Effects of large scale advection and small scale turbulence on vertical phytoplankton dynamics

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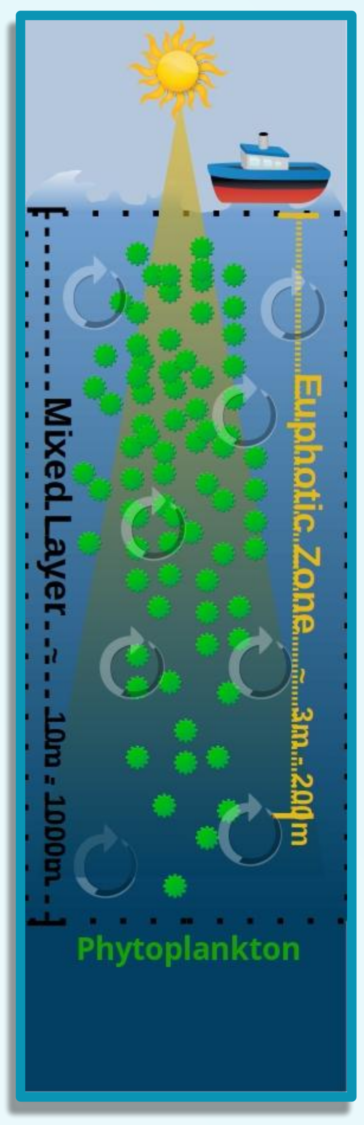
Introduction

The occurrence of phytoplankton blooms is a topic of considerable interest to oceanography given its relation to primary production and carbon export. Studies through modelling specifically have been useful on the construction of theories behind experimental observations. Among these theories, the ones debating spring phytoplankton blooms vertical dynamics have a rich history. Starting with Sverdrup's critical depth hypothesis [1], they have grown to include the importance of turbulence in phytoplankton life cycles. Amidst these studies, the work by Huisman and collaborators [2] on sinking phytoplankton provided an unifying framework for many of the previously discussed ideas into a unique phase diagram. This particularly focused on the effect of water column depth and turbulence. Here, aiming to generalize this picture, we develop a simple 2D model that allows to include the effects of both large-scale fluid motions and small-scale turbulence on phytoplankton dynamics in light-limited environments.



Methodology

We propose a 2D advection-reaction-diffusion model based on the solution of an equation for a phytoplankton population density field $\theta(x,z,t)$:

$$\frac{\partial \theta}{\partial t} = [p(I) - l]\theta - \mathbf{v} \cdot \nabla\theta + D\nabla^2\theta. \quad (1)$$

Growth is controlled by a production p and loss l rate, advection is realized by a 2D flow, including a sinking component, diffusion is represented by turbulent diffusivity D. Production accounts for water background turbidity K_{bg} and population self-shading k:

$$p(I(z,t)) = \frac{p_{max} I(z,t)}{H + I(z,t)} \quad (2), \qquad I(z,t) = I_{in} e^{-\int_0^z k\theta(\sigma,t)d\sigma - K_{bg} z}. \quad (3)$$

We chose periodic boundary conditions along the horizontal x and no flux boundary conditions in depth z. The velocity field is given by the sum of a sinking component v_{sink} along z and a 2D flow defined by the following streamfunction [3]:

$$\Psi(x,z,t) = -\sum_{i=1}^{n_k} \frac{U_i}{k_i} sin\left\{k_i[x - s_i sin(w_i t)]\right\} sin(k_i z), \quad (4)$$

$$v_x = -\partial_z \Psi(x,z,t) \ , \quad v_z = \partial_x \Psi(x,z,t). \quad (5)$$

Numerical Results

In the absence of large scale flow ($\Psi(x,z,t) = 0$), our model correctly reproduces the bloom/no bloom phase diagram of [2] (Fig. 1). **Bloom condition** is defined by $d\langle\theta\rangle_{x,z}/dt > 0$ ($\langle ... \rangle_{x,z}$ denotes a spatial average) satisfied at short times (enough to confirm persistent behaviour); correspondingly a **no bloom** situation is identified by $d\langle\theta\rangle_{x,z}/dt < 0$.

