Turbulence and the Spring Phytoplankton Bloom

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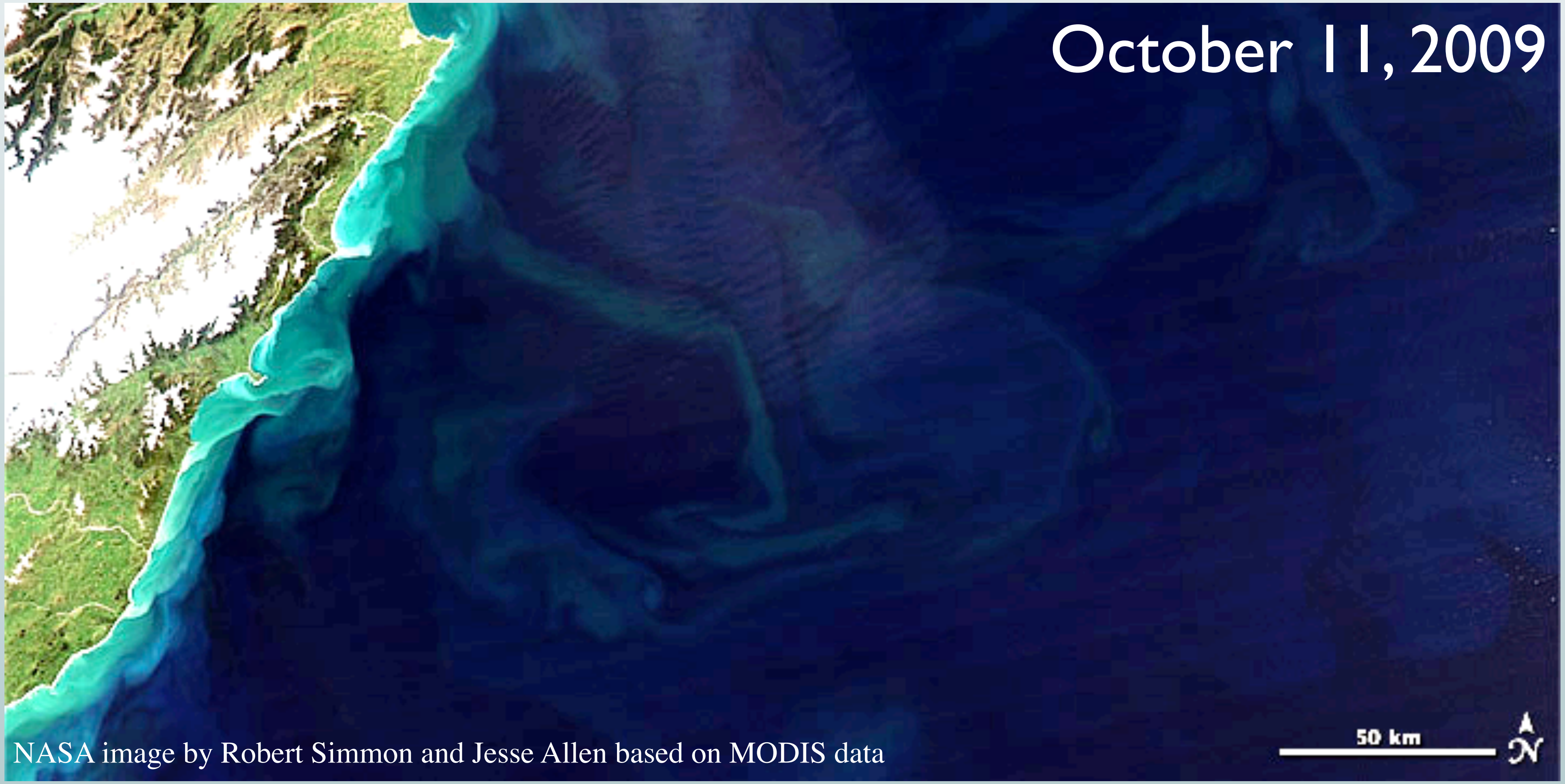
Phytoplankton Bloom

- Phytoplankton blooms can grow explosively over a few days or weeks
- The image shows a bloom that formed east of New Zealand



NASA image by Robert Simmon and Jesse Allen based on MODIS data

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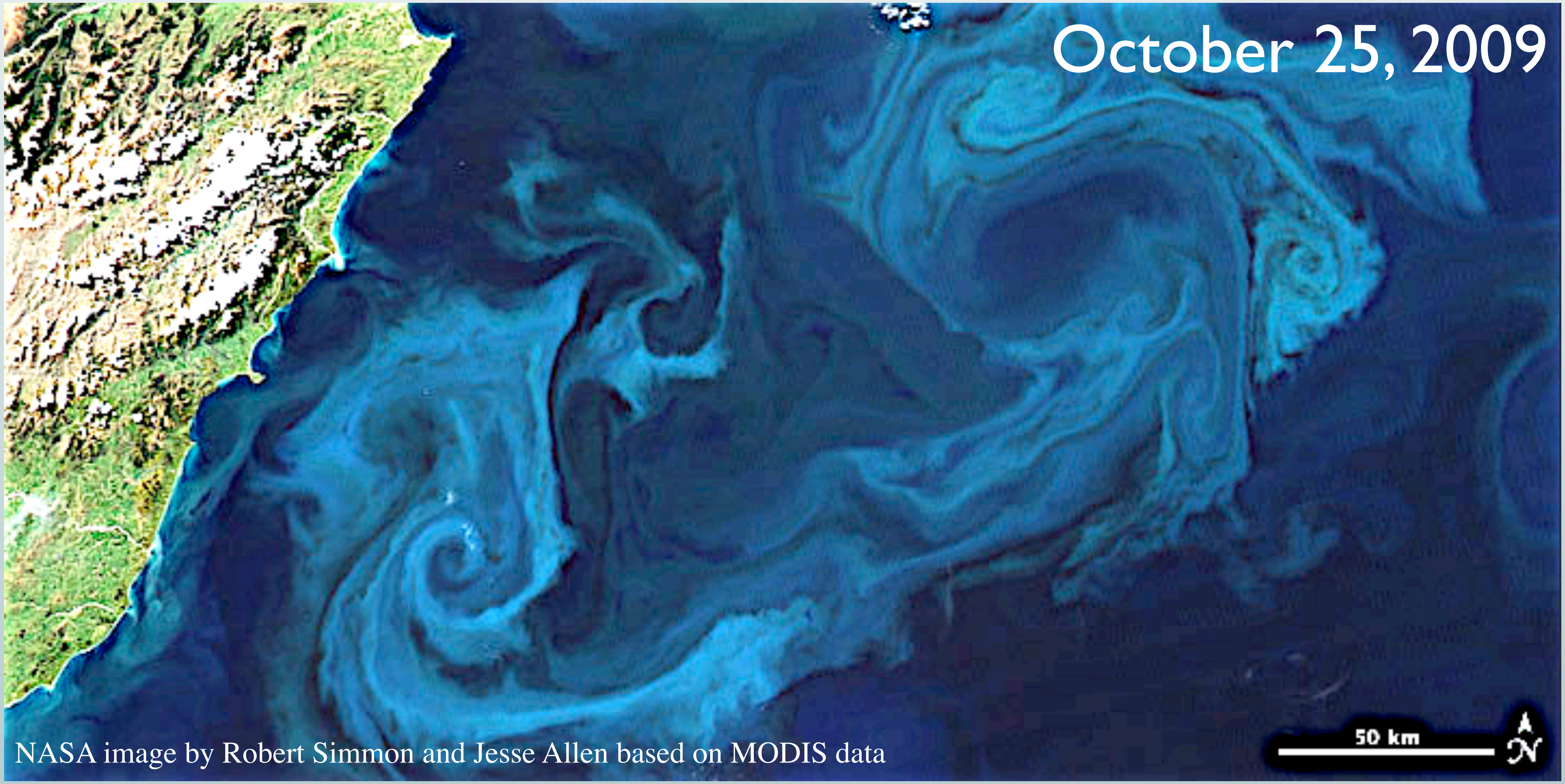

October 25, 2009

NASA image by Robert Simmon and Jesse Allen based on MODIS data

Phytoplankton Bloom

- Phytoplankton account for nearly half of the global primary production (45-50 Gt C/year, *Longhurst et al.* 1995)
- Large phytoplankton blooms occur in the spring at high latitudes, particularly in the North Atlantic.

