

Modelling reef connectivity in Seychelles and the SW Indian Ocean

Noam Vogt-Vincent¹, Helen Johnson¹, and April Burt²

¹ Department of Earth Sciences, University of Oxford, United Kingdom

² Department of Plant Sciences, University of Oxford, United Kingdom

Overview

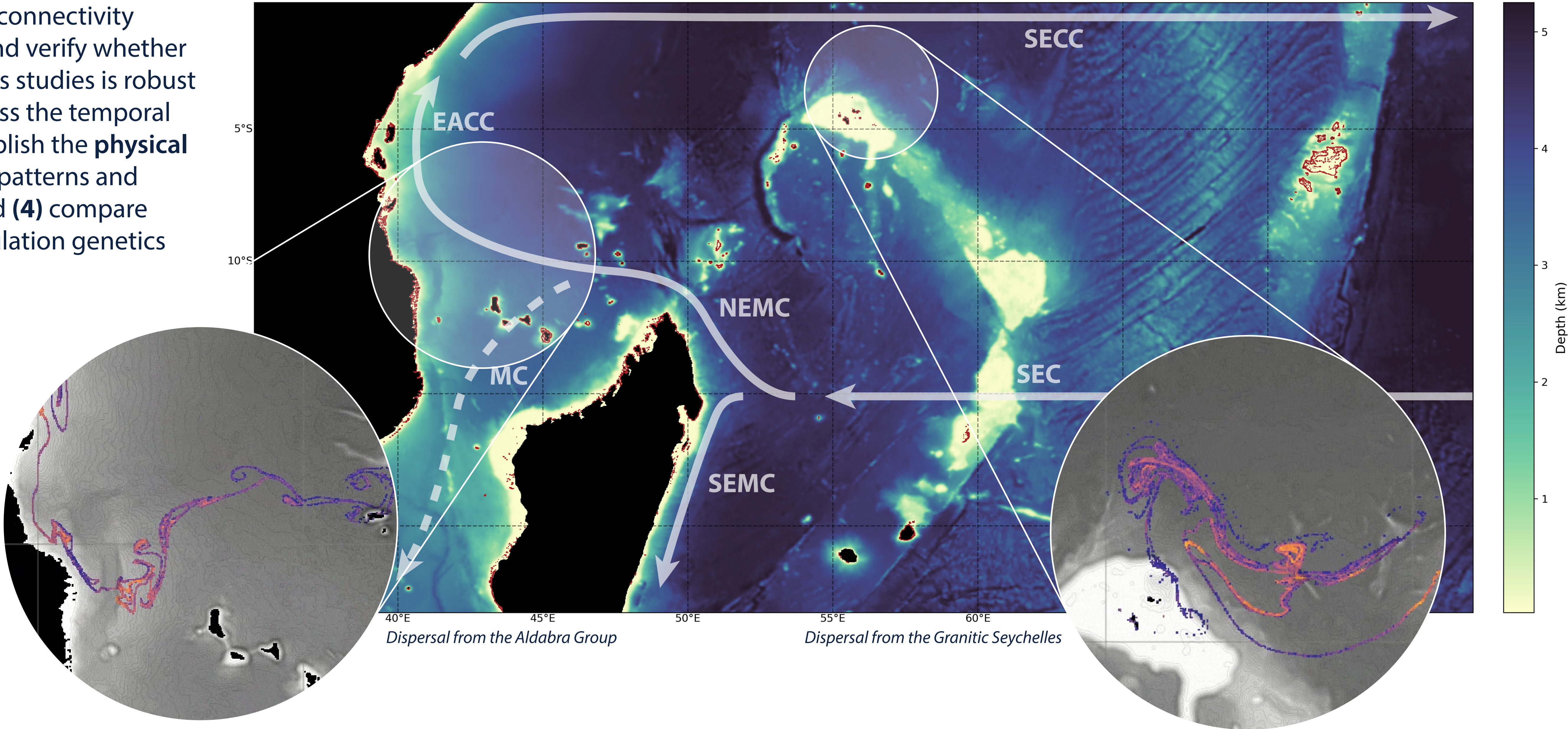
We are running a **2km-resolution** ocean model (CROCO) spanning the SW tropical Indian Ocean from **1993-2018** to **(1)** map patterns of connectivity between reefs across the region and verify whether connectivity inferred from previous studies is robust with respect to resolution, **(2)** assess the temporal variability of connectivity, **(3)** establish the **physical oceanographical drivers** of these patterns and persistent barriers to dispersal, and **(4)** compare model predictions with coral population genetics across Seychelles.

