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colin.scherpereel@uclouvain.be

Multi-scale biophysical modeling explains contrasted coral connectivity and genetic structure in the high-relief basin of the Aruba-Bonaire-Curaçao islands

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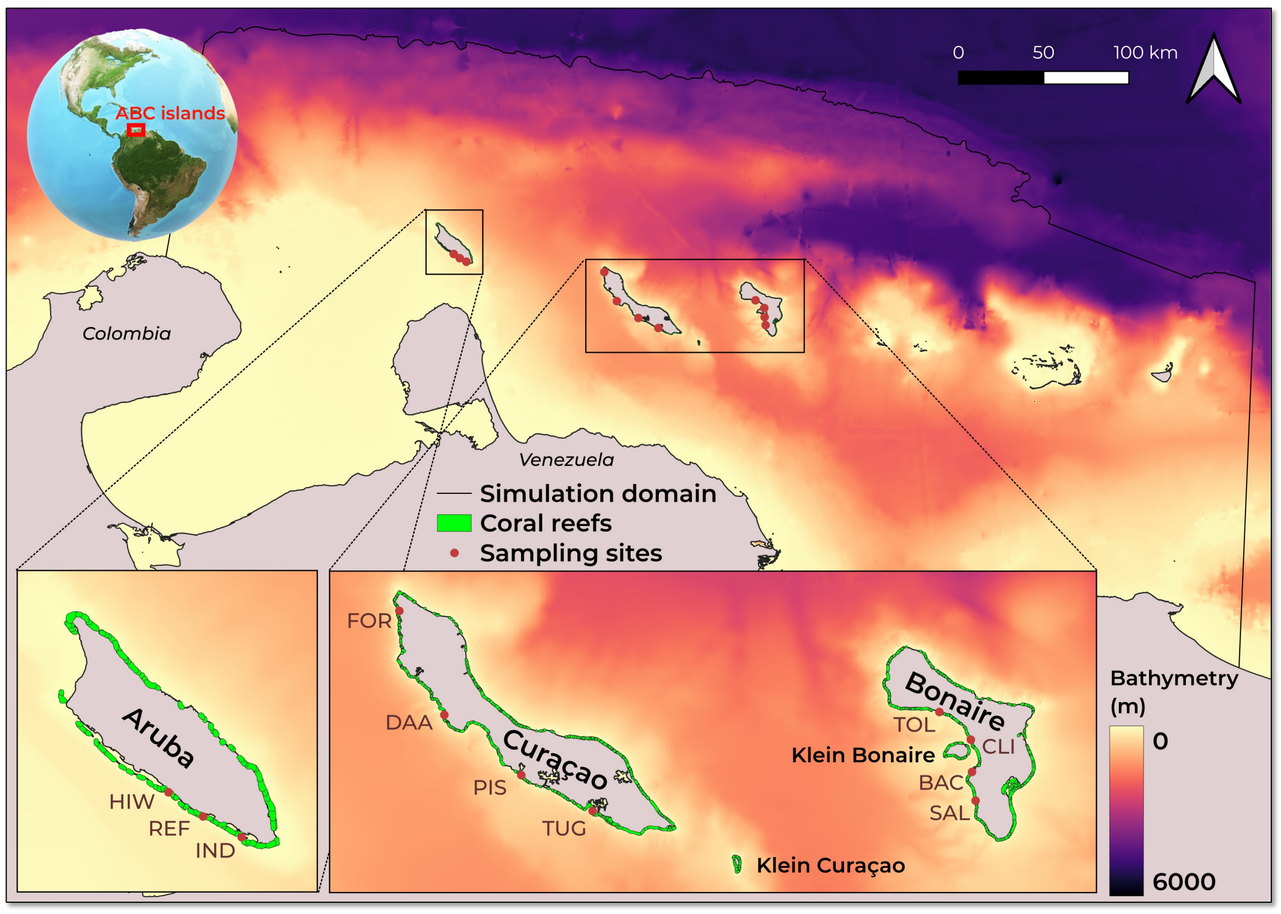
Colin Scherpereel[1], Violeta López-Márquez[2,3], Eric Mijts[2], Filip Volckaert[3], Thomas Dobbelaere[1], Miguel De Le Court[4], Jonathan Lambrechts[4], Emmanuel Hanert[1,4]

