Simulating Entrainment in Diel Vertical Migration

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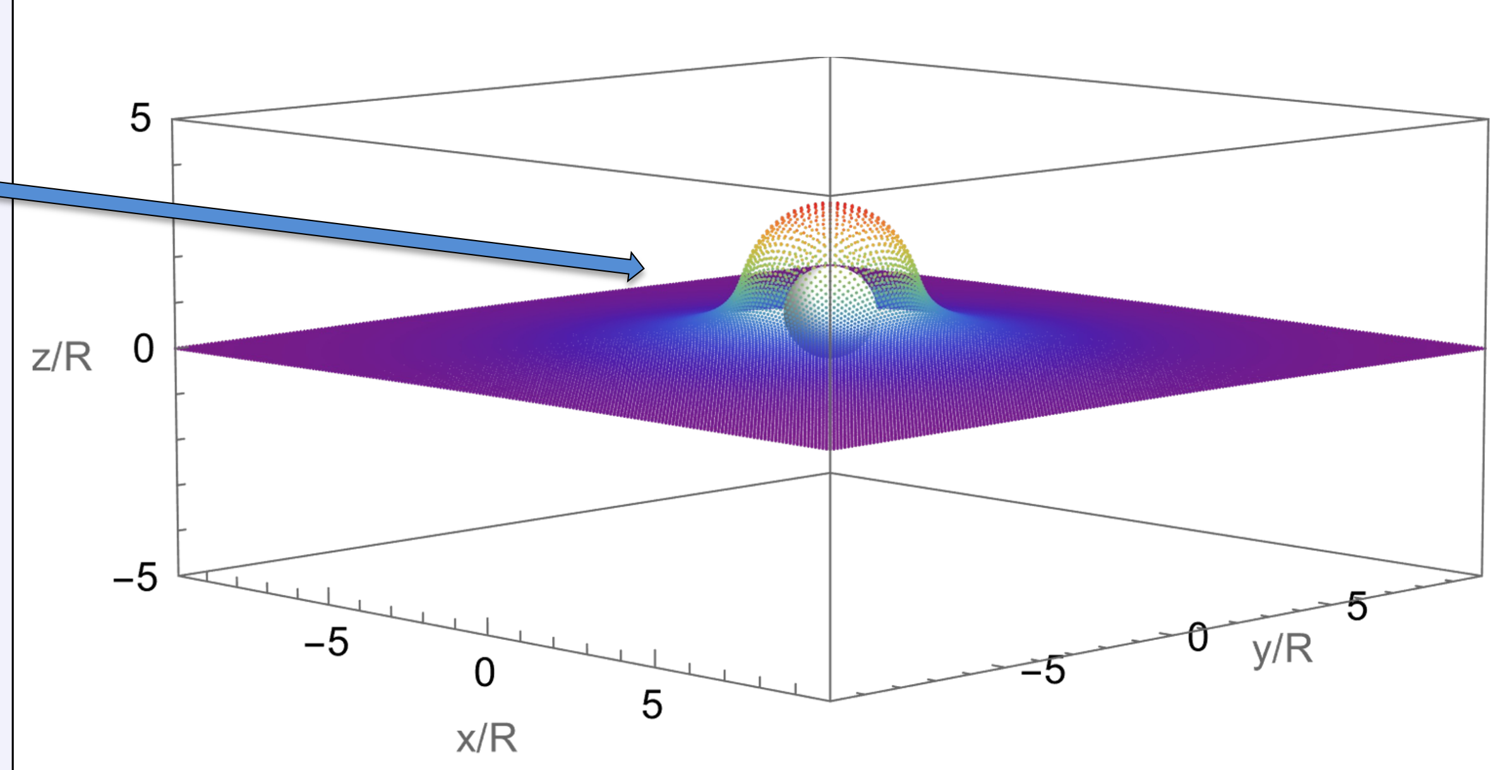
Introduction