SeaWiFs Animation

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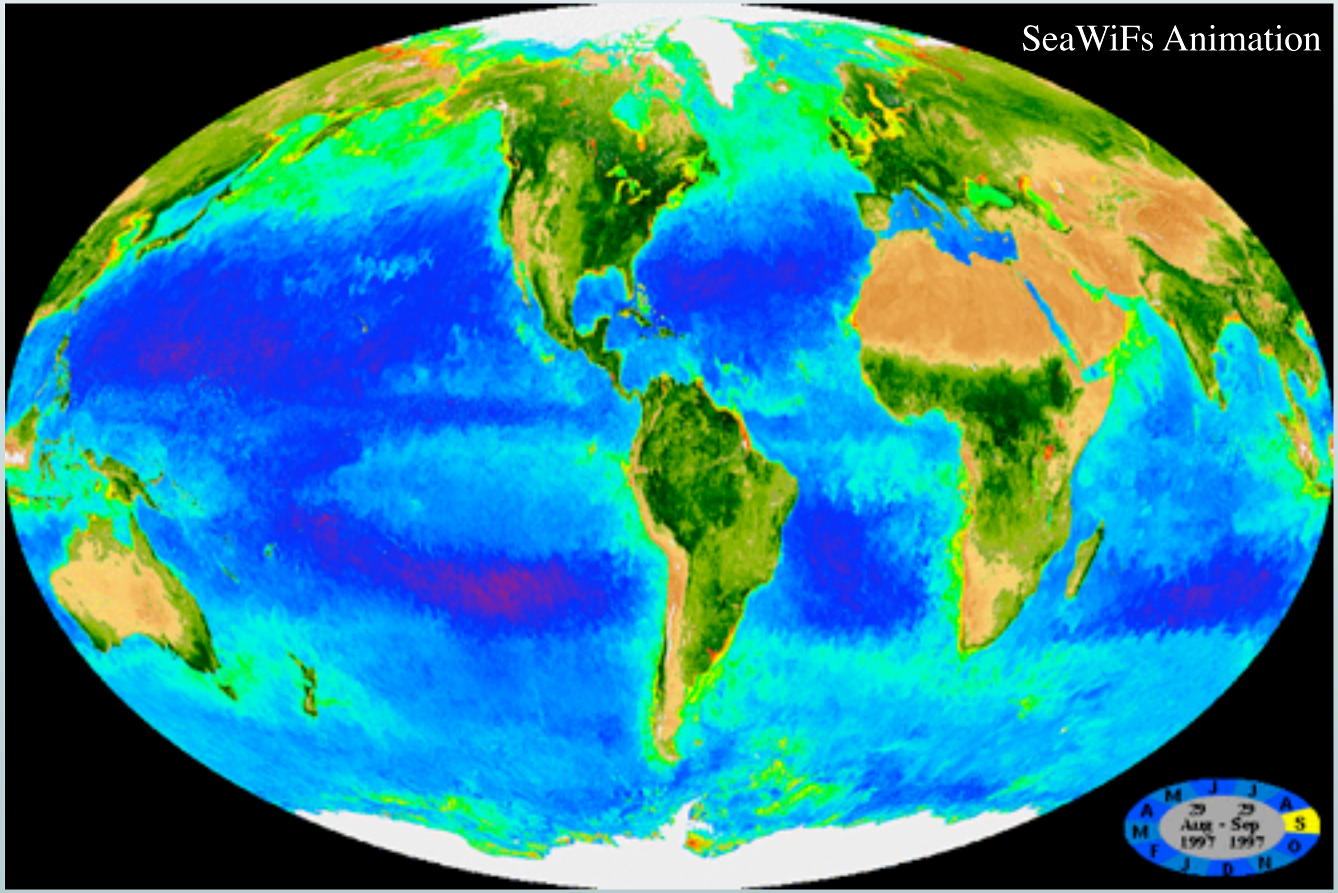

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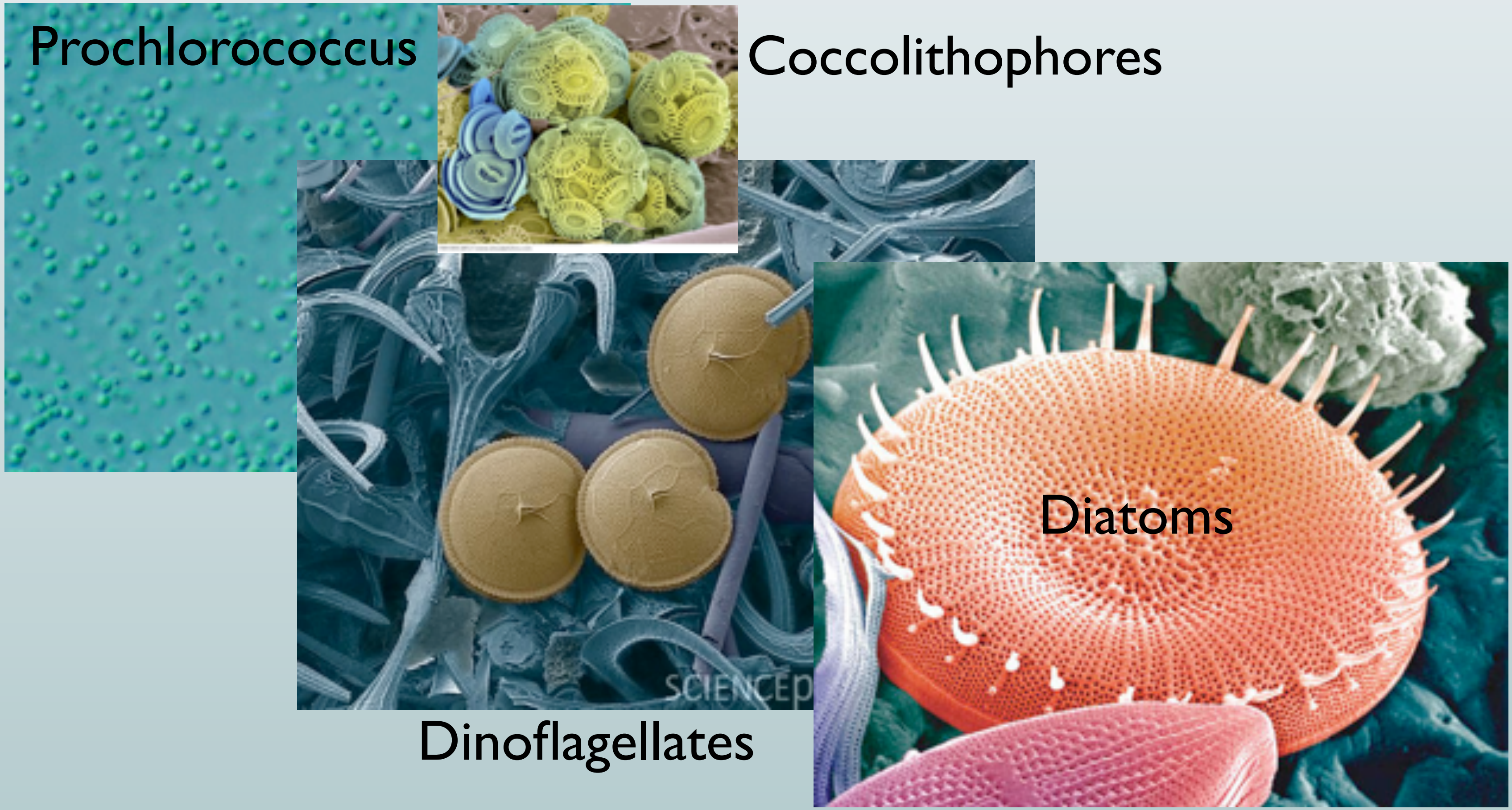


