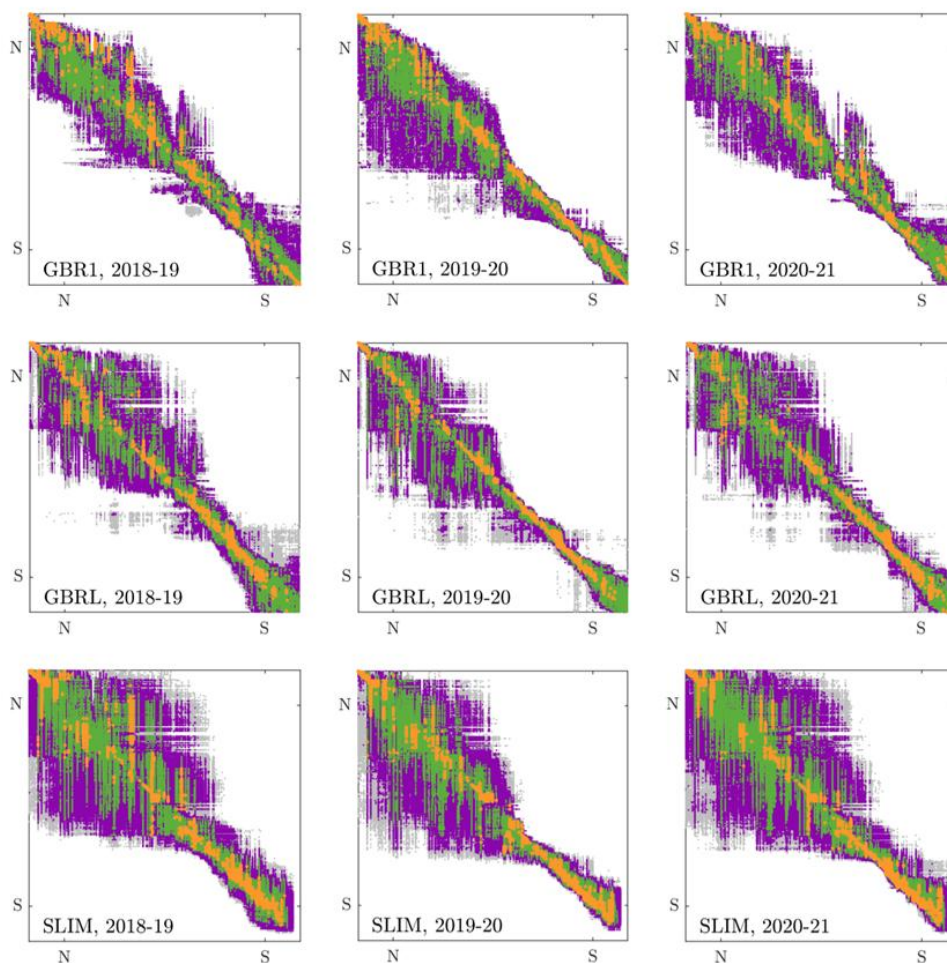


Crown-of-thorns starfish (COTS) connectivity modelling under multidimensional uncertainties on Australia's Great Barrier Reef

Severine Choukroun, Michael Bode, Owen Stewart, Clothilde Langlais, Javier Porobic, Jonathan Lambrechts, Lou Mason



Great Barrier
Reef Foundation



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COTS Control Innovation Program | A research and development partnership to better predict, detect and respond to crown-of-thorns starfish outbreaks



Great Barrier
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Traditional Owner Acknowledgement

The COTS Control Innovation Program extends its deepest respect and recognition to all Traditional Owners of the Great Barrier Reef and its Catchments, as First Nations Peoples holding the hopes, dreams, traditions and cultures of the Reef.

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Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profiler
AIMS	Australian Institute of Marine Science
AODN	Australian Ocean Data Network
CCIP	Crown-of-thorns starfish Control Innovation Program
CDF	Cumulative Distribution Function
CoCoNET	Coral Community Network model
COTS	Crown-of-thorns starfish
CRS	Coastal Reference Station
CSIRO	Commonwealth Scientific and Research Organisation
EAC	East Australian Current
EMS	Environmental Modelling Suite
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
IMOS	Integrated Marine Observing System
IPM	Integrated Pest Management
JCU	James Cook University
LPT	Larval Particle Tracking
LTMP	Long-Term Monitoring Program
NCI	National Computational Infrastructure
NRT	Near-Real-Time
PSU	Practical Salinity Units
QIMOS	Queensland Integrated Marine Observing System
QUT	Queensland University of Technology
RBM	Resilience-Based Management
Reef Authority	Great Barrier Reef Marine Park Authority)
RIMReP	Reef 2050 Integrated Monitoring and Reporting Program
RRAP	Reef Restoration and Adaptation Program

EXECUTIVE SUMMARY

The Great Barrier Reef (GBR) is under severe stress from cumulative threats including climate change, cyclones, declining water quality and recurrent population outbreaks of crown-of-thorns starfish (COTS, *Acanthaster cf. solaris*). Strategic management interventions are crucial for mitigating damage and assisting reef ecosystem recovery. The resilience-based management (RBM) approach is vital for identifying current and future drivers of environmental change to prioritise, implement, and adapt management actions to help ecosystems resist and recover from cumulative stressors. While large-scale threats like climate change impact coral reefs globally, COTS outbreaks can be directly managed through local actions such as culling programs, and targeted control efforts have been shown to mitigate COTS outbreaks and their contribution to coral loss on the GBR. These intervention efforts rely on systematic reef monitoring and precise selection of reefs for control operations, which in turn depend on models of larval dispersal and connectivity between reefs that help predict where COTS larvae released from one reef are likely to settle.

Predicting COTS larval dispersal is challenging. Adult COTS release enormous numbers of microscopic larvae that can travel up to hundreds of kilometres before settling, making empirical measurement of dispersal infeasible across the 3,861 reefs spanning ~2,400 km of the GBR. Instead, biophysical models that combine ocean circulation (hydrodynamics) with simulations of larval biology are used to predict connectivity between reefs. Previous work has demonstrated the value of this approach but used a single hydrodynamic model and simplified assumptions about larval behaviour, leaving some uncertainty in the resulting predictions. This project of the COTS Control Innovation Program (CCIP), CCIP-R-05, aimed to reduce that uncertainty by building an ensemble modelling framework combining multiple hydrodynamic and biophysical models to improve predictive accuracy and confidence for reef prioritisation. From the outset, experts in COTS larval biology, biophysical modelling, and COTS Control Program managers were consulted to identify these gaps and define the sensitivity analyses to be tested, ensuring the modelling improvements targeted the areas of greatest uncertainty and management relevance.

The project has generated advanced larval connectivity matrices from the GBR from 2018 to 2023 using three independently developed hydrodynamic models and updated biological parameterisations. The three models form the hydrodynamic ensemble. A further 33-model biophysical ensemble, with varying depths of dispersal, settlement radius and larval survivorship and competency (the point at which a larva is able to settle and grow into a juvenile) assumptions, was also developed and the results from this ensemble have been processed and integrated into the COTS reef prioritisation framework. This report presents validation against observations of the physical components and comparisons between the individual component of the biophysical models.

Results & findings

- Developed a novel mortality and competency model of COTS larvae, integrating up to date knowledge with input from key experts in the field of COTS ecology. The model has been shared with colleagues at CSIRO and has been implemented as part of RRAP (Reef Restoration and Adaptation Program).

- Developed a suite of tests to evaluate how dispersal responds to different stages of larval development, by varying the depth at which larvae disperse during two development phases. Results show that as dispersal depth increases, dispersal distance decreases, thereby enhancing local retention. Dispersal depth also changes which reefs cluster together into self-contained dispersal communities (i.e. groups of reefs that exchange larvae mostly among themselves).
- Improved the temporal resolution of larvae release: Increased the release frequency from 4 to 10 times per spawning season and extended the release window from 6 to 24 hours to better capture the uncertainty in COTS spawning timing during the monsoon season and the variability of circulation.
- Improved knowledge of the Far Northern GBR circulation, relevant to both larval dispersal and retention, by deploying 30 current meters over two summers near known COTS outbreak locations, in partnership with a complementary CCIP monitoring project.
- Developed an ensemble modelling framework combining higher resolution hydrodynamic models, improved larval biology parametrisation, and higher frequency larval release. By combining three independently developed hydrodynamic models, two particle-tracking approaches, and multiple biological parameterisations, the project captured a wider range of plausible dispersal outcomes than any single model and identified where predictions are robust versus where they diverge. This will help managers to understand which connectivity estimates they can have greater confidence in.

