Modeling the Dispersal and Connectivity of Marine Larvae with GenAI Agents

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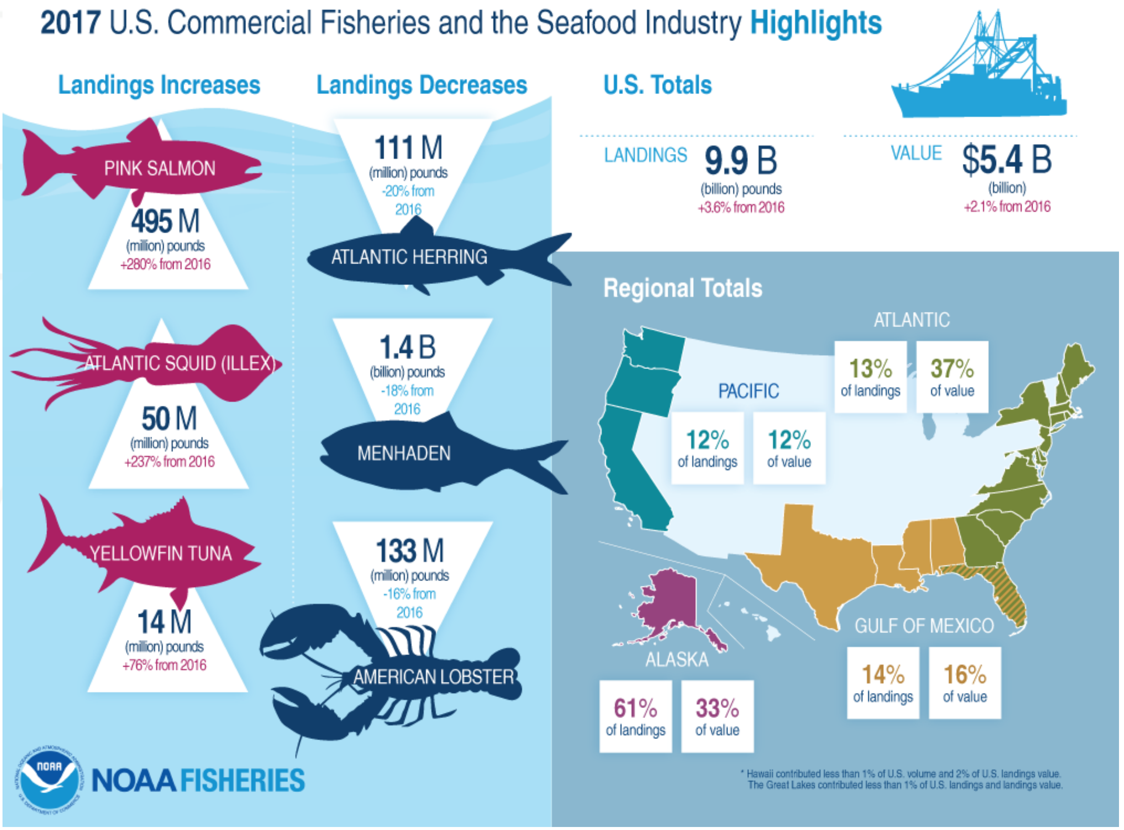
Importance of Marine Ecosystems



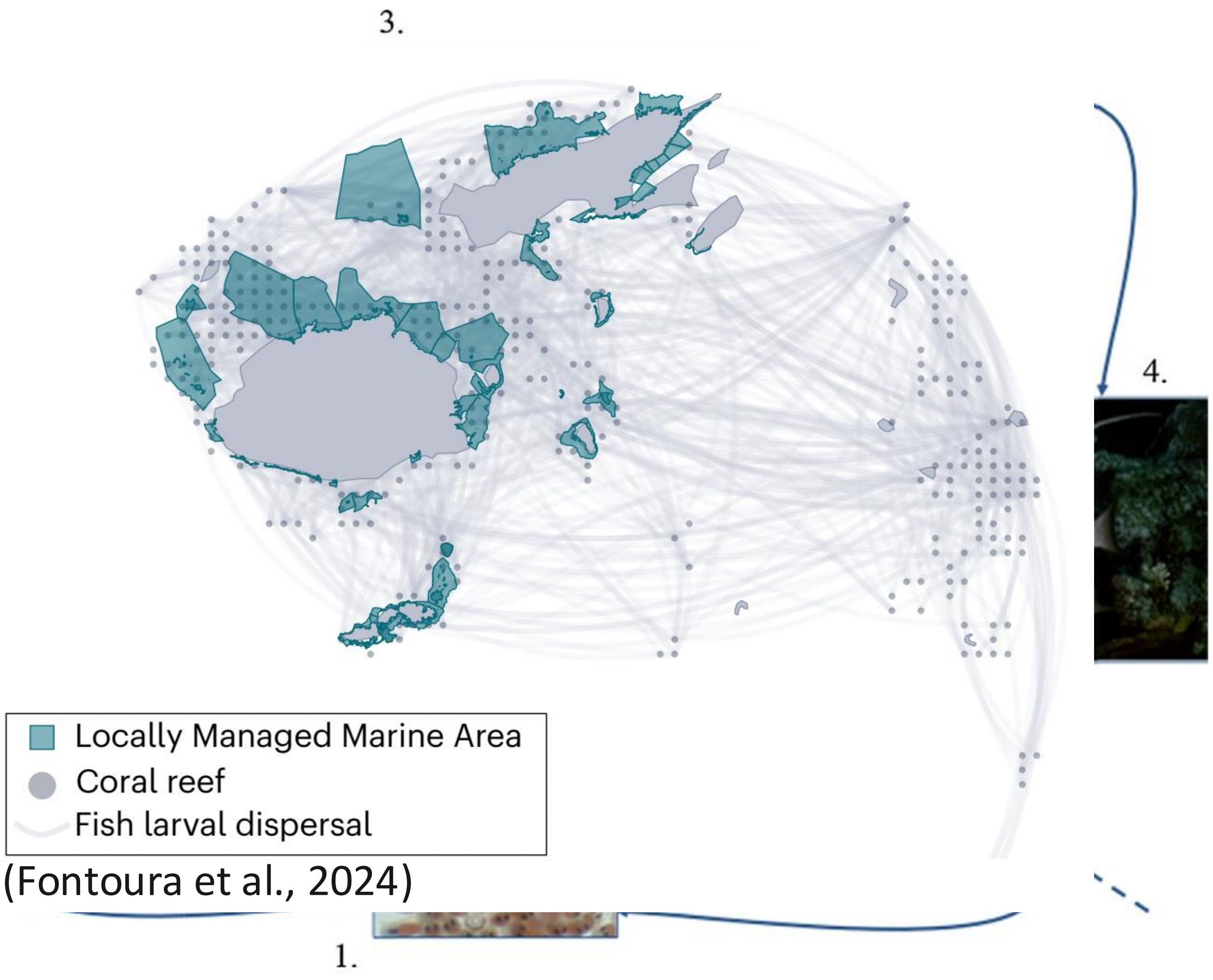
(https://www.fisheries.noaa.gov/national/fisheries-united-states-2017)

