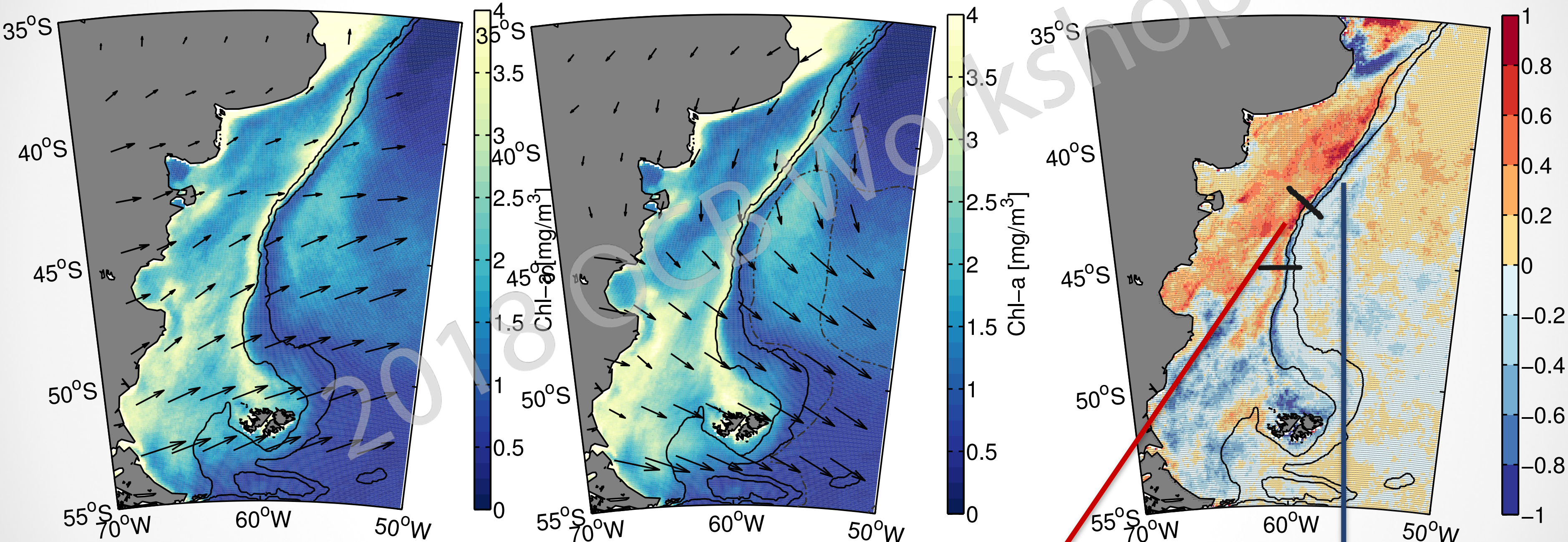



Chl-a is uniformly sustained at fronts

*Carranza et al. (2017), JGR*

# Satellite Chl-a response to along-front winds at the SBF

Composites of satellite Chl-a by along-front wind direction




(a) Southerly winds (from the south)