This project delivered an improved understanding of COTS connectivity, modelling uncertainty, and enhanced translation into management decisions contributing to more effective management of COTS outbreaks. The findings are already being used in the annual reef prioritisation process and will become more precise once the full 33-model ensemble is completed.

1. INTRODUCTION

The health and persistence of coral reefs globally have been increasingly under threat due to growing anthropogenic pressures (Hughes et al., 2003; Halpern et al., 2008; Hughes et al., 2017). The Great Barrier Reef (GBR) is no exception, facing increasing ocean temperatures and heatwaves (Hughes et al., 2018), pollution and runoff (Fabricius, 2005; Carlson et al., 2019), ocean acidification (Doney et al., 2009), and crown-of-thorns starfish (COTS) predation on corals. While many of these factors require global efforts to address, COTS predation is one of the few that can be directly managed at a local level. COTS predation is a primary cause of coral mortality on the GBR (Pratchett et al., 2021), with De'ath et al. (2012) estimating that coral cover on the GBR halved between 1985 and 2012 coral cover, with 42% of the decline attributed to COTS.

Currently, COTS populations are controlled via culling by the COTS Control Program (operated by the Great Barrier Reef Marine Park Authority (Reef Authority)), which has resulted in significant reductions to coral cover loss, comparative to counterfactual scenarios (Matthews et al., 2024). However, as resources are limited, crucial decisions must be made as to which subset of reefs culling actions are directed towards to maximise ecological and economic benefit. These decisions are based on five key metrics: COTS outbreak history, resilience and recovery potential, zoning, coral connectivity, and COTS sources and connectivity (dispersal). Reefs with the potential to amplify and spread COTS via dispersal are prioritised, ensuring that both the present and future benefits of culling are considered.

One aspect that contributes to the success of COTS outbreaks is their reproductive capacity (Deaker and Byrne, 2022). A single adult female can release millions of eggs during a single spawning event. Fertilised eggs develop into microscopic, free-swimming larvae that drift in the water column as plankton for several weeks before becoming competent to settle and metamorphose into juvenile starfish on the reef. During the pelagic phase, larvae can be transported substantial distances by ocean currents, meaning the reef where a larva eventually settles may be far from the reef where it was spawned. This dispersal process links reefs together into a connectivity network and means that outbreaks on one reef can seed future outbreaks on other reefs, sometimes at considerable distances. Understanding this network is therefore essential for identifying which reefs, if targeted for control, will do the most to prevent COTS spreading to new areas.

However, quantifying these dispersal dynamics empirically at a GBR-wide scale is infeasible, given the immense spatial and temporal scales over which tiny larvae disperse. As such, biophysical models are used, simulating both larval biology and oceanographic flows to produce predictions of dispersal strength between all reefs in the GBR, referred to as connectivity.

Strengths and limitations of dispersal modelling:

Resolving connectivity in reef ecosystems is a multi-step process that involves various scientific and computational methods, which can be grouped into three main stages:

- **Hydrodynamic modelling:** This stage involves resolving ocean processes to produce flow fields predicting the movement of water across the system, capturing

complex bathymetry to accurately simulate water flow through reef channels and the formation of eddies.

- **Larval Particle Transport models:** The flow fields produced in the hydrodynamic modelling stage are then used to drive simulations of the transport of larvae across the GBR. Doing so requires a detailed biological knowledge of the species being studied, including their spawning periods and the different stages of their life cycles (ontogeny). For example, factors such as egg buoyancy and the vertical positioning of larvae in the water column are critical inputs for 3-dimensional (3D) models, given they will determine the specific flow fields larvae are subjected to.
- **Post-processing analysis:** After the initial modelling stages, post-processing involves applying the remaining biological factors, primarily larval mortality and competency rates. Mortality rates can vary based on environmental conditions and predation, as well as with the time since spawning. If larvae survive long enough, they can become competent, which refers to the stage at which pelagic larvae can settle and metamorphose into juvenile forms.

Together, these stages comprise a comprehensive modelling approach that incorporates both physical oceanography and larval biology. However, each step introduces uncertainties due to the complex nature of environmental processes, and the variability in biological behaviours. For hydrodynamic models, the GBR's large spatial range and intricate bathymetry, with its myriad of channels, reefs, and eddies, poses a substantial challenge for modelling flow fields accurately. Furthermore, when developing hydrodynamic models, a number of often equally-defensible choices must be made that lack a single correct answer – sometimes because the oceanographic processes are uncertain, and sometimes because trade-offs are required between alternative approaches (e.g. higher horizontal resolution 2D vs. lower resolution 3D). As a result, multiple hydrodynamic models exist for the GBR, but due to sparse validation data there is no clear hierarchy regarding their suitability for use in biophysical modelling. Similar challenges are faced when modelling the biological processes defining the larval behaviour for COTS. The process of larval dispersal involves thousands – if not millions – of microscopic larvae being released by a single adult COTS, that can travel up to hundreds of kilometres in the open ocean (Dight et al., 1990a, 1990b). Empirical observations of larval biology are thus extremely difficult to gather, resulting in significant levels of uncertainty for some biological processes, and a complete lack of data for others.

Prior to this project, reef prioritisation decisions relied on connectivity estimates from a single biophysical model (Hock et al., 2017), using one hydrodynamic model at a relatively coarse spatial scale and simplified assumptions about larval behaviour. While an important foundation, using only one model meant decision-makers had no way to assess how much of the resulting connectivity estimates depended on that model's particular assumptions, versus genuine GBR circulation.

One approach for dealing with model-based uncertainty is the use of an ensemble modelling approach – that is, forming predictions based on outputs from multiple differing models. Ensemble modelling can help address uncertainty because it takes into account the different choices that could be made during the modelling process. Comparing several models can show which predictions are robust and areas where uncertainty is higher. Ensemble models are therefore capable of offering more robust and holistic predictions of dispersal than is possible with a single model. For example, these models can incorporate hydrodynamic

simulations at different spatial scales, each with different assumptions and parameters, providing a more nuanced understanding of how larvae disperse. Moreover, knowledge of biological aspects of COTS, such as their spawning periods, larval buoyancy, and vertical positioning in the water column, are limited. An ensemble modelling approach allows the integration of multiple biological models that explore different scenarios and life history traits, thus enhancing predictive power. Additionally, ensemble models are particularly valuable in addressing data gaps. In the case of COTS larvae, where empirical data might be sparse or uncertain, combining outputs from various models can mitigate the impact of incomplete or imprecise information. This approach not only improves the reliability of predictions, but also aids in identifying critical areas for further research and data collection.

The use of ensemble models in studying COTS larval dispersal on the GBR is essential for developing resilient and adaptive management strategies, which are crucial for the preservation and restoration of this vital ecosystem. The primary aim of this COTS Control Innovation Program (CCIP) project (CCIP-R-05) was to develop an ensemble model for COTS larval dispersal on the GBR, combining three independently developed hydrodynamic and biophysical models (SLIM COTS, the Commonwealth Scientific and Industrial Organisation (CSIRO) eReefs GBR1, and GBRL) to generate advanced larval connectivity estimates across the GBR for the 2018 to 2023 spawning seasons.

SLIM COTS is a depth-integrated, unstructured model with grid cell resolutions varying between 4 km and 250 m around the reefs. GBR1 is a 3D baroclinic model with a horizontal resolution of 1 km, while GBRL is a 3D barotropic model with a grid resolution of 1 nautical mile. These horizontal grid resolutions represent a substantial improvement (between 4 and 20 times finer) than the 4km hydrodynamic model used in previous COTS connectivity modelling (Hock et al., 2017), enabling this project to resolve finer-scale circulation features relevant to reef-to-reef dispersal. In collaboration with key experts in COTS larval biology, hydrodynamic and biophysical modellers, and COTS Control Program managers, this project focused on improving the COTS modelling framework described in Hock et al. (2017) by integrating higher resolution flow fields, updated biological parameterisations where possible, and developed sensitivity analyses to address remaining gaps. This approach has focused on enhancing the accuracy, robustness, and applicability of dispersal predictions to support effective reef management and conservation efforts.