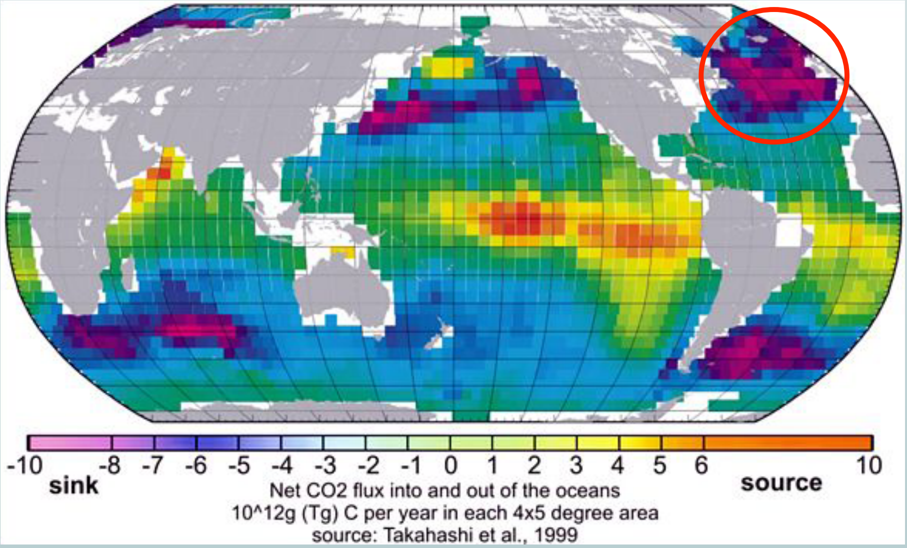
Importance of Blooms

Fisheries

– past, present, future

Seabirds

Marine Mammals

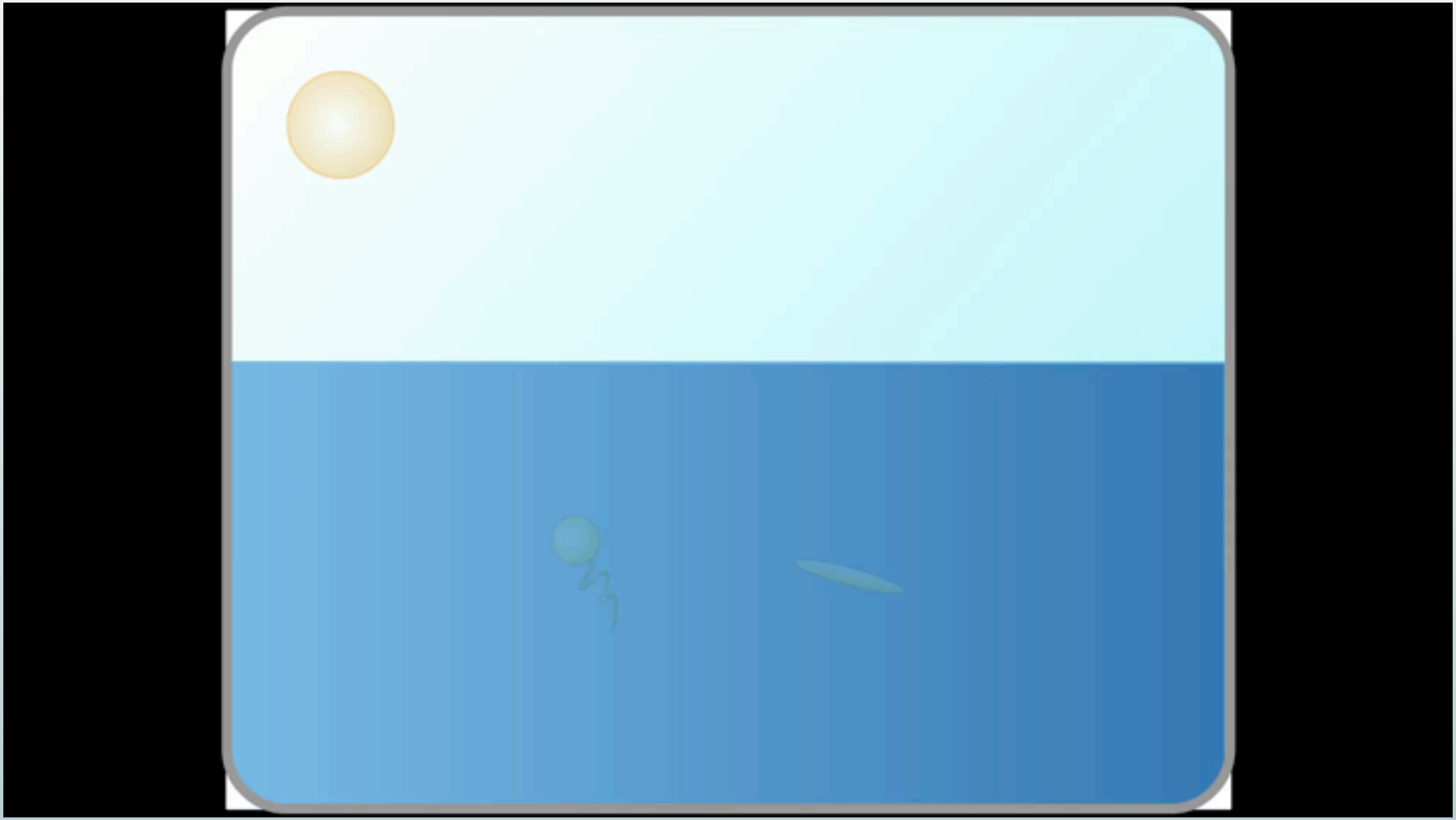


Net CO2 flux into and out of the oceans
10^12g (Tg) C per year in each 4x5 degree area
source: Takahashi et al., 1999

Carbon dioxide
& Climate

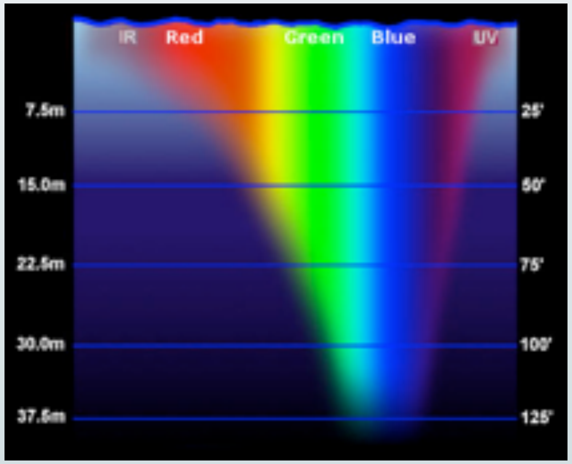
Recipe for a bloom

Recipe for a bloom



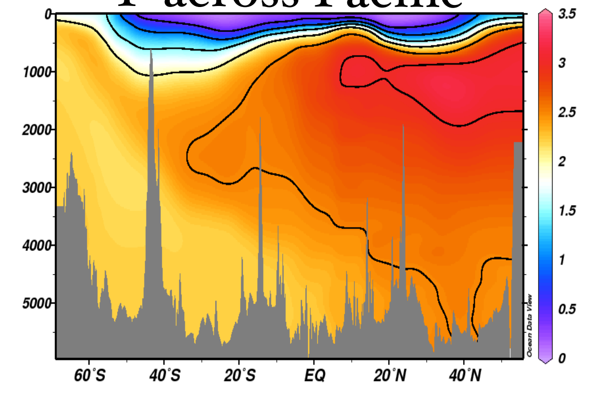
Recipe for a bloom

Light penetrates down to 40m

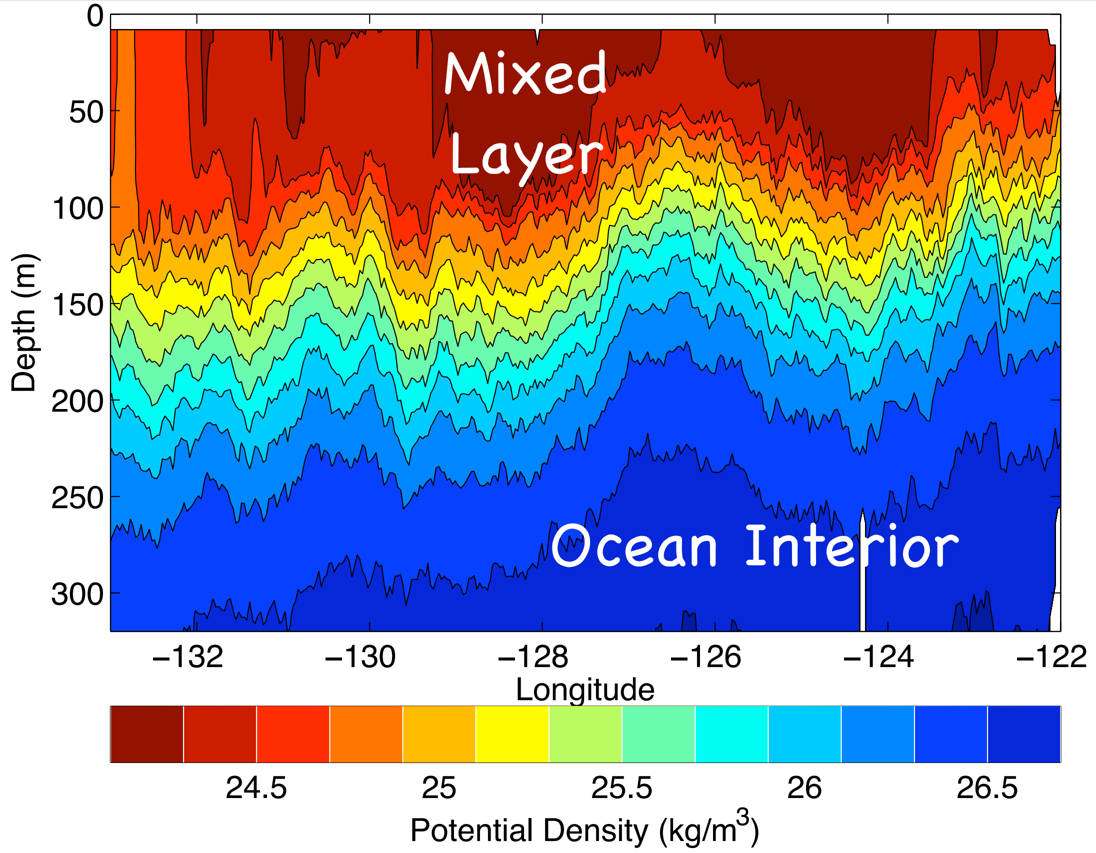


Nutrients are stored below top 100m

P across Pacific



Phytoplankton live in mixed layer



Outline

What triggers a spring bloom?

