Physical Controls of Biology/ Biogeochemistry

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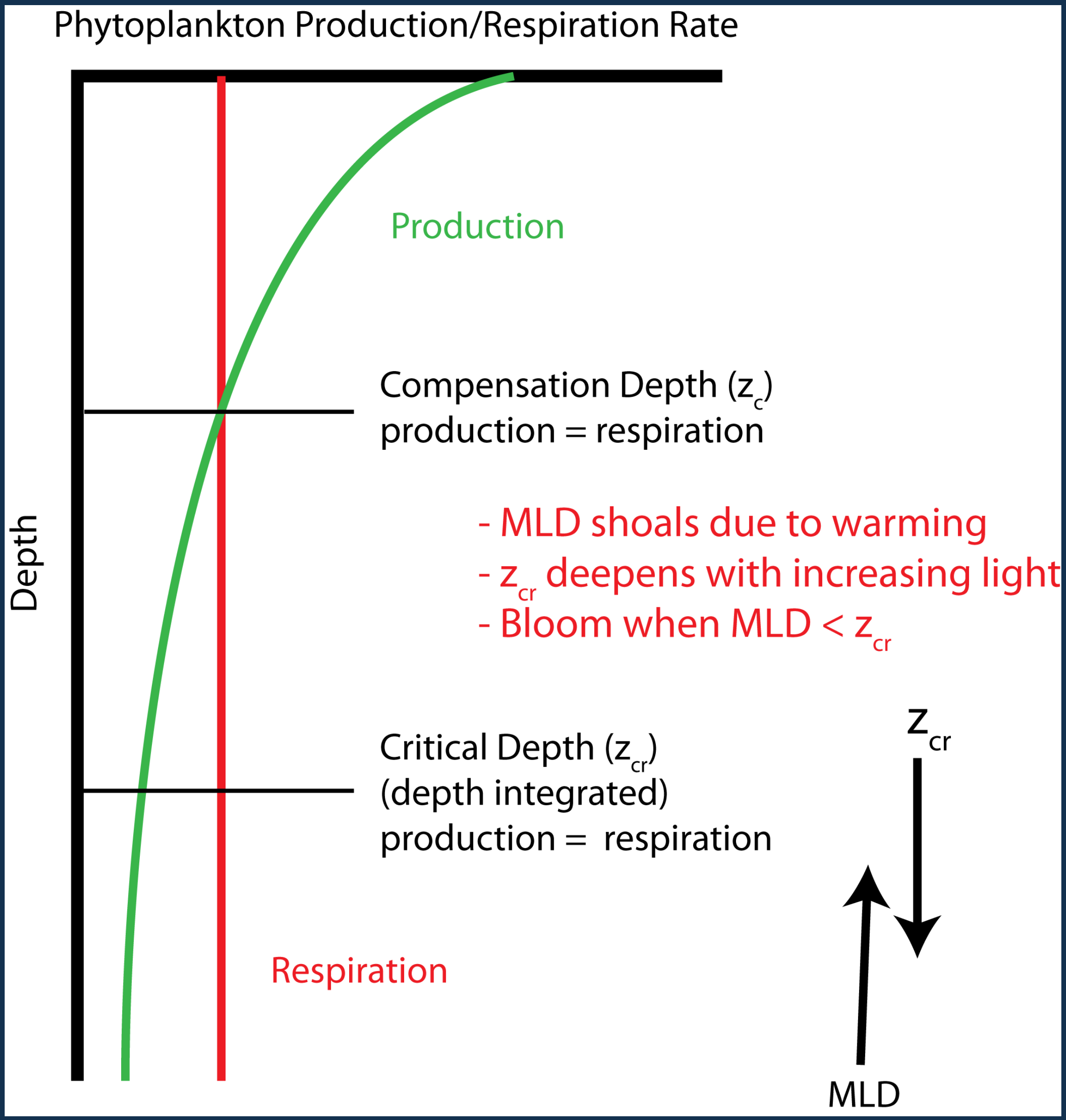
- Nutrient supply – mixing, advection
- Light – stratification, vertical exchange
- Export (flushing, sinking)
- Encounter rates
- Community structure

1. Sverdrup's critical depth hypothesis and new perspectives – mixing.
2. Large-scale circulation.
3. Mesoscale pumping,
4. Submesoscale dynamics.

Sverdrup's Critical Depth Hypothesis



Applied to mid- & high-latitude regimes:

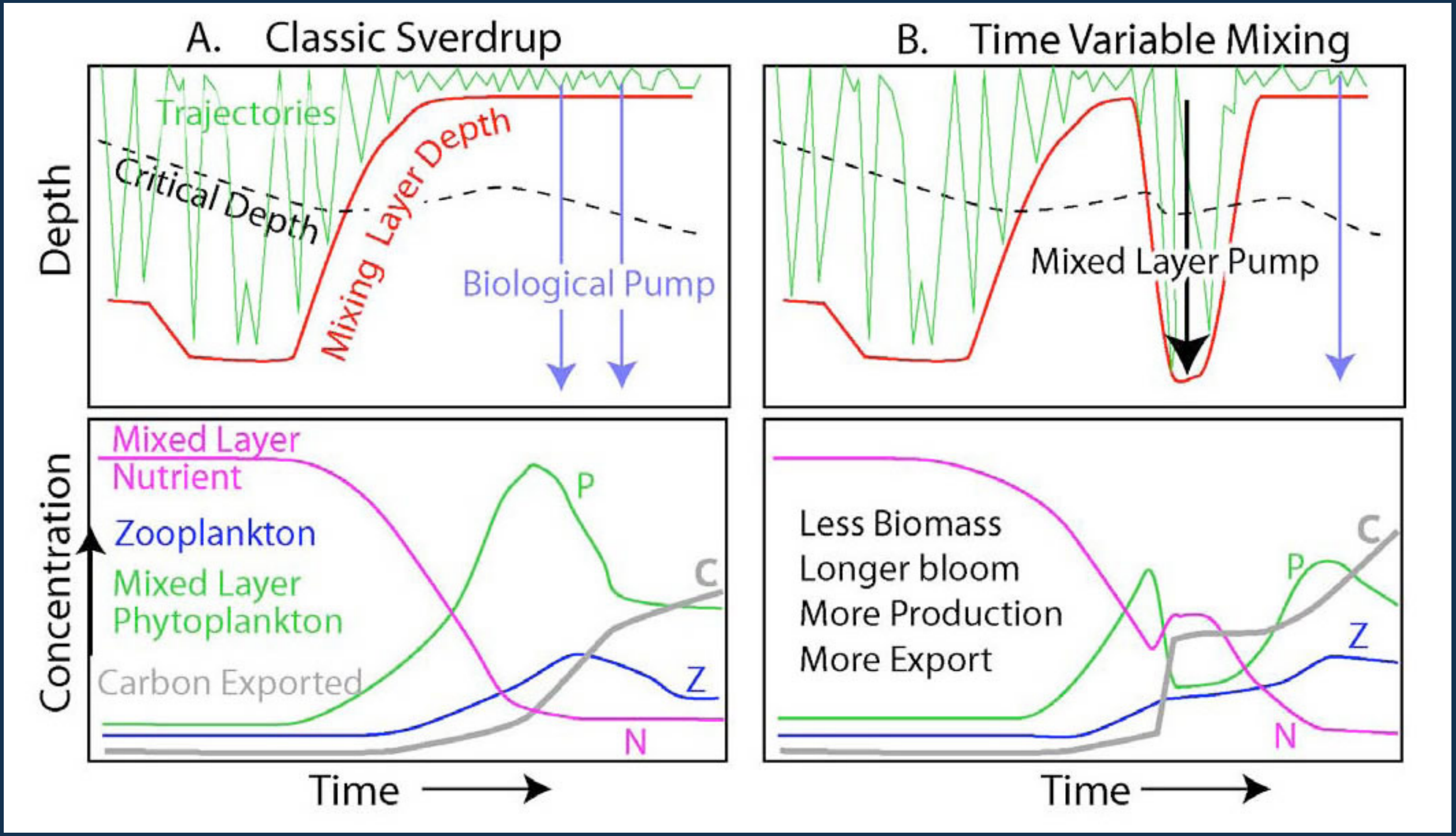
- Deep wintertime mixing supplies nutrients to ML.
- Seasonal cycle of surface irradiance and MLD controls availability of light.

Assumes

- Constant respiration rate encompasses grazing, linking, respiration.

Does not directly address observed patchiness.