Dispersal modelling improvement

The key aims were to:

1. **Improve predictive accuracy:** By integrating multiple models, the project will be able to capture a wider range of potential dispersal scenarios and reduce the uncertainty associated with COTS larval movement predictions. This is critical for effective intervention and control strategies.
2. **Address data gaps and uncertainty:** An ensemble approach will allow for the inclusion of various data sources and model assumptions, thereby mitigating the impact of limited or imprecise biological and environmental data on COTS larvae. As such, model predictions will be more informed and reliable.
3. **Support targeted management actions:** By offering more precise and reliable predictions, the ensemble model will help reef managers to identify critical areas for

COTS control measures. This would support the prioritisation of resources and efforts to protect the most vulnerable or valuable reef sections.

Management support improvement

The key aims were to:

1. **Enhance understanding of dispersal dynamics:** Comparing predictions from individual component models with differing assumptions has the potential to provide deeper insight into the ecological and oceanographic processes that drive COTS dispersal. This includes understanding how factors such as hydrodynamics, larval behaviour, and environmental conditions interact to influence larval distribution and settlement.
2. **Facilitate adaptive management:** This project aims to create a tool that can be continually updated and refined with new data and improved modelling techniques. This ensures that the model will remain relevant and can adapt to changing conditions or new scientific findings.
3. **Promote collaboration and knowledge sharing:** When attempting to effectively resolve a multi-faceted ecological problem, there is a clear potential to foster a multi-disciplinary approach by bringing together reef managers, key experts in COTS larval biology, and modellers. This can lead to the sharing of best practices, and the development of standardised methods.

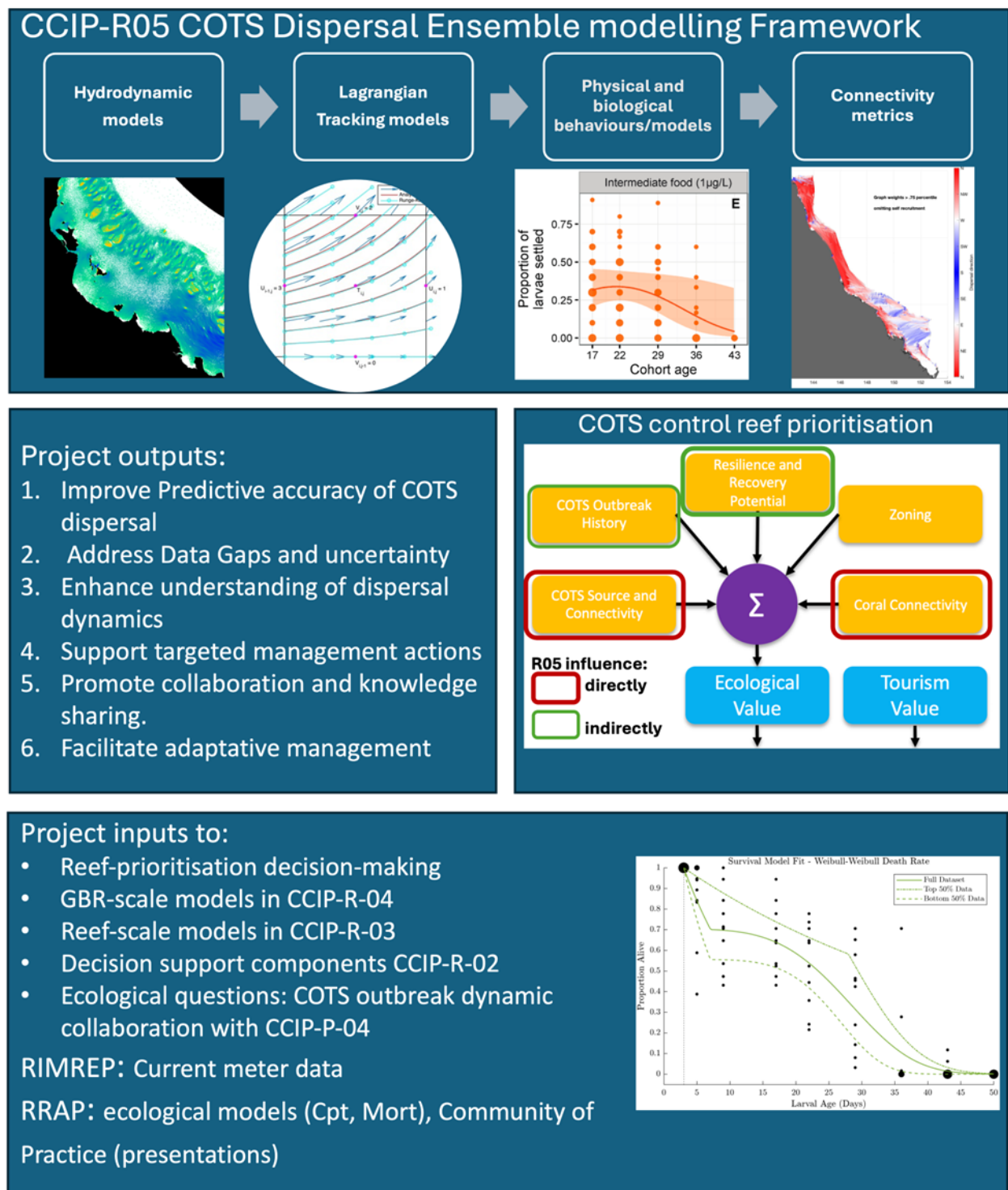


Figure 1. Diagram summarising the key components and processes involved in the ensemble modelling for COTS larval dispersal, the projects output and their applications, direct and indirect, into the COTS Control Reef prioritisation and the project's inputs to CCIP and others programs such as the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) and the Reef Restoration and Adaptation Program (RRAP).

Synergies with other CCIP projects

The project is highly synergistic (**Figure 2**) with: 1) current reef prioritisation decision-making processes in the current COTS Control Program, as well as innovations being proposed; 2) GBR-scale models in CCIP-R-04 (Regional Modelling, Skinner et al., 2025) and reef-scale models in CCIP-R-03 (Dynamic Models, Rogers et al., 2025) that use larval connectivity as a core model component; 3) decision support components in CCIP-R-02 (Empirical Decision Support, Fletcher et al., 2026a); and 4) data sharing components in CCIP-R-01 (Information Infrastructure, Fletcher & Rezvani, 2026). The project is also highly synergistic with monitoring studies in the Detection Subprogram and other field studies in the Prediction Subprogram.

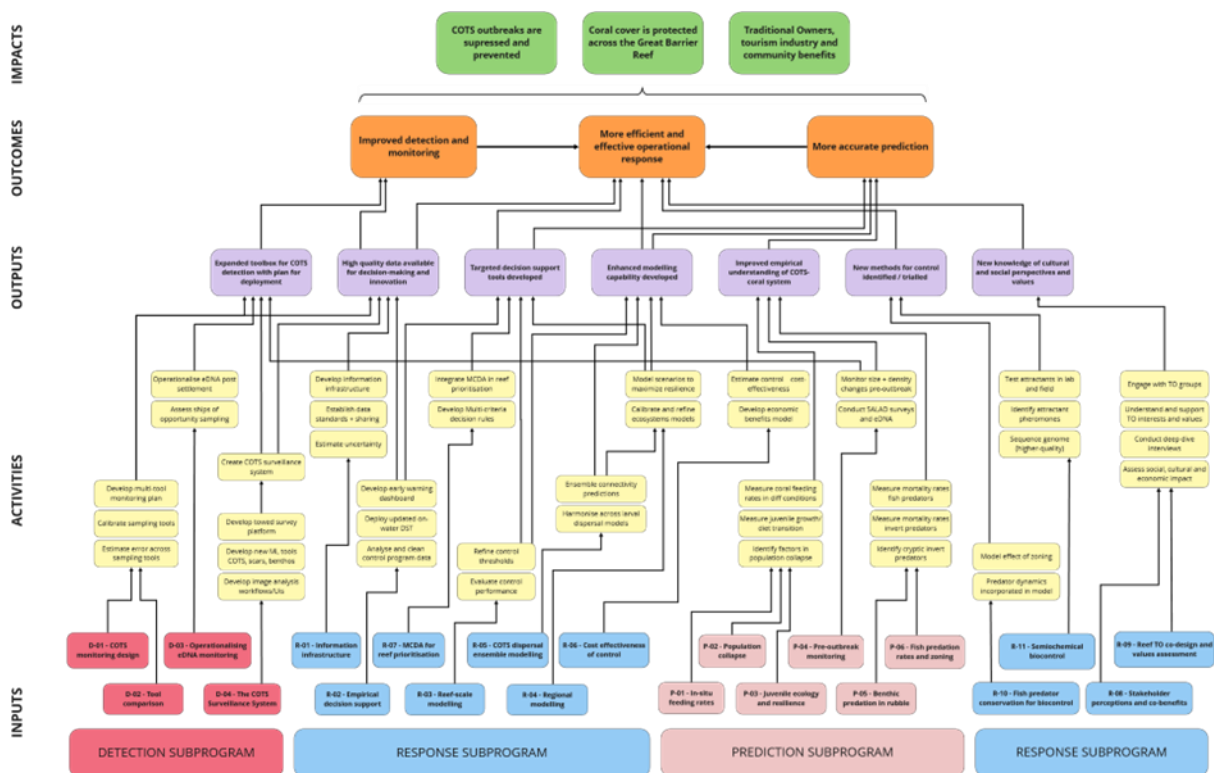


Figure 2. CCIP program logic, showing all the sub-programs included within the program, how the inputs are channelled into activities that produce outputs, which inform outcomes and ultimately add to the three primary intended impacts of the Program.