Management actions are urgently needed to ensure future ecosystem sustainability.

Marine ecosystems are under serious threats from human activities

- Overall, fish populations have declined by 87.7 % between 2003 and 2019. Declines concerned >70 % species regardless of migratory behavior (Chevalier et al., 2023).
- Over 8% of the 17903 marine species assessed are at risk of extinction (IUCN, 2024).
- Estimated 50% of global live coral cover has been lost over the last 50 years (Souter et al., 2020).

Marine Larvae



(Fontoura et al., 2024)

(Simpson et al., 2013)

Pelagic Larval Duration (PLD) is critically important for sustaining species populations and maintaining biodiversity

Observing larval dispersal and connectivity is extremely challenging

Dispersal: Describes the spatial scale of population replenishment (how far larvae travel and where they settle).

- High mortality and difficult identification
- Long transport by ocean currents
- Vast spatiotemporal scales

Connectivity: Refers to the magnitude and direction of ecological linkages among different populations and habitats.

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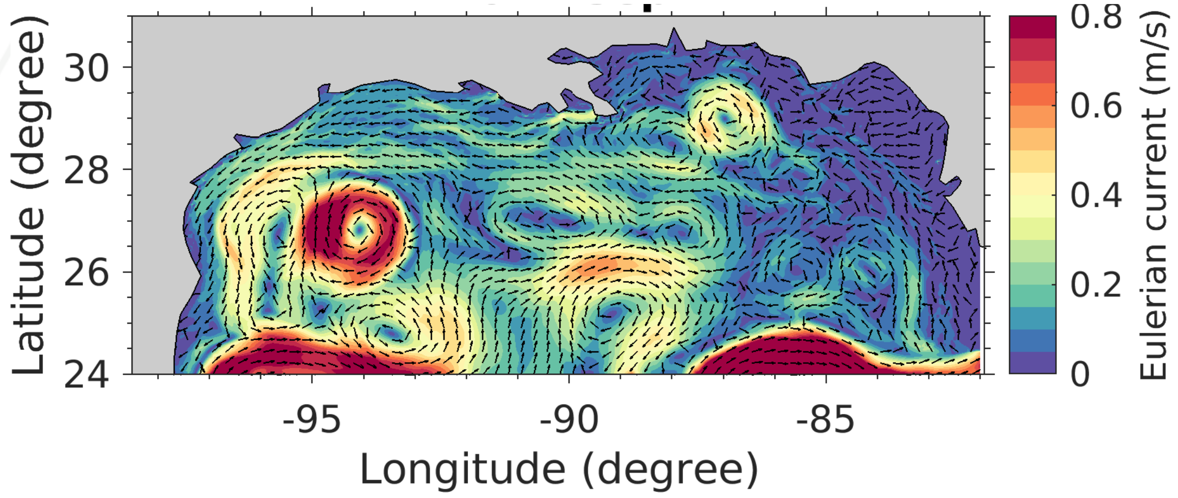
Biophysical model

Physical transport **Larvae behavior**

$$\frac{dX}{dt} = u(X,t) + \sqrt{2K(X,t)}\varepsilon(t) + W_s(d,\rho) + f_{swim} + \cdots + f_{OVM}$$

Example of flow fields for the Gulf of Mexico



Traditional approach: parameterized, hard-coded, and lacking adaptation to environmental changes.

Change to

Agentic framework: intelligent decision-making based on reasoning.

This is the first attempt worldwide to couple biophysical models with LLM agents to study connectivity and ichthyoplankton dynamics.