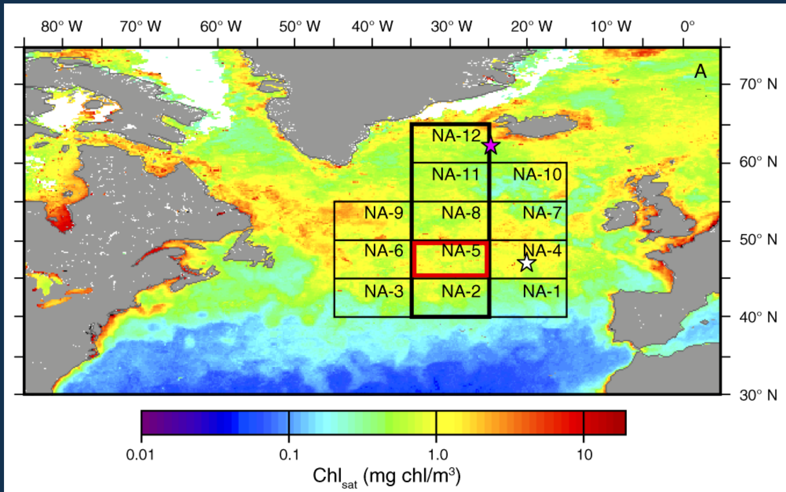
Bloom Evolution

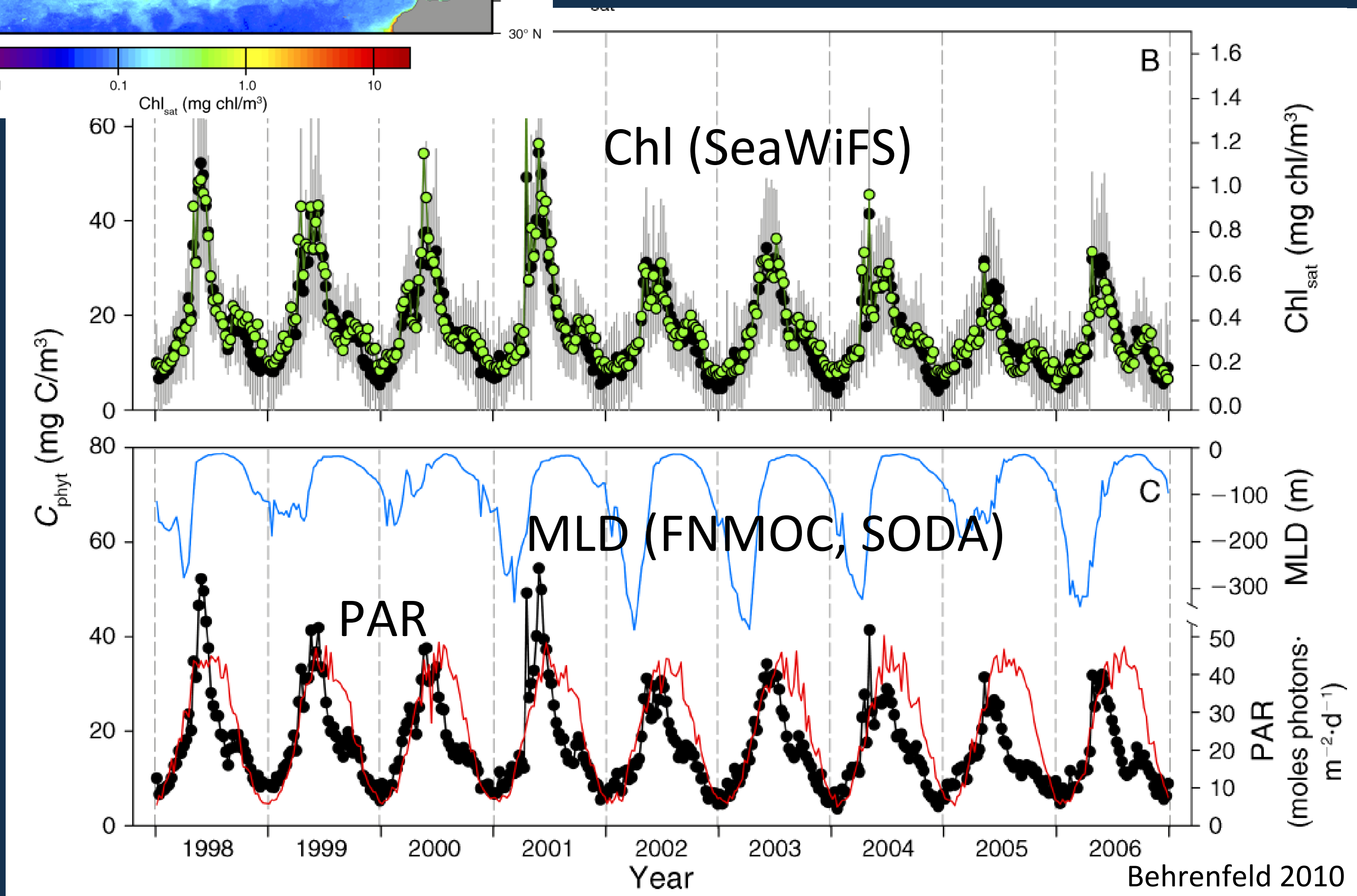


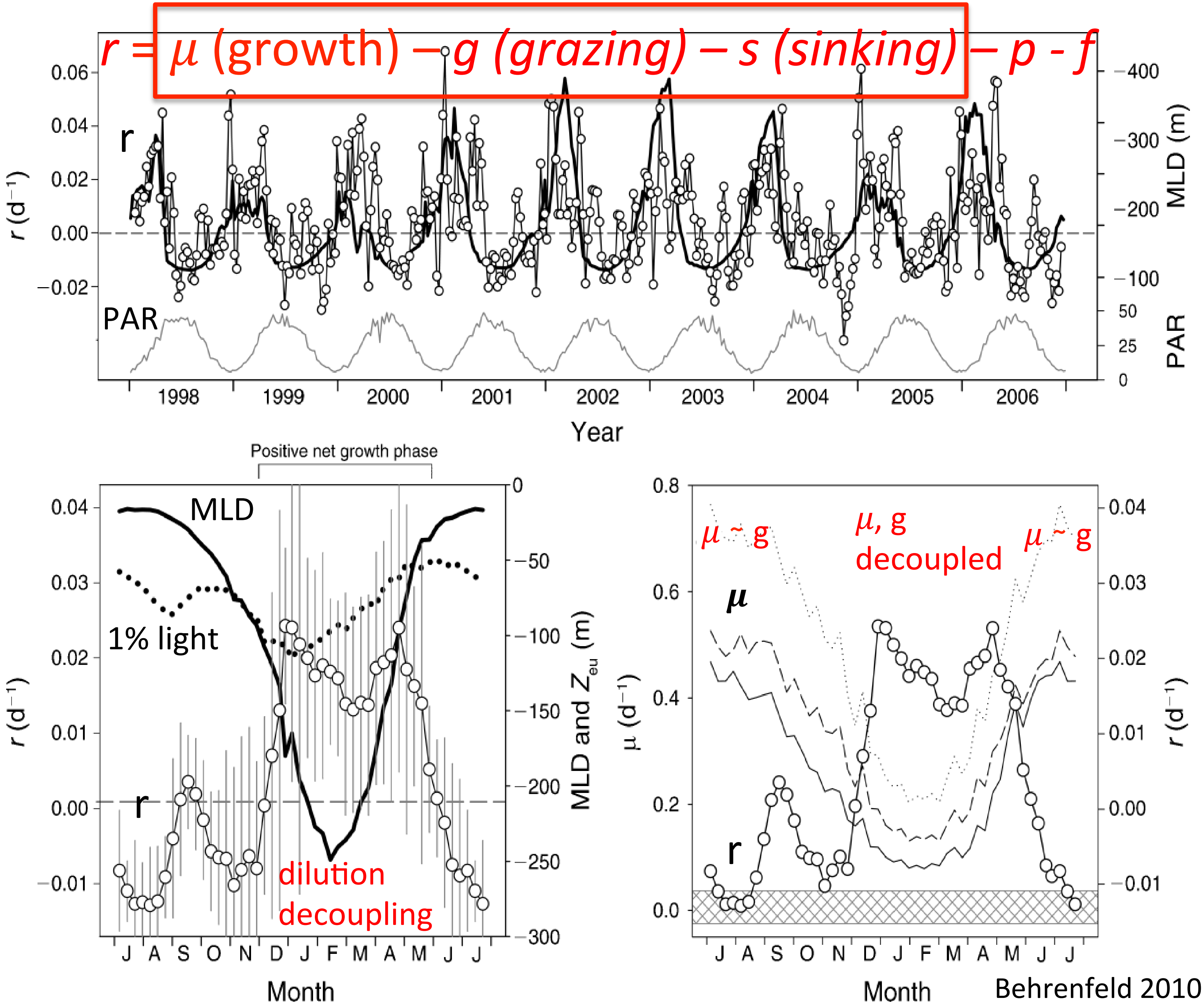
Decoupling Growth & Grazing – Blooms in Deep Wintertime Mixed Layers

Behrenfeld 2010

Chl grows through winter, under deep MLD.



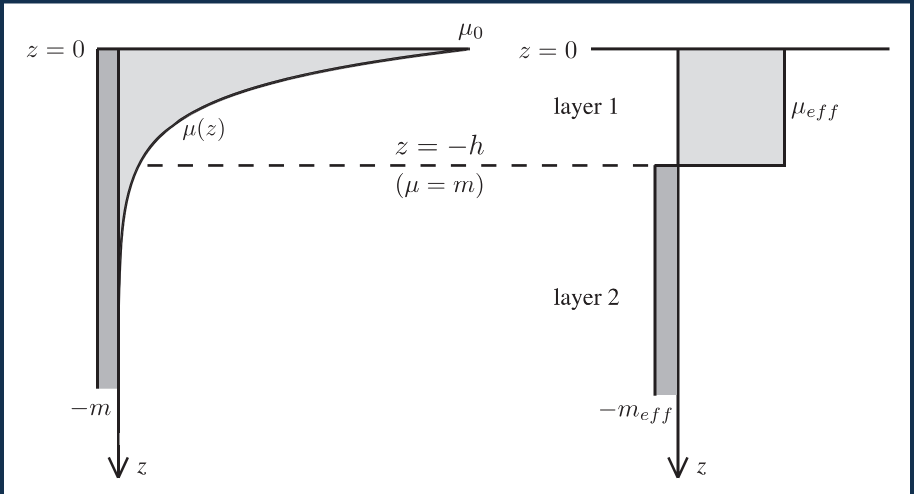




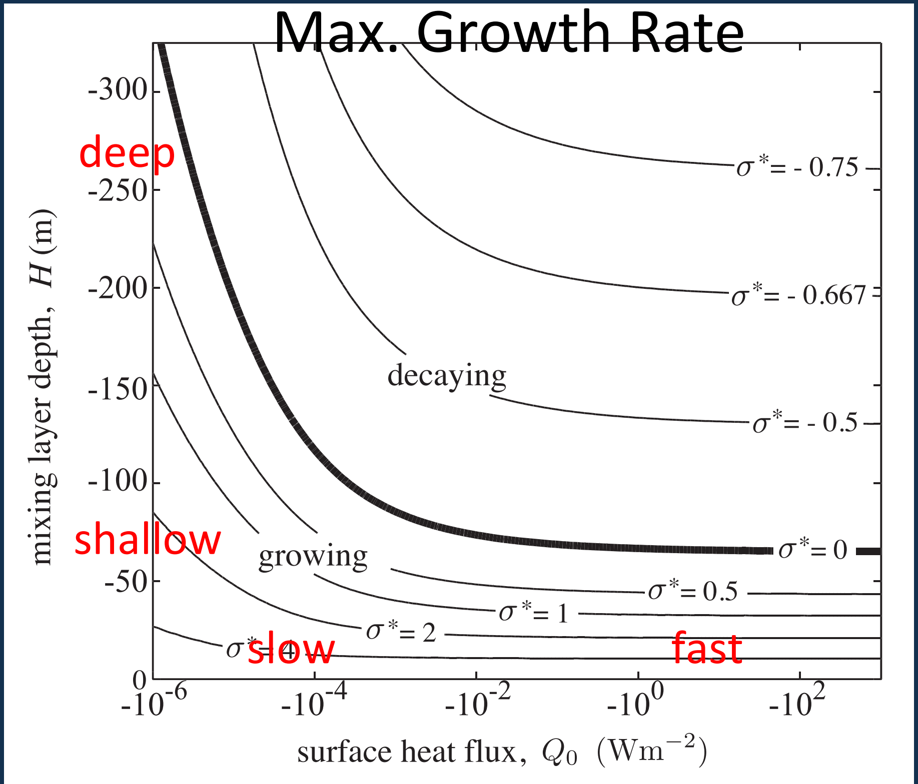
Behrenfeld 2010

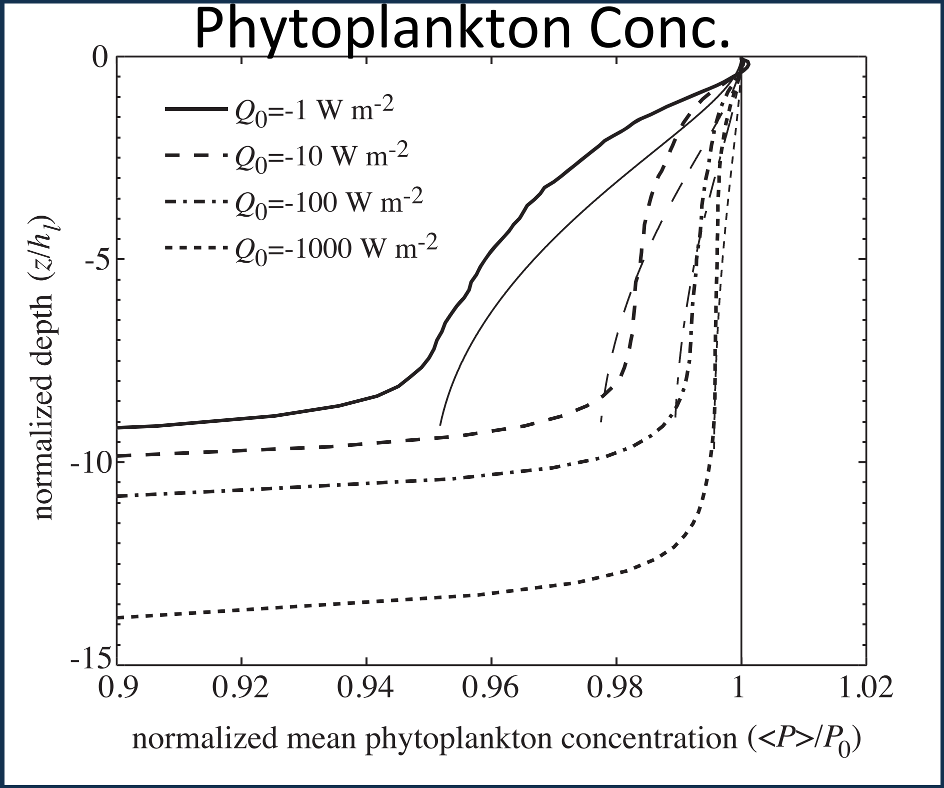
Blooms Initiated by Weakening Mixing

Taylor and Ferrari 2011

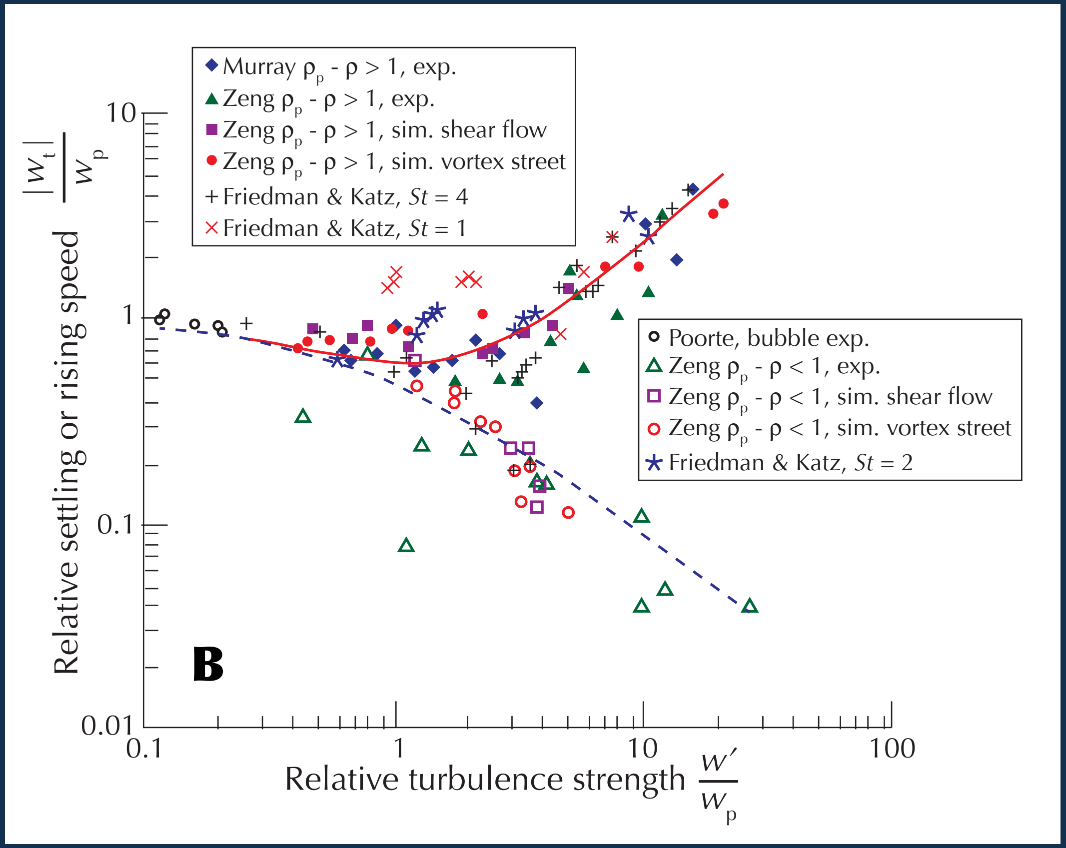


Mixing at timescales longer than growth/loss timescales provides residence times in euphotic zone long enough for growth.