Link to full presentation



Model domain, bathymetry and reefs

The full domain, bathymetry and land mask as used in the ocean model. Red cells are those identified to contain coral reefs. Major ocean currents have been represented schematically: SEC (South Equatorial Current), NEMC (Northeast Madagascar Current), SEMC (Southeast Madagascar Current), EACC (East African Coast Current), SECC (South Equatorial Countercurrent), MC (Mozambique Channel).

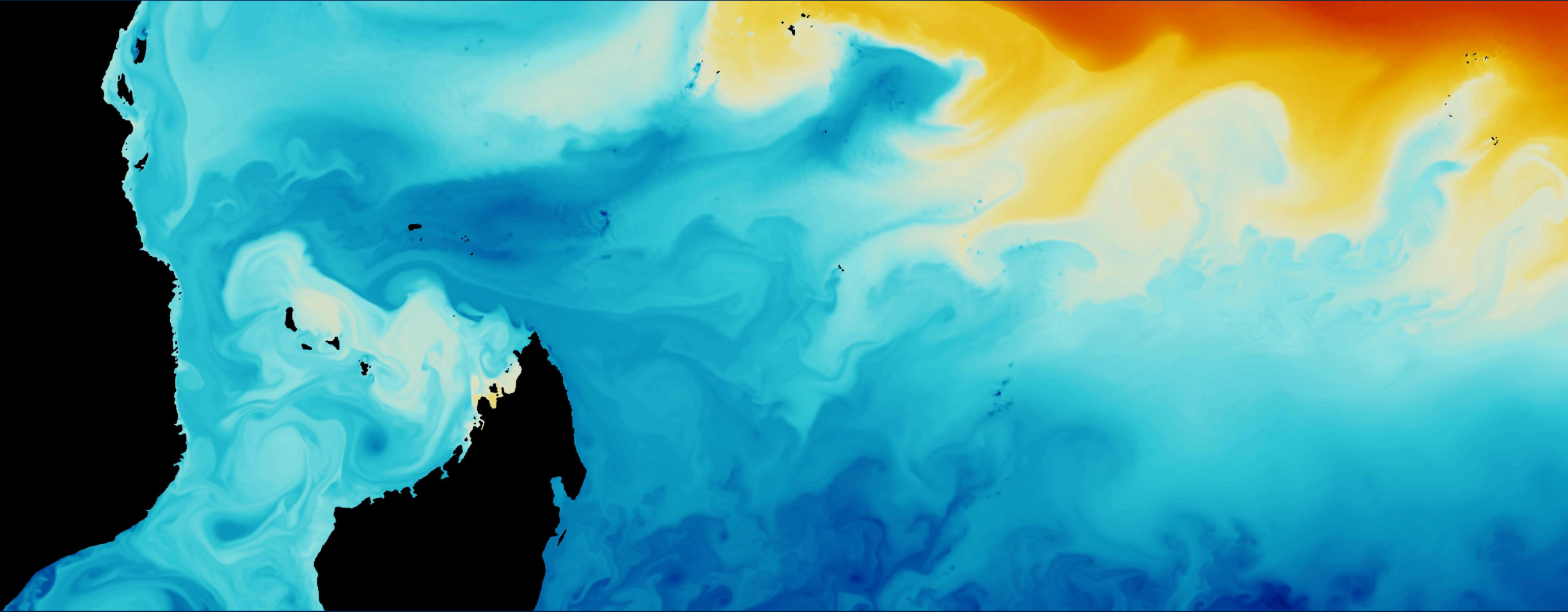


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✉ noam.vogt-vincent@st-annes.ox.ac.uk  @noam_vv



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Background

Steps involved in (benthic) larval dispersal

1. Larvae develop near the parent spawning site (**source**)
2. Larvae are transported by ocean currents and motility
3. Once competent, larvae attempt to settle if they sense a suitable environment (**sink**)
4. Larvae develop into later life stages

Successful movement from source → sink = connectivity

An understanding of reef connectivity is essential for informed marine spatial planning:

- Strong sources may be disproportional important for maintaining regional reef resilience, and strong sinks may be more likely to recover from mass mortality events.
- Weak sinks may be particularly vulnerable to mass mortality events.

How can we measure this?