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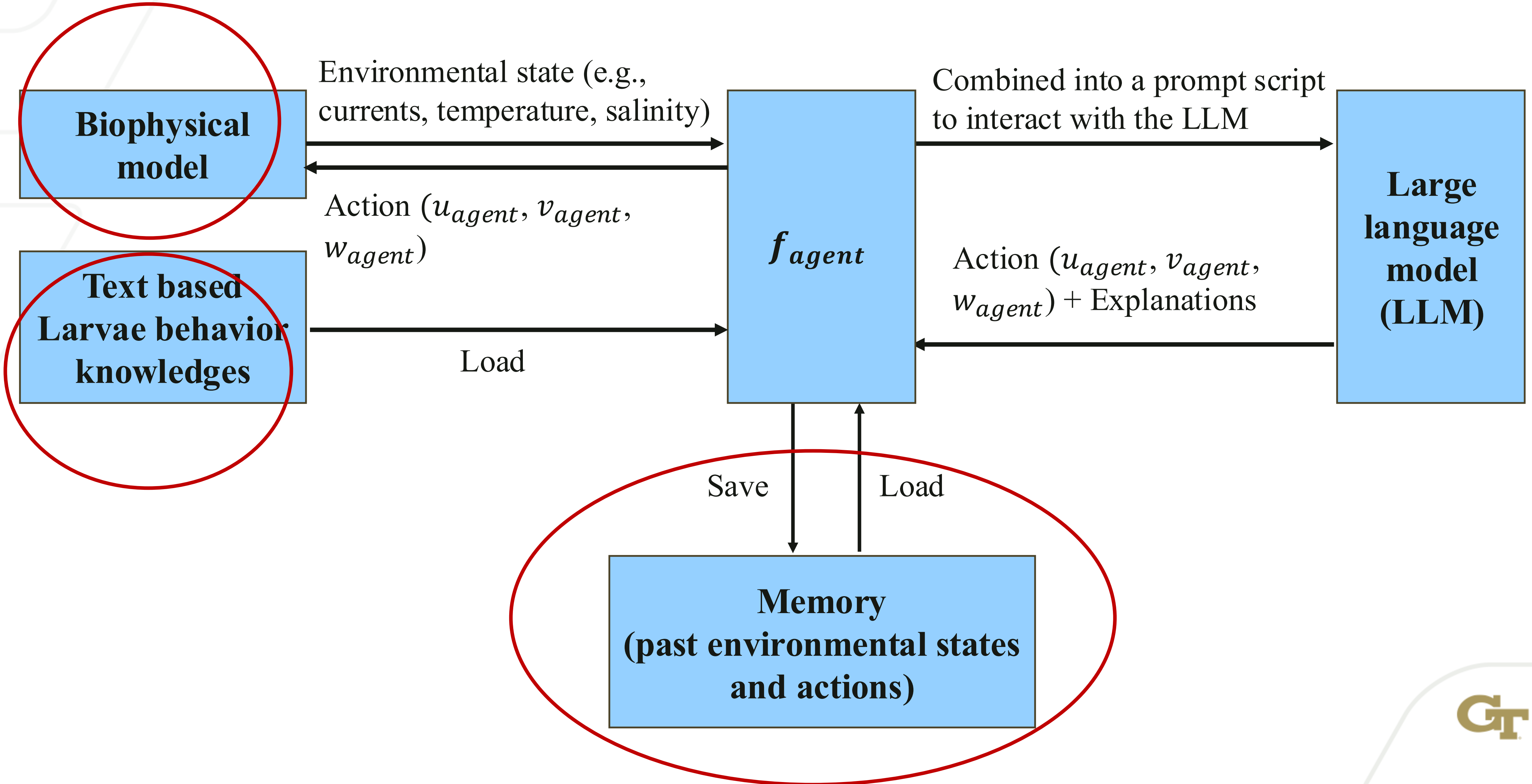
Agentic framework



