Spring Blooms

Observations and sketches

The term is used either for a large, narrow peak in biomass, in chlorophyll, or in primary productivity. But it also is used to describe the rapid rise in such properties. This means that "timing of the bloom" can mean different things to different people. In the NPZ model, the peak in biomass means $max(P)$, the primary productivity is $u(N, light, ...)P$, and the rate of rise is $\frac{\partial}{\partial t}P$. They can be quite different.

Examples

Much of our view of the NPZ... dynamics of the spring bloom comes from sketches such as the one from Riley.

The data is not always so neat.

- The Norwegian Sea has a sharp bloom but maintains high levels through the summer.
- The BATS 4 years of Chl (with the points showing the mean) shows significant inter-annual variability; in contrast the temperature cycle is much more regular.
- From Georges Bank site A and site B. The data from the Biowatt moored experiments gives much higher temporal resolution.
- Biowatt T , Biowatt Chl
- Biowatt paper T
- Biowatt paper MLD
- Biowatt paper PAR/Chl and Chl/T
- Biowatt2 T and Chl
- Biowatt2 PAR and Chl

Models

$$\frac{D}{Dt}b_i = \mathcal{B}_i(z,t,\mathbf{b}) + \nabla \cdot \kappa \nabla b_i$$

We start with the horizontally homogeneous case and look at the mean

$$\begin{aligned}
\frac{\partial}{\partial t}\overline{b}_i &= \overline{\mathcal{B}_i(z,t,\overline{\mathbf{b}}+\mathbf{b}')} + \frac{\partial}{\partial z}(-\overline{w'b_i'} + \kappa\frac{\partial}{\partial z}\overline{b}_i) \\
&\simeq \mathcal{B}_i(z,t,\overline{\mathbf{b}}) + \frac{1}{2}\frac{\partial^2 \mathcal{B}_i}{\partial b_j \partial b_k}\overline{b_j' b_k'} + \frac{\partial}{\partial z}(-\overline{w'b_i'} + \kappa\frac{\partial}{\partial z}\overline{b}_i)
\end{aligned}$$

$$\begin{aligned}
\frac{D}{Dt}b_i' &= \mathcal{B}_i(z,t,\overline{\mathbf{b}}+\mathbf{b}') - \overline{\mathcal{B}_i(z,t,\overline{\mathbf{b}}+\mathbf{b}')} \\
&\quad - w'\frac{\partial}{\partial z}\overline{b}_i + \frac{\partial}{\partial z}\overline{w'b_i'} + \nabla \cdot \kappa \nabla b_i' \\
&\simeq \frac{\partial \mathcal{B}_i}{\partial b_j}b_j' - w'\frac{\partial}{\partial z}\overline{b}_i + \frac{\partial}{\partial z}\overline{w'b_i'} + \nabla \cdot \kappa \nabla b_i'
\end{aligned}$$

Eddy diffusivity – round 1

$$\frac{D}{Dt}b_i' = \frac{\partial \mathcal{B}_i}{\partial b_j}b_j' - w'\frac{\partial}{\partial z}\overline{b}_i + \frac{\partial}{\partial z}\overline{w'b_i'} + \nabla\cdot\kappa\nabla b_i'$$

Let's assume the characteristic mixing length is h and scale time by h/W'. Then the terms have the orders

$$\begin{array}{cccccc} \frac{D}{Dt}b_i' = & \frac{\partial \mathcal{B}_i}{\partial b_j}b_j' & - w'\frac{\partial}{\partial z}\overline{b}_i & + \frac{\partial}{\partial z}\overline{w'b_i'} & + \nabla\cdot\kappa\nabla b_i' \\ W'b'/h & b'/T_{bio} & W'\overline{b}/H & W'b'/H & \kappa b'/H^2 \\ 1 & h/W'T_{bio} & h\overline{b}/Hb' & h/H & h^2/H^2(W'h/\kappa) \end{array}$$

Assume the mixing length is short and the biological time is long compared to h/W'; then $b' \sim (h/H)\overline{b} << \overline{b}$, and this just reduces to the advection equation

$$\frac{D}{Dt}b_i' = -w'\frac{\partial}{\partial z}\overline{b}_i$$

If we define the particle displacements as

$$\frac{D}{Dt}\zeta' = w'$$

then

$$b_i' = -\zeta'\frac{\partial}{\partial z}\overline{b}_i$$

(slowly varying $\overline{b}$ and $h << H$) and the eddy flux is

$$\overline{w'b_i'} = -\overline{w'\zeta'}\frac{\partial}{\partial z}\overline{b}_i$$

Thus the eddy diffusivity is

$$K = \overline{w'\zeta'}$$

In the even more over-simplified approximation where the $\frac{\partial}{\partial t}$ term is dominant,

$$K = \overline{w'(t)\int^t dt' w'(t')} = \int^t \overline{w'(t)w'(t')} = \overline{w'^2}\int_0^\infty C(\tau)d\tau$$

with C the autocorrelation function, or

$$K = \overline{w'^2}\, T_{turb}$$

where we now see that the time scale is the integral time scale given by $T_{turb} = \int d\tau\, C(\tau)$.