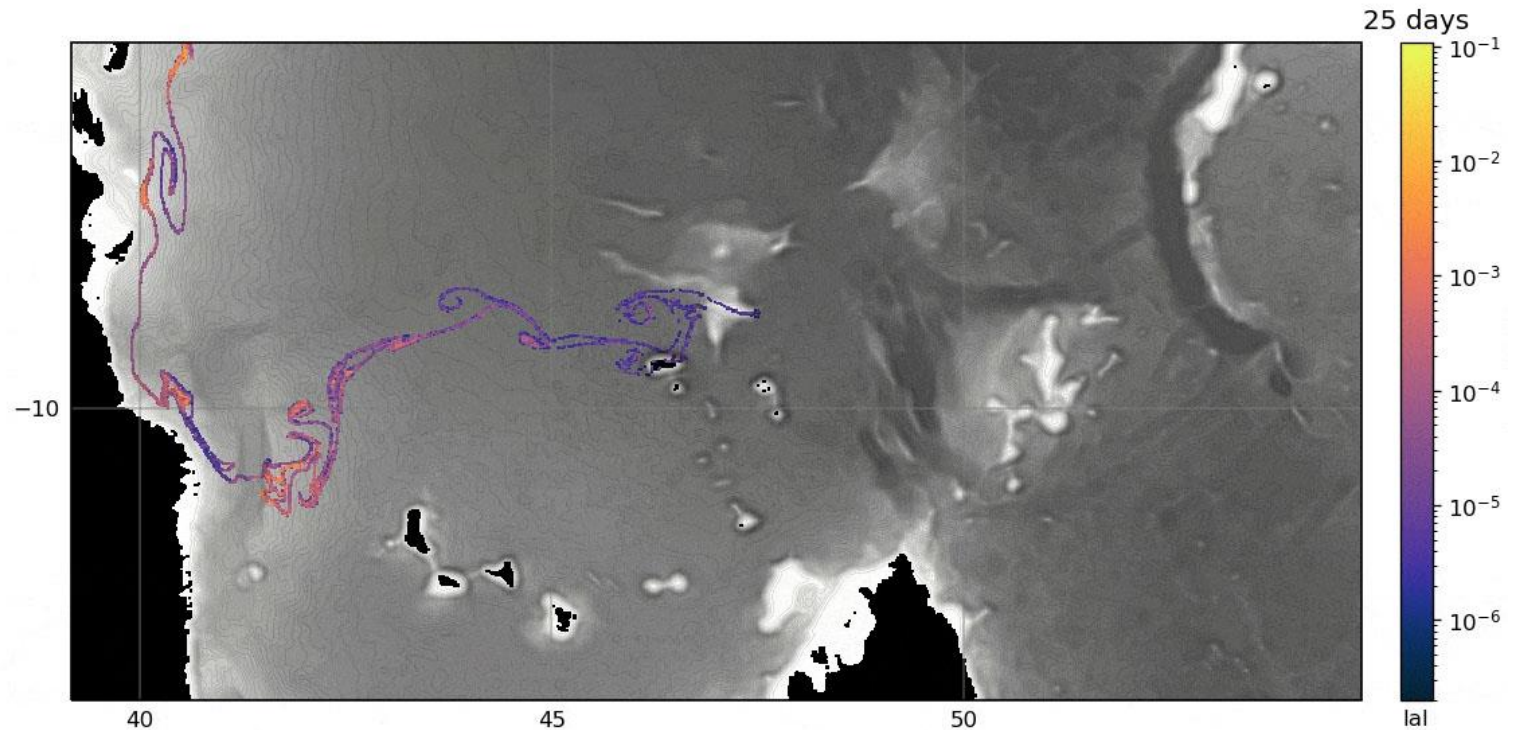
- Genetic methods:
 - Integrates the entire cycle but over very long timescales. Observational, but limited spatial and zero temporal resolution; expensive.
- Numerical modelling:
 - Directly predicts the movement of individuals; high spatial/temporal resolution. Not observational, only as good as model assumptions.



Background

How do we numerically model larval dispersal?

1. Decide where larvae will originate from and when they will be released (**spawning timing**)
2. Decide where larvae can settle
3. Decide larval 'behaviour':
 - When do they become competent?
 - When do they die?
 - Can they swim?
 - What do they do when they reach a settling site?
4. Combine all of this with ocean current data to predict what happens to larvae through **particle tracking**
5. A huge amount of data is generated. Generate a connectivity matrix which tells you the likelihood of larvae moving between all of your sites and cluster analysis for comparison with genetic data.



Lagrangian PDF (likelihood of finding a virtual particle in a particular grid cell) 25 days after an arbitrary release of ~200,000 virtual particles from Aldabra Atoll

Background

Where does the ocean current data come from?