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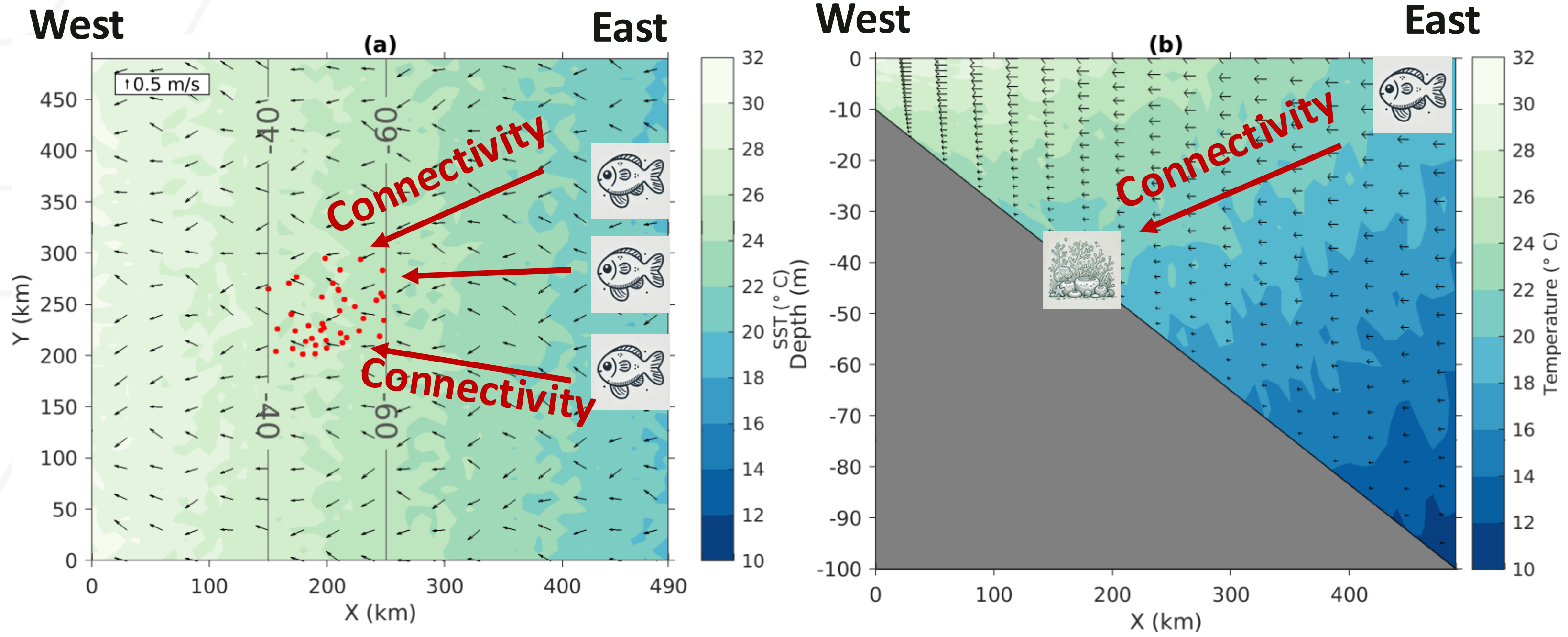
Idealized Experiment Design



Objective: Can agents self-develop behaviors that help them settle and survive, similar to those expected from mechanism-based approaches?

Idealized Fish Larvae

Pelagic Larval Duration (PLD): 10 days

Optimal temperature: 22°C-27°C

