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CE 200B Environmental Fluid Mechanics

NPZ Model with Whale Interactions

I recently watched the Netflix documentary "Seaspiracy" and it left me shook. The amount of destruction and plunder we humans have incurred on our oceans (not to mention planet) is astounding. Covering heavy topics from whale and dolphin hunting to overfishing to corruption to modern slavery, the documentary aims to highlight some key injustices occurring in our marine environments. Although there is much (questionable?) controversy surrounding the film's statistics and representations, there was one indisputable fact that struck a chord with me. When whales and dolphins surface to breathe, they fertilize (and consume) phytoplankton, "which every year absorb four times the amount of carbon dioxide than the Amazon rainforest does and generates up to 85% of the oxygen we breathe." I became curious as to the magnitude of influence these marine mammals have on their environments, especially as climate change accelerates and populations continue to diminish due to inhumane hunting, plastic pollution related deaths, etc. As such, I will explore the impacts of baleen whales on nutrient and plankton concentrations utilizing physical and NPZ models.

The NPZ model illustrates the evolution of nutrient, phytoplankton, and zooplankton concentrations through a set of transfer functions which account for growth and death rates, grazing losses, and irradiance. Based on an article by Peter Franks, "NPZ Models of Plankton Dynamics", and my kind GSI Lily (who has provided me with her own background research and code), I am modeling growth with the Michaelis-Menten formulation, death with linear processes, grazing with the Ivlev response (with messy eating), and irradiance with a saturating and photoinhibiting response. As such, the population dynamics I employ are as follows:

$$\text{Nutrients: } \frac{dN}{dt} = -\frac{f(I)V_m N}{K_S + N}P + mP + gZ + \gamma\alpha R_m(1 - e^{-\Lambda P})Z$$

$$\text{Phytoplankton: } \frac{dP}{dt} = \frac{f(I)V_m N}{K_S + N}P - mP - \alpha R_m(1 - e^{-\Lambda P})Z$$

$$\text{Zooplankton: } \frac{dZ}{dt} = -gZ + (1 - \gamma)\alpha R_m(1 - e^{-\Lambda P})Z$$

$$\text{Irradiance: } f(I) = \frac{I}{I_0}e^{\left(1 - \frac{I}{I_0}\right)}$$

The physical model, which is illustrated through a set of Navier-Stokes equations, incorporates these population dynamics with unsteadiness, advection, and diffusivity terms. Based on the water column code used throughout the semester, the evolution of NPZ concentrations is then iteratively determined via tridiagonal solvers (note: Lily kindly shared with me her code for an NPZ model in a water column).

As I am curious about the impacts of baleen whales on NPZ concentrations, I have incorporated their presence through various forcing scenarios, namely plankton consumption and nutrient addition via defecation. Through background research, I learned that baleen whales eat about 4% of their body weight each day during the feeding season[1] and they feed twice a day[2]. Assuming an average baleen whale weighs around 220,000 pounds[3] and a feeding lasts one hour[4], a whale consumes approximately 0.55 x 10^9 micrograms of phytoplankton and zooplankton per second per feeding. Thus, for modeling purposes, I will assume the whale consumes all phytoplankton and zooplankton in the portion of the water column through which it swims.

As for nutrient addition, baleen whales excrete approximately 10 kilograms of nitrogen per day[5]. Assuming the whale only relieves itself upon resurfacing for air, travels at 7.8 meters per second[6], and the diameter of the whale's wake is equivalent to the fin's diameter of 7.5 m[7], nitrogen deposition is approximately 4.03 micrograms per liter per second per feeding. Thus, for modeling purposes, I will assume the whale adds nutrients at the same rate as nitrogen to the portion of the water column through which it swims.

Modeling a 50-meter-deep water column with steady flow and salinity stratification, I assess three scenarios: plankton consumption, nutrient addition, and plankton consumption + nutrient addition. For plankton consumption, I assume the whale eats all plankton (phyto- and zoo-) in its fin-sized-diameter wake for a period of an hour. For nutrient addition, I assume the whale defecates in its fin-sized-diameter wake instantaneously. All scenarios occur at the middle time step of the model's duration.

Figure 1 displays the base NPZ states given no plankton consumption or nutrient addition. Figures 2-4 display the NPZ states for the plankton consumption, nutrient addition, and plankton consumption + nutrient addition scenarios respectively.