2. METHODS

The modelling framework is composed of three hydrodynamic models and their associated larval transport models, encompassing the Great Barrier Reef Marine Park (GBRMP). Each model was run for five consecutive spawning seasons, from 2018 to 2023, and aimed at estimating COTS larval dispersal in the GBR.

2.1 Hydrodynamic modelling

The three hydrodynamic models have been specifically developed to study GBR circulation. The models extend from ~10 to ~27°S, from the tip of Cape York to K'gari (Fraser Island), encompassing 3,861 reefs, over ~2,400 km.

2.1.1 eReefs GBR1km

The eReefs GBR1 hydrodynamic model is an application of the Sparse Hydrodynamic Ocean Code, Herzfeld et al. 2006), part of the Environmental Modelling Suite (EMS) publicly available from <https://research.csiro.au/cem/software/ems/>. GBR1 is nested within a 4 km regional model GBR4. GBR1 is a 3D finite difference hydrodynamic model, uses an orthogonal curvilinear grid, with 47 vertical (depth) layers and has a horizontal resolution of ~1 km. The model is based on the equations of momentum, continuity and conservation of heat and salt, employing the hydrostatic and Boussinesq approximations. GBR1 model outputs are part of the near-real-time (NRT) eReefs ocean simulations, which are a growing archive made publicly available through the National Computational Infrastructure (NCI) THREDDS catalogue (<https://dapds00.nci.org.au/thredds/catalogs/fx3/catalog.html>). The model is forced by wind, atmospheric pressure gradients, surface heat and water fluxes provided by ACCESS-G (the Bureau of Meteorology's operational regional atmospheric forecast model), and open boundary conditions provided by GBR4, including tidal current and elevation and low frequency ocean currents. At its open boundaries, GBR4 is driven by OceanMAPS (Bluelink's operational ocean forecast model, the Ocean Modelling and Analysis Prediction System) and the Coastal Reference Station (CRS) tides. GBR1 hydrodynamic outputs are available from October 2014 to December 2023.

2.1.2 SLIM

SLIM 2D is an unstructured-mesh depth-integrated coastal ocean model (Thomas et al., 2014). The model was forced by tides and large-scale oceanic currents provided by eReefs GBR4 hourly transport and sea surface elevation (<https://research.csiro.au/ereefs/models/models-about/models-hydrodynamics/>). Wind at 10 m was acquired from ACCESS-R, at a 10 m resolution. The bathymetry file used in the model is the 3DGBR at 100 m (Beaman, 2010) (<https://www.deepreef.org/2010/07/06/gbr-bathy/>), which captures the complex topography of the domain. The model was run for five successive summer periods, from 2018 to 2023, from the 1st of October to the 1st of May.

The mesh grid, generated with the open-source mesh generator GMSH (Geuzaine and Remacle, 2009), was comprised of 880,768 triangles with a resolution varying between 250 m and 4 km, depending on the distance to the reef and coast, with higher resolutions close to the reef and the coast.

2.1.3 GBRL

The hydrodynamic model is solved using the numerical scheme developed in James et al. (2002) and Luick et al. (2007). The results of both were validated with data from current meters. Currents in the GBR are forced by tides, wind, and oceanic influences of the seasonally varying East Australian Current (EAC). The model employs a version of the finite difference hydrodynamic model of Bode and Mason (Bode and Mason, 1994). It also incorporates a reef parameterisation scheme (Bode et al., 1997) that allows the dynamical effects of the reef matrix to be assimilated into flow simulations without requiring the reefs themselves to be fully-resolved by the model grid (which would require a prohibitively small grid size). The model was run for five successive summer periods, from 2018 to 2023, from the 1st of October to the 1st of May.

2.1.4 Validation

Queensland Integrated Marine Observing System (QIMOS)

The models were compared to Acoustic Doppler Current Profiler (ADCP) velocity and water pressure from eight QIMOS mooring locations across the GBR domain. Data are publicly available and were downloaded from the Australian Ocean Data Network (AODN) portal (<https://portal.aodn.org.au>).

Marotte current meters: Far Northern GBR

There are very limited observations of oceanographic data in the Far Northern GBR to validate the hydrodynamic models as the IMOS mooring array does not extend past -15°S, off Lizard Island. To address this gap, the project team partnered with a complementary CCIP pre-outbreak monitoring project (CCIP-P-04, Pratchett et al., 2025), deploying 30 Marotte current meters over two summers (2022–23 and 2023–24) alongside transects on the reef slope at shallow (1–3 m) and deep (4–7 m) sites. This included two transects across channel entrances (the Quon Channel and the channel north of Wilson Reef) to evaluate water exchange between the Coral Sea and the GBR lagoon. Velocity data from the 2022–23 deployment were compared against the three hydrodynamic models' flow fields. Due to late recovery of instruments, the 2023–24 dataset could not be compared within the timeframe of this report but will be incorporated into future work. The current meter dataset is available from Research Data JCU (<https://researchdata.jcu.edu.au/published/45ba3e009b9211f1a4c2235f17345359/>).

2.2 Particle Tracking Models (PTM)

The SLIM and GBRL particle tracking models were forced by their respective flow fields. As part of the Reef Restoration and Adaptation Program's (RRAP) Modelling and Decision Support (MDS), CSIRO has developed a particle tracking model based on Ocean Parcels (<https://oceanparcels.org/>) and adapted to the GBR, forced by the flow field from GBR1. These three models provide an ensemble of dispersal conditions.

Previous work in this area used the release methodology described in Hock et al. (2017) of four releases per spawning season (fortnightly on the 1st and 15th of each month), lasting 6 hours from dusk. Following consultation with COTS larval biology experts, we updated this scheme and increased the release frequency to ten times per spawning season (approximately weekly) and extended the release window to 24 hours (**Table 1**). These changes were made for the following reasons:

1. Extending the COTS spawning period from 6 to 24 hours, both starting from dusk: This update was made because there is evidence that COTS spawning can occur during the day, not only at night (pers. comm. Morgan Pratchett).
2. Number of releases increased from fortnightly (4 times per season) to approximately weekly (10 times over 2 months): The circulation in the Far Northern GBR is significantly influenced by the prevailing winds. These winds generate a correlated mean longshore flow that drives oceanic water. However, during the summer (monsoon), increased variability in wind patterns can alter the dynamics of water movement, potentially affecting the distribution of nutrients and larval dispersal within the reef system (Wolanski and Lambrechts, 2020). Increasing the frequency of release helps to capture this variability.
3. Sensitivity analysis on more complex ontogeny phases (i.e. differentiating between development phases compared to previous modelling that treated COTS pelagic larvae as a single, uniform life stage). Following advice from COTS biology experts, we tested the dispersal response to larvae occupying different depths in the water column during the pelagic larval development phases, to evaluate how depth-dependent behaviour changes over the course of larval development and how this affects dispersal (see **Appendix B**).

The particles were released from 3,861 locations corresponding to the GBR reef locations (Reef Authority, Great Barrier Reef Features – Reef <https://geohub-gbrmpa.hub.arcgis.com/>). A set number of particles were released from each individual reef, randomly over the spatial extent of the polygon area, and randomly over the release period (6 h or 24 h). This was repeated for each release during the 2-month spawning season: 4 times (fortnightly releases on the 1st and 15th) or 10 times (~weekly releases on the 1st, 7th, 14th, 21st and 28th of each month). The peak spawning season for COTS was defined as December to January following Hock et al. (2017). Particle positions were recorded hourly for 45 days post-release, reflecting the upper range of the observed COTS pelagic larval duration.

In GBR1 and SLIM, the larvae were considered passive and neutrally buoyant. GBRL larval particle tracking (LPT) was used to test the more complex ontogeny phases, including position in the water column as a function of the development phase of the larvae.