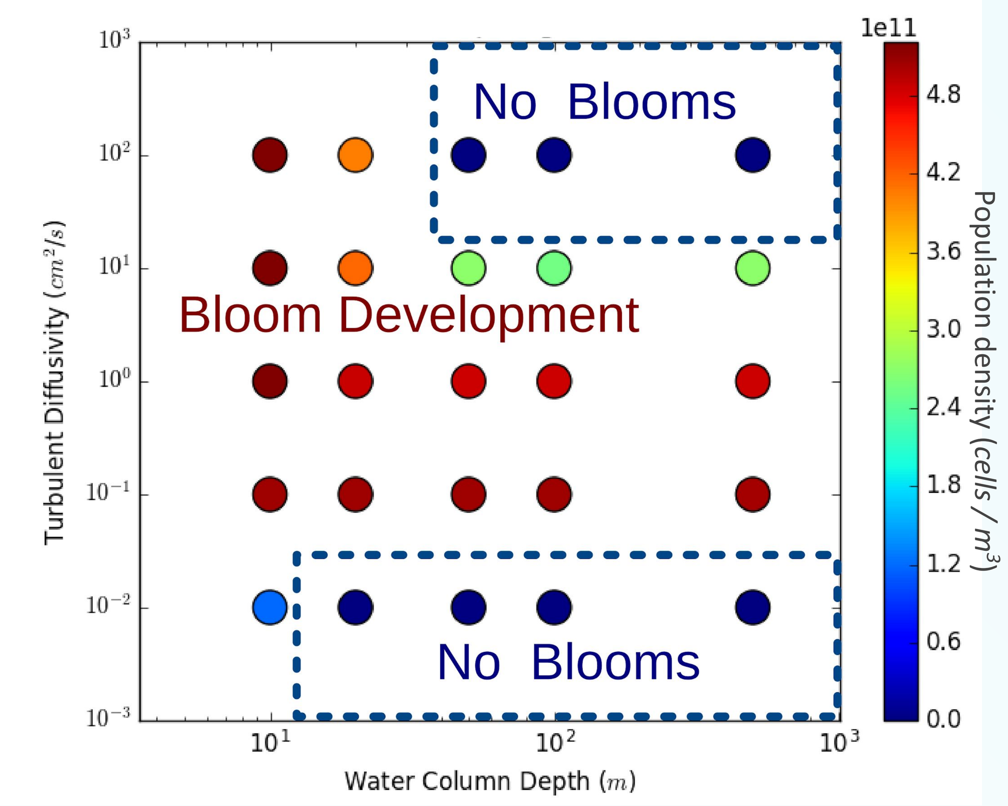


Figure 1: Phase diagram without a large scale flow.

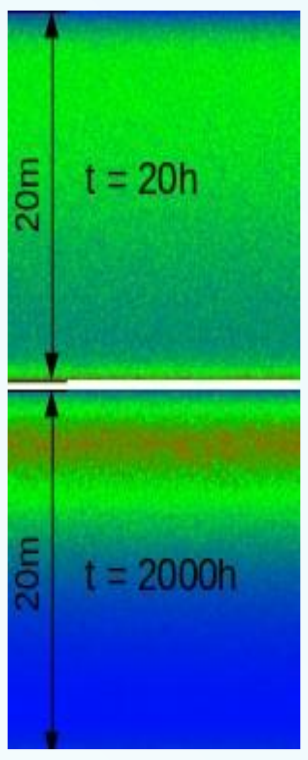


Figure 2: Spatial distribution of sinking phytoplankton at two different times for an initially homogeneous system with 20m depth.

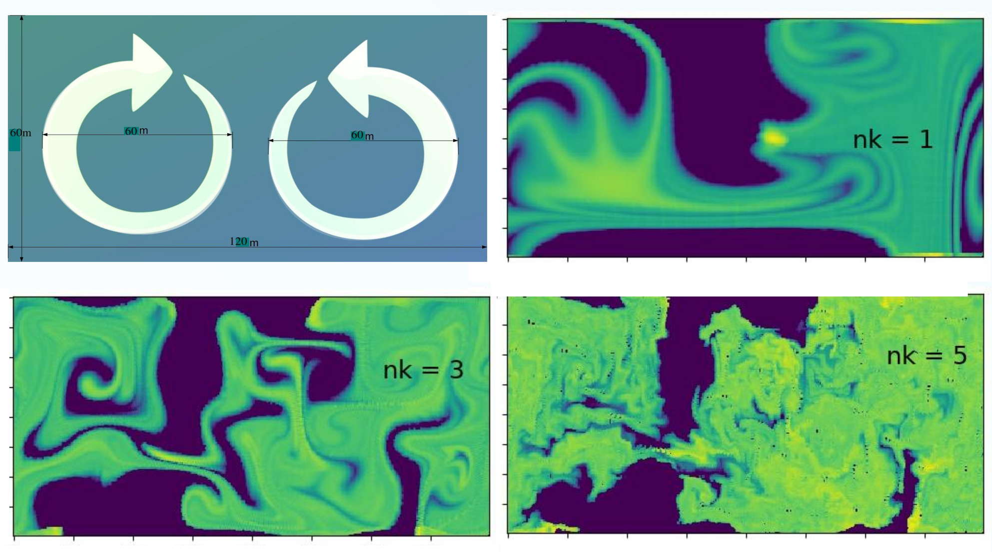


Figure 3: Spatial phytoplankton distribution at large times for flow fields from Eqs. (4,5) characterized by a progressively larger number of cellular modes (**n_k**). Clearer green indicates higher density.