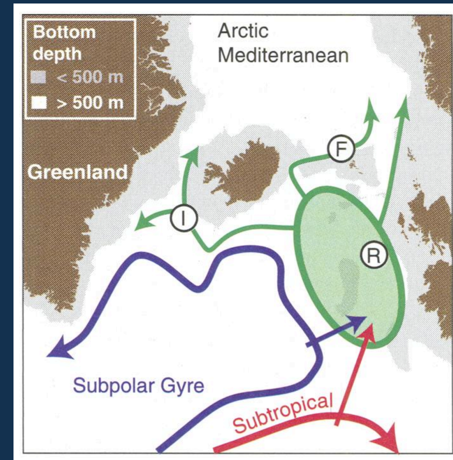
Other Impacts of Ocean Turbulence



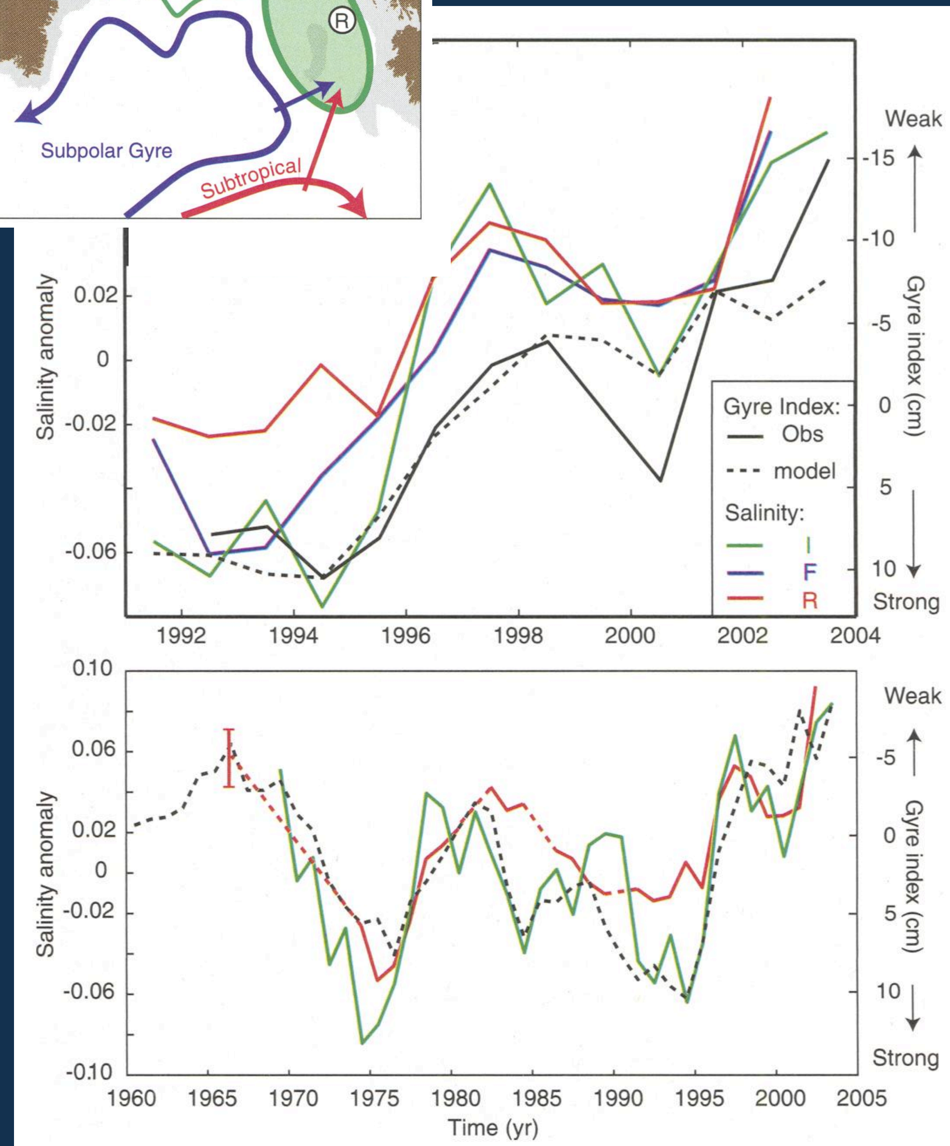
Jumars and Karp-Boss, 2013

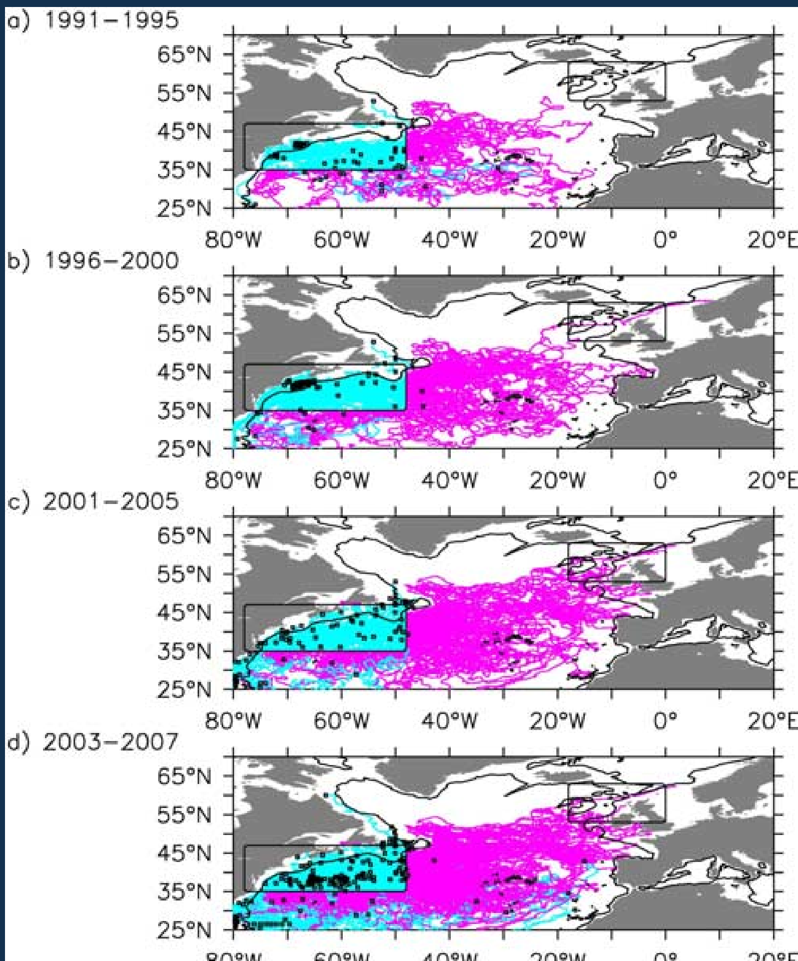
- Particle sinking rates.
- Aggregate formation.
- Predator-prey encounter rates