Egg stage: Days 0–3; **Larvae stage:** Days 3-8; **Settlement stage**: Days 8-10

Settlement Criteria: Larvae must settle near a coral reef, with a 2.5 km radius used to determine successful settlement

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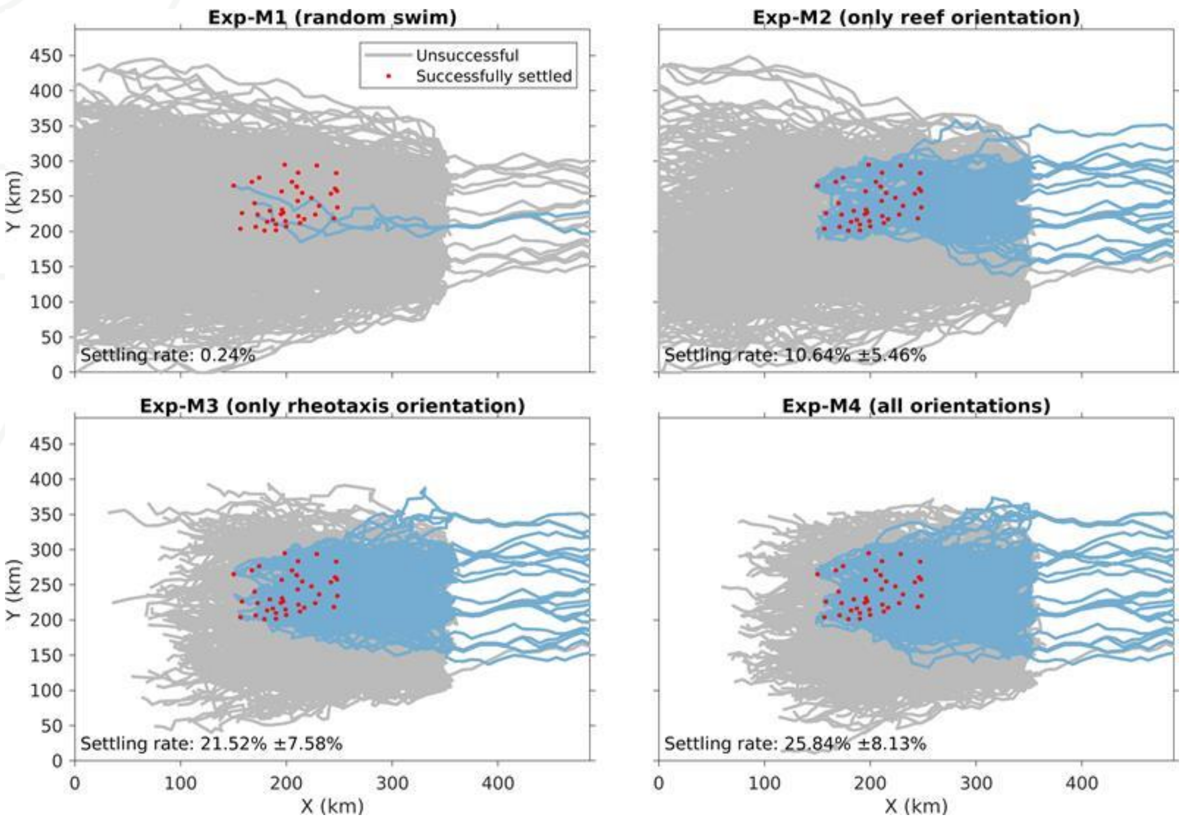
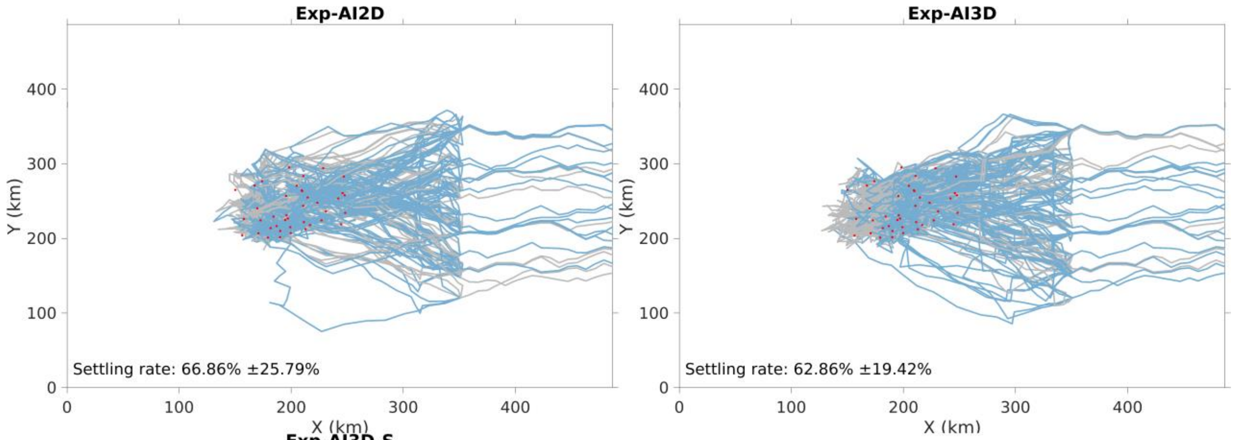
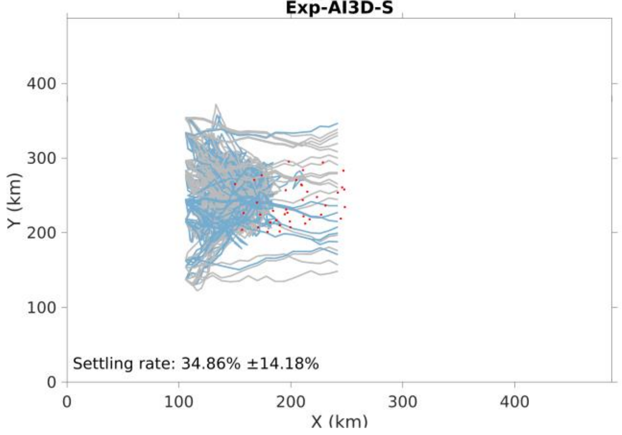
Idealized Experiment Design