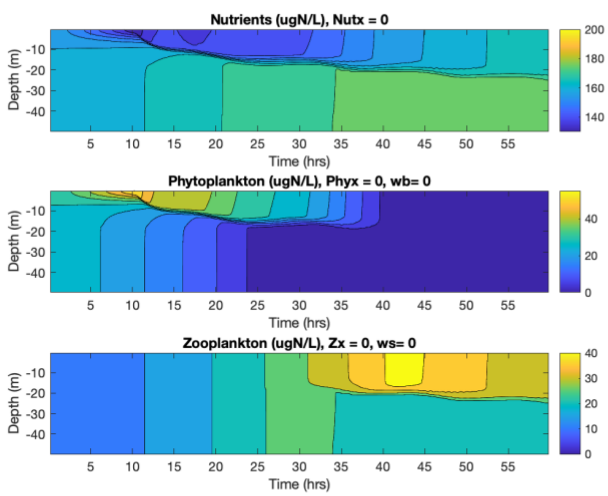

Figure 1: Base Scenario

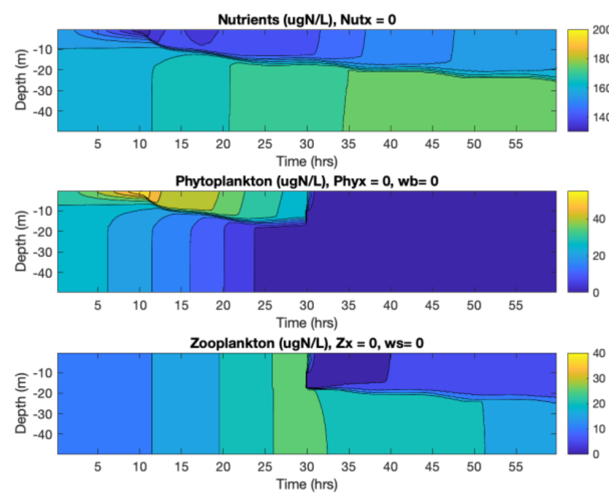

Figure 2: Plankton Consumption Scenario

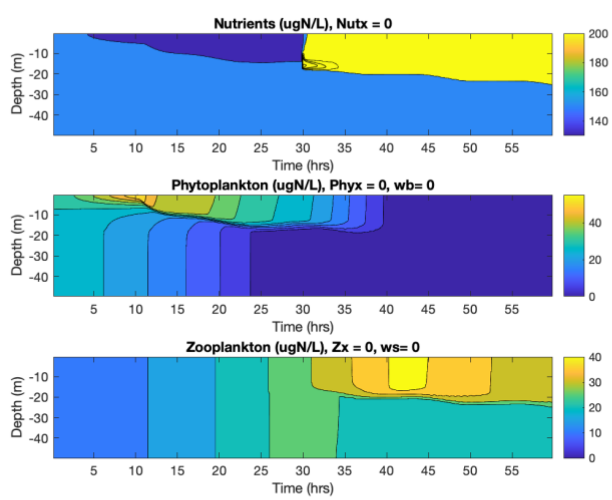

Figure 3: Nutrient Addition Scenario

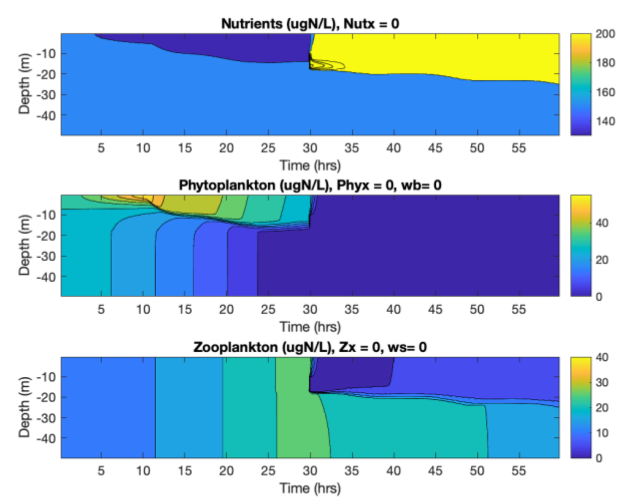

Figure 4: Consumption + Addition Scenario

For the plankton consumption scenario, one can notice that post-consumption the phytoplankton are unable to regenerate, meanwhile the zooplankton regenerate after a bit of time and are largely unaffected in the lower depths. The phytoplankton's behavior is largely in-line with the base scenario, being that phytoplankton concentrations become negligible over time, as grazing exceeds growth. Similarly, the zooplankton's behavior is largely in-line with the base scenario, with regeneration occurring and dropping off over time due to grazing catching up with phytoplankton presence. The nutrient profile remains relatively unchanged.

For the nutrient addition scenario, only the nutrient profile is affected. Post-addition, the nutrient levels skyrocket, with a diffusive Gaussian distribution. Due to stratification, the high nutrient levels are contained to the upper depths of the water column. Both plankton profiles are unchanged.

Lastly for the plankton consumption combined with nutrient addition scenario, the plankton profiles are the same as that in the plankton consumption scenario and the nutrient profile is the same as that in the nutrient addition scenario. Due to the population dynamics, the phytoplankton are unaffected by the heighted nutrient levels post-consumption, and thus the zooplankton are unaffected as well.

As evidenced by the modeling scenarios, baleen whales have a significant effect on the evolution of nutrient and zooplankton concentrations. Unfortunately, the interactions between plankton consumption and nutrient addition did not spur regeneration as I expected; a more complex model is needed to express such dynamics. Nevertheless, conceptually the addition of nutrients via defecation by whales is an impactful and vital component of marine ecosystems. NPZ and baleen whales form a dependent food cycle, in which whales excrete nutrients for phytoplankton to consume, increasing phytoplankton populations for zooplankton to feed off, and then eventually whales to consume. As predator prey relations go, it is extremely important that the two keep each other in check to maintain a healthy ecosystem. That was a key insight I took away from the "Seaspiracy" documentary, and I hope that resonated with others as well. Current waste management and commercial fishing practices are very set in their ways, and it will take persistent revelations and corrective action to maintain and improve NPZ and baleen whale interactions.