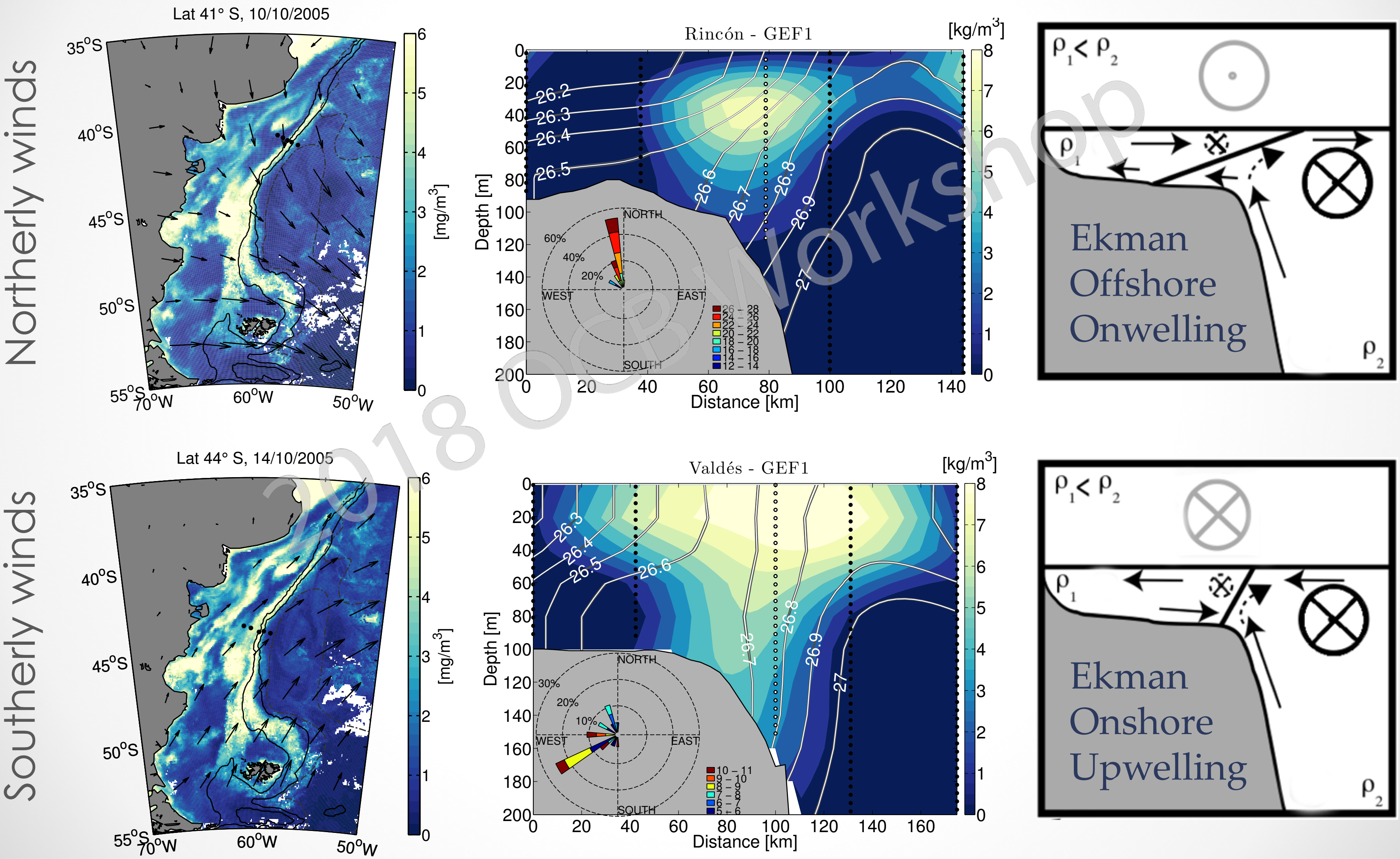
(b) Northerly winds (from the north)

Difference (a)-(b)