[1] Earth and Life Institute (ELIe), UCLouvain, Louvain-la-Neuve, Belgium
[2] SISSTEM Programme, University of Aruba, Oranjestad, Aruba
[3] Laboratory of Biodiversity and Evolutionary Genomics, KU Leuven, Leuven, Belgium
[4] Institute of Mechanics, Materials and Civil Engineering, UCLouvain, Louvain-la-Neuve, Belgium



1. Context:

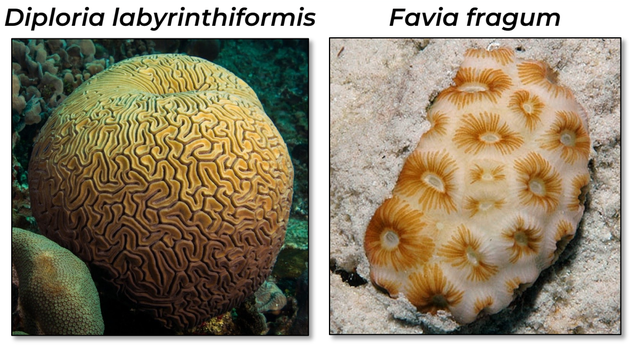
Coral larval dispersal and recruitment arise from a tight coupling between **multi-scale flow patterns** and **species-specific larval traits**. While key pelagic behaviors remain poorly described for corals, studies of other marine species, such as fish or crabs, have demonstrated how **vertical swimming can alter connectivity between populations** [1,2].

These uncertainties are amplified in the **Aruba–Bonaire–Curaçao (ABC) islands**, where steep bathymetric gradients challenge hydrodynamic modeling. Additional variability occurs in the contrasted strategies of broadcasters, such as *Diploria labyrinthiformis* (Dlab), and brooders like *Favia fragum* (Ffra), whose differences in dispersal distances introduce significant discrepancies in connectivity pathways at the regional scale.

2. Objectives of the study:

We simulate larval dispersal for both species in the ABC basin using **2 years of fine-scale (up to 100m) hydrodynamics** generated with the GPU-accelerated model **SLIM3D**. We incorporate a wide spectrum of natural variability in larval biological traits while considering several **vertical migration scenarios** to quantify how this feature modulates larval dispersal/retention in the region. Simulated connectivity pathways are further compared with in-situ genetic assessments and clustering.