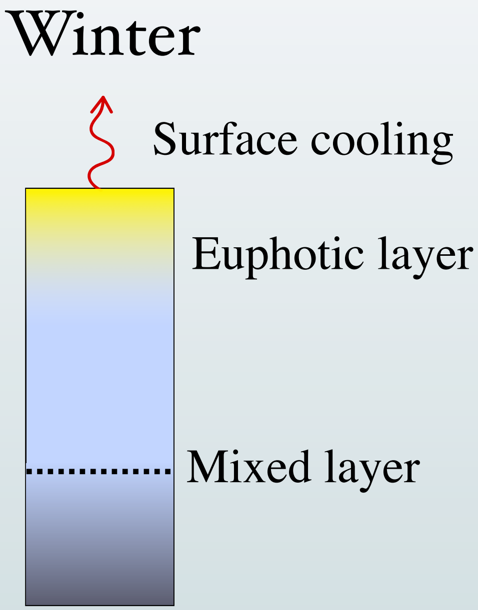
1. Classical theory for North Atlantic Spring Bloom
2. New theory for North Atlantic Spring Bloom
3. Test of new theory with remote sensing data
4. Test new theory with in-situ data

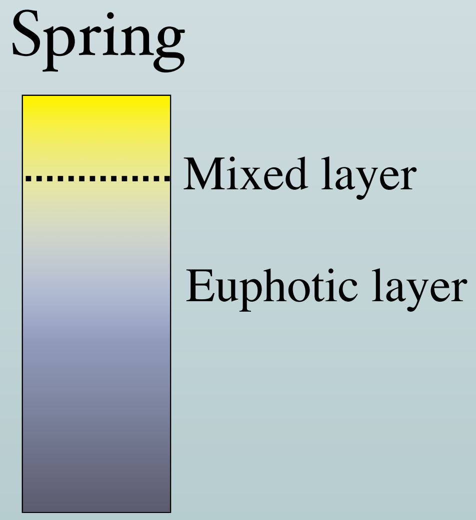
Classical Theory of Phytoplankton Blooms

Classical theory

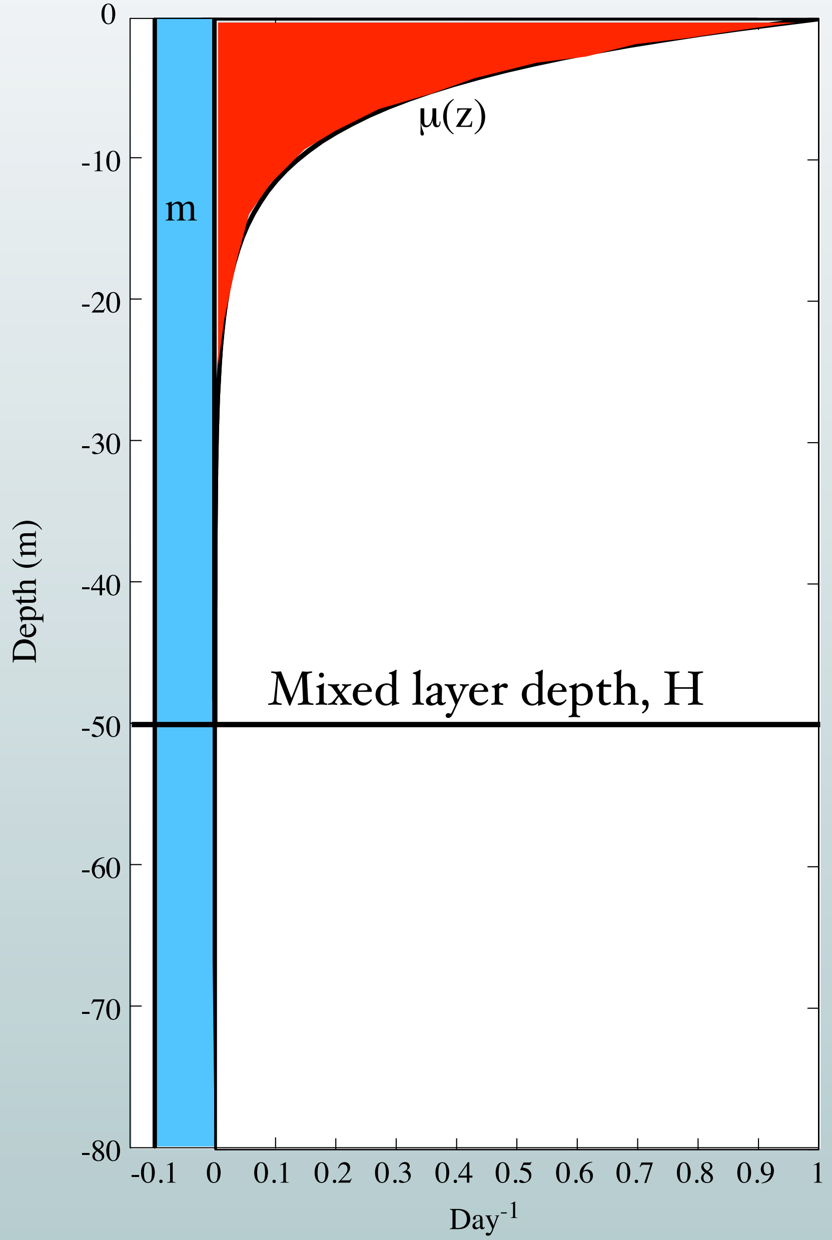
Traditional Description

1. In winter, surface cooling leads to convection and deep mixed layers.
2. Nutrients are abundant, but growth is limited by low light exposure.
3. In the spring, the mixed layer depths are shallower on average.
4. Abundant nutrients and light lead to rapid phytoplankton growth.





Phytoplankton Model



$$\frac{\partial P}{\partial t} = (\mu(z) - m)\, P + \frac{\partial}{\partial z}\left(\kappa_T \frac{\partial P}{\partial z}\right)$$

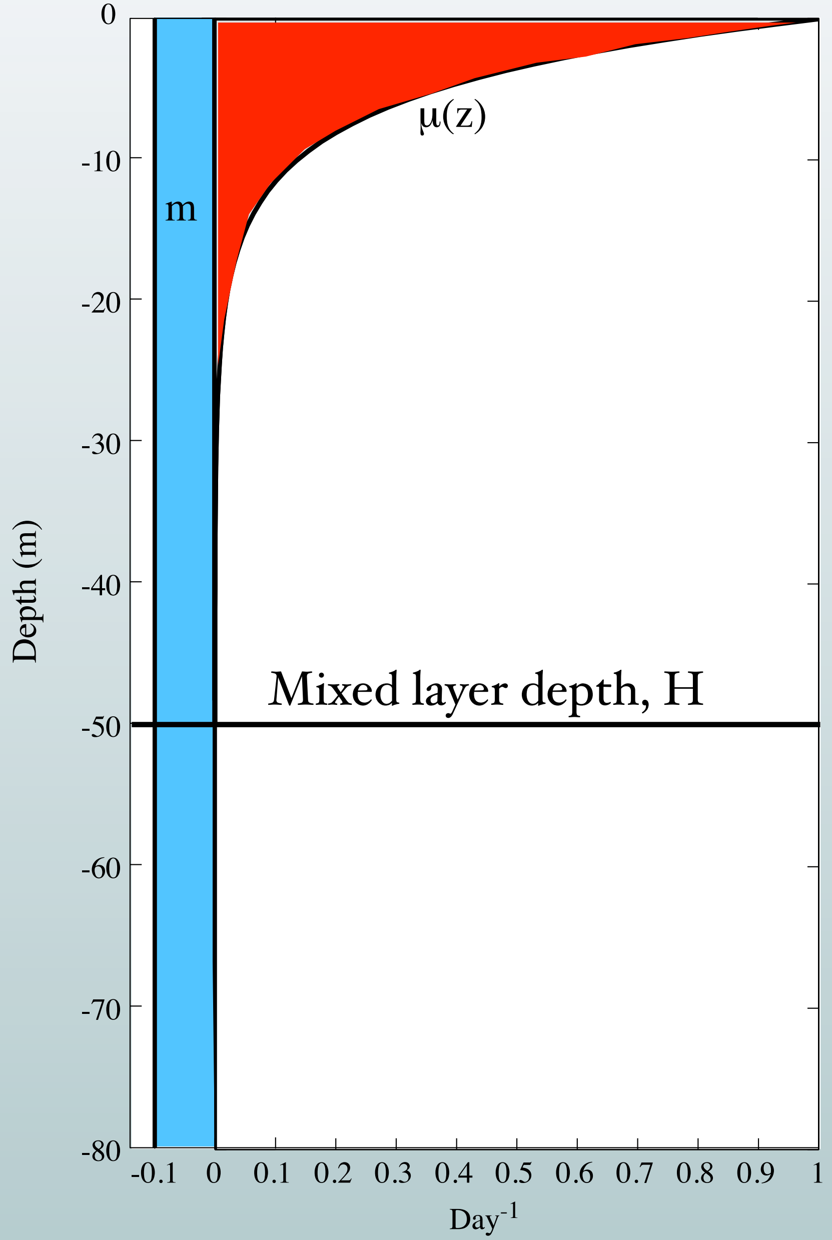
- Growth rate depends only on light available for photosynthesis

$$\mu = \mu_0 e^{z/h_l}$$

- Mortality is constant
- Mixed layer turbulence mixes plankton in the vertical

Under what conditions does plankton grow in the mixed layer?