Option 1: Satellites (sea-surface altimetry)

The only way to *observe* ocean currents on a regional scale

Advantages:

- Easy and free to obtain (as an end-user)
- Based on real observations

Disadvantages:

- Low resolution (~10s km, limited by physics)
- Can have significant errors in regions such as coastal currents

Option 2: Hydrodynamical models

A computer solves fluid dynamics equations to predict ocean currents based on supplied boundary conditions and parameterisations

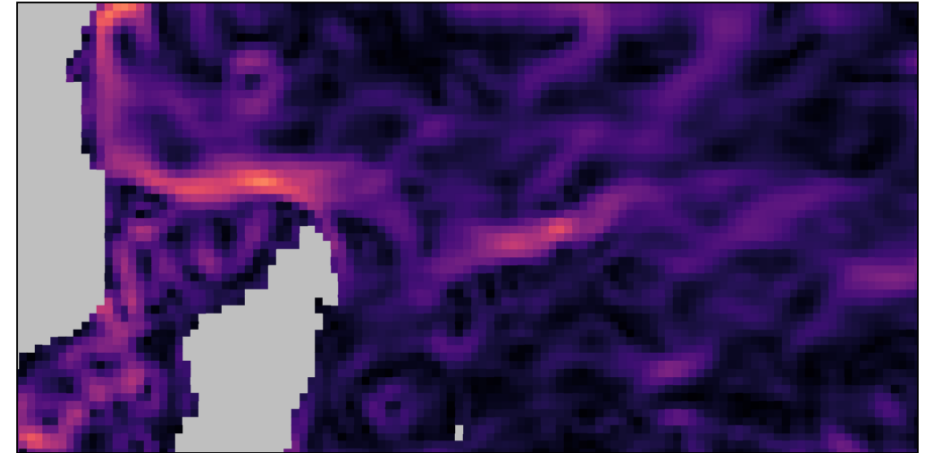
Advantages:

- Resolution is only limited by computing resources

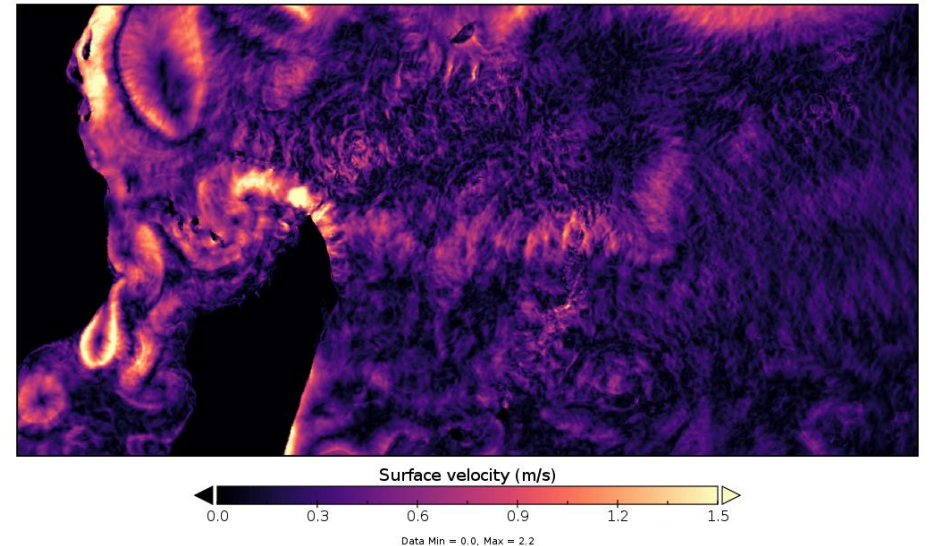
Disadvantages:

- Not observational – relies on good quality boundary conditions and parameterisations
- More expensive and time consuming

OSCAR



CROCO WIOMonClim



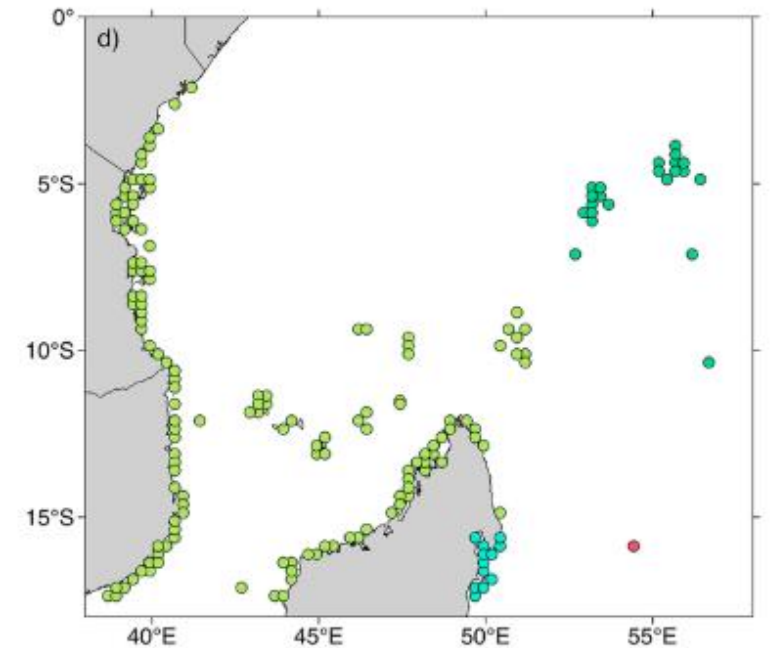
Background

Some previous studies in this region...