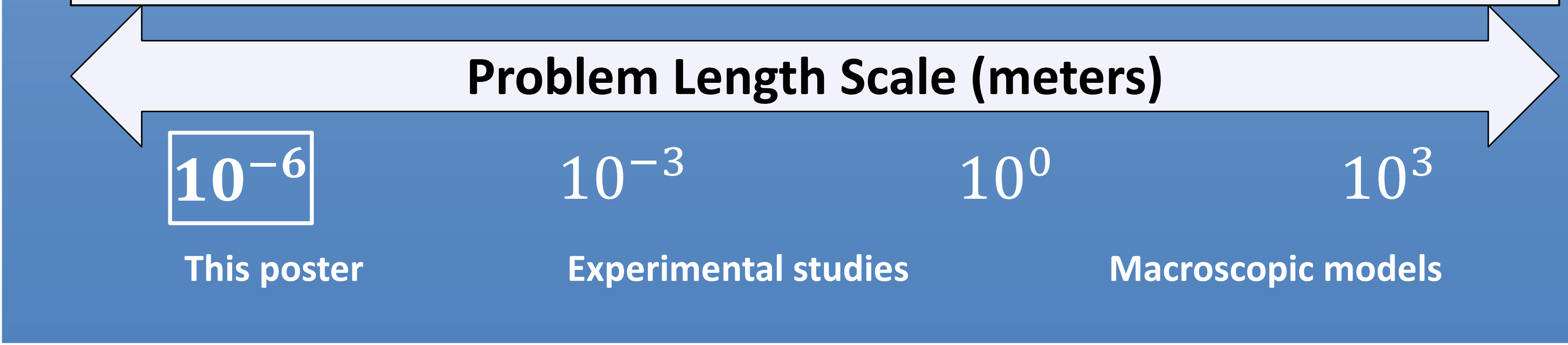
- I attempt to study DVM using simulations of **microswimmers and tracer particles in Stokes (low Reynolds number) flows**
- Reynolds number: Ratio of inertial to viscous forces
- Principal question: Do vertically migrating organisms create significant **mixing** by entraining (dragging) the surrounding water and its contained nutrients?
- This question is relevant to our understanding of natural water bodies and how **nutrients and carbon** are transported vertically across stratified layers. Once understood more completely, biologically generated mixing could be implemented in **ocean and climate models**[1]

A microswimmer (gray sphere) swims in the +z direction and entrains tracer particles that initially lay on the x-y plane. Particles near the swimmer are moved greatly forward, while further particles are moved slightly backward.



Diel Vertical Migration

- **Diel vertical migration**: The daily movement of organisms in the ocean and lakes to and from the surface
- Perhaps the **largest synchronous migration in the world** by total biomass
- Most organisms migrate downward at dawn and upward at dusk, effectively **avoiding sunlight**
- “**Active transport**” of nutrients and carbon – a key part of the biological pump that removes carbon from the atmosphere[2]
- In our group, we combine numerical and experimental methods to study DVM at numerous length scales



Problem Length Scale (meters)

$\boxed{10^{-6}}$ 10^{-3} 10^{0} 10^{3}

This poster **Experimental studies** **Macroscopic models**

Simulation

- Begin with the **“Squirmer”** model for the fluid flow on the surface of a cilia-covered spherical microswimmer[3]
- $P_n(\cos\theta)$ are the Legendre polynomials, and B_n are coefficients that determine the swimmer’s speed and “pusher”/”puller” status:

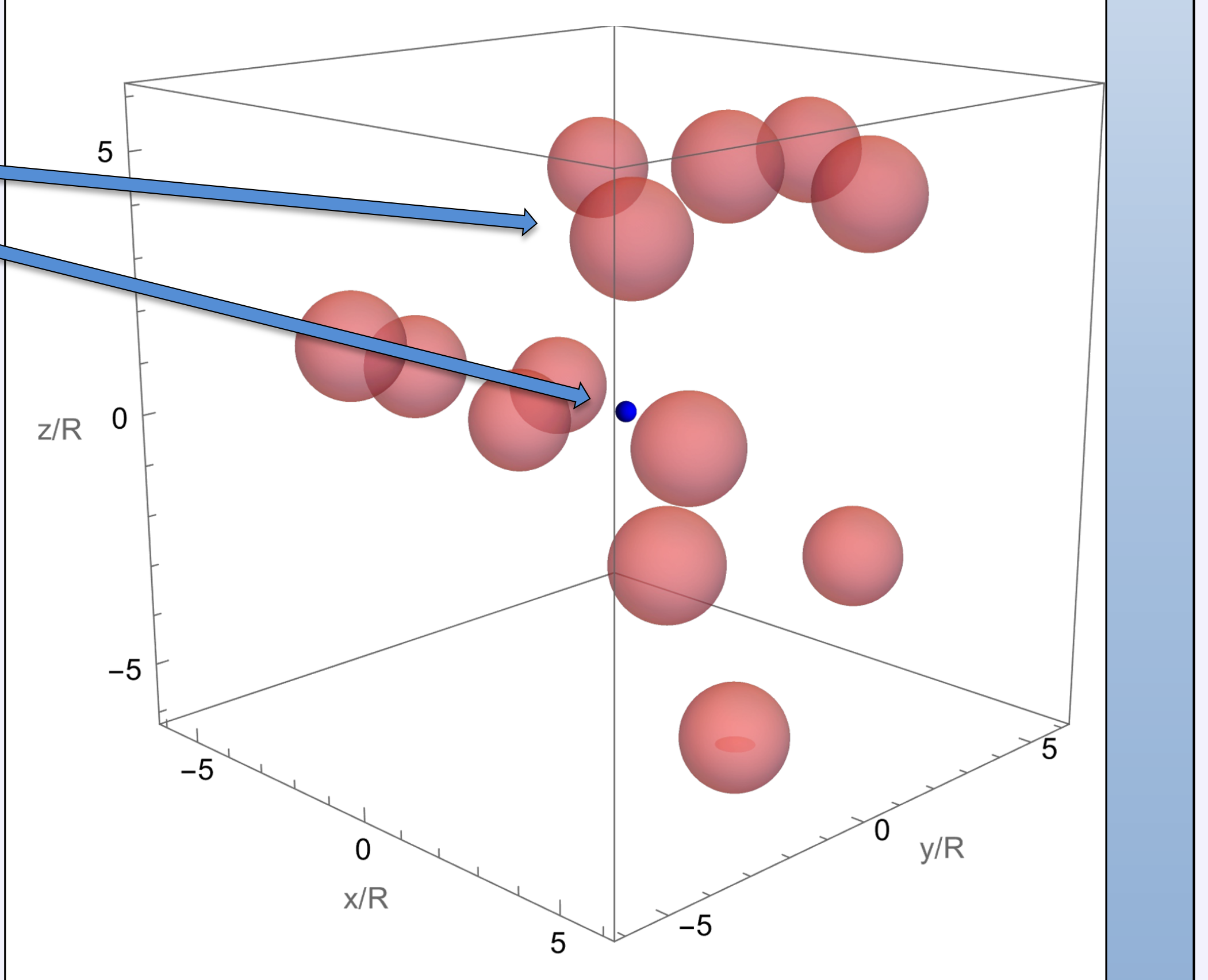
$$u_\theta|_{r=R} = -\sum_{n=1}^{\infty} B_n \frac{2}{n(n+1)} \partial_\theta P_n(\cos\theta)$$

Initial conditions:

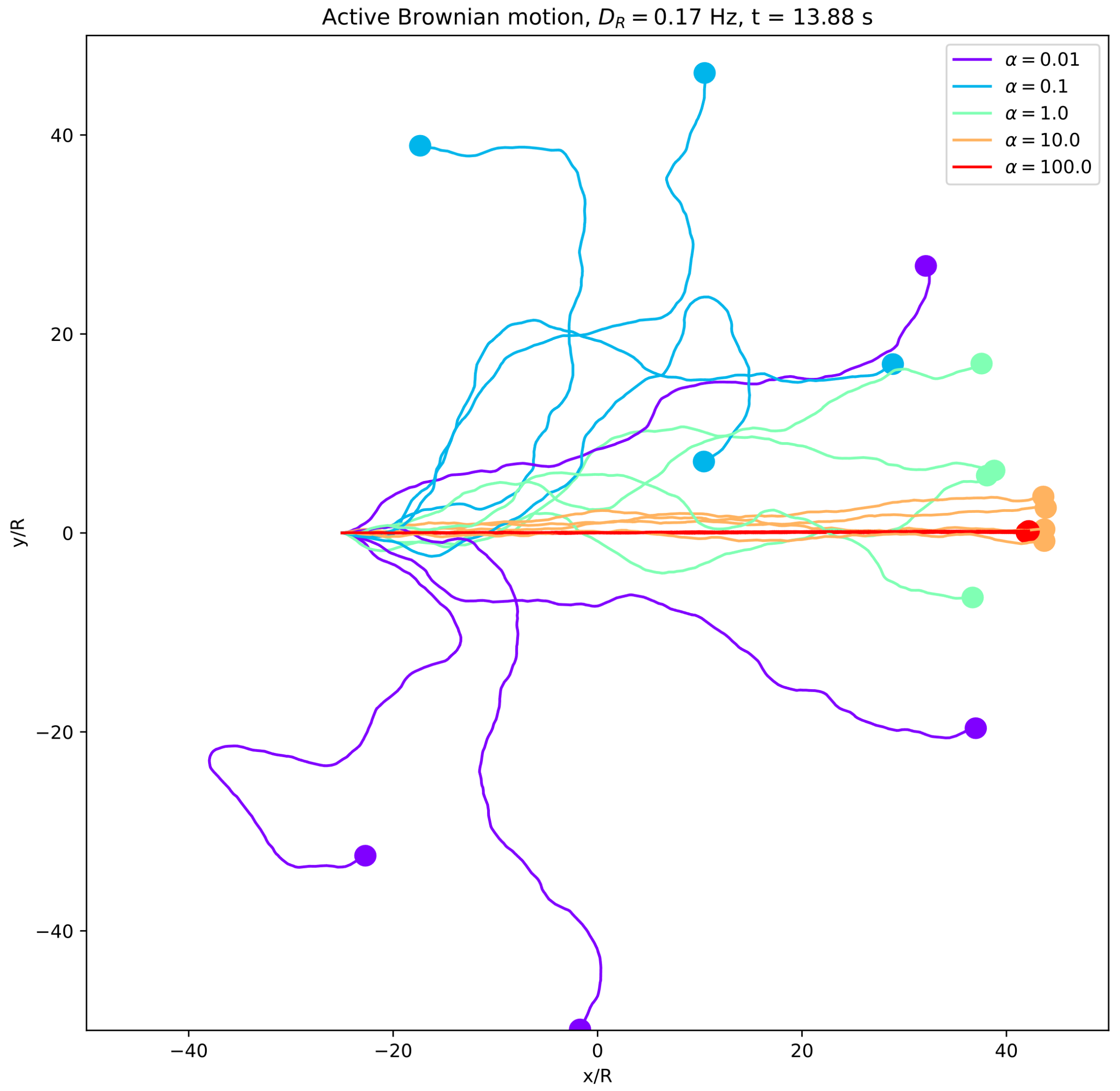
- N microswimmers placed using a uniform random distribution in a box of side length L
- Tracer particle located at origin
- Swimmers given initial velocities with magnitude U and directions randomly distributed but biased toward +z direction

Advancing time:

- Calculate new object positions using RK4 method
- Continue random reorientations of swimmers
- Account for possible overlap between tracer and swimmer positions
- Reset swimmer positions to random locations at lower bound when they reach upper bound
- Move box with tracer



- We make use of a **phototactic susceptibility variable** α (Hz) to quantify the bias of microswimmers’ movement toward the preferred direction (either toward or away from light)
- The figure to the right shows the trajectories of 20 swimmers swimming to the right with different values of α. All swimmers begin at the same location, but swimmers with lower α meander away from the direct path
- In future simulations, phototactic susceptibility could be expanded as a nonlinear function of light intensity[4], and light intensity could be expanded as a function of time to replicate day/night cycles

