Turbulence and the Spring Phytoplankton Bloom

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- 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.
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Importance of Blooms

Fisheries
– past, present, future
Seabirds
Marine Mammals

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

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
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.
Growth rate depends only on light available for photosynthesis.

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

- 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?
Strong turbulence:

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

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

- Winter: \( H > H_c \rightarrow \) light limited
- Spring: \( H < H_c \rightarrow \) bloom

Sverdrup’s Critical Depth
Spring Bloom

Winter:
Deep mixed layers
High nutrients
Low Chlorophyll

Summer:
Shallow mixed layers
Low nutrients
High Chlorophyll

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

Stratification
Chlorophyll
Nutrient
The onset of the spring bloom precedes re-stratification!

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

Phytoplankton biomass above winter levels was indeed present in March. The subsequent weak increase indicates that the phytoplankton population was no longer light-limited although no bloom occurred at this time. Our results are in accordance with Halldal and Brettum who observed an increase in phytoplankton population from February to March. There were no indications of increased stability in the upper 20 m at this time. Since the depth of the mixed layer generally is at its maximum in February and being deeper than 20 m until the end of April, it is assumed that the phytoplankton population growth was kept low due to deep vertical mixing.

For nitrate, silicate, and chlorophyll a measurements, data from 5 m are shown. Data from 20 m are denoted with a superscript S. No Chl a data in 2002.
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

\[ \kappa_T \leq \kappa_c \equiv \frac{\mu_0^2}{m} h_i^2 \]  
(Taylor & Ferrari, 2011)

- Winter: \( \kappa_T > \kappa_c \) \quad \rightarrow \quad \text{light limited}
- Spring: \( \kappa_T < \kappa_c \) \quad \rightarrow \quad \text{bloom}
New Theory for North Atlantic Spring Bloom
Convective scaling (Deardorff 1972): \( \kappa_T \sim H^{4/3} B_0^{1/3} \)

\[ B_0 \sim \frac{\kappa_T^3}{H^4} \]

Critical buoyancy flux:

\[ B_c \sim \frac{\kappa_c^3}{H^4} \]

\[ B_c \sim \left( \frac{h_i^2 \mu_0^2}{m} \right)^3 / H^4 \]
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:

\[
B_c \sim \kappa_c^3 / H^4
\]

\[
B_c \sim \left( \frac{h_l^2 \mu_0^2}{m} \right)^3 / H^4
\]
New Theory

Bloom starts when heat flux becomes positive

\[ B_c \sim \frac{h_i^6 \mu_0^6}{m^3 H^4} \]

\[ Q_c = \frac{c_P \rho_0 \omega g}{B_c} \]
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: $\mu_0 = 1.0 \text{day}^{-1}$, $m = 0.1 \text{day}^{-1}$, $h_l = 7m$
$Q_0 = -1 \text{W/m}^2$

Plankton Concentration

Top View

Bottom View

$P/P_0$

0.93 0.97 1.01 1.05 1.09 1.13

Thursday, February 2, 12
Spindown Experiment

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.