Shrinking Subpolar Gyre- Increased Penetration of Subtropical Waters



Hatun et al., 2005

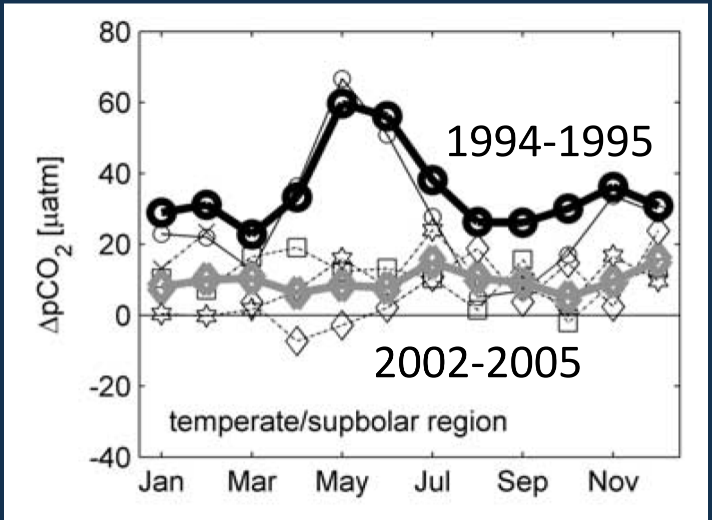


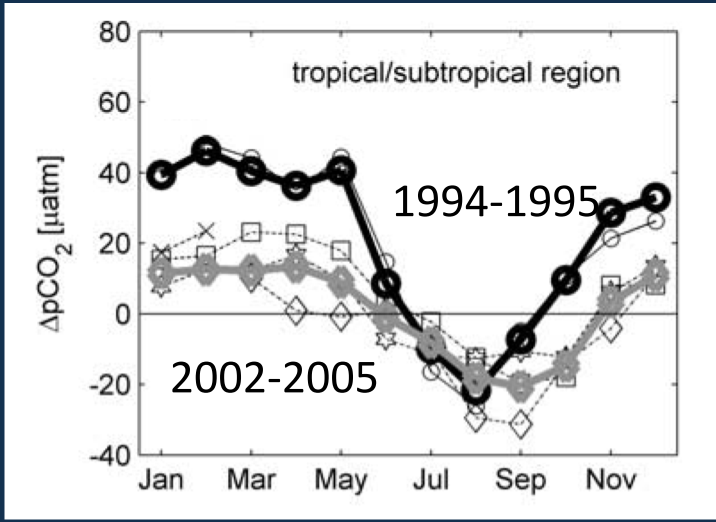


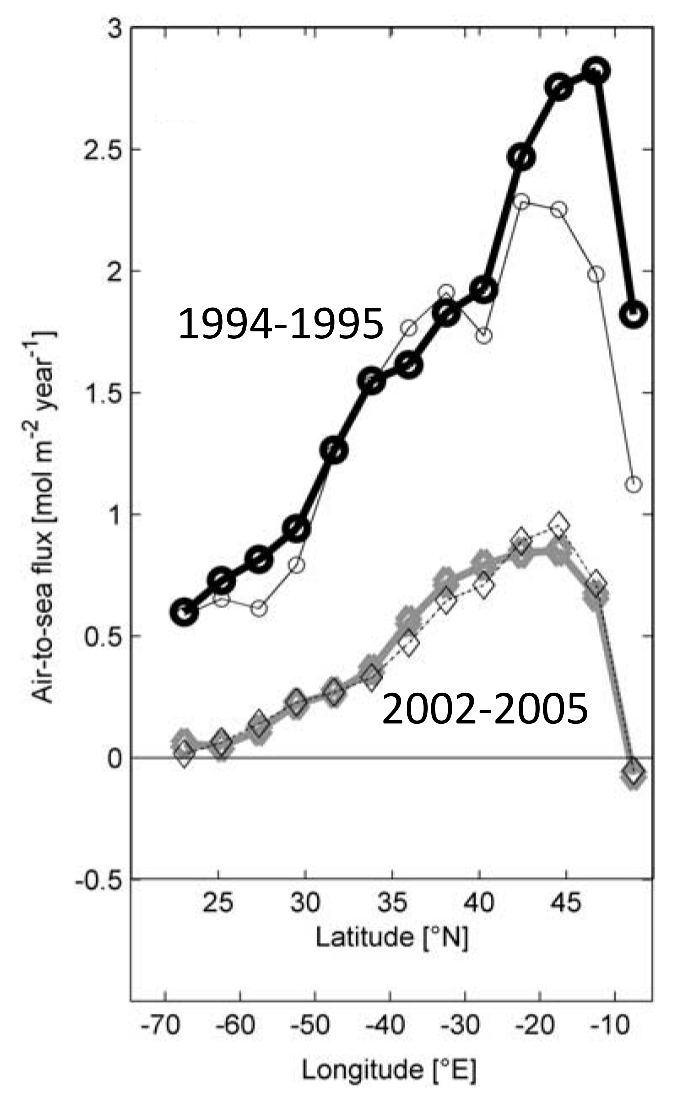
Hakkinen and Rhines, 2009

Decrease in N. Atlantic CO_2 Uptake

Schuster and Watson, 2007

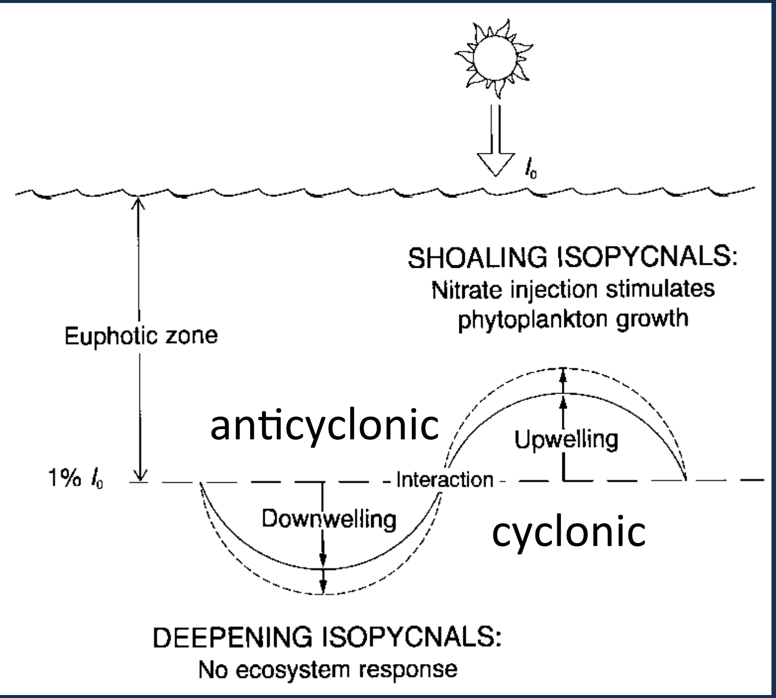


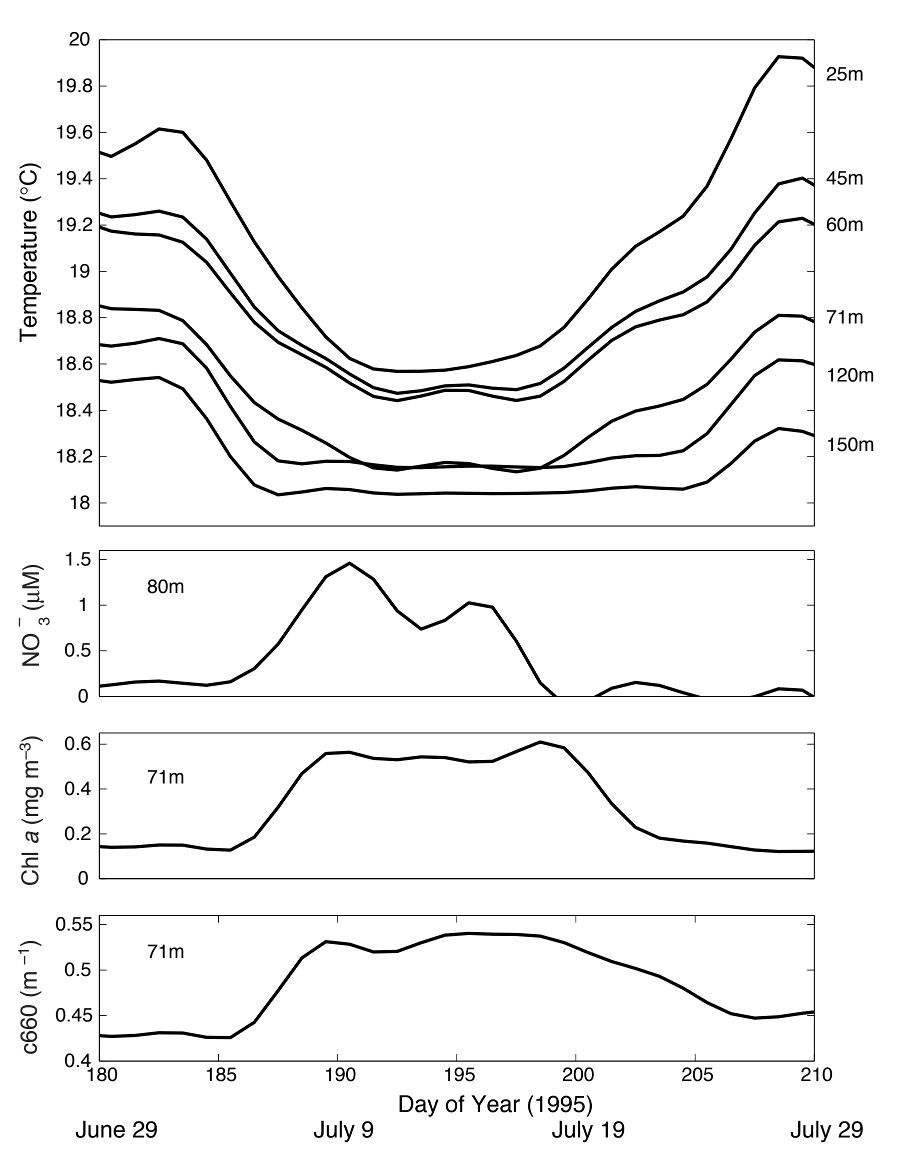




- Increased stratification - weakening wintertime mixing and ventilation.
- Warming sea surface temperatures.

Pumping by Mesoscale Eddies

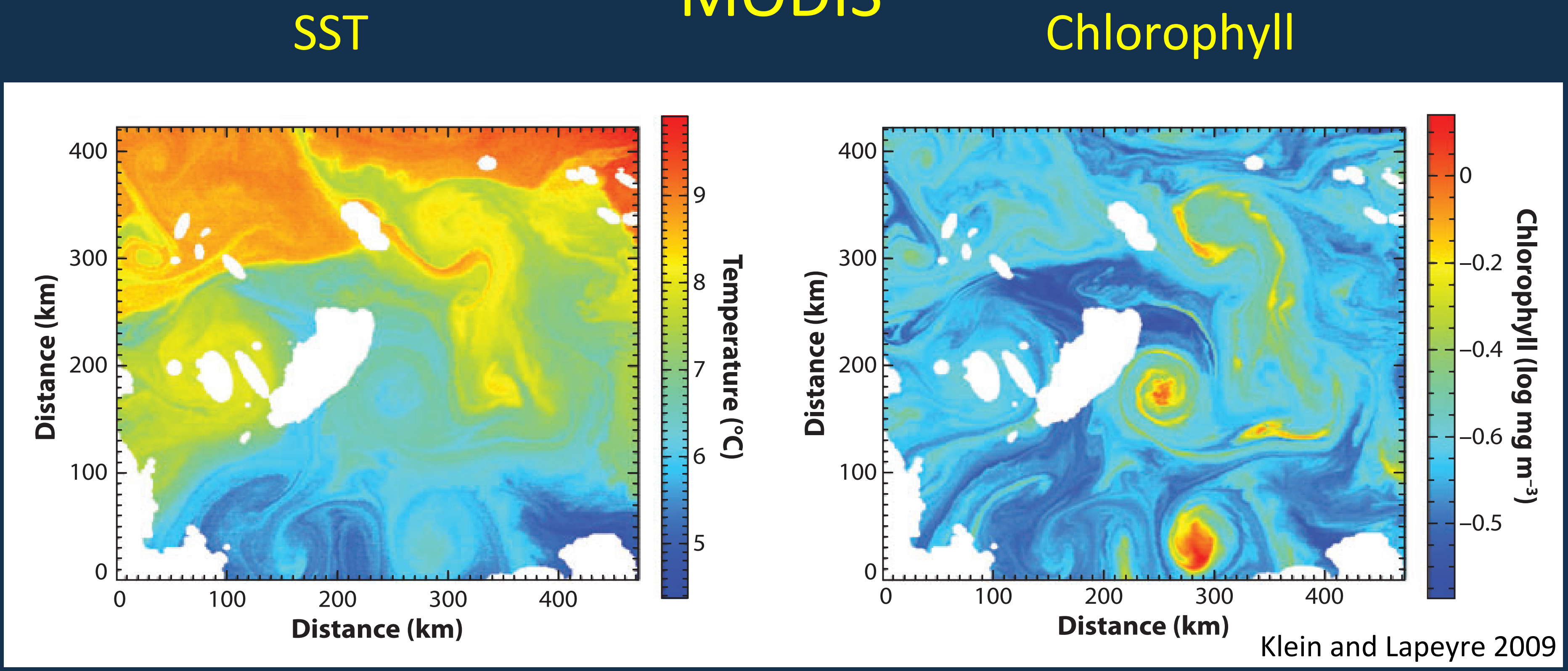




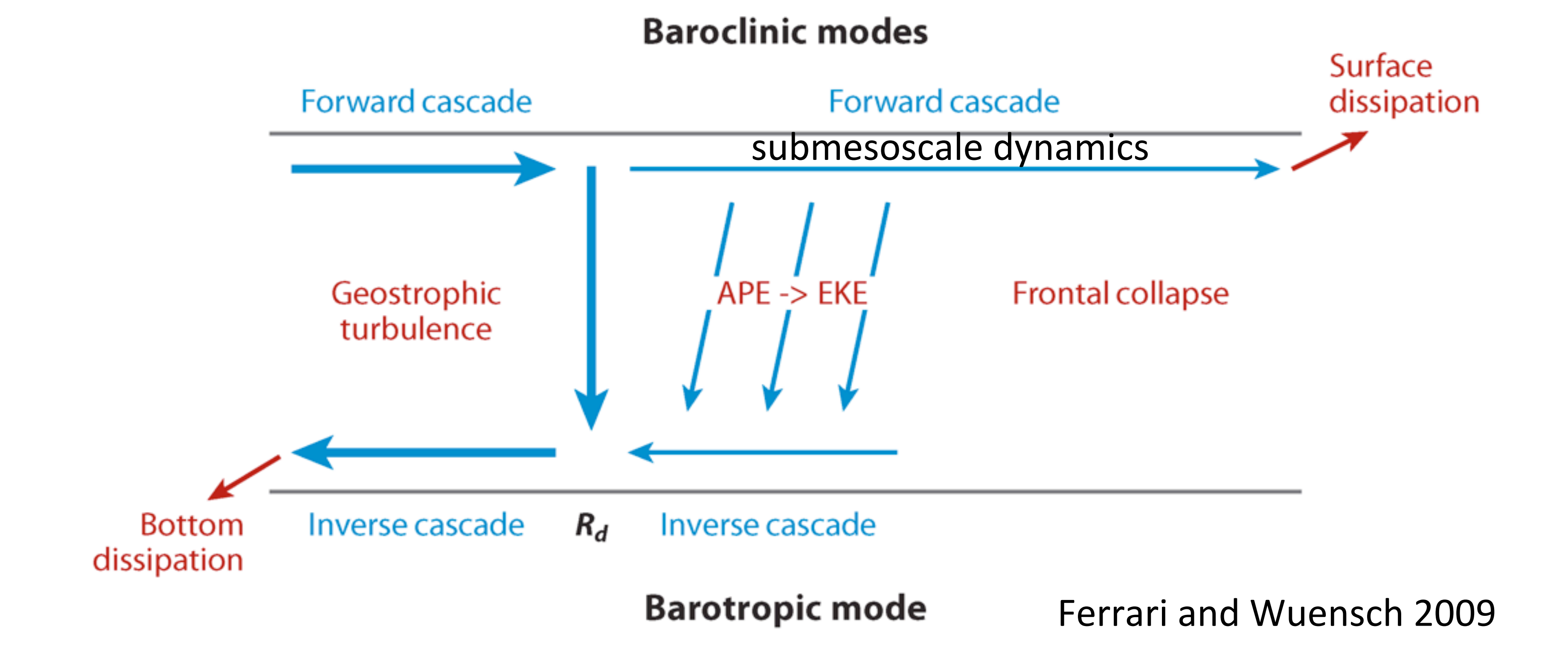
- Geochemical estimates of new production roughly twice nutrient input by wintertime convection.
- Mesoscale pumping ~30% of shortfall.
- What accounts for the rest...?

McGilliccudy et al.2007

MODIS

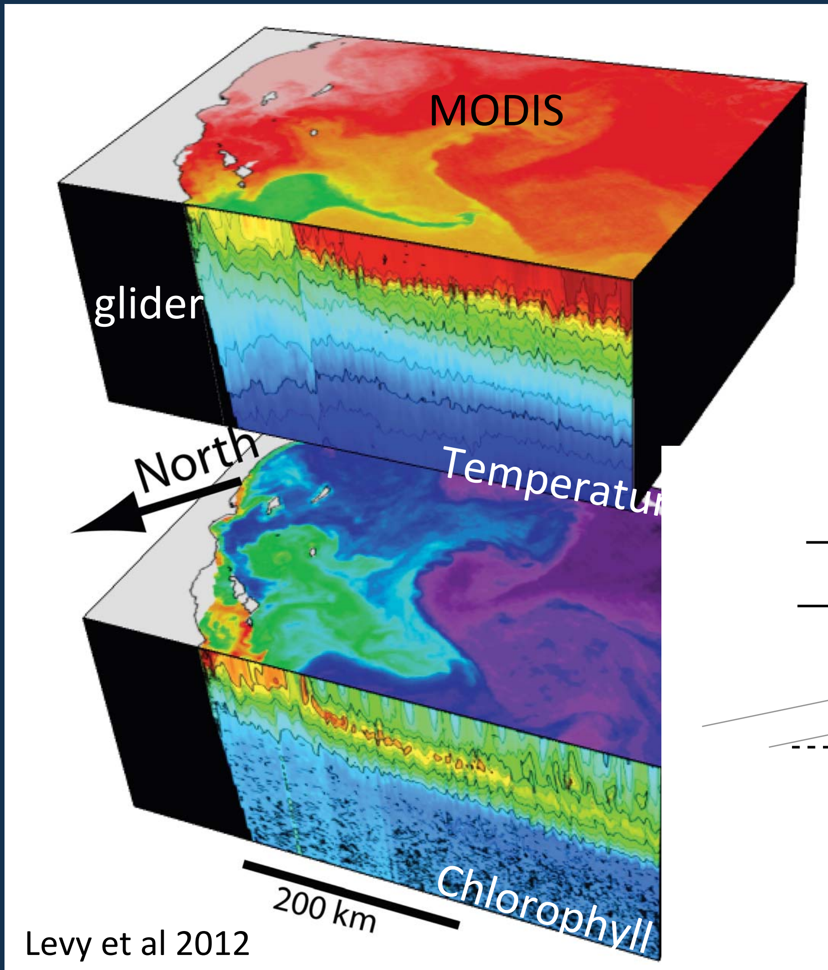


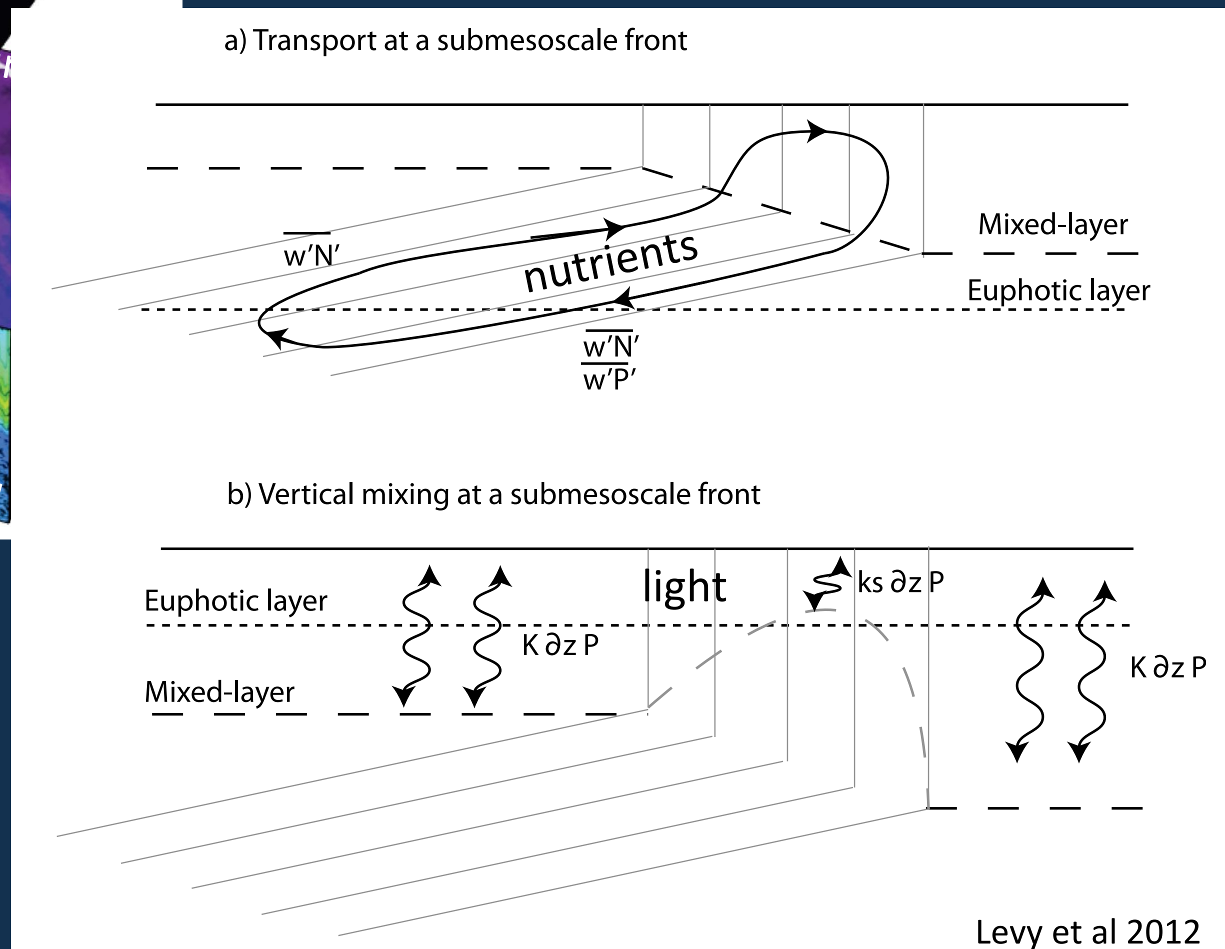
- Eddy interiors can exhibit elevated chlorophyll.
- Eddy boundaries, mesoscale fronts show *submesoscale* structures 100 m – 10 km. Fronts, filaments, eddies. Elevated chlorophyll.