Table 1. Summary table of the hydrodynamic and particle models set-up and parametrisation. CDF stands for cumulative distribution function. Hor. Res. = Horizontal Resolution. The fortnightly (2018–2021) rows represent the earlier release scheme (Hock et al., 2017), which were superseded by the weekly (2018–2023) scheme used in the main ensemble in this project.

Hydrodynamic			Particle tracking model							
Model		Hor. Res.	Model	Frequency of release December to January			Egg buoyancy	Depth of dispersal post hatching	Depth @ competency	Output: 45 days
SLIM	2D- barotropic	4 km to 250 m	SLIM	fortnightly	2018– 2021	6h from 4pm	NA	NA	NA	If particle over a reef, position saved hourly
				weekly	2018– 2023	24h from 4pm				
GBRL	3D- barotropic	1 nm to 70 m	GBRL	fortnightly	2018– 2021	6h from 4pm	Particle remains in 0.5 m below surface for 45 days			Trajectories hourly
				weekly	2018– 2023	24h from 4pm	0–24h positive	3 scenarios: CDF centred on ¼, ½, ¾ height of water column	¾ height of water column	
eReefGBR1	3D-baroclinic	1 km	Ocean-Parcel	fortnightly	2018– 2021	6h from 4pm	Particle remains in 0.5m below surface for 45 days			Trajectories hourly
				weekly	2018– 2023	24h from 4pm				
FLOW FIELDS			PARTICLE TRAJECTORIES							

2.3 Post-Processing

The post-processing analysis was applied to the hourly output dataset from the particle tracking models. The post-processing was applied to 286 particle tracking dataset of ~1,000 particles per reef over five spawning seasons (2018–2023), over the 3 hydrodynamic models, to form the ensemble.

2.3.1 Ensemble Groups

The ensemble modelling process was completed in two phases. The first phase involved creating a 4-member ensemble referred to as the hydrodynamic ensemble, where members differed in the hydrodynamic model used while keeping other biological factors constant. For this ensemble set, GBRL results with particles at the top and bottom of the water column were treated as separate “GBRL Up” and “GBRL Deep” models respectively. In the second phase, a 33-model ensemble, referred to as the biophysical ensemble model, was built from this initial ensemble, this time varying a number of biological characteristics detailed below.

2.3.2 Settlement Radius

To account for the fact that hydrodynamic models cannot resolve sub-grid scale processes, we specified a radius extending from the borders of each reef polygon. We refer to this radius as the settlement radius, and stipulate that it is only when a simulated larva is within this radius that it has the possibility of settling at the corresponding reef. For the ensemble modelling approach, we simulated larva with three different settlement radii: 0.5 km, 1 km, and 1.5 km. SLIM was the exception to this because SLIM particle positions were only recorded when particles were within 1 km of a reef, therefore only the 0.5 km and 1 km settlement could be applied to this model.

2.3.3 Settlement and Competency Functions

Survivorship refers to the probability that a larva remains alive at a given time since spawning. Competency refers to the probability that a surviving larva has developed the ability to settle and metamorphose into a juvenile. Both probabilities change over the course of the pelagic larval period, and both are informed by laboratory experiments in which COTS larvae are reared under controlled conditions and monitored over time. The dataset used here (Pratchett et al., 2017) reared larvae under three food availability treatments (low, intermediate and high algal cell density, and we opted to use the intermediate treatment as the most representative scenario for fitting our survivorship and competency curves. We fit survivorship and competency curves following the functional form and methodology from Moneghetti et al. (2019), with some slight adjustments. Specifically, survivorship was fit using a Weibull-Weibull piecewise model, and a Weibull-exponential piecewise model for competency loss, with an initial exponential gain in competency. Given the survival data from Pratchett et al. (2017) began at day 3, a slight alteration to the models provided by Moneghetti et al. (2019) was applied to fill this time period: for $t < 3$, survival was modelled with an exponential decay of rate parameter 0.954, as taken from Wilmes et al. (2018).

Additionally, to account for a range of potential competency and survivorship outcomes in the biophysical model, both the competency and survivorship function parameters were fit three times each. Once, using the full intermediate food treatment dataset, and then on the top and bottom 50% of this dataset separately. For survivorship, we split the dataset into the top and bottom 50% by the area under the curve for population size for each replicate, with values normalised by initial population. For competency, data points were split separately for each timestep rather than replicate, based on the proportion of larvae that had perished comparative to the previous timestep. For the hydrodynamic ensemble, models were simply fit to all data for both survival and competency.

As such, the piecewise survivorship dynamics were represented with:

$$S_2(t) = \exp(-0.0954t), \quad t < 3$$

Equation 1

$$S_2(t) = \exp(-0.0954 \times 3) \exp(-(u_1 t)^{w_1} + (3u_1)^{w_1}), \quad 3 \leq t < T_{cp}^{(s)}$$

Equation 2

$$S_2(t) = \exp(-0.0954 \times 3) \exp\left(-\left(u_1 T_{cp}^{(s)}\right)^{w_1} + (3u_1)^{w_1}\right) \exp\left(-(u_2 t)^{w_2} + \left(u_2 T_{cp}^{(s)}\right)^{w_2}\right), \\ t \geq T_{cp}^{(s)}$$

Equation 3

Where t is the time in days since spawning, and $S_2(t)$ is the probability that a larva survives until t . The parameter $T_{cp}^{(s)}$ corresponds to changeover time between the piecewise Weibull functions, and was constrained within $4 \leq T_{cp}^{(s)} \leq 49$ as the data spans 3 to 50 days. All other parameters relate to the first and second Weibull functions (indicated by subscripts), and so were constrained to be non-negative based on the definitions of their probability distributions. All parameters in the above model were fit using maximum-likelihood methods over multiple repetitions with randomised initial conditions. The fitted parameter values for the survivorship model are included in **Table 2**, and visualised in **Figure 3**.

Table 2. Fitted parameter values for the piecewise Weibull-Weibull COTS survivorship dynamics, with an initial exponential death rate of 0.954 for $t < 3$.

Model Fit	$T_{cp}^{(P)}$	u_1	w_1	u_2	w_2
All Data	7.0812	0.0869	1.0256	0.0326	3.9993
Top 50%	27.9649	0.0216	0.9941	0.0329	3.7249
Bottom 50%	7.0507	0.1441	1.01	0.0357	5.1780

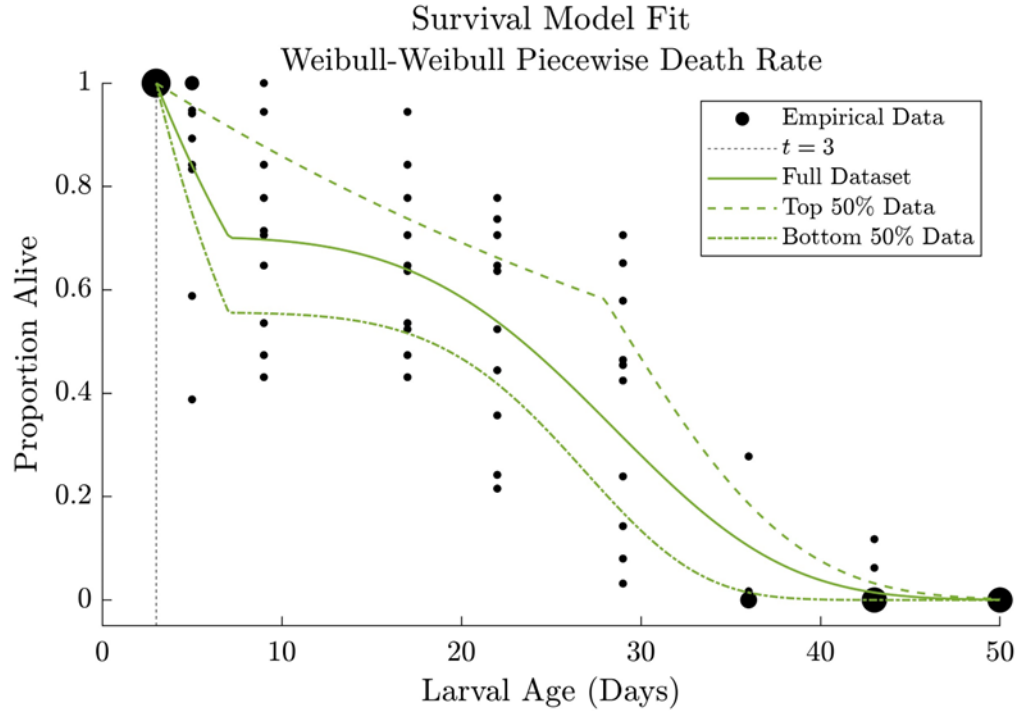


Figure 3. Piecewise model fit for COTS larval survivorship dynamics based on the form described in Moneghetti et al. (2019), using a piecewise Weibull to Weibull functional form. The model is fit to data from Pratchett et al. (2017), represented by black dots with increasing size relative to the number of repetitions with the same value.