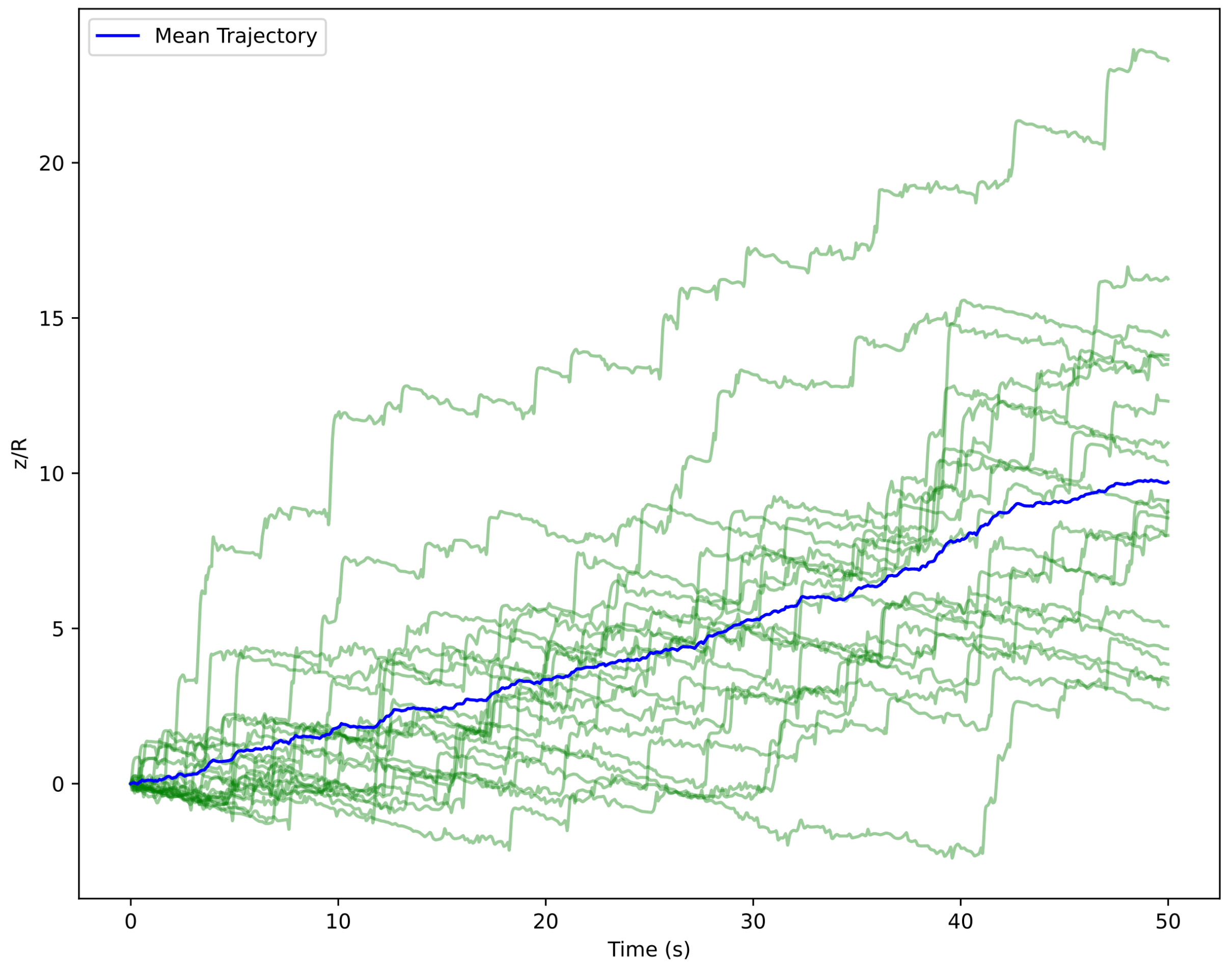


- In the future, plan on implementing **run-and-tumble motion** and downward drift due to **negative buoyancy** with realistic parameters

Analysis

- Tracer particles experience “jumps” in the +z direction when “collision” events with swimmers occur
- For a given swimmer number density and α, a mean **drift velocity** can be calculated from data from many simulations
- **Effective diffusivity** can be measured from the spread of tracer z-positions over time

Example plot after 20 independent simulations. This data is for $\alpha = 1$ and N = 10 in a box of L = 10R. (If each swimmer represents an organism of radius ~5 microns, then this equates to a density of 8e7 indiv. mL^{-1}.) A linear fit shows the drift velocity here to be about 0.203 s^{-1}.



- A shortcoming of this model is that it does not consider molecular scalar diffusion, which reduces transport[5]
- Two other mixing mechanisms for future study: **turbulence created by larger swimmers**, and **bioconvection**, a process centered around local changes in fluid density[6]

References

1. Katija K. 2012. Biogenic inputs to ocean mixing. J Exp Biol. 215:1040-1049.
2. Archibald K, Siegel DA, Doney SC. 2019. Modeling the impact of zooplankton diel vertical migration on the carbon export flux of the biological pump. Global Biogeochemical Cycles. 33:181-199.
3. Lighthill MJ. 1952. Comm. Pure Appl. Math. 5:109-118.
4. Ramamonjy A, Dervaux J, Brunet P. 2022. Nonlinear phototaxis and instabilities in suspensions of light-seeking algae. Physical Review Letters. 128:258101
5. Kunze E. 2019. Biologically generated mixing in the ocean. Annual Review of Marine Science. 11:215-226.
6. Sommer T, et al. 2017. Bacteria-induced mixing in natural waters. Geophysical Research Letters. 44:9424-9432.

Acknowledgements

Thank you to CURF for individual funding through PURM.