Phytoplankton dynamics

I. BACKGROUND

Phytoplankton - tiny free-floating algae - are responsible for about half of the primary production on the planet and form the foundation of the food web in oceans and lakes. The increase or decrease in a population of phytoplankton cells is set by a balance between cellular division (growth) and losses due to a variety of factors including predation and viruses. When growth is sufficient to overcome net losses, the phytoplankton concentration can grow exponentially - a phytoplankton 'bloom'. At a fundamental level, phytoplankton need light and nutrients to grow. Recent studies have shown that upper ocean dynamics can influence both of these important factors and control whether a phytoplankton population flourishes or dies. In this project, you will add a biological model to Diablo and explore coupled ecosystem dynamics with a simple three-component model.

FIG. 1: Phytoplankton bloom off the coast of England and France (source: NASA).

II. INTRODUCTION

We can build a simple model for phytoplankton by adding growth and death terms to the advection/diffusion equation for a passive scalar. Start by considering the following equation

$$\frac{\partial P}{\partial t} + \mathbf{u} \cdot \nabla P = \left(\mu_0 e^{y/h_l} - m\right) P + \kappa \nabla^2 P. \tag{1}$$

Here, $y < 0$ represents depth in the ocean and decreases downwards from the surface where $y = 0$, μ_0 is the maximum growth rate that can be achieved by a phytoplankton population, h_l is an e-folding depth associated with light penetration into the ocean, and m is a constant mortality rate. Note that this model does not explicitly include nutrients, grazing, sinking, etc. Nevertheless, it is useful for examining the influence of fluid dynamics on phytoplankton growth. Taylor and Ferrari [1] (a pdf is in your project folder) used this model in large-eddy simulations (LES) of turbulent convection, and showed that phytoplankton growth is possible when the surface heat loss is smaller than a critical value.

III. NUMERICAL SIMULATIONS

The goal of this part of the project will be to add a phytoplankton model following Eq. (1) into Diablo. To do this, add growth and loss terms to the right hand side of one of the scalars in *user_rhs.m*. Note that you will need to designate which scalar will be phytoplankton, and which will be density (or buoyancy). It might also be helpful to set the parameters and boundary conditions in Diablo to correspond to dimensional (mks) units.

Start with some of the parameters listed in the Taylor and Ferrari [1] paper and try simulating turbulent convection. Note that since you are using a 2D model instead of a 3D LES, your results will not match exactly, but you should be able to reproduce some of the same qualitative features. You will also probably need to decrease the domain size somewhat and/or lower the resolution to get the simulation to run fast enough to see phytoplankton growth.

Experiment by changing the surface forcing. You might try adding a wind stress (0.1 N/m^2 is a reasonable magnitude), or changing the surface buoyancy flux from cooling to heating. How do phytoplankton respond? How well mixed are the phytoplankton? Do you see coherent structures in the phytoplankton concentration?

IV. COUPLED PREDATOR-PREY MODEL

Although Eq. (1) is useful for examining the influence of fluid dynamics on phytoplankton, notice that the equation is linear in P. This limits the complexity of the population dynamics. In reality, the dynamics of the marine ecosystem are complex and interesting in their own right. NPZ models are a simple class of marine ecosystem models that exhibits interesting biological dynamics with three components: phytoplankton (P), nutrients (N), and zooplankton (N) (herbivores that consume phytoplankton). The following is an example of an NPZ model:

$$\frac{dN}{dt} = -\mu P\left(\frac{N}{N+N_s}\right) + rP, \tag{2}$$

$$\frac{dP}{dt} = \mu P\left(\frac{N}{N+N_s}\right) - \alpha PZ - rP, \tag{3}$$

$$\frac{dZ}{dt} = \alpha\beta PZ - mZ. \tag{4}$$

Phytoplankton consume nutrients when they grow at a rate $\mu(t)$ that can be a prescribed function of time. When the nutrient concentration is much smaller than a saturation value N_s, phytoplankton growth will be limited by the lack of nutrients. When phytoplankton die at a rate r, their organic material is broken down and recycled back into usable nutrients. Phytoplankton are grazed by zooplankton at a rate α. Zooplankton grow through grazing, but only a fraction β of the phytoplankton biomass gets converted into zooplankton. Zooplankton also die at a rate m.

An advantage of models like Eqns. 4 is that they allow us to explore coupled ecosystem dynamics quickly. In your project directory, there is a script called *NPZ.m* that solved these equations. Experiment with this model, changing various parameters. Does the model reach an equilibrium state? If so, which terms in Eqns. 4 balance at equilibrium?

V. SUGGESTED FURTHER INVESTIGATIONS

A. Spring bloom

A remarkable feature of phytoplankton populations in many regions of the ocean is a dramatic growth event in the spring - the spring bloom. Evans and Parslow[2] (a pdf is in your project folder) used a model very similar to the one above to simulate the spring bloom. Try making the growth rate, μ a function of time to mimic the annual cycle in light availability. Do you see any evidence for a spring phytoplankton bloom? Try replicating one of the cases in Evans and Parslow[2] by modifying the equations in *NPZ.m*

B. NPZ fluid dynamics model (ambitious)

Try adding equations for nutrients and zooplankton into Diablo to create an NPZ model. How does the model respond to a given fluid dynamical environment? Does this change any of the conclusions that you came to in the first part of the project?

VI. REFERENCES

[1] J. R. Taylor and R. Ferrari, Limnology and Oceanography (2011).

[2] G. T. Evans and J. S. Parslow, Biological oceanography **3**, 327 (1985).