The piecewise competency dynamics are represented by $P_2(t)$, which corresponds to the probability of a larva being competent at time t :

$$P_2(t) = 0, \quad t < t_c$$

Equation 4

$$P_2(t) = \int_{t_c}^t a \exp(-a(\tau_1 - t_c)) \exp(-(b_1(t - \tau_1))^{v_1}) d\tau_1, \quad t_c < t \leq T_{cp}^{(P)}$$

Equation 5

$$P_2(t) = \int_{t_c}^{T_{cp}^{(P)}} a \exp(-a(\tau_1 - t_c)) \exp\left(-\left(b_1(T_{cp}^{(P)} - \tau_1)\right)^{v_1}\right) \exp\left(-b_2(t - T_{cp}^{(P)})\right) d\tau_1 \\ + \int_{T_{cp}^{(P)}}^t a \exp(-a(\tau_2 - t_c)) \exp(-b_2(t - \tau_2)) d\tau_2, \quad T_{cp}^{(P)} < t$$

Equation 6

The parameter t_c corresponds to the earliest possible time at which competency can emerge for COTS larvae. This value was set at $t_c = 9$ based on Lucas (1975), that indicate COTS can develop competency as early as 9 days. However, given Pratchett et al. (2017) only observed a capacity to settle in all treatments at day 17, their competency data begins at day 17. As a result, initial fits of the model set the exponential gain in competency extremely high, resulting in an instantaneous gain for all larvae at $t = 9$. To avoid this issue, the exponential

growth rate parameter a was constrained within $0 < a < 2$, to produce a smoother gain in competency.

Similarly, as the competency data ends at day 50, the changeover between the Weibull and exponential loss in competency, $T_{cp}^{(P)}$, was constrained within $18 \leq T_{cp}^{(P)} \leq 49$. All other parameters relate to the Weibull and exponential losses in competency, and are constrained to be non-negative based on the definitions of the probability distributions they represent. Once again, all parameters were fit using maximum-likelihood methods with randomised initial conditions, following Moneghetti et al. (2019). The fitted parameter values for the competency model are included in **Table 3**.

Table 3. Fitted parameter values for the piecewise Weibull-exponential loss in competency, with an initial exponential gain in competency.

Model Fit	$T_{cp}^{(P)}$	t_c	a	b_1	v_1	b_2
All Data	32.1717	9	0.4556	0.2970	0.1260	0.11441
Top 50%	42.9997	9	0.1308	0.0560	1.0767	2005.9
Bottom 50%	35.3403	9	0.7417	14.1569	0.1469	2.6165

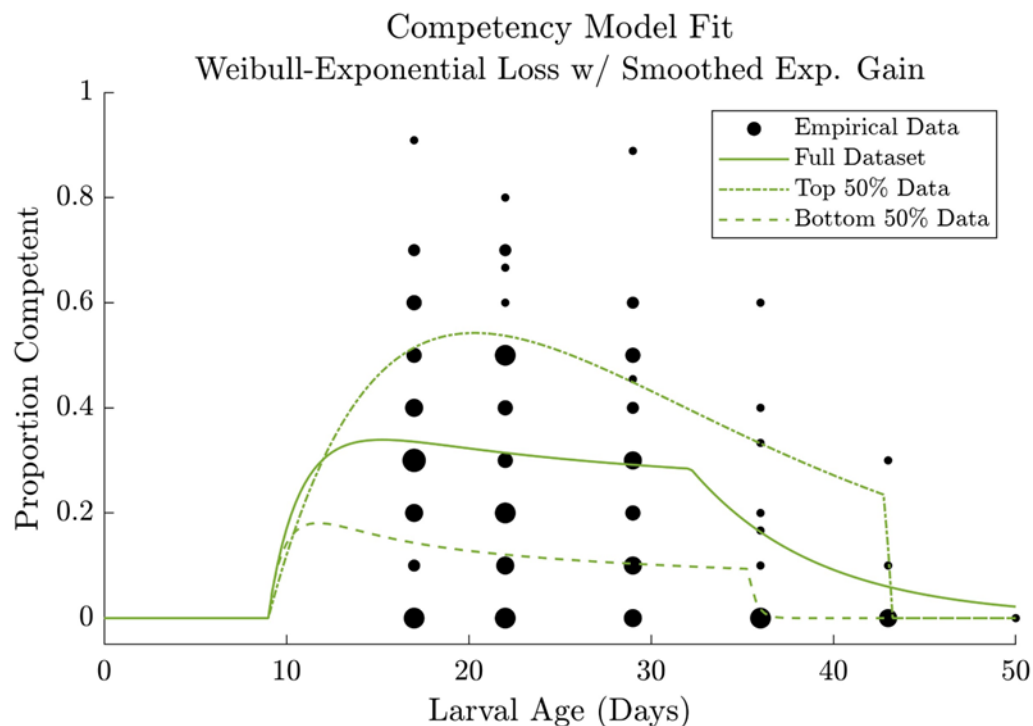


Figure 4. Piecewise model fit for larval competency dynamics based on the form described in Moneghetti et al. (2019), using an initial exponential function for gain in competency, followed by a Weibull then exponential function for loss in competency. The model is fit to data from Pratchett et al. (2017), represented by black dots with increasing size relative to the number of repetitions with the same value.

Finally, the probability that a larva is alive and competent at time t can be found by simply multiplying the probability it is alive at time t by the probability it is competent at time t :

$$f(t) = S_2(t)P_2(t)$$

Equation 7

When forming $f(t)$, we use survivorship and competency models fit on equivalent sections of their respective data. That is, we have three models for COTS survivorship and competency: one fit with all data, one fit on the top 50% of data, and one fit on the bottom 50%.

Probability Calculations

The probability values that comprise the entries of the connectivity matrix were calculated using the results from the random sampling approach described in Section 2.3.1 for the biophysical ensemble model. The random sampling process is repeated 10,000 per release points (**Figure 5**) and is used to compute the probability of settlement value in the connectivity matrix.

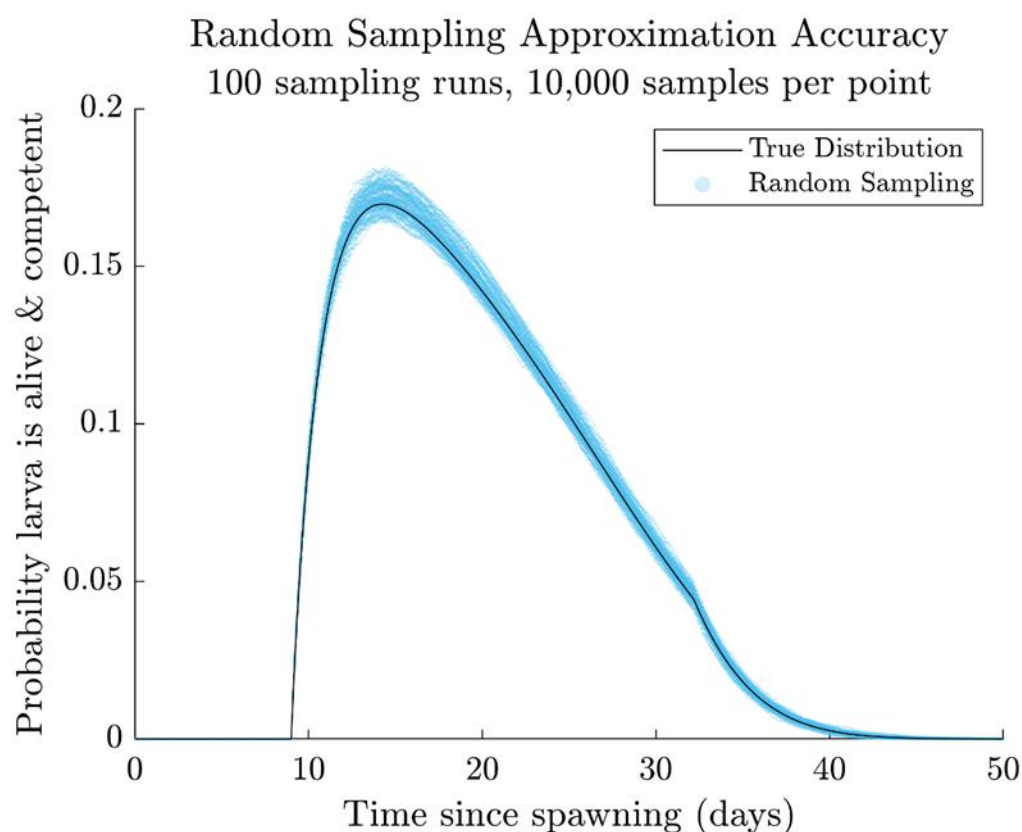


Figure 5. Accuracy of the random sampling approach to approximate fitted competency and survivorship curves. Each blue dot represents the probability that a larva is alive and competent at a discrete time t , as determined through random sampling. The black line is the true distribution, fit to all data, included for reference. This process was repeated 100 times for each value of t to demonstrate the distribution of these stochastic approximations via random sampling.