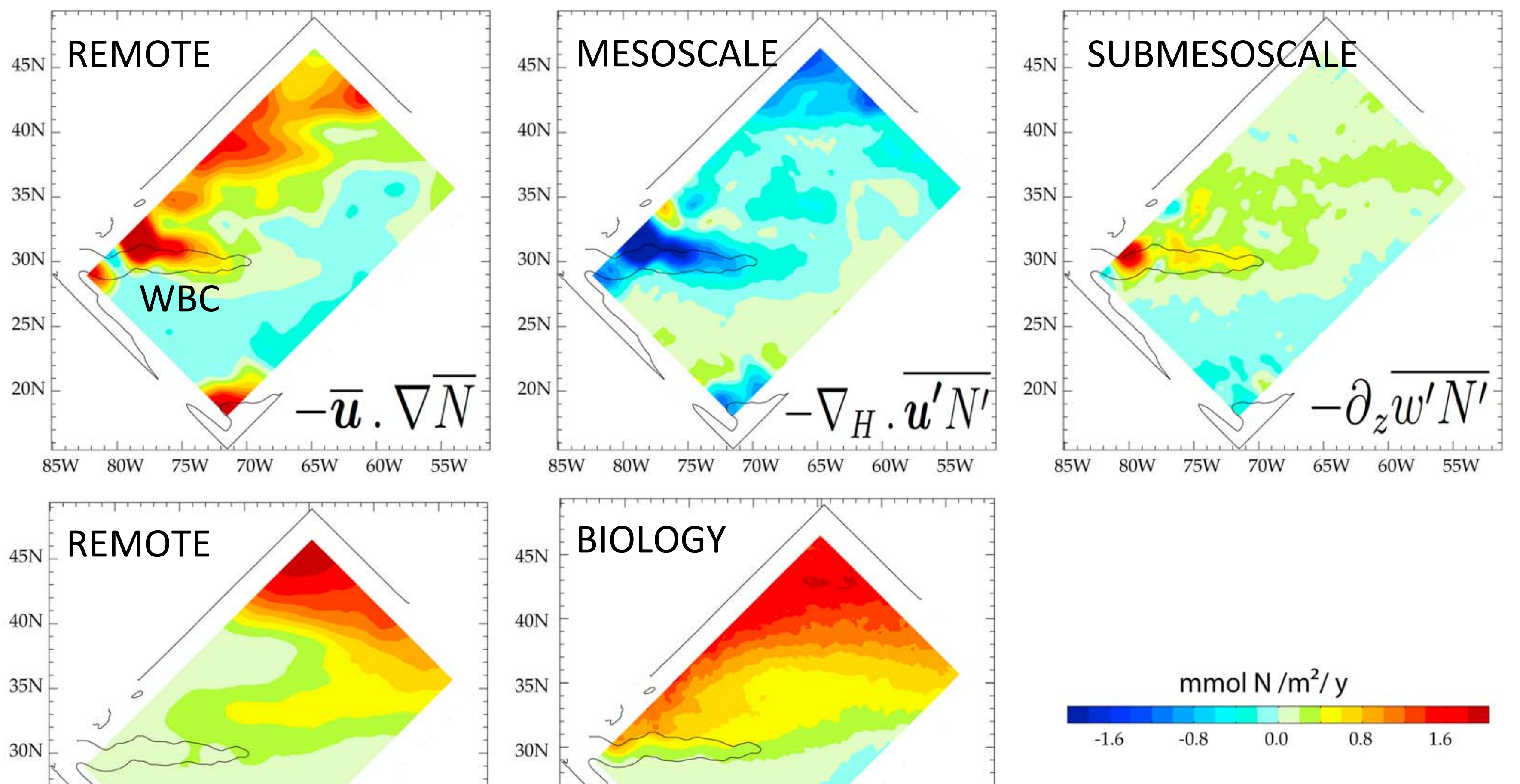
- Submesoscale frontal dynamics bridge mesoscale to dissipative scales to provide path for forward cascade.
- Very efficient at driving vertical exchange, communicating between boundary layer and interior.
- Simulation possible in regional and smaller models. Must parameterize for large-scale circulation and bio-physical simulations.
- Tight coupling between theory, numerical simulation and observations. Led by theory and simulations…

Submesoscale Isopycnal Advection and Mixing





Regional Simulation: Annual-Average Nitrate Budget (euphotic zone)



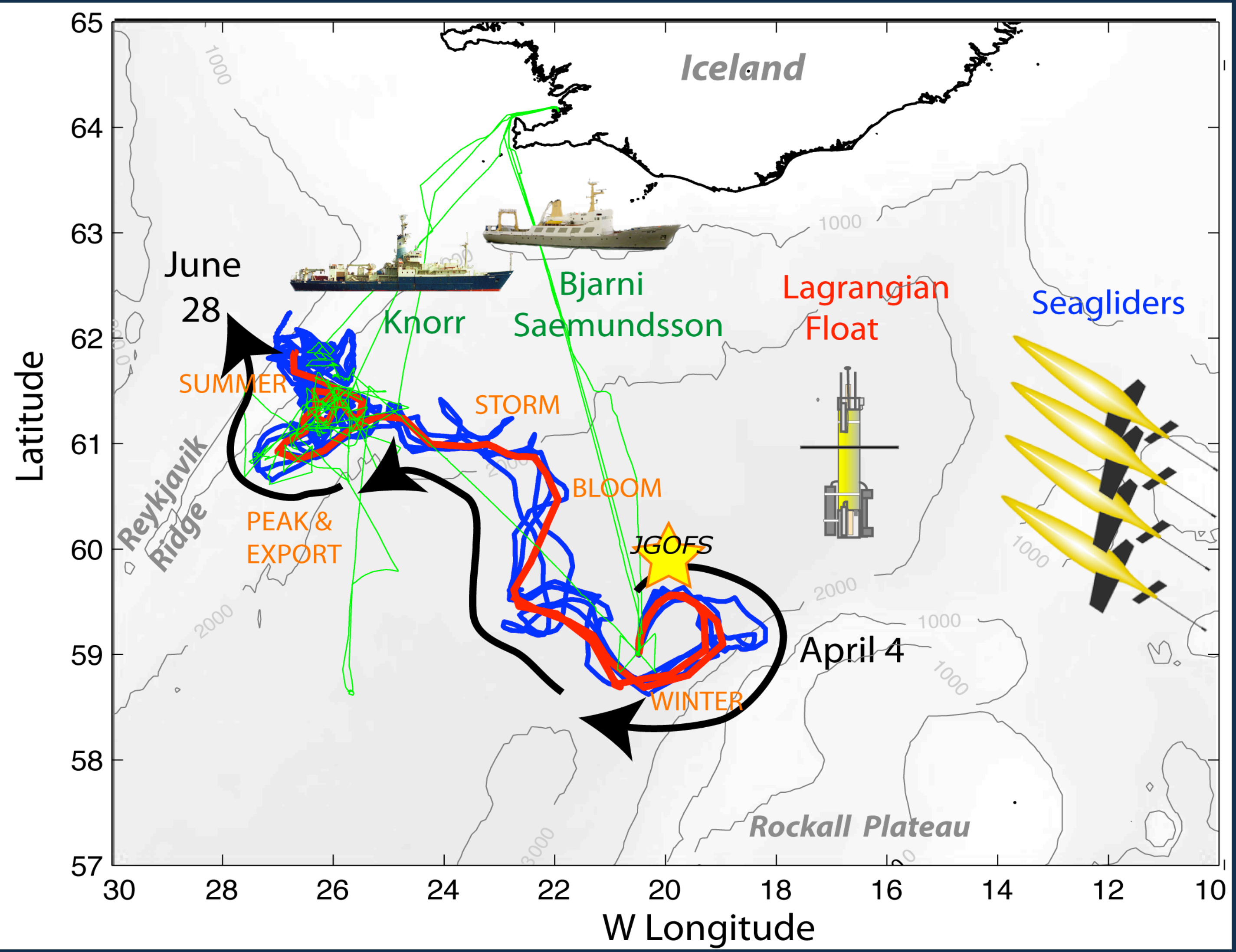
$$\int_{1year}\int_{z=0}^{Zeupho}\Big[\underbrace{-\overline{u}.\nabla\overline{N}}_{remote}-\underbrace{\nabla_H\cdot\overline{u'N'}}_{mesoscale(local)}-\underbrace{\partial_z\overline{w'N'}}_{submesoscale(local)}+\underbrace{\partial_z(\overline{k_z\partial_z N})}_{remote}\Big]dzdt=\int_{1year}\int_{z=0}^{Zeupho}\underbrace{\overline{B(N)}}_{biology}\,dzdt.$$

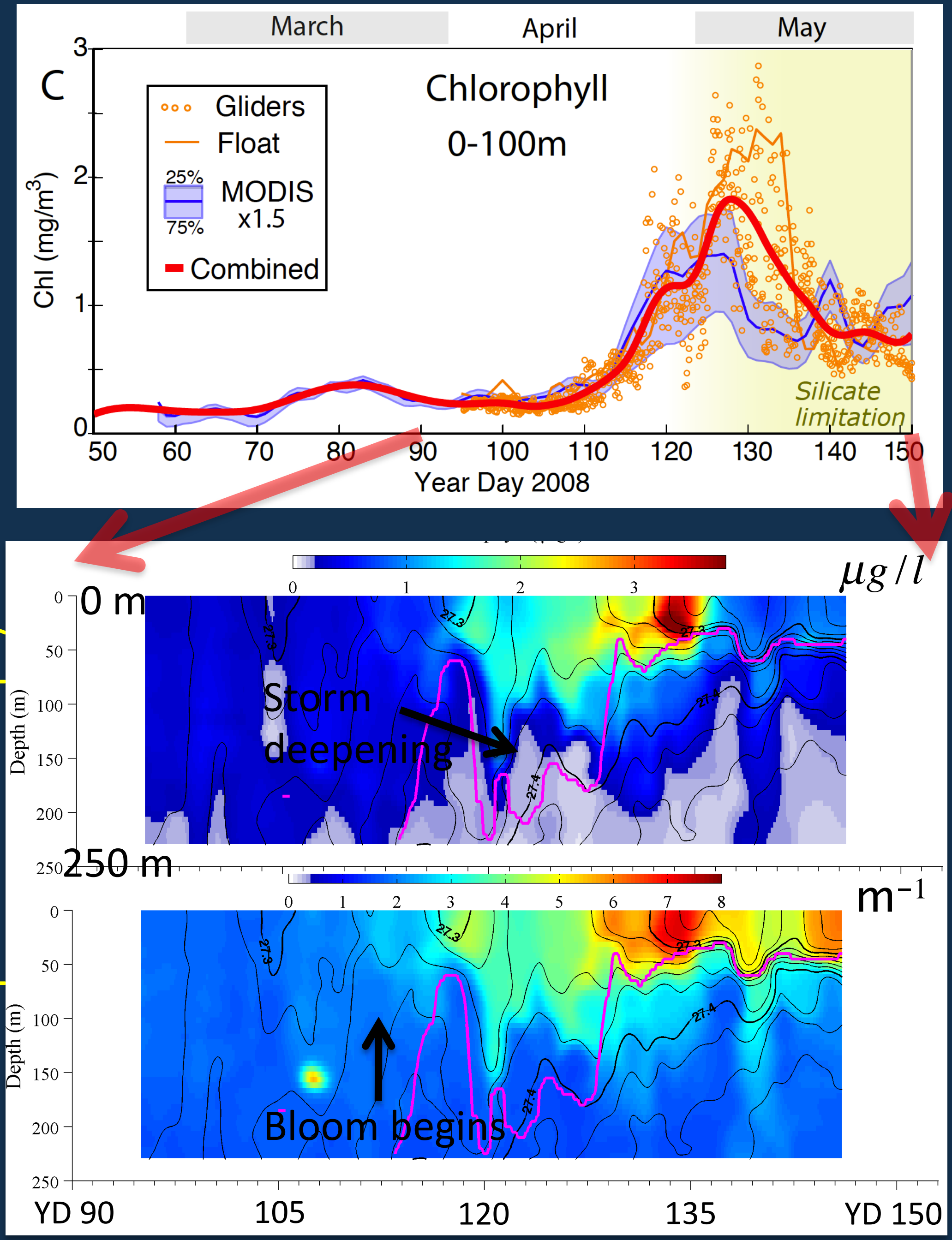
Submsosocale-resolving regional simulation.