Southerly winds (down-front) → high Chl-a onshore

Northerly winds (up-front) → high Chl-a offshore

# Evidence of isopycnal tilting due to changing winds: synoptic evidence

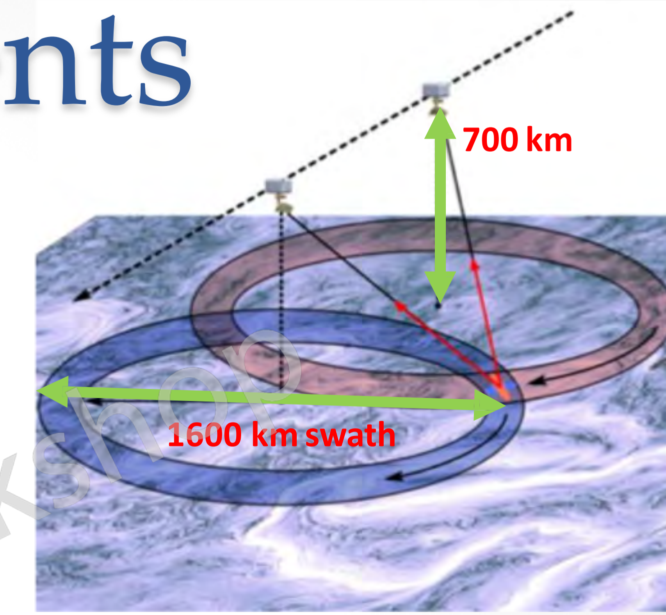



*Siedlecki et al. (2011)*

# Conclusions

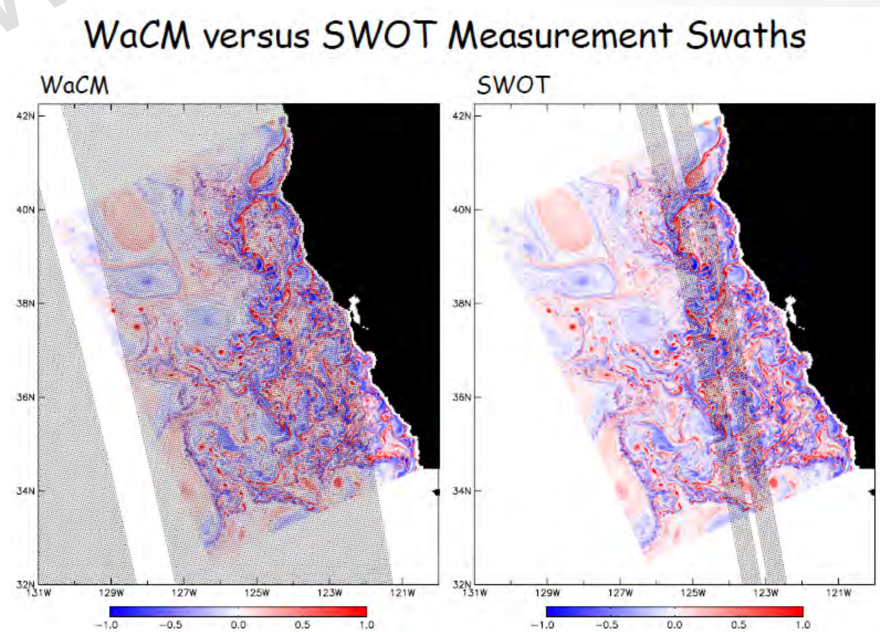
- ✓ Synoptic winds impact MLD and Chla variance within the ML: enhanced ML variance during periods of quiescensce between high wind events. Seasonal asymmetry in storm timescales (longer interstorm periods in summer) could impact annual means
- ✓ Mesoscale eddies modulate MLD variability. Asymmetric contribution of eddies to MLD variability (greater for anticyclones vs cyclones). Stronger signal in winter vs summer, and over localized regions. Impacts on surface Chl-a through changes in light and nutrient supply
- ✓ Highly energetic submesoscale dynamics downstream of topography that can be active in the summertime!, enhance Fe supply and support along-isopycnal subduction of Chla below the seasonal MLD
- ✓ Wind-mesoscale interactions can potentially enhance nutrient fluxes.. and modulate Chla (e.g. at a shelf-break front)

# Winds and Currents Mission (WaCM)




- ✓ Ka-band rotating pencil beam Doppler scatterometer
- ✓ Winds measured from Ka or Ka/Ku s0 measurements at multiple azimuth angles or jointly with Doppler for direction ambiguity removal.
- ✓ Surface currents from Doppler measurements
- ✓ Temporal coverage > 1/day

- Wide-swath and fast sampling result in less aliasing of time-averaged currents and derivatives (D. Chelton)
  - Mitigates noisier single-pass measurements
  - True surface currents (ageostrophic & surface)



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