Ensemble Formation

To form our biophysical ensemble, we took combinations across the previously discussed factors: the four hydrodynamic/particle tracking models (as GBRL is split into Up and Deep), the three settlement radii (2 for SLIM), and the three survivorship and competency distributions. As such, we formed a total of 33 biophysical models: 6 based on SLIM, 9 based on GBR1 and 18 based on GBRL.

2.4 Ensemble Comparison

This section describes how the individual component models comprising the COTS dispersal dataset were compared against one another, to characterise the degree of agreement and disagreement between them. This comparison step is a necessary precursor to understand differences between the model outputs as this will help inform how their outputs might need to be weighted or combined.

We measured the differences in dispersal predictions of three of the four models comprising the hydrodynamic ensemble (GBRL Deep was excluded), using three sets of comparisons: reef-to-reef connectivity (four comparisons), reef-level network importance, and regional-scale community structure.

Reef-to-reef connectivity

The first set of comparisons focused on the connections between individual reefs: the c_{ijt}^m values that make up the connectivity matrices using four complementary comparisons.

Comparison 1 visualised the entirety of the connectivity matrices for each model.

Comparison 2 produced graphs of reefs linked by connectivity. Because the full GBR connectivity matrices contain millions of edges, visualising the entire graph for all 3,861 reefs was not practical. We therefore focused this comparison on small sets of reefs in different locations across the GBR.

Comparison 3 calculated the size of the aggregate absolute difference between pairs of models and pairs of years. We report the absolute difference rather than the relative difference, since we did not want small differences between low-value connections to appear important (e.g., if $c_{ij}^n = 10^{-5}$, but $c_{ij}^m = 10^{-7}$):

$$\Delta_{t_1 t_2}^{mn} = \frac{\sum_i \sum_j |c_{ijt_1}^m - c_{ijt_2}^n|}{\sum_i \sum_j c_{ijt_1}^m + c_{ijt_2}^n}$$

Equation 8

The metric $\Delta_{t_1 t_2}^{mn}$ can be thought of as the number of released larvae that the two models m and n at times t_1 and t_2 disagree about, as a proportion of the total larvae released.

Error! Reference source not found. sets a very precise definition of agreement between the models – it is not enough for two models to agree approximately on where larval exchange occurs. For example: if model m predicts a single strong connection between reef a and reef b , but model n predicts that there is a single strong connection between reef a and reef c ,

then $\Delta^{mn} = 0$, regardless of whether reefs b and c are close together, or 500 km apart. For some purposes, however, it is enough for a biophysical model to predict the broader spatial pattern of agreement, rather than matching individual reef-to-reef connections exactly.

Comparison 4 therefore relaxes the precision of Δ^{mn} , considering reef-to-reef connections aggregated with neighbouring reefs within a set radius. We denote this quantity $M_{i,j}^{(m,n)}(r)$ for some reef pair i and j and model comparison m to n , which is calculated as follows:

$$M_{i,j}^{(m,n)}(r) = \frac{1}{|I||J|T} \sum_t \left| \sum_{i' \in I, j' \in J} c_{i'j't}^{(m)} - \sum_{i' \in I, j' \in J} c_{i'j't}^{(n)} \right|$$

Equation 9

Here, I is the set of reefs whose centroids are within a radius r of reef i 's centroid, with J defined equivalently for reef j . We then sum $M_{i,j}^{(m,n)}(r)$ across all possible i and j pairings, including self-recruitment (when $i = j$), and average across all possible connections (dividing by the number of reefs squared).

Reef-level network importance

The second set of comparisons focus on the reefs themselves, rather than on individual connections between them. Beyond examining individual reef-to-reef connections, it is also valuable to identify which reefs are most influential within the wider dispersal network, for example, reefs that seed many other reefs. These reefs are natural candidates for control prioritisation, since managing COTS there has flow-on benefits across the system. Hock et al. (2017) proposed identifying such “priority reefs” using network metrics calculated from the connectivity matrices, classifying a reef as high value if its metric score was above the GBR-wide median.

We investigated the three network metrics from Hock et al. (2017) that are most widely used in ecological network analysis:

- **Node out-degree:** the number of *different* reefs that a given reef is directly connected to (i.e. how many distinct reefs it can send larvae to).
- **Total node-strength:** the sum of strength of all incoming (in degree) and outgoing (out degree) connections from that reef.
- **Out-component:** the number of reefs that could eventually be reached by the descendants of individuals from a given reef, even over multiple generations. We modified this metric to count only reefs reachable within three generations, since almost all of our matrices are irreducible (i.e., the out-component of each reef is effectively the entire system). Reducible matrices are generally the result of simulations that release too few larvae.

We calculated these three metrics for each reef under each of the three hydrodynamic models, and measured the overlap between the resulting priority sets – those reefs with above-median network values. Since roughly 25% of above-median values would be expected to coincide based on random chance alone, we compared the observed overlap against this baseline expectation.

Regional-scale community structure

Our final comparison operated at a regional scale – larger than an individual reef, but smaller than the entire GBR. We use spectral community detection methods from network theory (Girvan & Newman, 2002) to identify groups of reefs within the GBR with high modularity. High modularity means groups of reefs that exchange a lot of larvae among themselves, but exchange comparatively little with reefs in other groups (Saint-Amand et al., 2023).

Ecosystem variables: Temperature, Salinity and Chlorophyll

As a part of the project review, ecosystems variables such as sea temperature, salinity and chlorophyll were identified by experts in COTS larval biology as having a great influence on the timing of spawning and the development of COTS larvae.

We created a database of temperature, salinity and chlorophyll, extracted from eReefs GBR1 hydrodynamic and biogeochemical models for the period spanning December 2018 to March 2023. The data was extracted as a daily average, from November to March, over the GBR1 domain and averaged over the reef extent, following the Reef Authority reef outline. The datasets can be used to interrogate the spatial extent of low salinity (<30 psu) across the GBR and the temporal accumulation (number of days under 30 psu).

2.5 Ensemble Evaluation

The three-model hydrodynamic ensemble described in Section 2.4 is complete for all five spawning seasons (2018–2023), and its outputs currently inform the COTS dispersal input to the annual reef prioritisation process (Section 3.4). The 33-model biophysical ensemble described in Section 2.3 (Ensemble Formation) which varies settlement radius and larval survivorship/competency assumptions, is a further refinement of this work, intended to better quantify the uncertainty bounds around these connectivity estimates.

Due to the computational demand of generating connectivity matrices for all 33 models, the larger ensemble is still being processed for the full 2018–2023 period. Preliminary results for a single spawning date (1 December 2019) are available for 30 of the 33 models. The remaining three models, using SLIM with a 1 km settlement radius, are still being processed.

In this section, rather than presenting combined ensemble outputs which require the full processed dataset, we use this preliminary subset to check that individual component models behave as expected given their known differences in biological modelling assumptions, as a validation step ahead of forming the combined ensemble product.

We first investigated the influence of settlement radius on a number of dispersal characteristics, beginning with the probability a larva settles. Clearly, we should observe that larger settlement radii result in higher probabilities of settlement, which we investigated by the distribution of settlement probabilities from the connectivity matrices. We defined the settlement probability as the probability that a larva released from a reef will settle at any other reef, which we denote as $SP_i(t)$ for some reef i and time t , and calculate using:

$$SP_i(t) = \sum_{j=1}^M C_{i,j}(t)$$

Equation 10

Similarly, we also examined the influence of settlement radius on the number of outgoing connections from each reef, referred to as the out-degree (see Section 2.4 for calculations). Here, we should see that as the settlement radius increases, so too does the out degree given simulated larva will have the potential to settle at an increased number of reefs during their lifecycle.