Sverdrup's Critical Depth



$$\frac{\partial P}{\partial t} = (\mu(z) - m)\, P + \frac{\partial}{\partial z}\left(\kappa_T \frac{\partial P}{\partial z}\right)$$

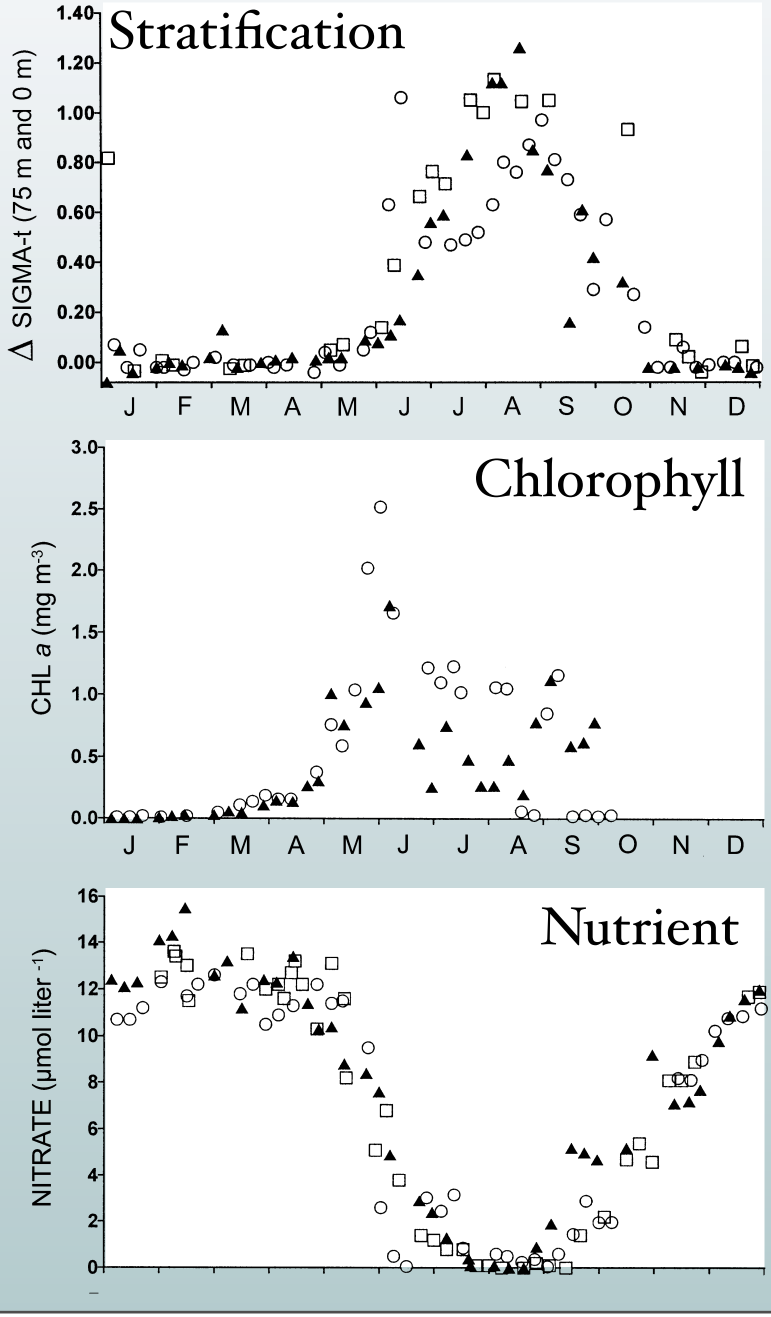
Strong turbulence:

- mixing is faster than growth/decay
- ML depth controls whether bloom occurs

  $H \leq H_c \equiv \frac{\mu_0}{m} h_l$ (Sverdrup, 1953)
- Winter: $H > H_c \longrightarrow$ light limited
- Spring: $H < H_c \longrightarrow$ bloom

Spring Bloom

Dale et al. 1999, Sarsia **84**:419-435
Weather Station M (66°N, 2°E)



Winter:

Deep mixed layers
Nigh nutrients
Low Chlorophyll

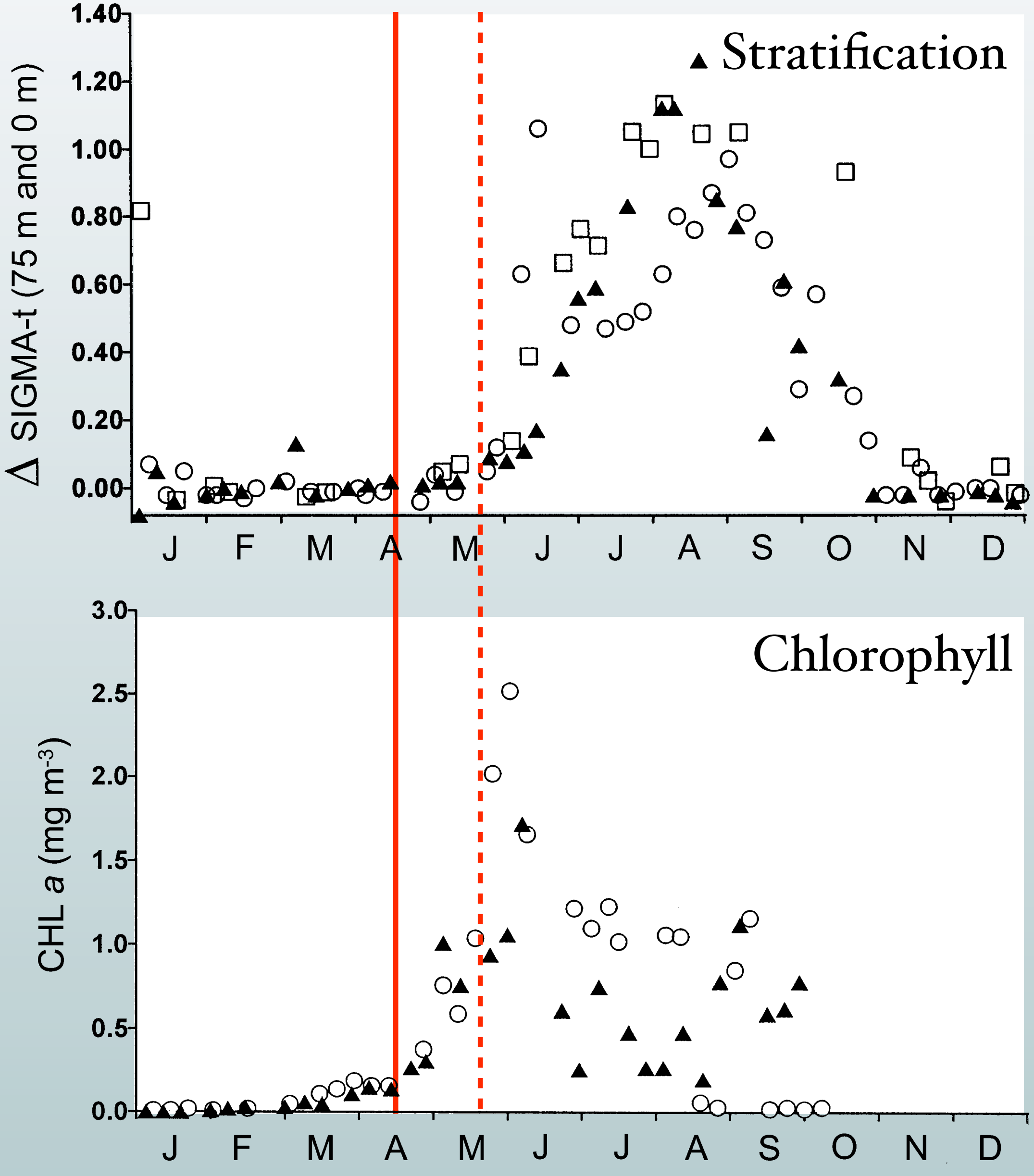
Summer:

Shallow mixed layers
Low nutrients
High Chlorophyll

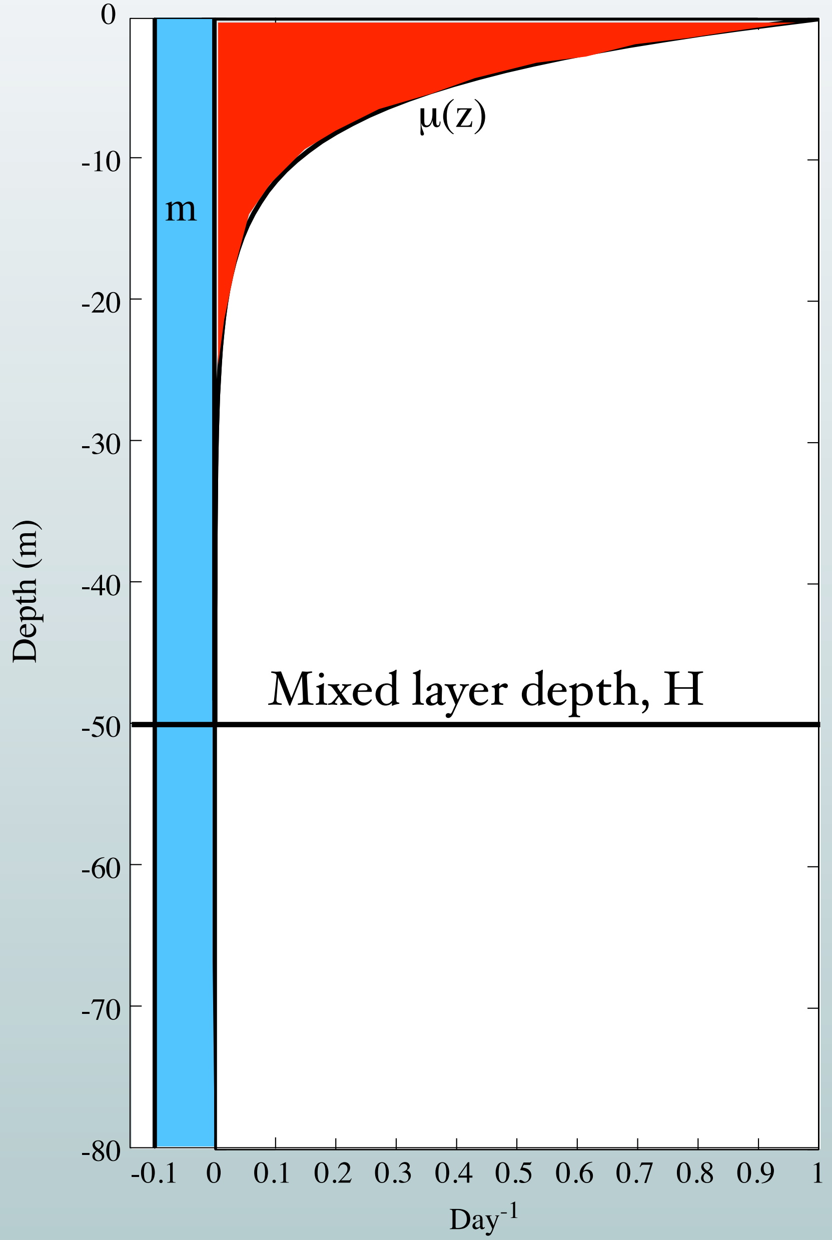
Spring Bloom Timing

Dale et al. 1999, Sarsia **84**:419-435
Weather Station M (66°N, 2°E)

The onset of the spring bloom precedes re-stratification!