Diploria labyrinthiformis ***Favia fragum***

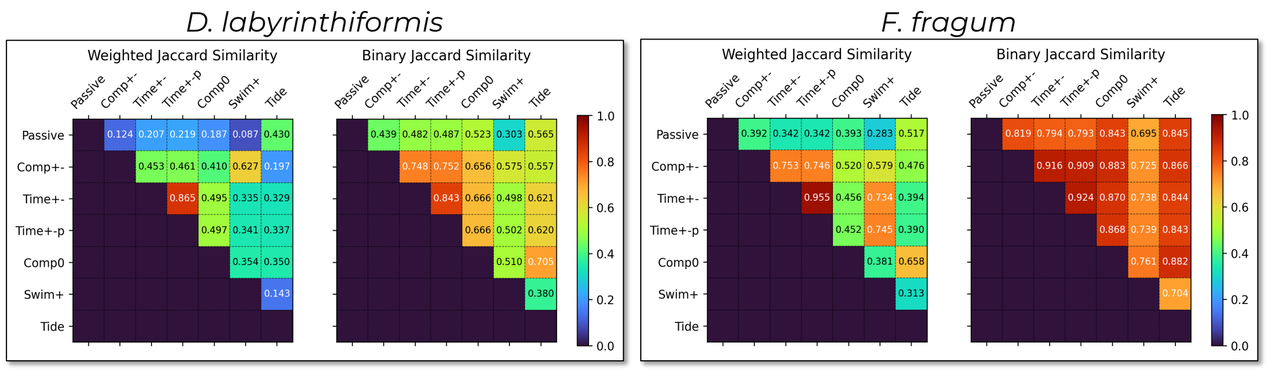


3. Vertical migration scenarios:

Seven scenarios are designed to span **realistic individual strategies**, following observations for Caribbean corals by Limer et al. (2024) [3]. Scenarios range from passive drift to upward/downward swimming, including downward motion when suitable habitat is detected within 10 m of the seabed.

Dlab is seeded during regional spawning windows around full moons (May–August), whereas Ffra is seeded continuously over the two-year period. Dispersal is simulated with SLIM's GPU-accelerated Lagrangian Particle Tracker, allowing millions of trajectories per scenario and simulated month.

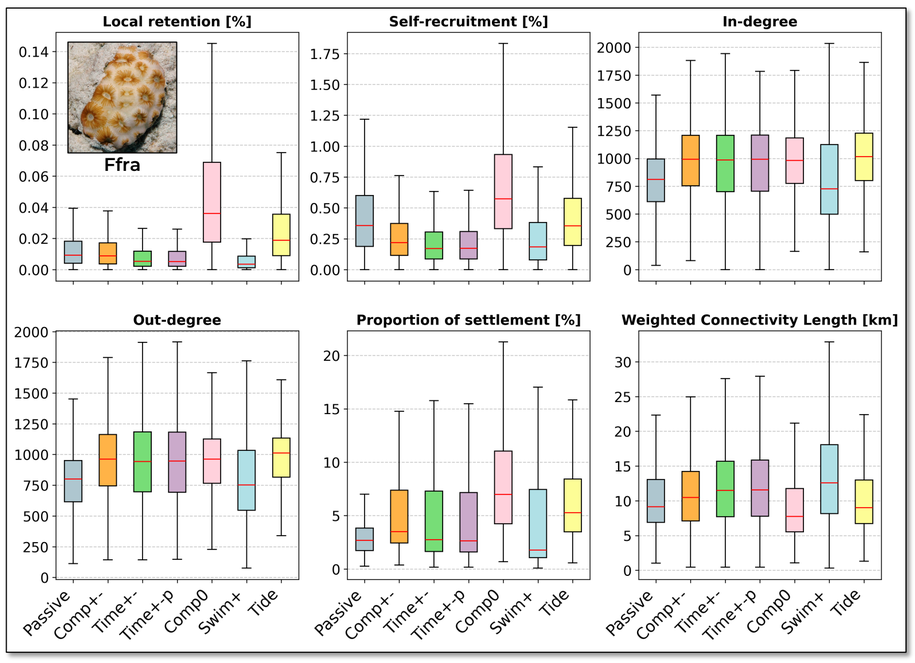
Binary and weighted Jaccard similarities between final connectivity matrices reveal **clear divergences among most scenarios**, with the notable exception of a close agreement between (3) and (4).