Experiments	Approaches	Behaviors
Exp-M1	Mechanism-based approach	Random swim
Exp-M2		Reef orientation
Exp-M3		Rheotaxis orientation
Exp-M4		Rheotaxis orientation + Reef orientation
Exp-AI2D	2D AI agent-based approach	Self developed
Exp-AI3D	3D AI agent-based approach	Self developed
EXP-AI3D-S	Sensitivity test of the 3D AI agent-based approach with the release location shifted to the reef region.	Self developed

Trajectories







- Agents develop rheotaxis orientation
- Each agent's trajectory is "customized," as they actively adapt and attempt to maximize their chances of successful settling

Settling rate serves as a quantitative proxy for explaining the relative importance of different behaviors in shaping connectivity.

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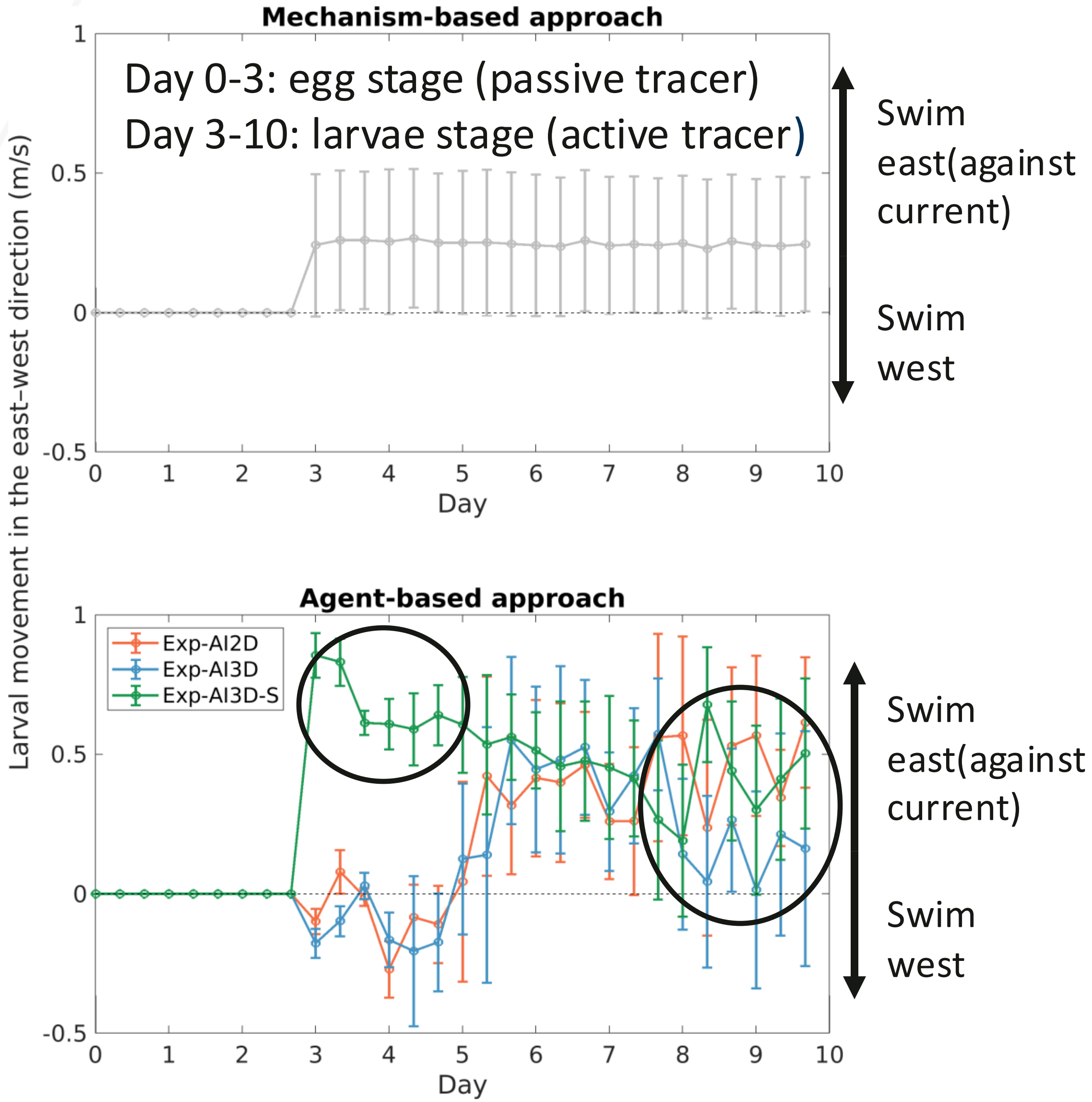
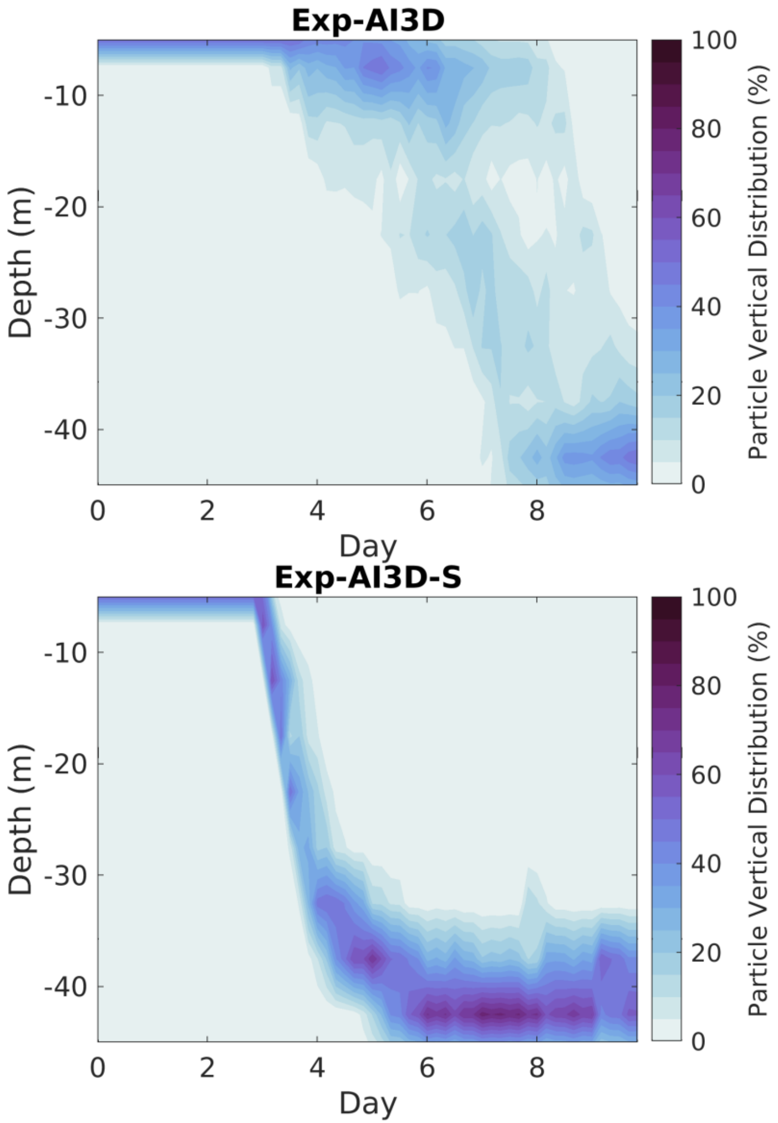
Insight from Movements