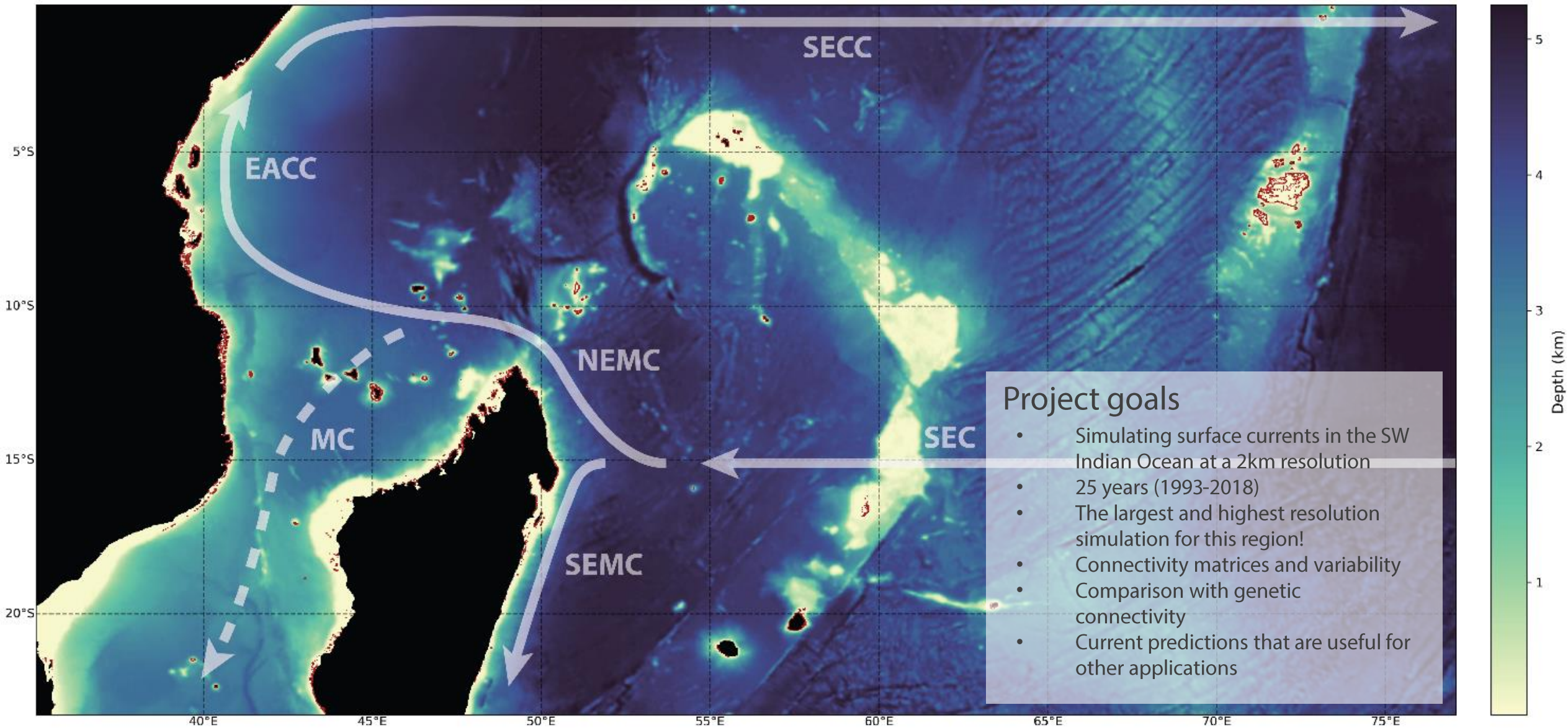
- Crochelet et al. (2016): Satellite-derived 2D reef connectivity across the SW Indian Ocean for 5 years.
- Mayorga-Adame et al. (2017): Investigate 3D reef connectivity along the Kenya-Tanzania Coast at a 2km resolution for two years at key spawning times.
- Gamoyo et al. (2019): Investigate 3D reef connectivity across the SW Indian Ocean at an 8km resolution with monthly releases for 7 years.