The transport by a multiscale flow has an apparent effect on the distribution of the biological population, whose organization becomes more complex as smaller and smaller scales (higher number of flow modes) are added (Fig. 3). A major feature, however, is the impact of large scale motions, on which we then focus.

We consider a domain of horizontal size ***L_x = 120m*** and vertical size ***L_z = 60m***. We chose L_z as the smallest depth for which a turbulence window of bloom development can occur (see Fig. 1). Large scale motion is represented by two vortices (Fig. 3 *top left*) of size ***$L = L_x/2$ = 60m***, flow speed ***U*** (Eqs. 4,5) and ***n_k = 1***.

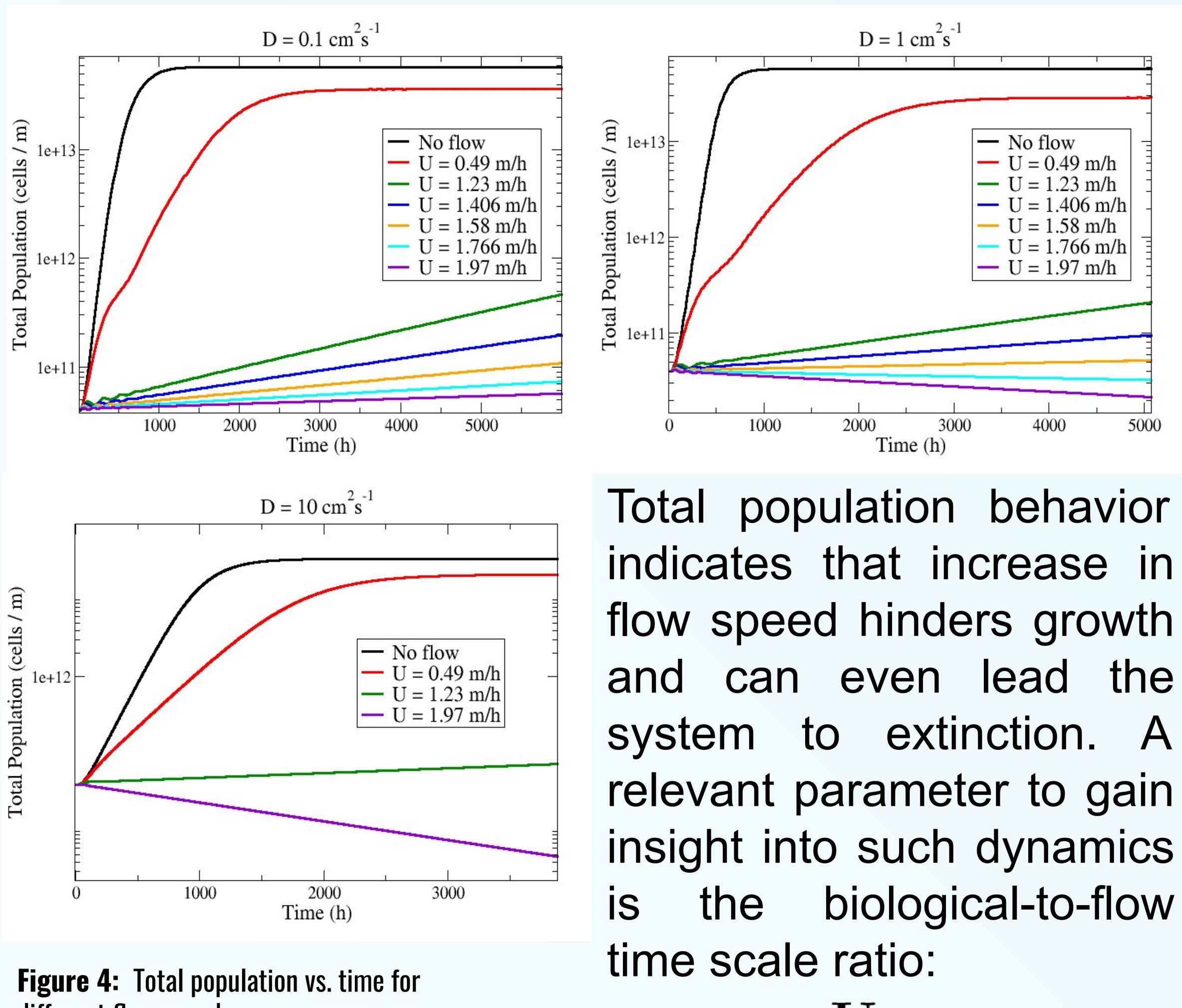


Figure 4: Total population vs. time for different flow speeds.