Levy et al. 2012

Patch-Scale Dynamics in the Subpolar North Atlantic Spring Bloom – NAB08

Craig M. Lee, Eric A. D'Asaro, Mary Jane Perry, Katja Fennel

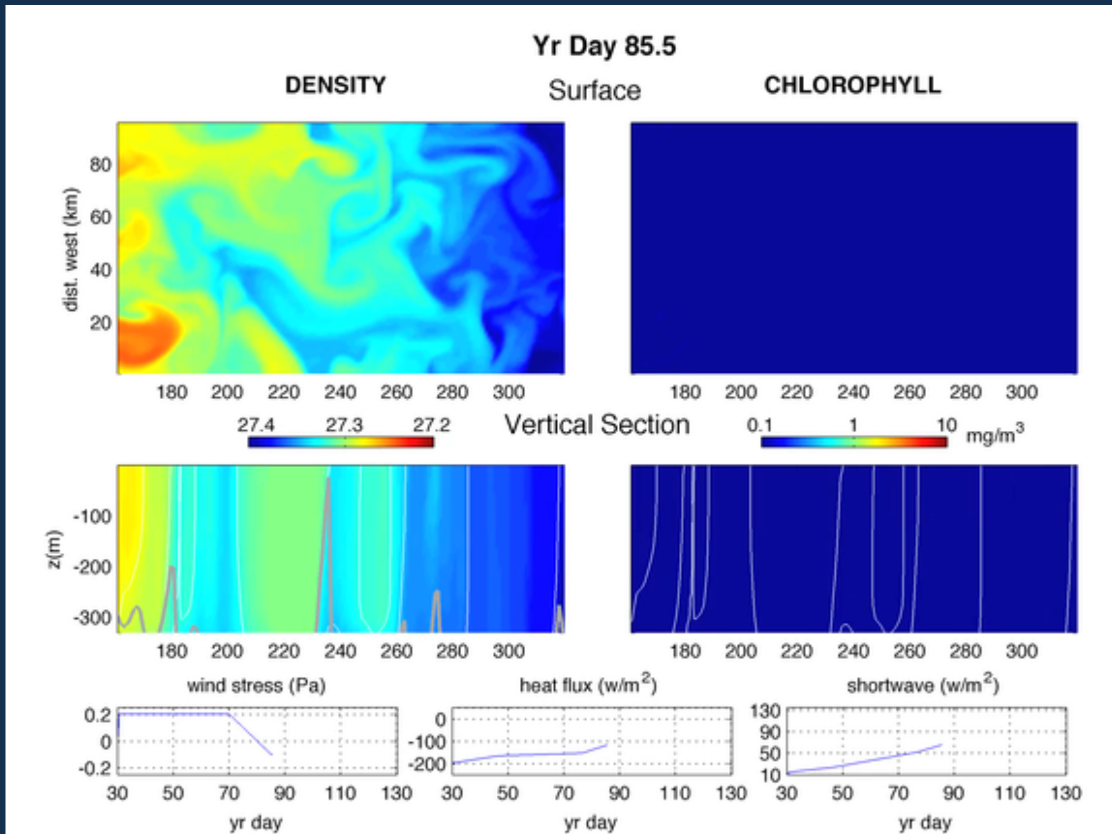


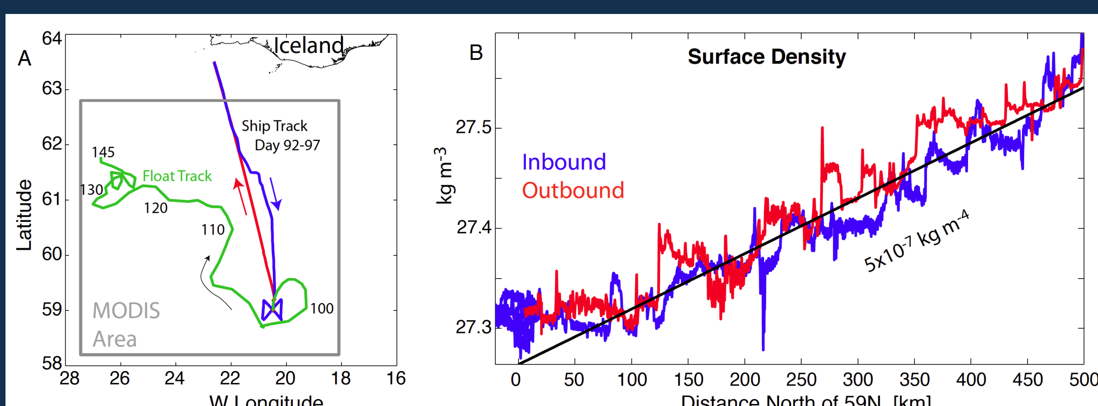


Evolution Following the Float

- ML shallows rapidly and bloom begins YD 110.
- Backscatter and beam attenuation rise.
- Dissolved oxygen concentration rises, ML nitrate decreases.
- Previous studies (e.g. Waniek 2003; Henson et al. 2006) attribute ML restratification to solar warming, but…
- ML cools during bloom initiation.
- What initiates ML stratification?

Eddy-Driven Restratification





Submesoscale (1-10 km) ML eddies 'slump' lateral density gradients.

Converts horizontal density contrasts to vertical stratification.

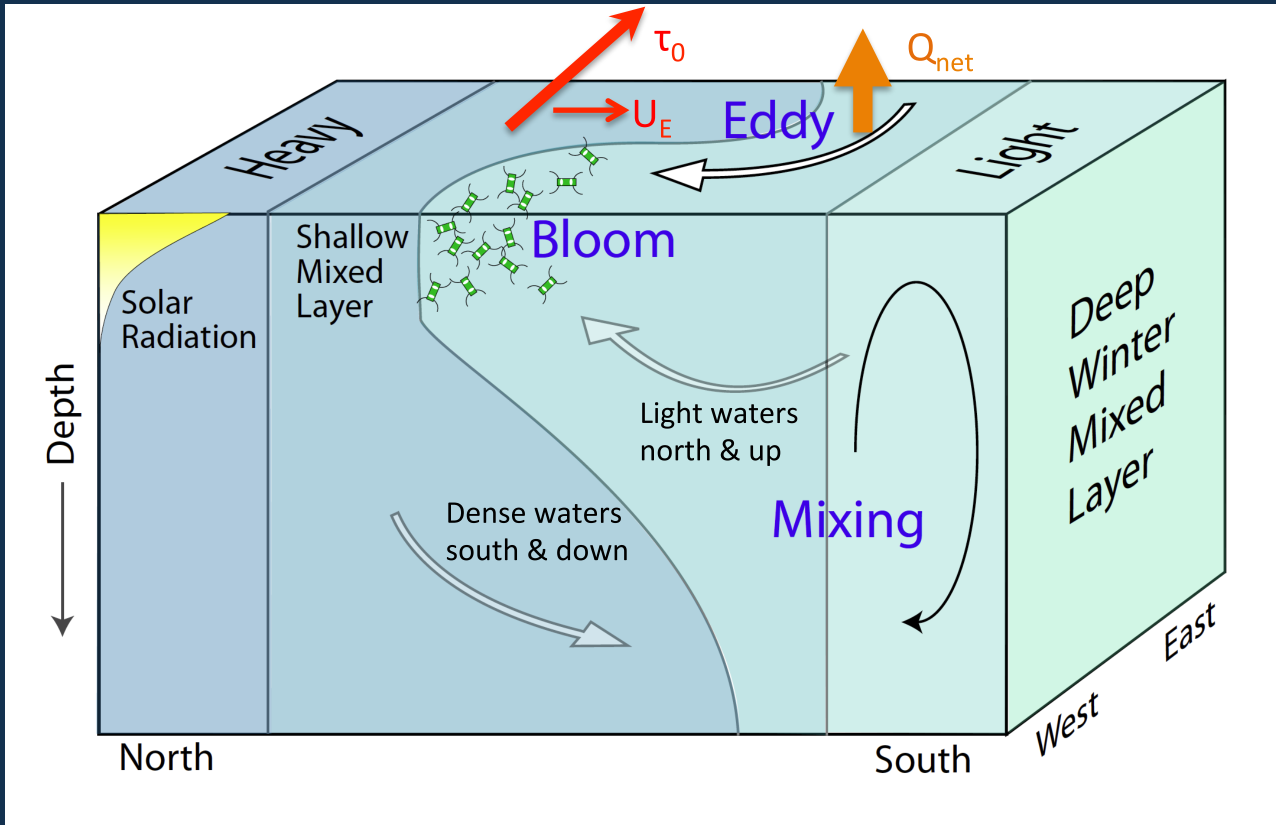
Boccaletti et al, 2007
Fox-Kemper et al. 2008

Buoyancy flux driven by ML eddies:

$$F_{MLE}^{B} \propto \left(b_y H\right)^2$$

> Vertical mixing opposes ML eddy restratification, deepens ML.

Mahadevan el al. 2012



Stratifying buoyancy flux driven by ML eddies:

$$F_{MLE}^{B} \propto \left(b_y H\right)^2$$

Vertical mixing opposes ML eddy restratification, deepens ML.

- Surface cooling
- Wind forcing

Drive destratifying buoyancy flux.

Surface Cooling

Convective overturning.

Destratifying/Stratifying buoyancy flux:

$$F_{Q}^{B} \big/ F_{MLE}^{B} \propto \frac{Q_{net}}{\left(b_y H\right)^2}$$

= 1 for Q_{net} ~ -90 W/m^2

Wind Forcing

Ekman transport by down-front winds- heavy water over light, convective overturning.

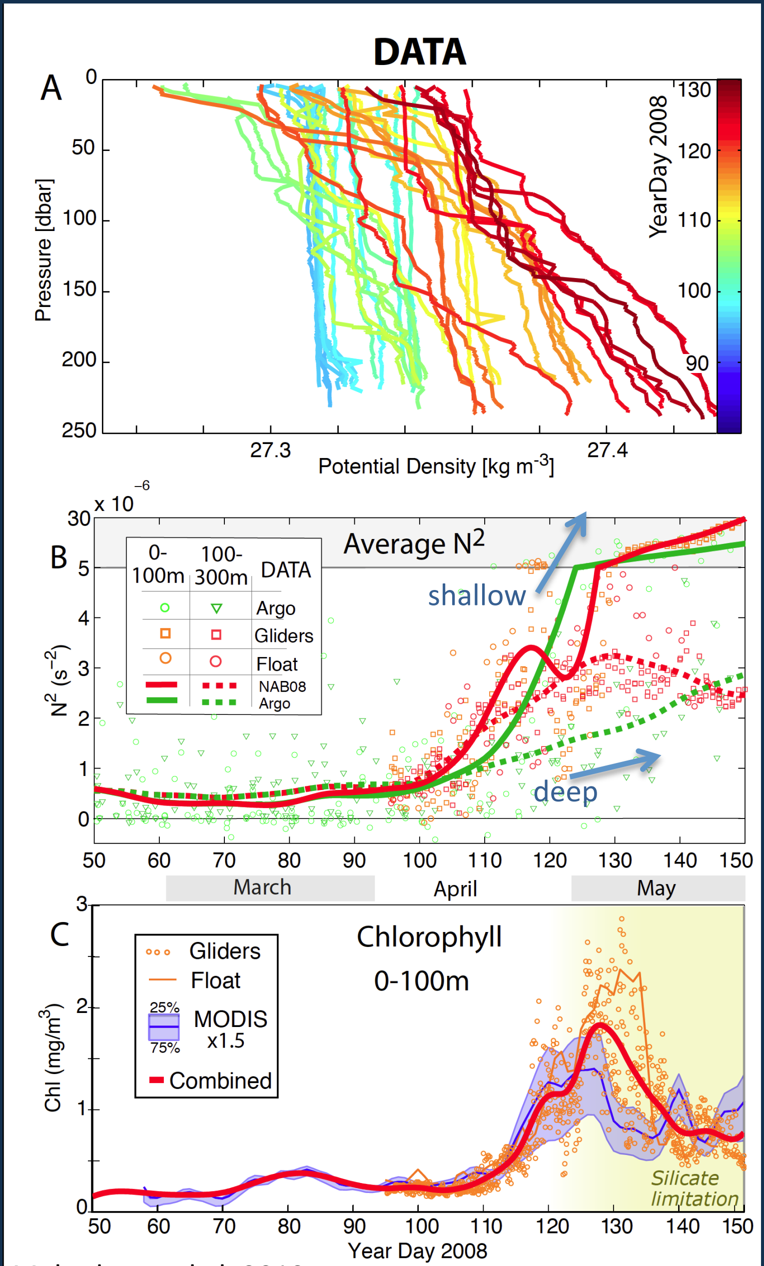
Destratifying/Stratifying buoyancy flux:

$$F_{\tau_0}^{B} \big/ F_{MLE}^{B} \propto \frac{\tau_0}{b_y H^2}$$

= 1 for τ_0 ~ 0.15 Pa

Mahadevan el al. 2012

NAB08: Observed Restratification and Bloom Onset



Mahadevan el al. 2012

Density profiles:

Vertically uniform (YD 90)

Uniform stratification (YD 110)

Some storm-driven ML deepening (YD 120)

Layers: shallow (0-100 m) & deep (100-300 m)

Initially mixed to ~300 m (before YD 100)

Stratification proceeds in 2 phases:

1. Stratifies uniformly (0-300 m) YD 100-120
   - Q_{net} cooling, τ_0 weakening
   - Magnitude consistent with slumping (conversion of lateral density gradient)
2. Shallow stratification accelerates (YD 120+)
   - Q_{net} changes sign (warming) ~ YD 120