Surface-dwelling behavior facilitates long-distance dispersal

Deeper-dwelling behavior promotes local retention

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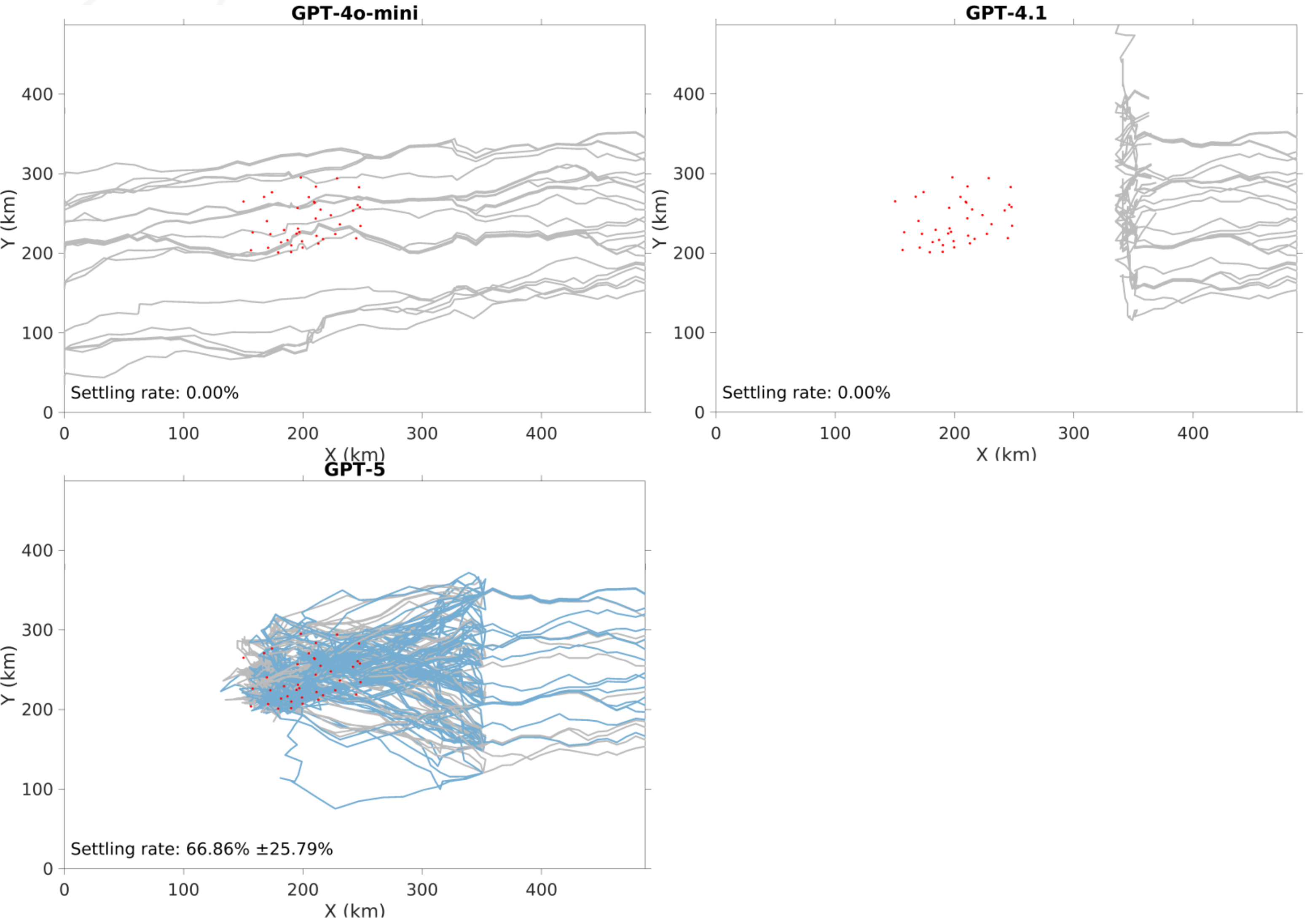
LLM intelligence level



GPT-4o-mini: No understanding of swimming agains current behavior.
GPT-4.1: Shows adaptive swimming-against-current behavior but tends to overthink.
GPT-5: Demonstrates strong adaptation.