Total population behavior indicates that increase in flow speed hinders growth and can even lead the system to extinction. A relevant parameter to gain insight into such dynamics is the biological-to-flow time scale ratio:

$$\gamma = \frac{\mathbf{U}}{\mathbf{p_{max} L}} \quad (6)$$

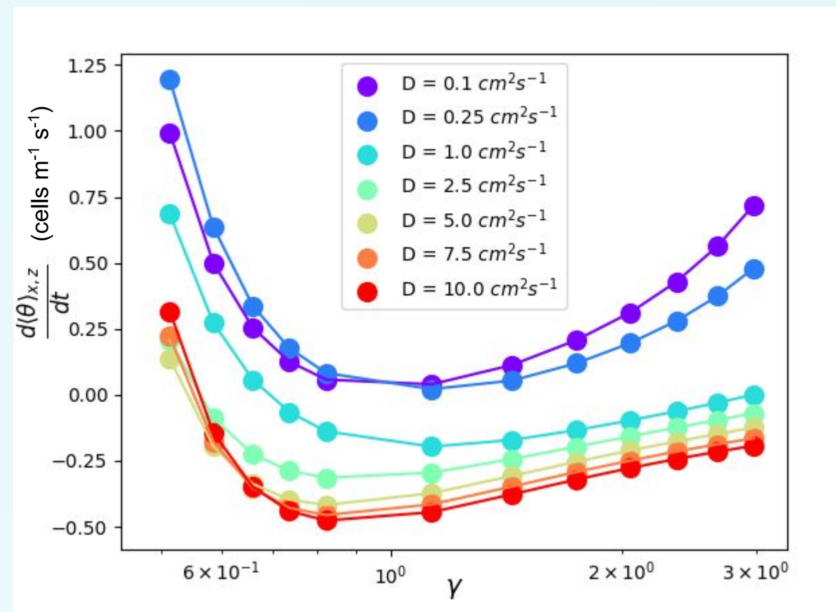


Figure 5: Early-time average population growth rate (average over a 1000 hours) vs γ.

Figure 5 confirms that larger *U* unfavors population survival. The early-time average population growth rate is minimal when *γ ~ 1*. For large enough diffusivities this effect can cause extinction.

Figure 6: Diagram illustrating $d\langle\theta\rangle_{x,z}/dt$ for multiple simulations with different *D* and *U*.

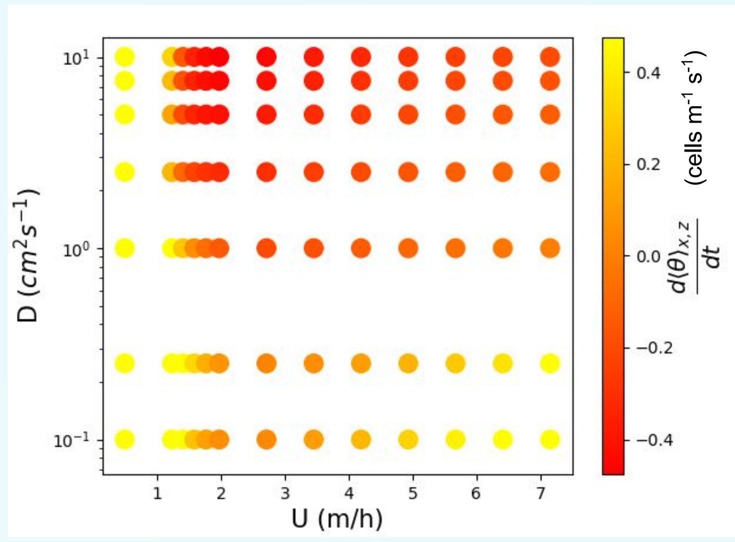


Figure 6 summarizes our results. The large-scale flow reduces the population growth, an effect that increases with larger *D*. Extinction phenomena are only seen for *D > 0.75 $cm^2 s^{-1}$*.

Conclusions & Perspectives

We considered an extension of previous models accounting for the effect of turbulence on vertical phytoplankton dynamics, by including advection by a large-scale flow. We find that the large scale flow typically negatively affects population survival and can even lead to extinction of an otherwise surviving population. An important parameter controlling such an effect is the ratio between the characteristic biological and flow timescales, similarly to what occurs for plankton horizontal dynamics stirred by mesoscale ocean eddies [4]. In the present case at very large values of U, the system rapidly homogenizes and the dynamics appear more similar to purely diffusive ones, though with larger diffusivity.

In future developments, it would be interesting to extend this study to different water depths. Furthermore, we aim to analyse more realistic flow models (e.g. to account for winter convection), characterized by a broader range of scales, in both two and three dimensions.

References:

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