However, all of these studies have used a relatively coarse resolution ($>1/12^\circ$) and/or limited spatial extents, and relatively short timespans. We can therefore ask the following questions:

- Are regional patterns of connectivity derived from coarser resolution studies robust when numerical model resolution is increased to resolve finer-scale circulation?
- How robust are patterns of connectivity to biological parameters such as mortality rate and recruitment rates at reef sites, and effects such as Stokes drift?
- What is the interannual variability of reef connectivity? Is there any significant dependence on ocean modes such as the IOD or ENSO?
- How well does potential connectivity calculated by a numerical model agree with genetic connectivity?
- What are the major physical oceanographic barriers to dispersal in the southwestern Indian Ocean? What is the role of structures such as eddies in facilitating larval transport?



Connectivity clusters identified by Gamoyo et al. (2019) based on a 60 day larval pelagic lifespan

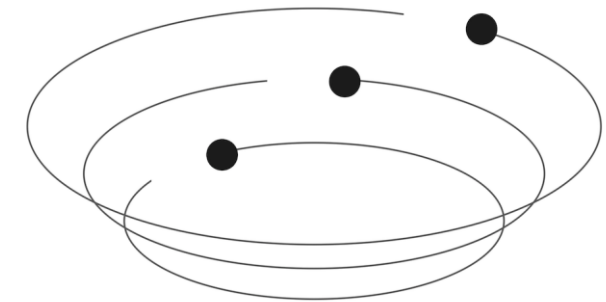


Full model domain and bathymetry (as used in the numerical model), with reef cells identified in red, and the major ocean currents represented schematically.

Technical specifications

Hydrodynamical model

- Coastal and Regional Ocean Community Model (CROCO) 1.1 with XIOS 2.5 for I/O
- $1/50^\circ$ in the horizontal ($\sim 2\text{km}$) and 50 vertical s-coordinate layers, concentrated towards the surface ($\sim 2\text{m}$ vertical resolution at the surface)
- Forced at the lateral boundaries by CMEMS GLORYS12V1 $1/12^\circ$ reanalysis (NEMO) and barotropic tides from TPXO9
- Forced at the surface by the ERA5 reanalysis
- Climatological freshwater forcing at major rivers
- Bathymetry obtained from GEBCO 2019 and augmented by Admiralty hydrographic charts
- Run on the ARCHER2 supercomputer (NERC)
 - 130×10^6 grid points, Approximately 30k core-hours per model year on 2048 cores
 - Surface currents output every 30 model-minutes; other surface fields output every model-day. Full 3D fields output every 5 model-days.
- 10-year climatological run (monthly climatology from 1993-2018) and a 26-year interannual run (daily means from 1993-2018)