Huisman's Critical Turbulence



$$\frac{\partial P}{\partial t} = (\mu(z) - m)\, P + \frac{\partial}{\partial z}\left(\kappa_T \frac{\partial P}{\partial z}\right)$$

Weak turbulence:

- mixing is slower than growth/decay
- turbulence controls whether bloom occurs

$$\kappa_T \leq \kappa_c \equiv \frac{\mu_0^2}{m} h_l^2$$ (Taylor & Ferrari, 2011)

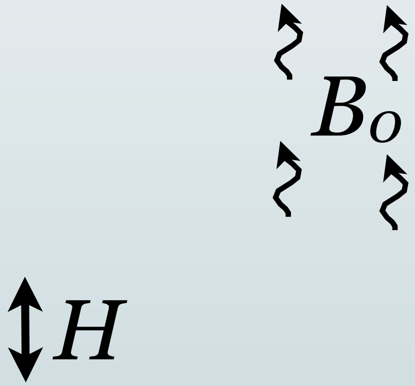
- Winter: $\kappa_T > \kappa_c$ ⟶ light limited
- Spring: $\kappa_T < \kappa_c$ ⟶ bloom

New Theory for North Atlantic Spring Bloom

Critical Buoyancy Flux

Convective scaling (Deardorff 1972): $\kappa_T \sim H^{4/3} B_0^{1/3}$

$$B_0 \sim \kappa_T^3 / H^4$$



Critical buoyancy flux:

$$B_c \sim \kappa_c^3 / H^4$$

$$B_c \sim \left(\frac{h_l^2 \mu_0^2}{m} \right)^3 \Bigg/ H^4$$

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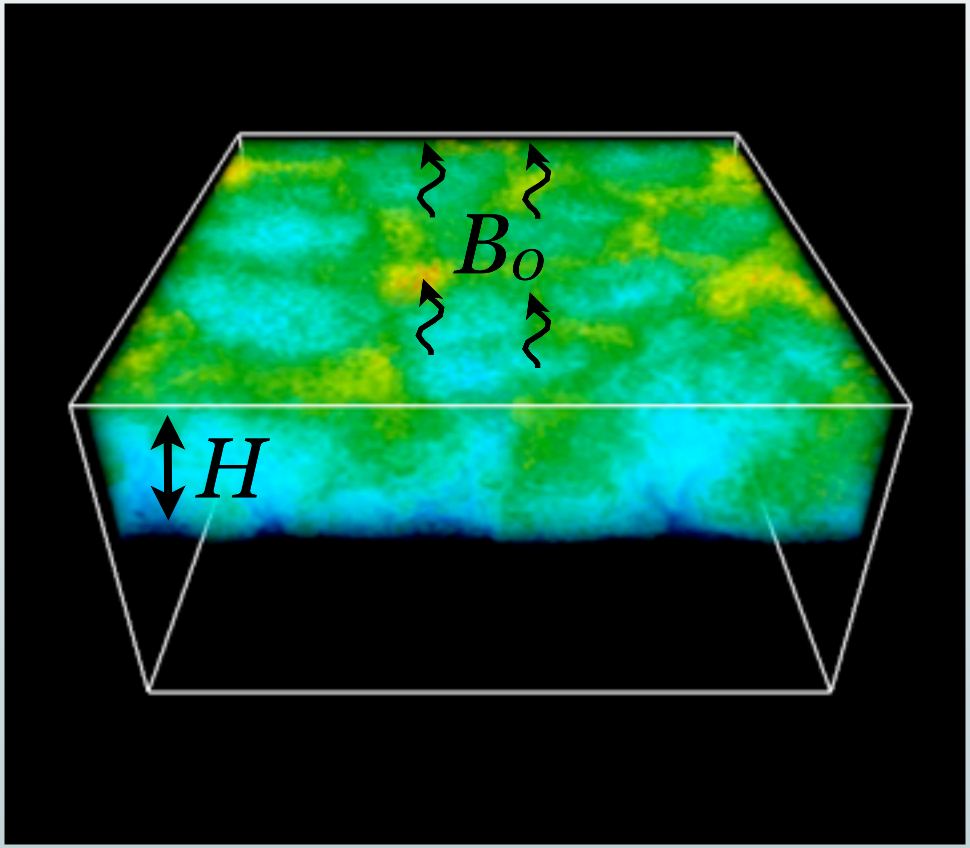


Critical buoyancy flux:

$$B_c \sim \kappa_c^3 / H^4$$

$$B_c \sim \left(\frac{h_l^2 \mu_0^2}{m} \right)^3 \Big/ H^4$$

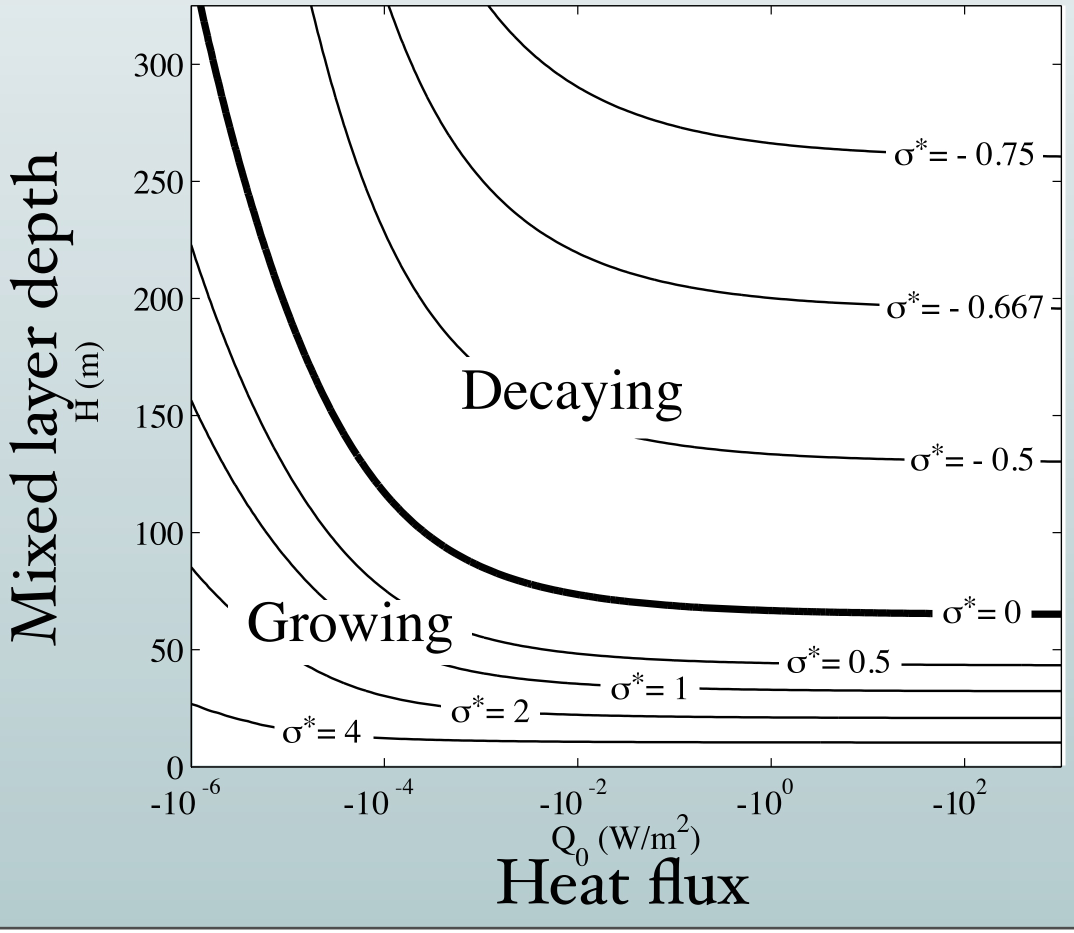
Critical Heat Flux

New Theory

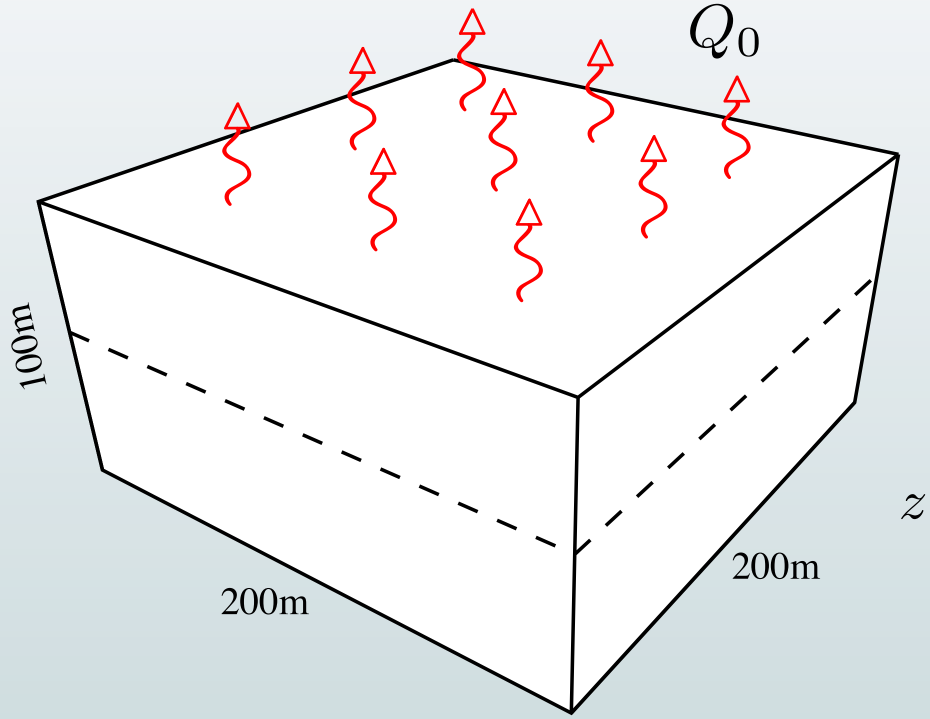
Bloom starts when heat flux becomes positive

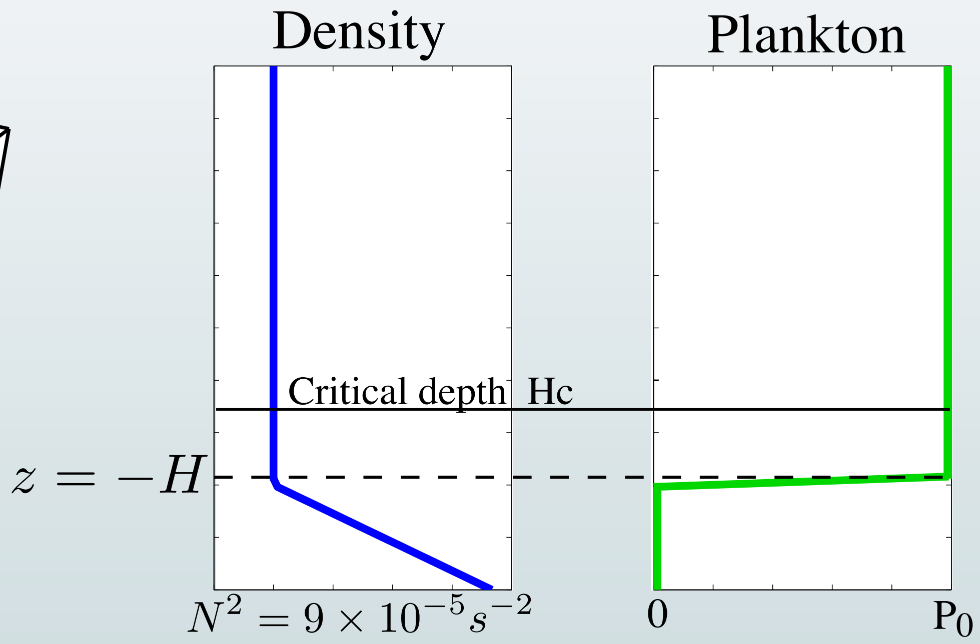
$$B_c \sim \frac{h_l^6 \mu_0^6}{m^3 H^4}$$

$$Q_c = \frac{c_P \rho_0}{\alpha g} B_c$$



Numerical Simulations

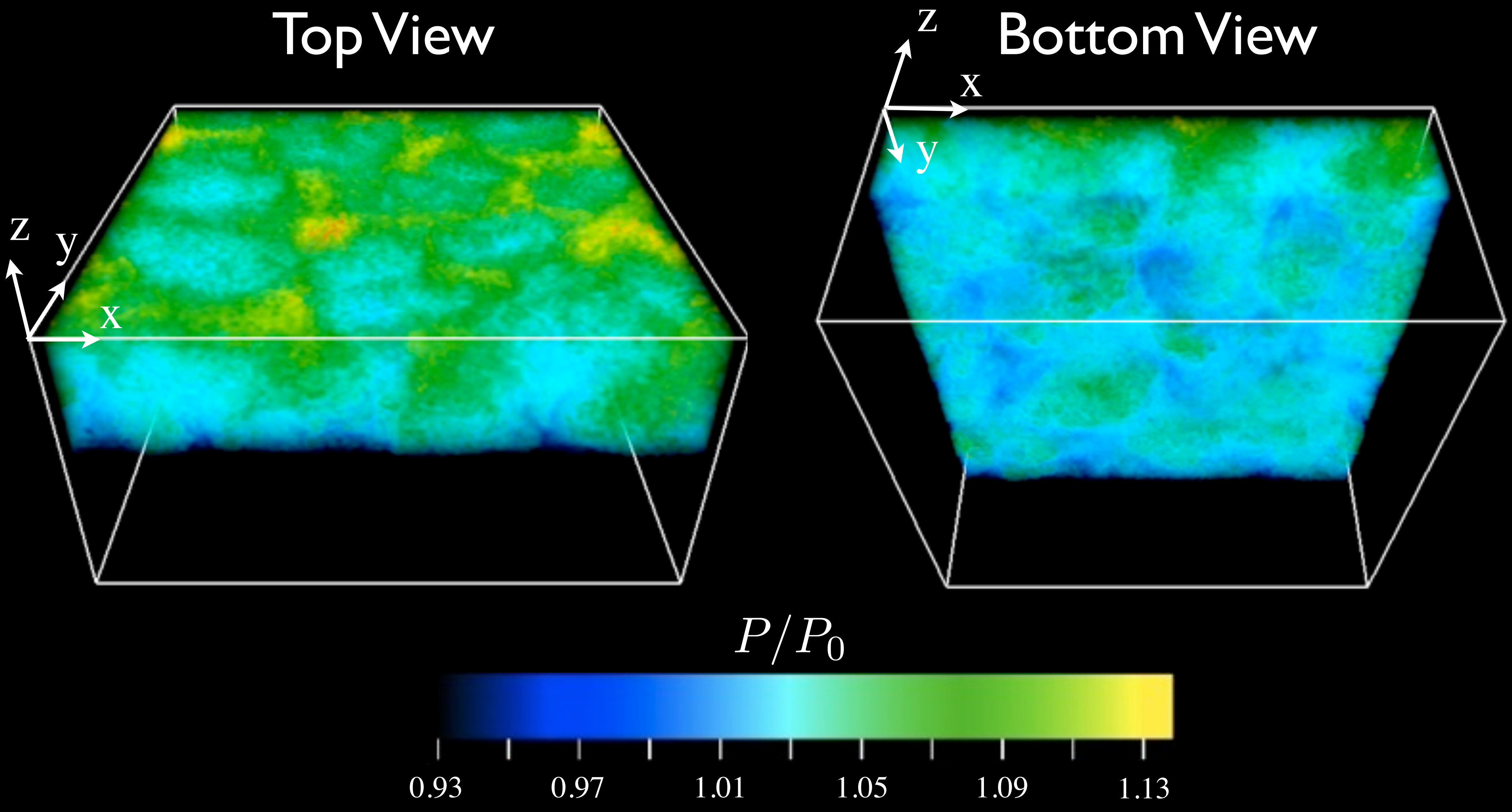




- Start with a deep mixed layer $H > H_c$
- Drive convection with a uniform surface heat flux $Q_0 < 0$
- Grid resolution O(1m): $(N_x, N_y, N_z) = (192, 192, 100)$
- Biological parameters: $\mu_0 = 1.0\text{day}^{-1}, \quad m = 0.1\text{day}^{-1}, \quad h_l = 7m$