More generally, we solve the trajectory equation backwards and relate K to the Lagrangian autocorrelation (Taylor, 1922, but modified for inhomogeneous turbulence).

Dynamics of blooms

We now deal with the mean equations

$$\frac{\partial}{\partial t}\overline{b}_i = \mathcal{B}_i(z,t,\overline{\mathbf{b}}) + \frac{\partial}{\partial z}K(z,t)\frac{\partial}{\partial z}\overline{b}_i$$

Light only

A one variable system P or P with $N = N_T - P$

$$\frac{\partial}{\partial t}P = g(t,P)P$$

is unlikely to exhibit spring bloom behavior – you might find rapid growth, but it is not likely to decay before the light level goes back down.

Modelbuilder - np0 to ($d = 0.25$)

But a two variable system can – P can overshoot and then return to something closer to its equilibrium. Of course, it's not in an equilibrium since g continues to change.

As a first example, consider an NP system, replacing the mixing term by exchanges with below

$$\frac{\partial}{\partial t}P = \mu(t)NP - (d_p + \lambda)P$$
$$\frac{\partial}{\partial t}N = -\mu(t)NP + \lambda(N_0 - N)$$

Modelbuilder - np

$u = 2$, $\lambda = 0.001$, $\lambda = 0.1$

Next consider the conservative NPZ system.

$$N = N_T - P - Z$$
$$\frac{\partial}{\partial t}P = \mu(t)M(N)P - g_0G(P)Z - d_PP$$
$$\frac{\partial}{\partial t}Z = ag_0G(P)Z - d_ZZ$$

- quadratic
- adjustment
- mm/iv
- mm/h3
- multeq

  q: $M(N) = N$, $G(P) = P$

  mm: $M(N) = N/(N+k)$

  iv: $G(P) = 1 - \exp(-P/P_0)$

  h3: $G(P) = P^2/(P^2 + P_0^2)$

  multeq: mm+h3 and $d_ZZ \to d_ZZ^2$
- mm/iv
- mm/iv dz=0.01

Mixing and Critical Depth

Suppose the mixing is very rapid to the MLD (really the mixing layer depth here) $h(t)$ so that the mixing time h^2/K is much less than the biological time. Within the upper layer

$$\frac{\partial}{\partial z} K \frac{\partial}{\partial z} b_i \simeq 0$$

which implies to this order

$$b_i = b_i(t)$$

At the next order

$$\frac{\partial}{\partial t} b_i = \mathcal{B}_i(z, t, \mathbf{b}) + \frac{\partial}{\partial z} K \frac{\partial}{\partial z} b_i^{(1)}$$

If we integrate from just below h to the surface, we have

$$\int_{-h^+}^{0} \frac{\partial}{\partial t} b_i = \int_{-h}^{0} \mathcal{B}_i$$

or

$$\frac{\partial}{\partial t} \int_{-h^+}^{0} \frac{\partial}{\partial t} b_i - b_i(-h+) \frac{\partial h}{\partial t} = \int_{-h}^{0} \mathcal{B}_i$$

$$\frac{\partial}{\partial t} h b_i - b_i(-h+) \frac{\partial h}{\partial t} = \int_{-h}^{0} \mathcal{B}_i$$

$$\frac{\partial}{\partial t} b_i = \frac{1}{h} \int_{-h}^{0} B_i(z, t, \mathbf{b}) + \frac{1}{h} \frac{\partial h}{\partial t} [b_i(-h^+) - b_i]$$

For the dynamics we've been using the first term on the rhs simply replaces

$$\mu(t) \leftarrow \frac{1}{h(t)} \int_{-h(t)}^{0} \mu(z, t)$$

in the ODEs. The entrainment term tries to bring b_i to the value underneath the ML when h is increasing; when it is detraining, we presume the value just below is the same as within the ML so that this term is 0. Later, we presume that the dynamics restores the deep values before the fluid is re-entrained.

- light,mort 0.016
- light,mort 0.1
- npzd
- npzd
- npzd smaller dz
- npzd smaller dz

Convective adjustment

We can take the model, apply the heating and cooling for one time step, and then mix (homogenize) all boxes which have $\rho(z+dz) < \rho(z)$ with all b_i fields mixing similarly. Here d_z was reduced since the daily light cycle results in a different light pattern.

- npzd
- t-z P,Z,N,D,T
- integrated

Price-Weller-Pinckel

This mixed layer model adds winds, so that horizontal flow is generated, and additional mixing when the vertical shear is strong enough so that the Richardson number $N^2/\frac{\partial U}{\partial z}^2 < 1/4$ and Kelvin-Helmholtz instability sets in. The assumption is that neighboring boxes are partially mixed until Ri is subcritical again.

- npzd
- t-z P,Z,N,D,T
- integrated

2D model

The following figures show the evolution of a 2D mixed layer model with an NPZD system (no sinking, however). bPZD or scaled version shows the daily cycle. The surface fields show the bloom, grazing reduction in P and then decreases as the mixing deepens. It's hard to pinpoint bloom onset in relation either to mixed-layer depth which has a strong daily cycle or net heating.

- vs depth
- strat
- b
- P
- Z
- q