OceanParcels

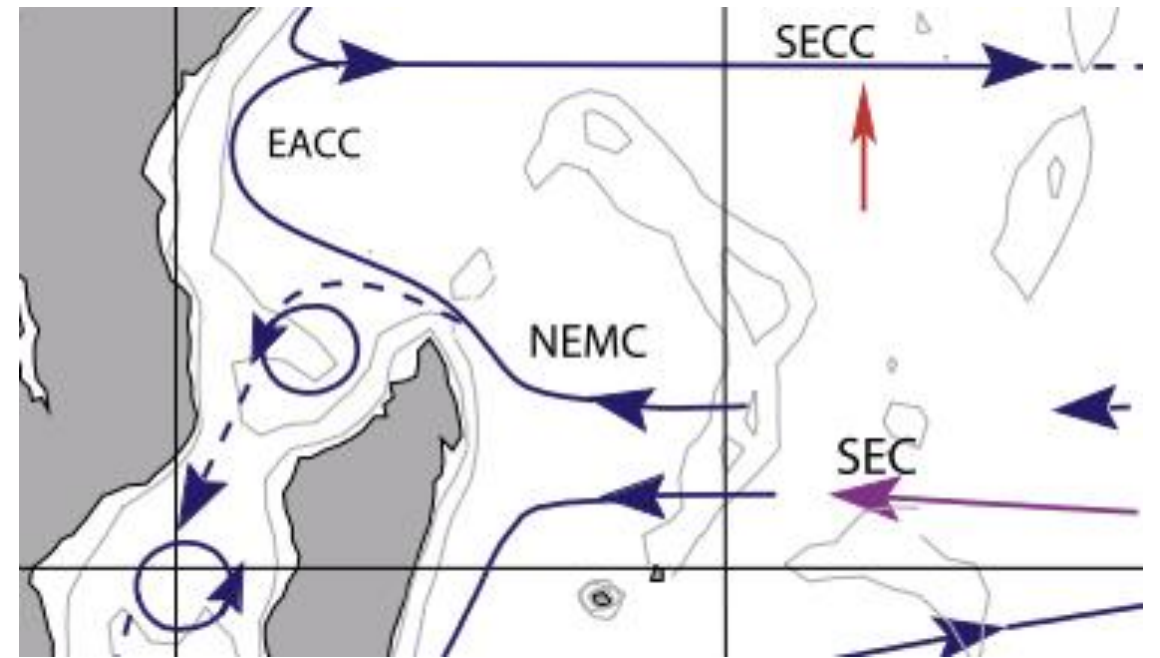
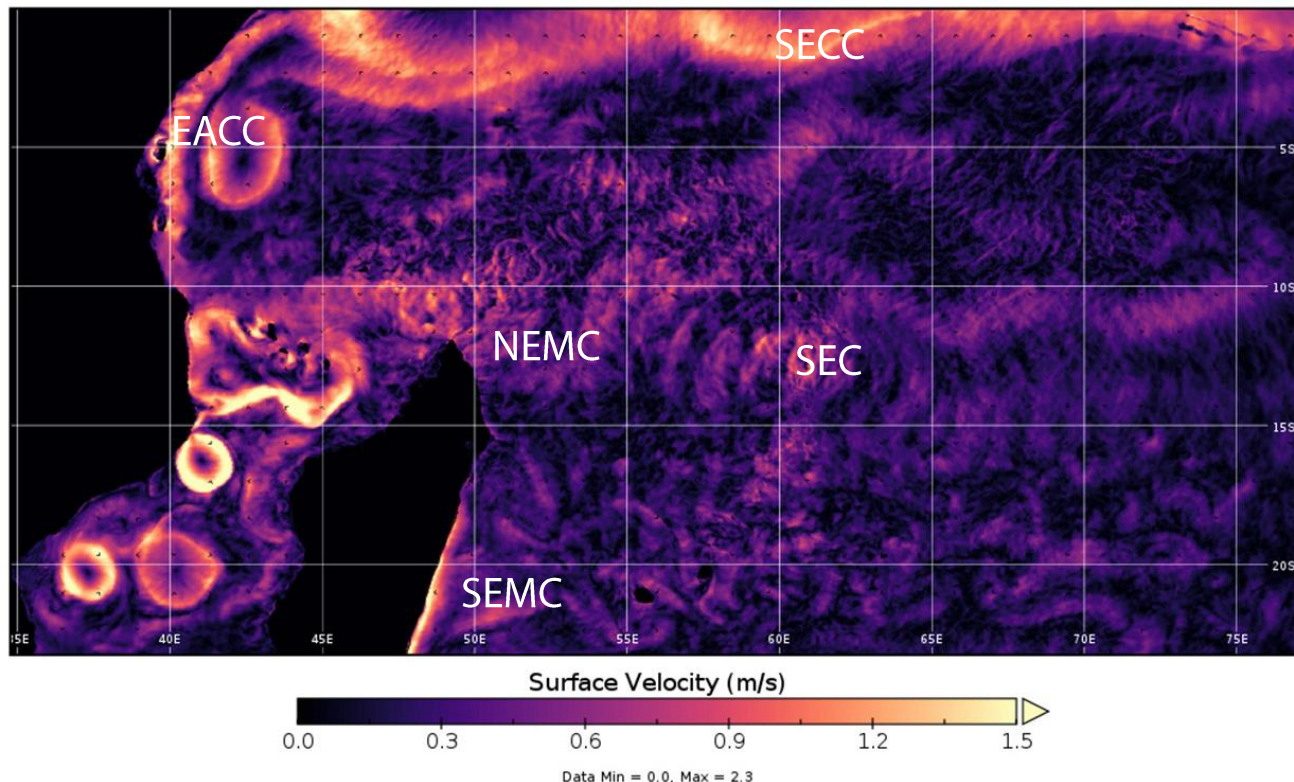
Lagrangian particle tracking

- OceanParcels 2.0 run in a 2D configuration (surface currents every 30 model-minutes) with custom kernels
- 4000 virtual larvae released each month from each of the ~ 7000 4km^2 reef cells identified in the model domain, and advected for 100 days

Results of early work

Validation

- All major current systems (South Equatorial Current, South Equatorial Countercurrent, Madagascar Currents, East African Coastal Current...) are reproduced.
- Current velocities are reasonable but likely overestimated in some regions such as the Mozambique Channel eddies.
- Tides are reproduced very well in most regions (e.g. M2 amplitude error < 5cm in most sites).
- Some challenges with validation due to a lack of in-situ observations in the SW Indian Ocean region