NAB08 observations and ARGO

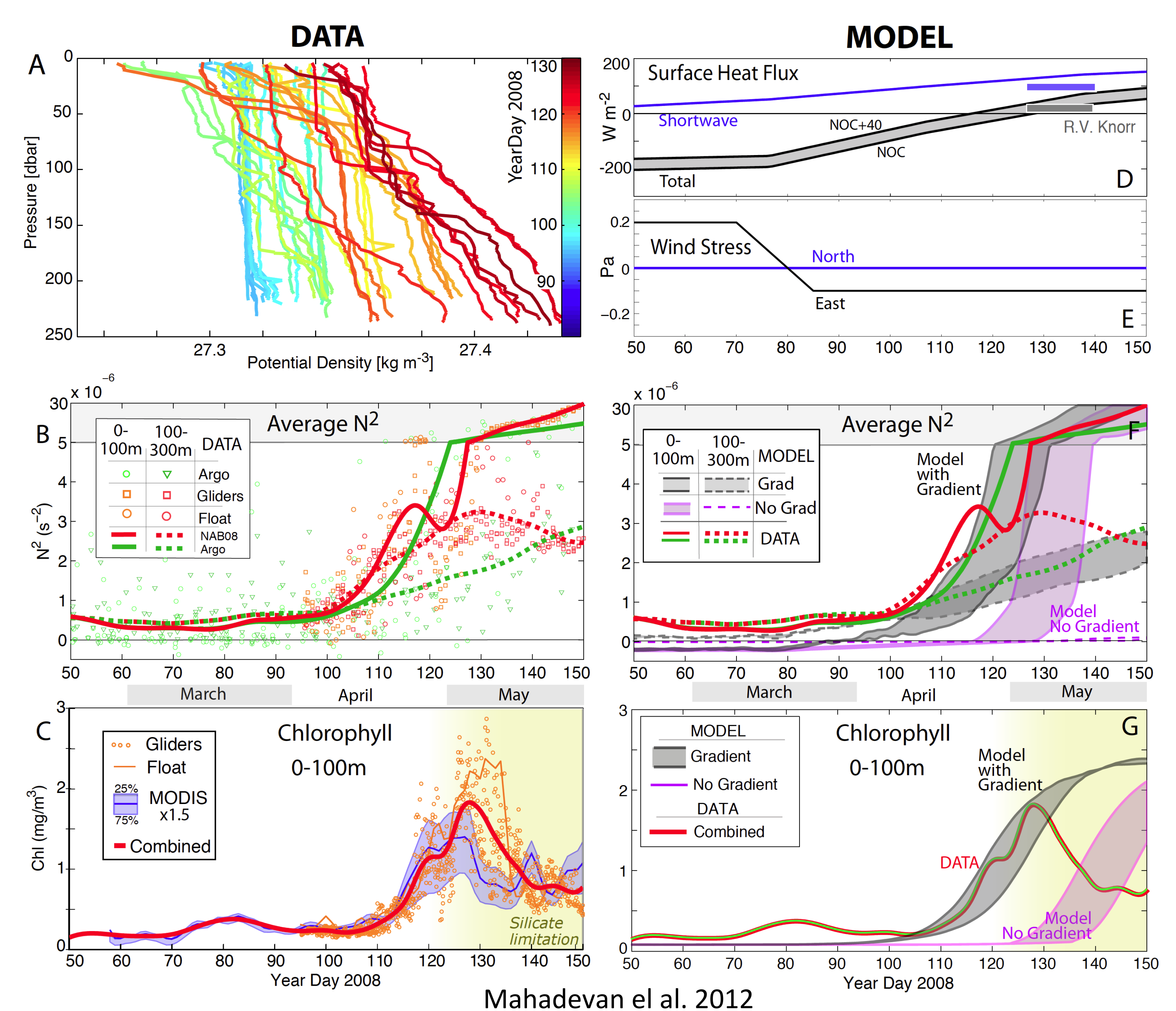
Bloom initiation:

Coupled to onset of stratification

Similar timing across all platforms

Ends when silicate is exhausted

ML Eddy Restratification: Observations and Models



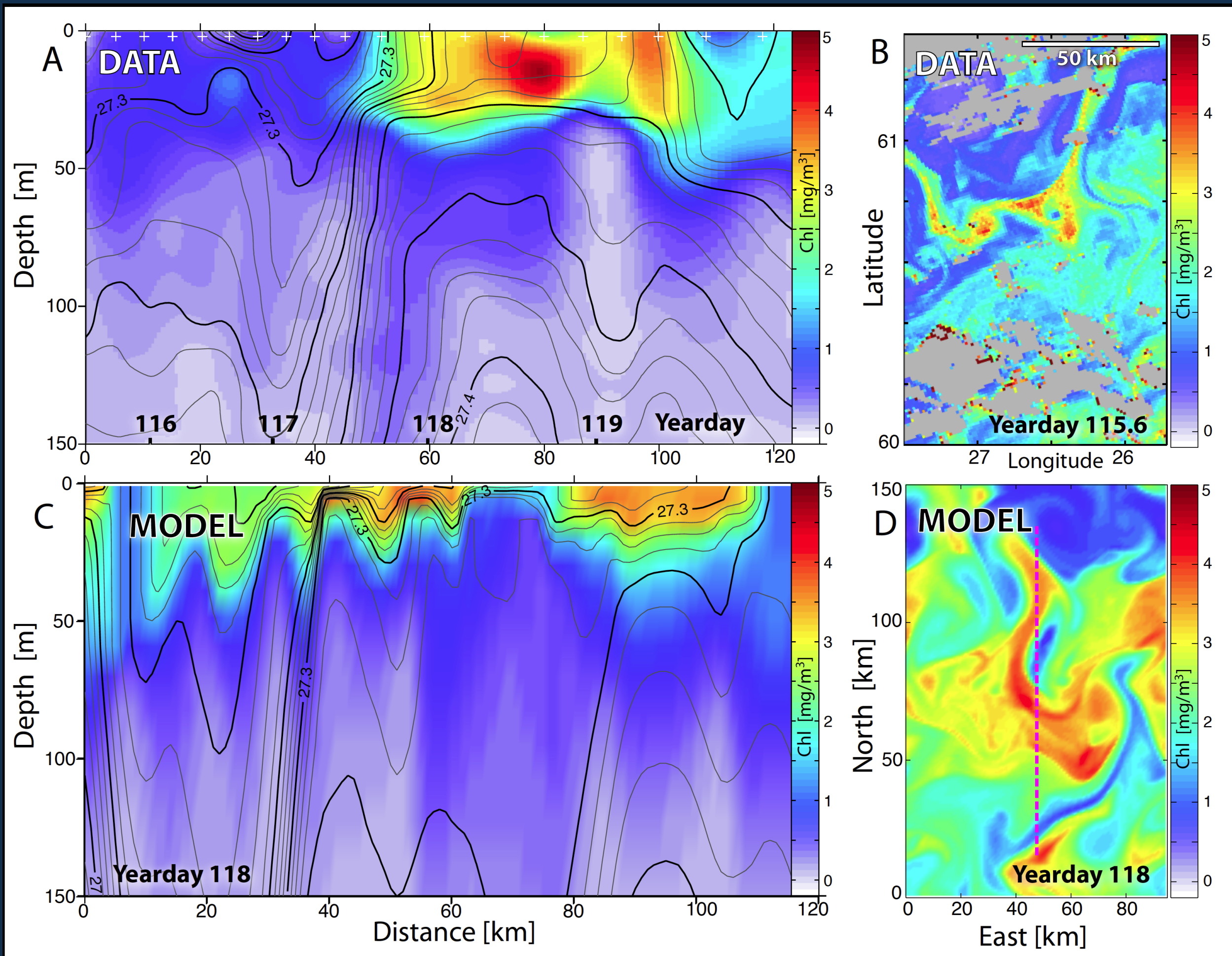
Configurations:

1. Initialized with lateral density contrasts – stratifies by Q_{net} and ML eddies
2. No initial lateral density gradients – stratifies by Q_{net} alone

Simulations with ML eddies reproduce timing and structure of restratification & bloom.

Without ML eddies, stratification and bloom delayed 20-30 days.

Why is the Bloom Patchy?



Mahadevan el al. 2012

Phytoplankton growth highest in regions of strong stratification (increased light exposure).

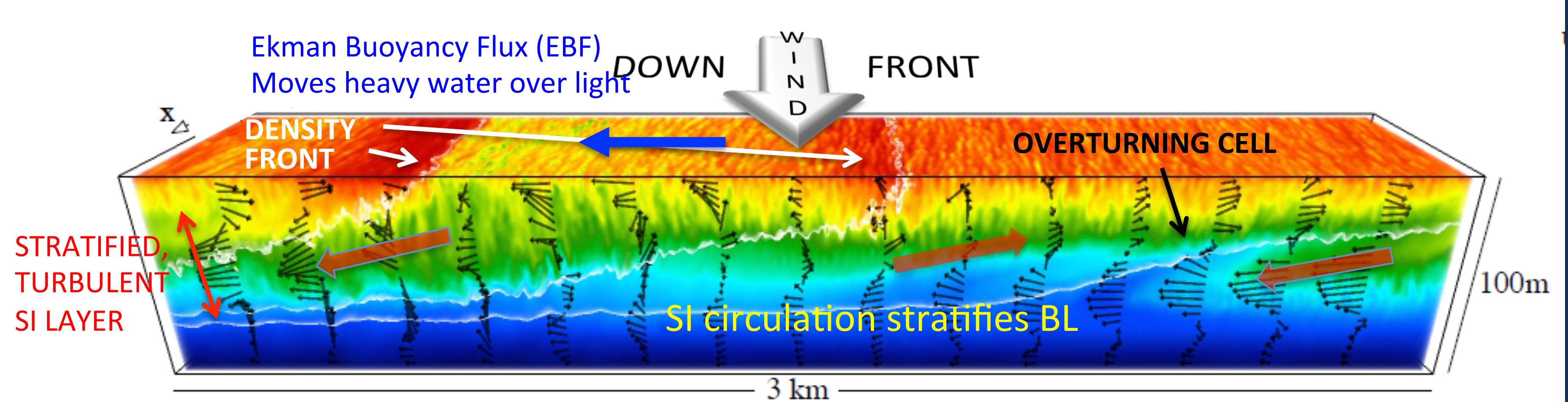
Stratification controls bloom patchiness…. Scales and shapes contain information about dominant processes.

Solar warming should act uniformly over large scales.

ML eddies produce patchy (1-10 km) stratification, straining into elongated filaments. Consistent with NAB08 observations & simulations.

Other factors (e.g. differential nutrient supply, grazing) also drive patchiness.

Models and Theory → Symmetric Instability



Thomas and Taylor

- Boundary layer stratified

- Ertel Potential Vorticity (PV) < 0

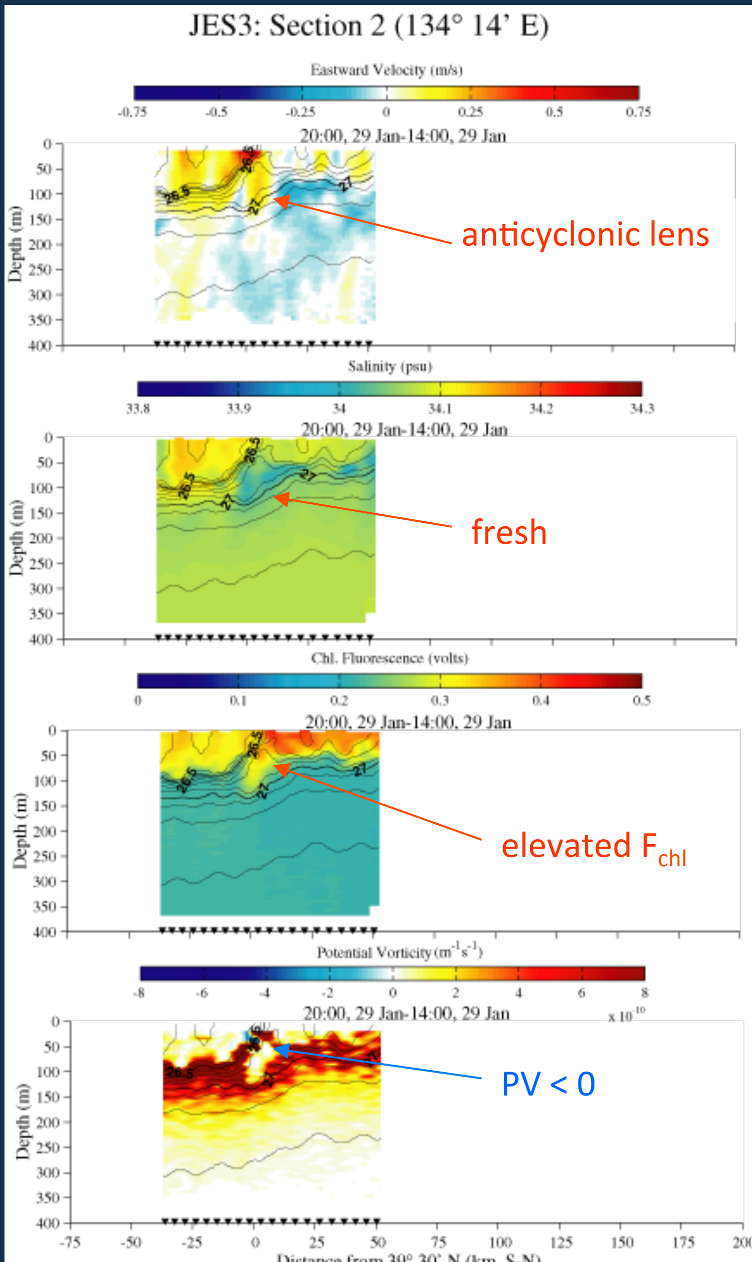
$$PV = -\frac{1}{\rho}\left[\underbrace{(f+\zeta)\frac{\partial \sigma_\theta}{\partial z}}_{\text{absolute vorticity}} + \underbrace{\frac{\partial u}{\partial z}\frac{\partial \sigma_\theta}{\partial y}}_{\text{tilting}} \right]$$