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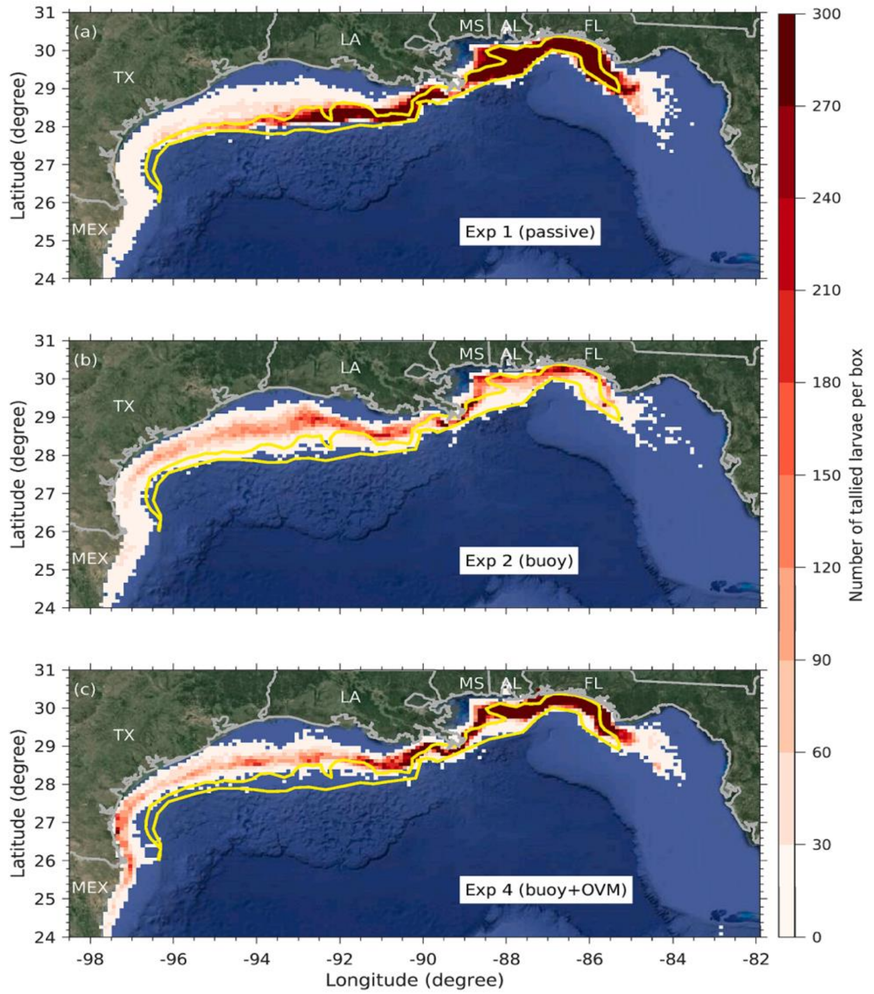
Real case application (ongoing work)

Red Snapper

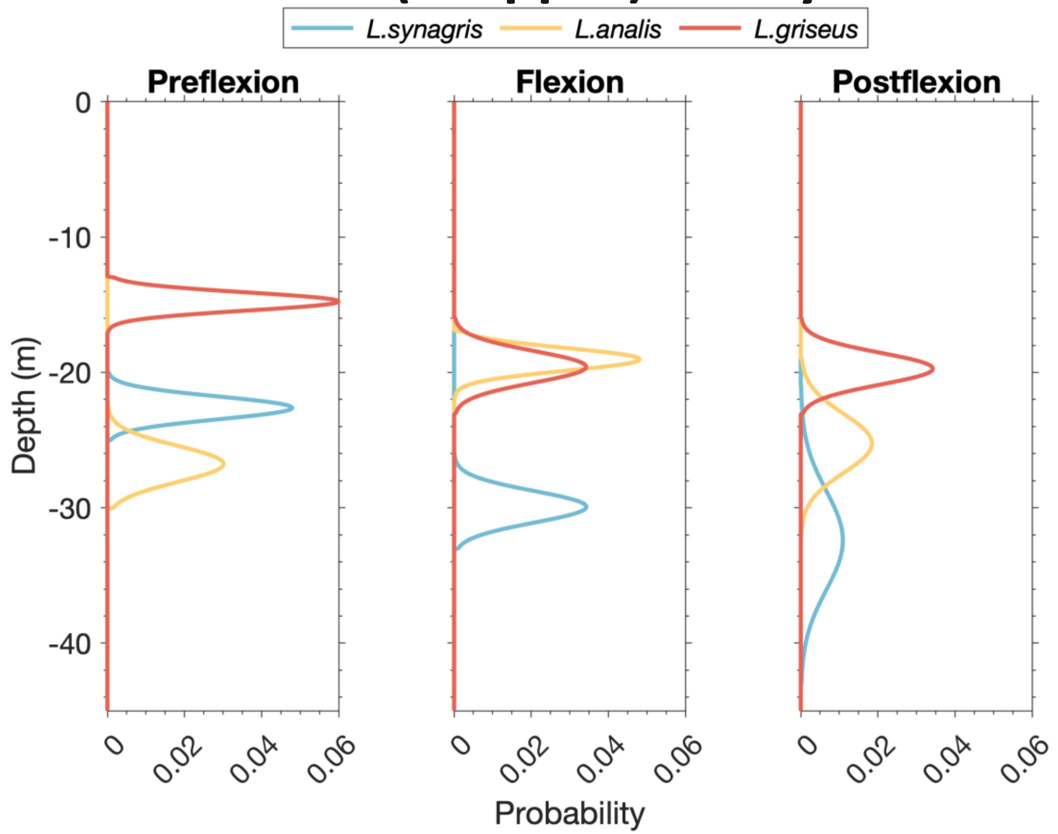
Predicted settling maps from Zhou et al., (2024)



1. What does the agent-generated vertical distribution look like?

2. What does the map look like for the agent runs?

Observed vertical distribution of species from the *Lutjanidae* (snapper) family



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Conclusion

- We developed the first framework that couples biophysical models with LLM agents to study larvae dispersal and connectivity, and we are preparing to release it to the community.

- An idealized case study demonstrates the effectiveness of this framework, showing that agents can self-develop realistic larval behaviors, such as swimming against currents, by adapting to changing ocean conditions.

- There is an emergence of vertical and horizontal distribution patterns through each individual agent's decision-making process, which may provide new insights into marine larval connectivity, dispersal processes, and ichthyoplankton dynamics.

QR code for GitHub repository