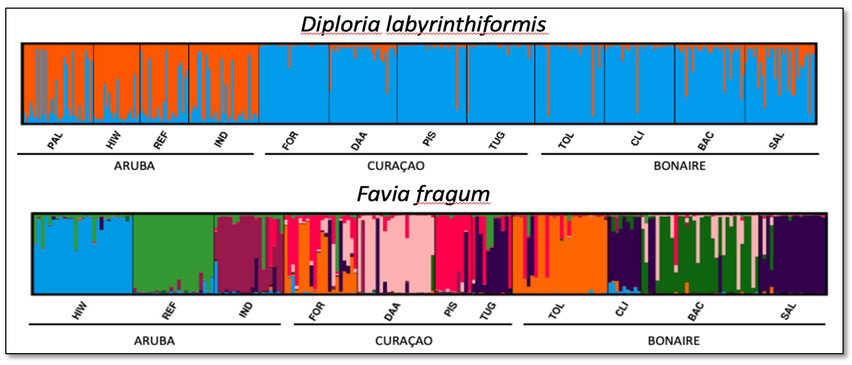


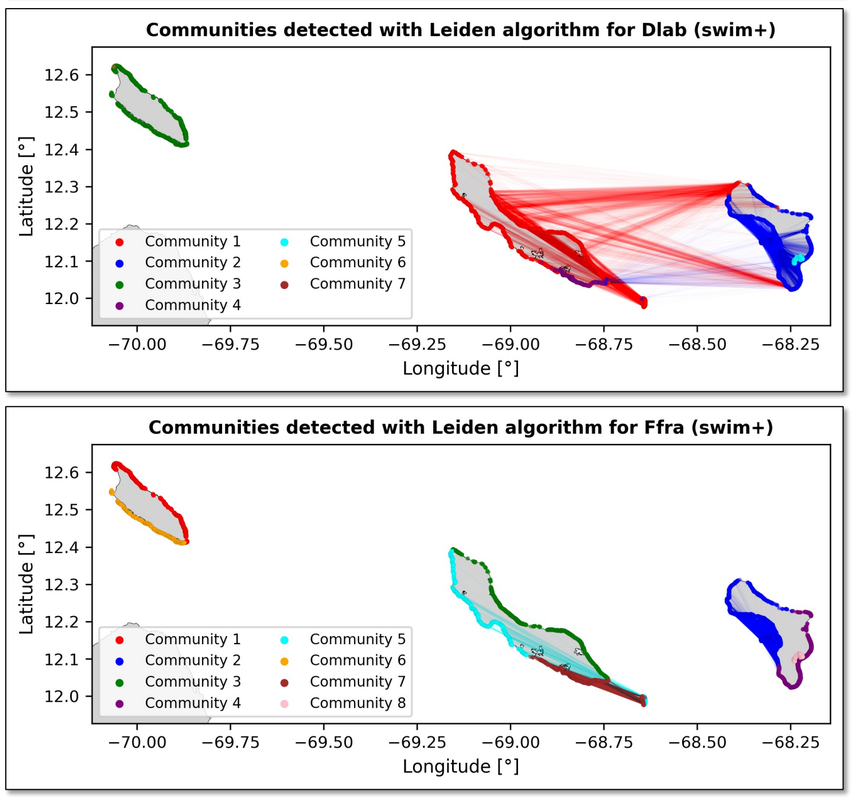
Name	Vertical migration scenario	Purpose
1. Passive	None	Reference/control
2. Comp+-	Upward before competency, then downward	Diving at competency
3. Time+-	Upward before shift (before comp.), then downward	Diving before competency
4. Time+-p	Upward before shift, then downward, then passive	Exhaustion of larvae after diving
5. Comp0	0-centered distribution after competency	Maximum variability in dispersal
6. Swim+	Upward starting on release	Maximum dispersal potential
7. Tide	Upward during flood currents and downward during ebb	Tidal synchrony

4. Connectivity indicators:

Connectivity indicators quantify settlement success, and import/export potential at the reef scale. Their distributions (*see boxplots below*) reveal **consistent responses to vertical migration behaviors**. Scenarios spanning both upward and downward swimming enhance total settlement locally and remotely. Diving strategies increase both in- & out-degree and weighted connectivity length (WCL). Consistent upward swimming (Swim+) generally yields the weakest performances, except for producing the longest WCL, whereas high internal variability (Comp0) emerges as the best-performing scenario, except for the WCL.