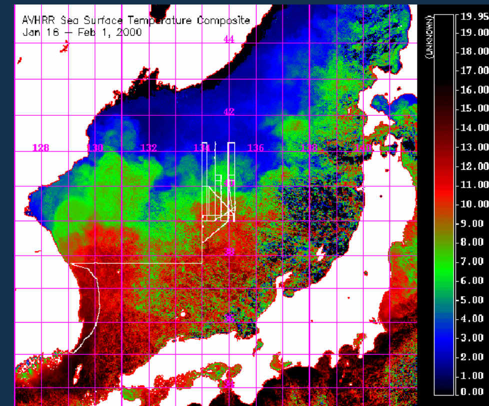
absolute vorticity: weakened by EBF

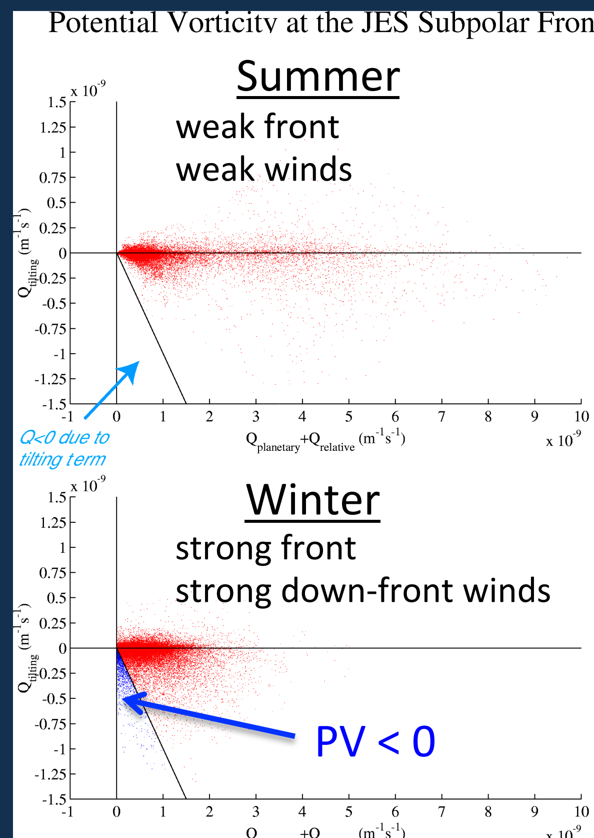
tilting: strong in surface-intensified fronts

- Extracts kinetic energy from the frontal jet (mesoscale).
- Overturning cells mix laterally along density surfaces.
- Secondary instabilities feed turbulent cascade to dissipative scales.
- <u>SI provides a path from the mesoscale to dissipation.</u>

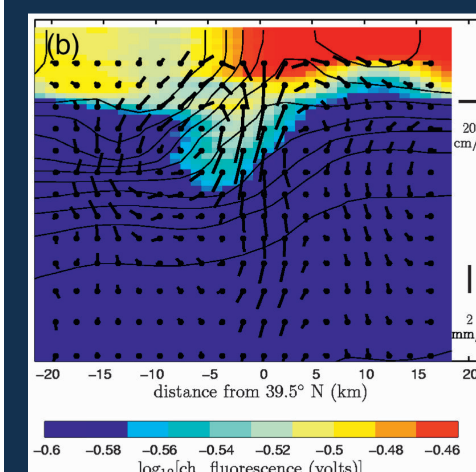
Japan/East Sea DRI- Subduction at the Subpolar Front (1998-2002)





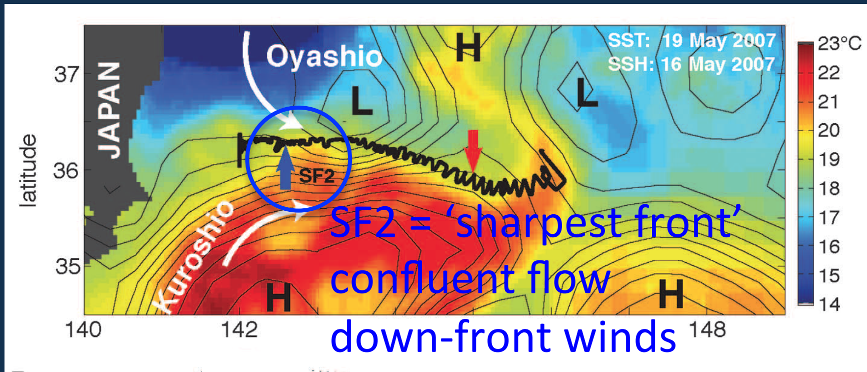


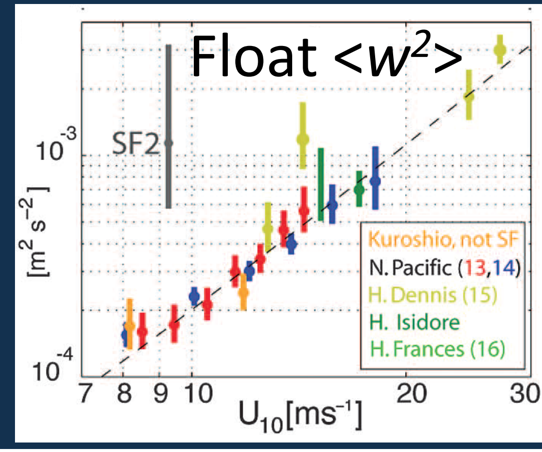
- First observations of negative PV – Symmetric Instability?
- Diagnoses of ageostrophic secondary circulations, subduction.
- Subduction, PV < 0 confined to front during forcing.



Thomas and Lee, 2005; Lee, Thomas & Yoshikawa, 2006; Thomas, Lee & Yoshikawa, 2010; Yoshikawa, Lee & Thomas, 2012

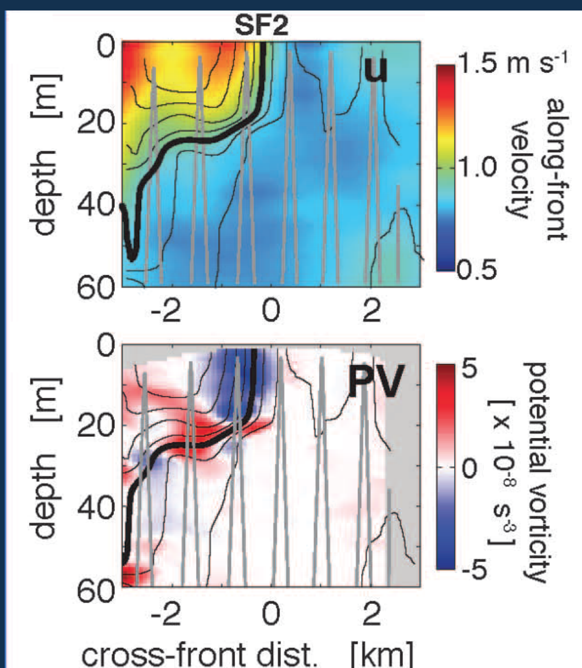
AESOP DRI – Kuroshio Extension (2005-2009)

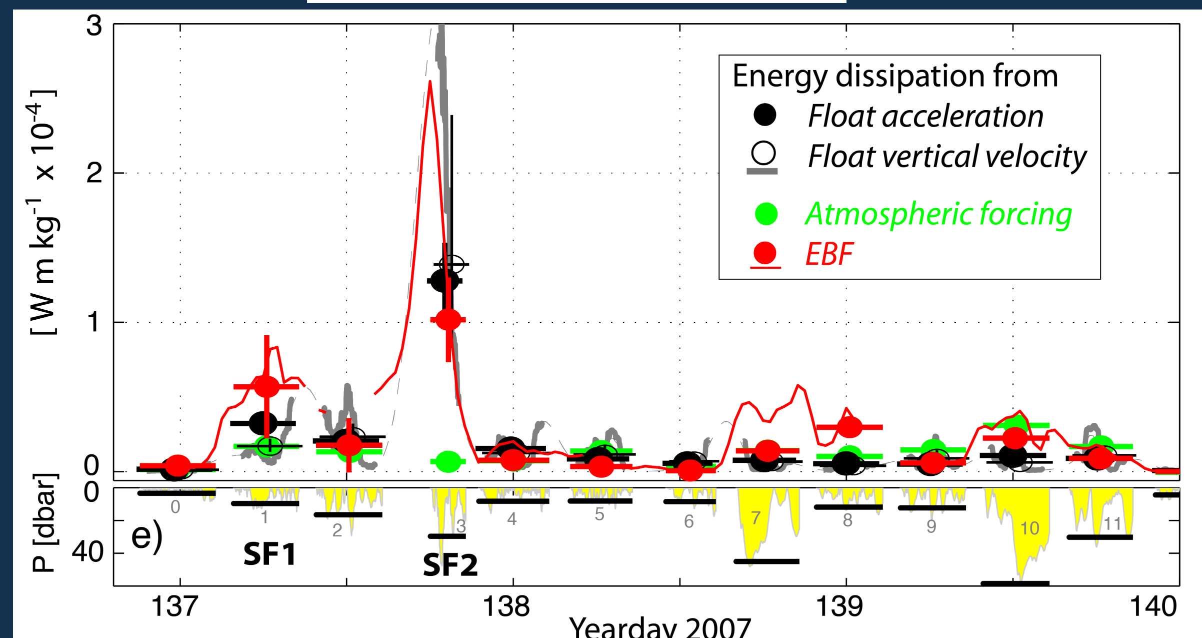




$\langle w^2 \rangle$ scales with wind *except at SF2*

PV < 0 → Symmetric Instability?

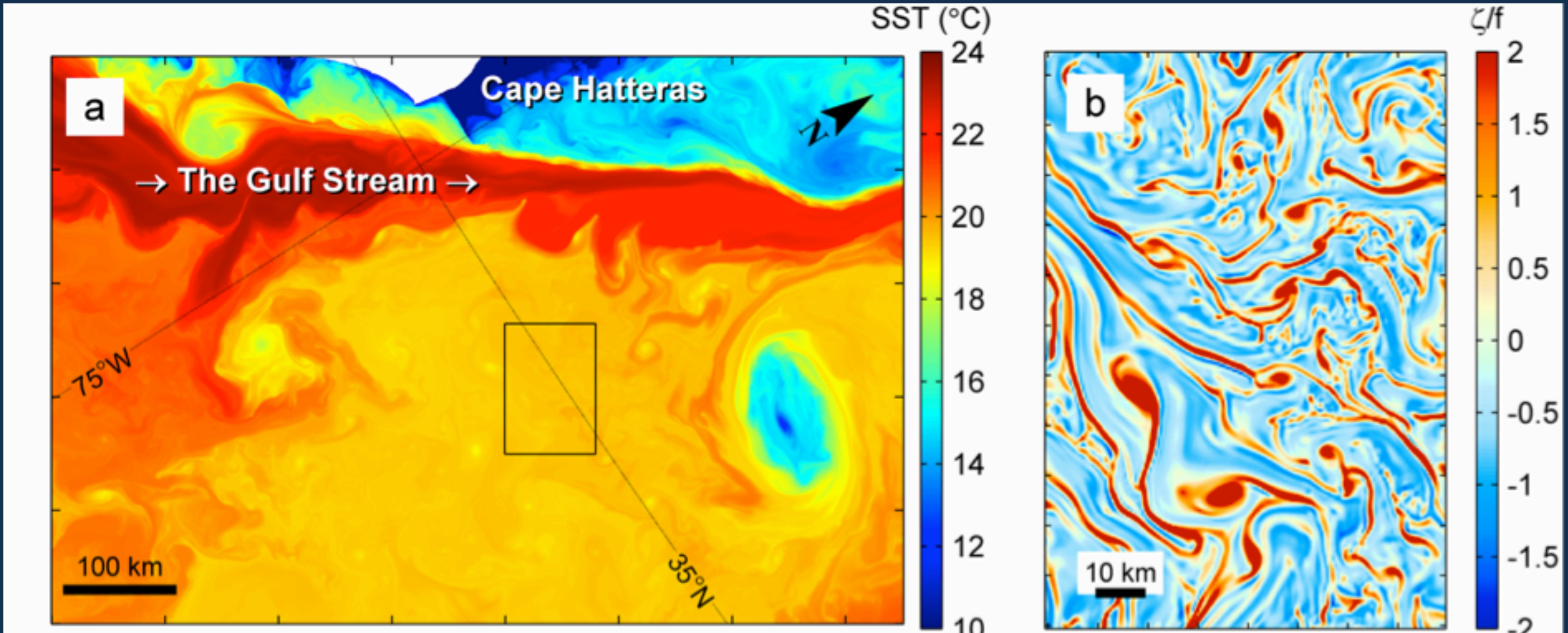




- Dissipation elevated at SF2
- Larger than atmospheric, similar to EBF.
- Energy from the front, rather than wind forcing

D'Asaro, Lee, Rainville, Harcourt and Thomas, 2010

Models and Theory → Submesoscale Turbulence



Molemaker and McWIlliams

- Submesoscale turbulence produced by instabilities in deep, wintertime mixed layers interacting with mesoscale eddies.
- Forward cascade of energy from mesocale to dissipation.
- Models depict distinctive, sinuous filaments of strong cyclonic vorticity embedded in a weak, anticyclonic background.
- Testable predictions of vorticity, divergence and strain statistics.

Challenges

- Broad range of spatial and temporal scales. Processes inherently multi-scale. Patches to basins… how do we upscale and generalize?
- Persistence – maintain observations through complete annual cycles, capture decadal shifts.
- Physical variables are easy- need matching measurements of biogeochemical and ecological parameters.
- Process experiments to refine parameterizations for models, broaden utility of remote sensing.
- Persistent observing to constrain models, detect and understand environmental change. Remote sensing and autonomous approaches.