Plankton Concentration

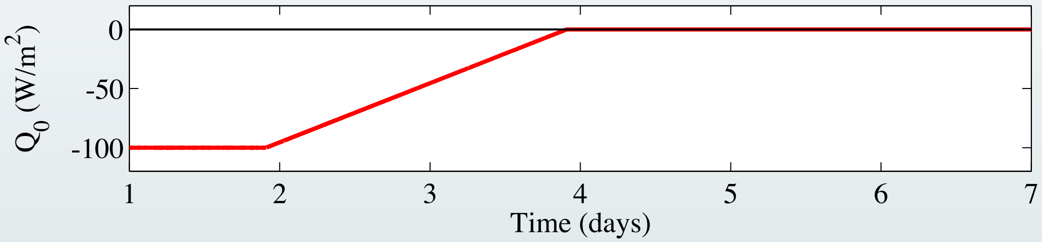
$$Q_0 = -1\mathrm{W/m^2}$$



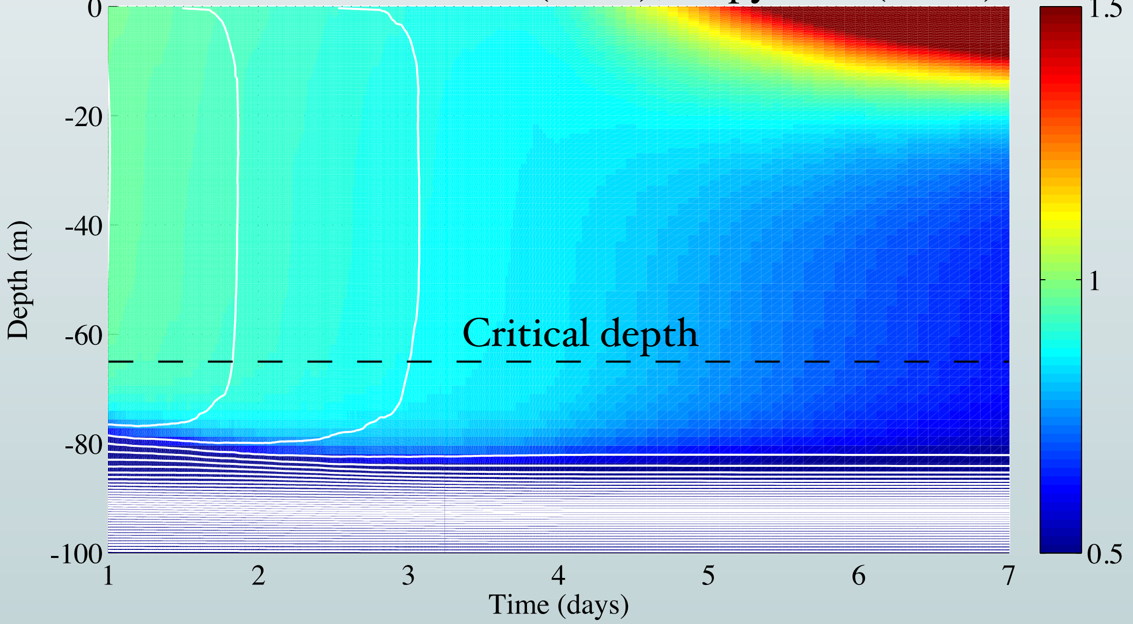
Top View

Bottom View

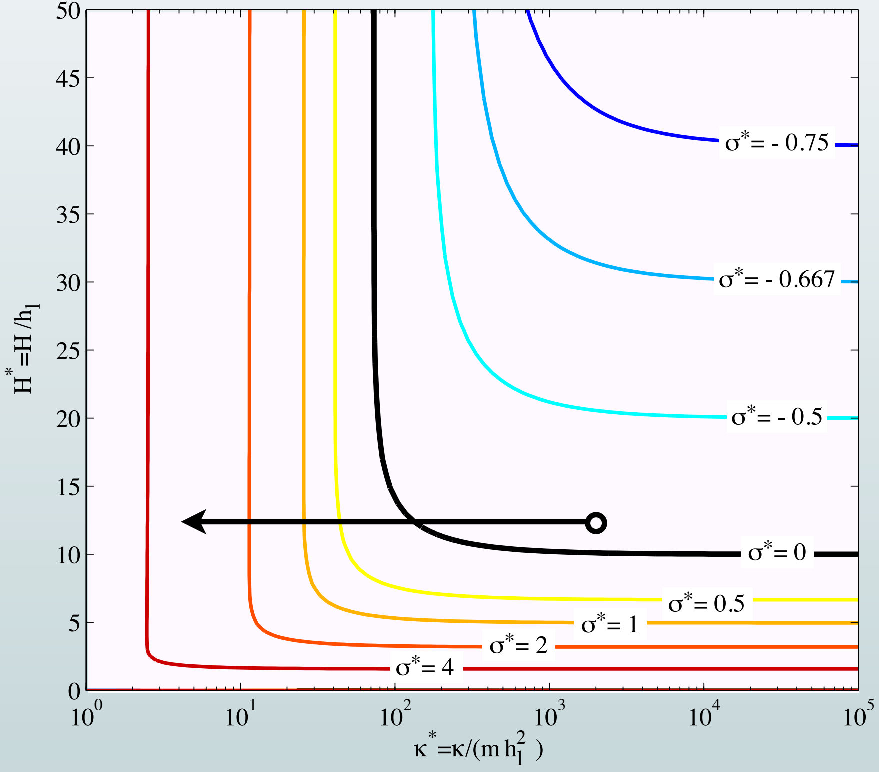
Spindown Experiment



Surface heat flux



Plankton concentration (color), Isopycnals (white)

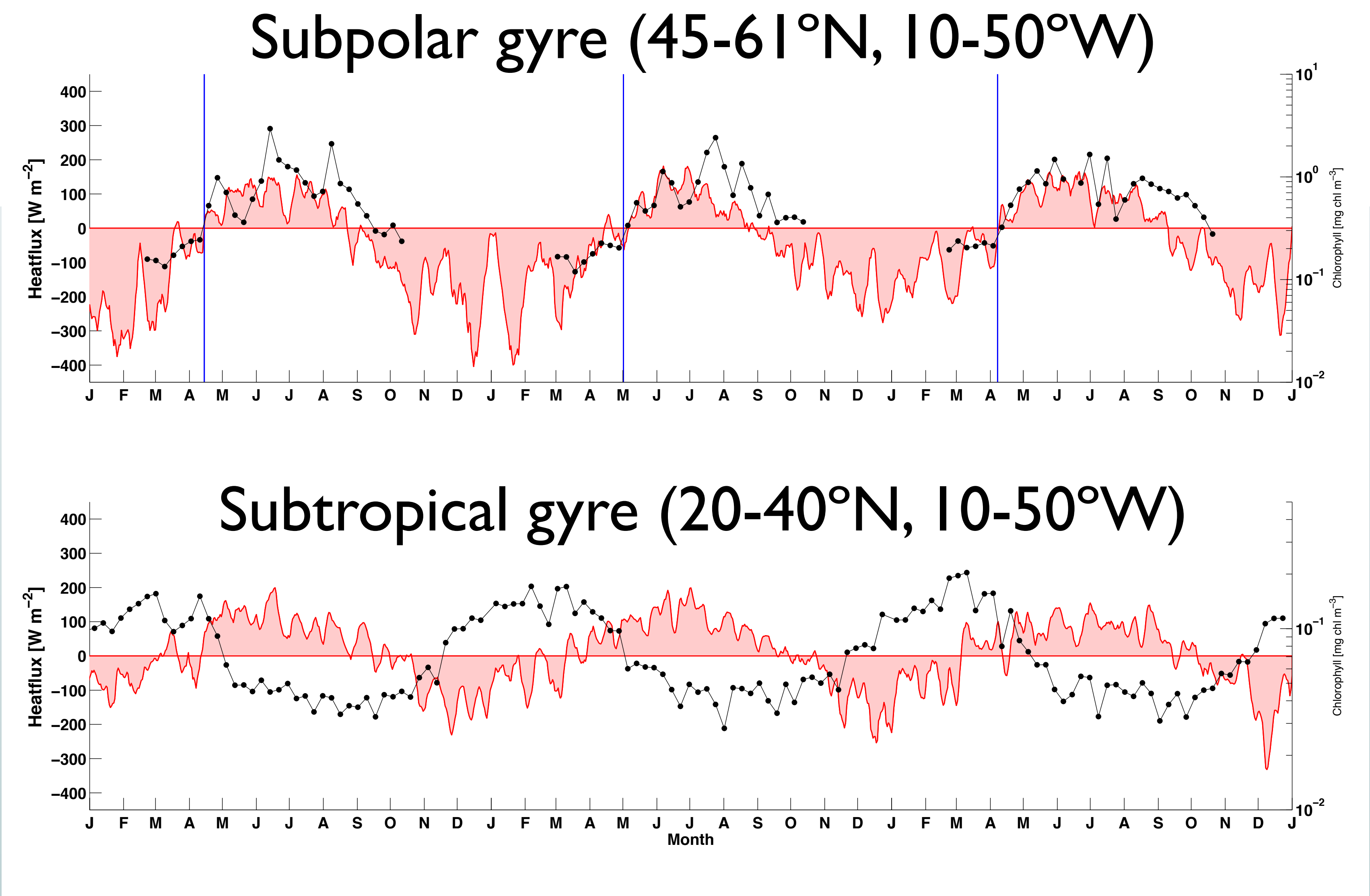


Analytical growth rate

The onset of the bloom immediately follows change in sign of surface heat flux

Testing New Theory with Remote Sensing Data

Bloom Timing



Subpolar gyre (45-61°N, 10-50°W)

Subtropical gyre (20-40°N, 10-50°W)

- NCEP heat flux averaged over 8 days
- SeaWIFS Cholorphyll data averaged over 8 days

Conclusions

- The onset of the North Atlantic Spring bloom coincides with the change in sign of the surface heat flux.
- The change in heat flux is a better indicator of bloom initiation than the critical depth.
- Deep mixed layers and weak turbulence can lead to large depth-integrated biomass.
- Locally the bloom first starts at submesoscale fronts, where turbulence is suppressed.