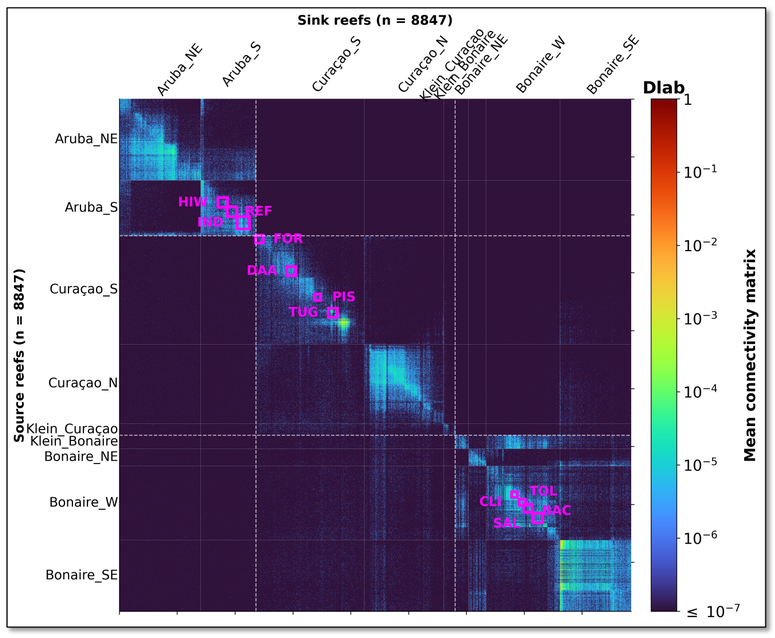






5. Pathways and communities:

Mean connectivity matrices indicate **dominant self-recruitment** across reefs, with limited exchanges between islands. For Dlab, inter-island pathways still emerge **between Bonaire and Curaçao**, particularly under scenarios featuring upward swimming. Community detection using the Leiden algorithm supports patterns consistent with genetic clustering (*see colored bar plots on the left*), yielding two large clusters for Dlab (Aruba and Bonaire-Curaçao), whereas Ffra forms several more isolated groups as a result of weak inter-island connectivity.



Take-home messages:

1. Vertical migration scenarios highlight **significantly distinct connectivity pathways**
2. Exports of larvae form **Bonaire to Curaçao** can occur for *Diploria labyrinthiformis* and imply upward swimming motion
3. Connection strength increases with **vertical migration variability**, conversely to connection length
4. Isolated genetic clusters of *Favia fragum* can be explained by **limited inter- and intra-island connectivity**

Limitations & perspectives:

- Use of a **regional wind forcing** instead of a global, coarser one (ERA5)
- Base larval **biological traits** for *Favia fragum* require further investigation
- **Simulated period** should be extended to include more inter-annual variability
- **Spatial extent of reefs** could be further refined along coastlines

- Including two more species of interest: **P. astreoides** & **P. strigosa**
- Comparing **multi-generational pathways** with genetic similarity of sampled reefs
- Identifying the **most probable migration scenarios** matching these results

References:

[1] Szmant, A. & Meadows, M.G.. (2006). Developmental changes in coral larval buoyancy and vertical swimming behavior: Implications for dispersal and connectivity. Proc 10th Int Coral Reef Symp. 1. 431-437.
[2] Savina, M., Lacroix, G., & Ruddick, K. (2010). Modelling the transport of common sole larvae in the southern North Sea: Influence of hydrodynamics and larval vertical movements. Journal of Marine Systems, 86-98. https://doi.org/10.1016/j.jmarsys.2009.12.008
[3] Limer, B. D., Payne, O., Brancato, A., Mitchell, M., Abu-Kubie, C., Figueiredo, J., & Holstein, D. M. (2024). Life history and early ontogeny determine vertical swimming behaviors in the larvae of Caribbean corals. Journal of Experimental Marine Biology and Ecology, 578, 152035.