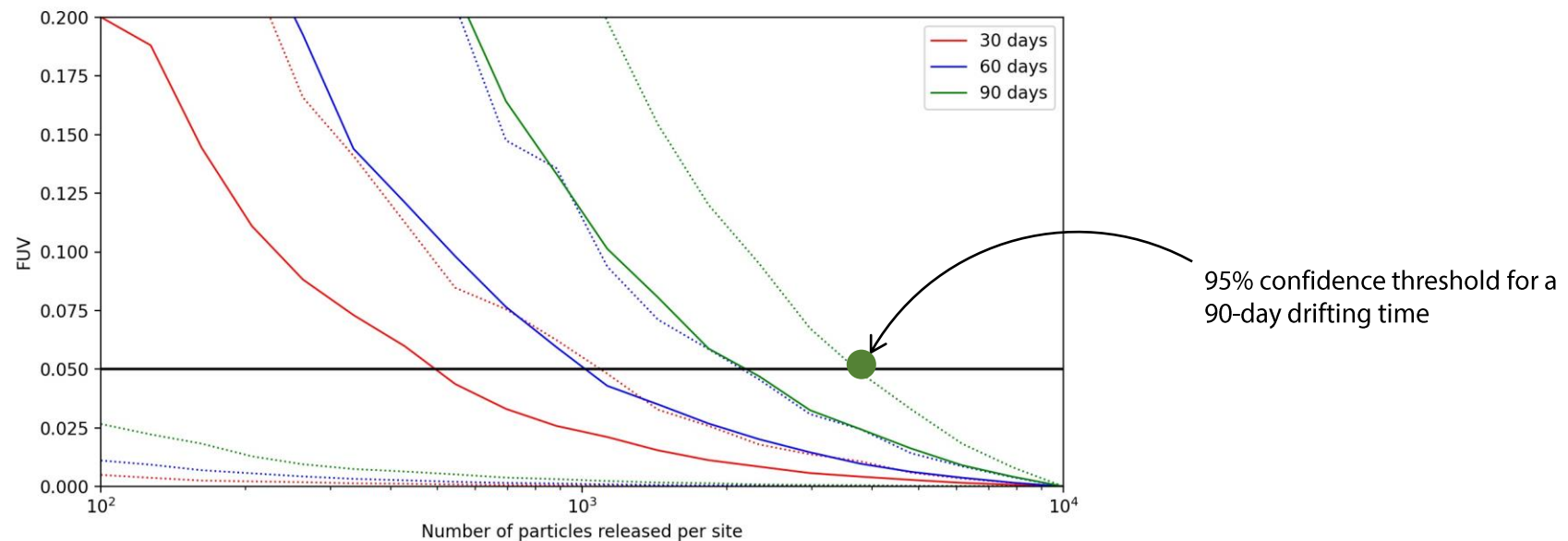


Schematic from Schott et al. (2009)

Results of early work

Sensitivity analyses

- Online particle tracking is currently not possible with CROCO using MPI. We are therefore using offline particle tracking using OceanParcels 2.0 to take advantage of the ability to easily design custom kernels, which are very useful for implementing biological behaviour.
- Our sensitivity analyses show:
 - c. 4000 particles must be released per 4km² reef cell for particle distributions to remain robust over 100 days of advection.
 - A 30-minute output frequency (for the hydrodynamical model) is required for accurate particle tracking.
 - Due to the very high output frequency required, it is not possible to carry out 3D particle tracking (this would take up 1.2PB storage!)
 - Larvae are therefore assumed to remain at the surface of the ocean – not ideal, but a necessary compromise (and biophysically justifiable to some extent as coral larvae are vertically motile).
 - It is also currently challenging to use s-coordinates with a moving surface in OceanParcels 2.0



Questions to investigate once simulations are complete

- Are regional patterns of connectivity derived from coarser resolution studies robust when numerical model resolution is increased to resolve finer-scale circulation?
- How robust are patterns of connectivity to biological parameters such as mortality rate and recruitment rates at reef sites, and effects such as Stokes drift?
- What is the interannual variability of reef connectivity? Is there any significant dependence on ocean modes such as the IOD or ENSO?
- How well does potential connectivity calculated by a numerical model agree with genetic connectivity?
- What are the major physical oceanographic barriers to dispersal in the southwestern Indian Ocean? What is the role of structures such as eddies in facilitating larval transport?

Further applications

- High-resolution model output will be made available for other applications and stakeholders (e.g. fisheries)
- Results are also applicable to modelling marine debris dispersal and attribution in the southwestern Indian Ocean
- This simulation will act as the basis for further, higher resolution, nested simulations to investigate larval retention around ocean islands

References

Crochelet et al. (2016) A model-based assessment of reef larvae dispersal in the Western Indian Ocean reveals regional connectivity patterns - Potential implications for conservation policies. *Regional Studies in Marine Science*.

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Mayorga-Adame et al. (2017) Modeling larval connectivity of coral reef organisms in the Kenya-Tanzania region. *Frontiers in Marine Science*.

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CROCO is provided by <https://www.croco-ocean.org>