Alongside the impact of changes to the settlement radius, we also considered the influence of changing the data with which the survivorship and competency models are fit. We first examined the settlement probabilities across these different models, with the assumption that curves fit to the top 50% of data should result in higher settlement probabilities than those fit to all, and the bottom 50% of data, in that order. We also investigated the impact of these models on out degree, and expected a similar hierarchical structure to emerge.

2.6 Stakeholder engagement

Throughout the project, the project team has regularly engaged with stakeholders to provide updates, and where appropriate for consultation or input. COTS Control Program managers have been involved since the start of the project, particularly in terms of developing the ensemble framework. We have attended bi-yearly CCIP meetings and the results of the hydrodynamic ensemble modelling have been integrated into the COTS Control annual reef prioritisation. This collaborative working approach has led to rethinking the suitable spatial scale of intervention from reefs to clusters of reefs.

3. RESULTS

The results presented below draw on two components of this project's modelling framework. Sections 3.1 and 3.2 present the complete hydrodynamic ensemble (three independently developed models, five spawning seasons, 2018–2023). Section 3.3 presents sensitivity analyses exploring individual biological assumptions (i.e. dispersal depth, settlement radius, and survivorship/competency curves) using subsets of the wider biophysical ensemble model. As the full 33-model biophysical ensemble is still being processed (Section 2.5), combined ensemble outputs are not yet available, these will be reported separately once processing is complete. The comparisons below are therefore a validation and characterisation step to establish how much predictions vary with modelling choices.

3.1 Hydrodynamic models

The hydrodynamic models were validated against *in situ* measurements of velocity and sea surface elevation at sites occupied by the Integrated Marine Observing System (IMOS) long-term oceanographic moorings across the GBR, operated by the Australian Institute of Marine Science (AIMS) for the period 2018–2023. ADCP data were downloaded from the IMOS portal for this period. Velocity and elevation were extracted from the GBRL, GBR1 and SLIM flow fields and compared against the observed mooring data using a range of statistical measures (**Figures S11 to S13 and Table S2**).

To compare model performance, we used a Taylor diagram (a plot summarising a model's overall skill by combining its correlation and variability relative to observations in a single point, Taylor, 2001), shown in **Figure S10**. All three models performed similarly to one another and performed well in predicting circulation on the reef shelf. Performance was reduced at ADCP sites deployed off the continental shelf (e.g. the Myrmidon and Lizard Slope moorings, MYR and LSL).

3.2 Preliminary comparison

This preliminary comparison isolates the effect of hydrodynamic model spatial resolution and settlement potential specifically. We compared SLIM, GBR1 and GBRL Up using a single settlement radius (1 km) and survivorship/competency curves fit to the full dataset, holding these biological assumptions constant across all three models that any differences observed can be attributed to the choice of hydrodynamic model alone (GBRL Deep was excluded from this particular comparison). The comparison was restricted to the first three spawning seasons, 2018–2021 due to model processing times. This allowed us to test the sensitivity of dispersal predictions to the hydrodynamic model choice and assess how predictions change when the underlying ocean circulation model varies, while every other modelling decision is held fixed.

When comparing the three component models of the hydrodynamic ensemble, the larval dispersal patterns they predicted were broadly congruent at the scale of the entire GBR (**Figure 6**). Connectivity is strongest between nearby reefs, and decays in strength with distance. The northern reefs display higher long-distance connectivity than the southern

reefs, with dispersal strength decaying more slowly in the north. However, comparing reef-to-reef connectivity between models, revealed substantial variation in connectivity patterns between years and between hydrodynamic models (**Table 4**).

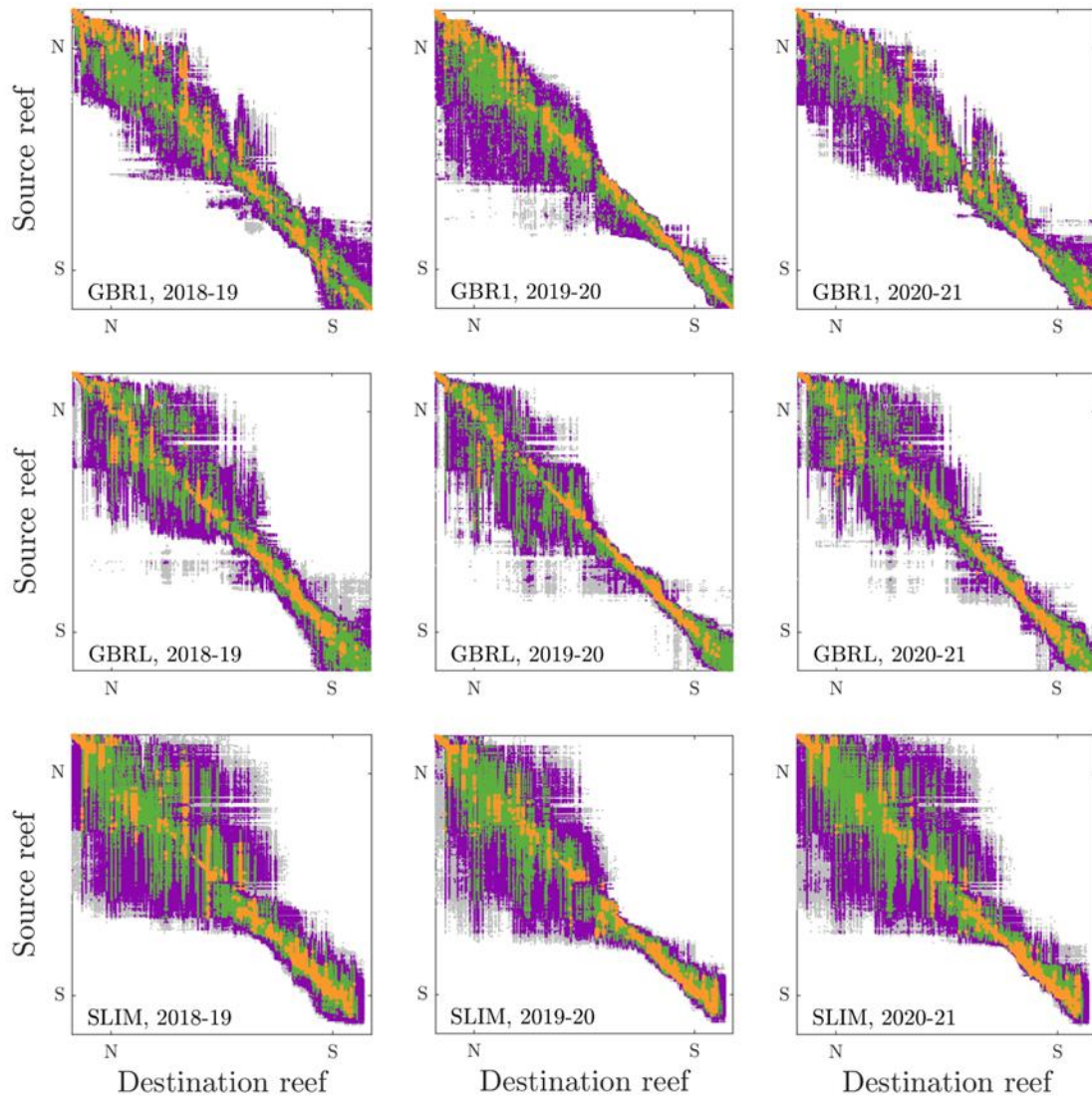


Figure 6. Each row of panels shows connectivity matrices for three different years, predicted by one of the hydrodynamic models. Reefs are ordered latitudinally, from north (N) to south (S). The first row shows the GBR1 model, the second shows GBRL, the bottom shows SLIM. Each point represents a single nonzero connection, i.e. a reef pair for which at least one larva was predicted to disperse from one reef to the other, colour-coded by the value of c_{ij}^m . Purple points fall in the upper 25th percentile of nonzero connections, green in the upper 5%, and orange are in the upper 0.5%. Readers can use this colour scale to identify the strongest predicted dispersal pathways in each panel.

We observed the most reef connectivity alignment between GBRL and SLIM, and the greatest divergence between GBR1 and the other two models. While GBRL and SLIM larval

releases were both performed on the same day and over the same 24-hour period, GBR1's releases were performed over a 10-day period at a specific time, therefore capturing differing pathways in dispersal. This result highlights the high variability in the circulation over a few days and the impact of release period and timing on connectivity.

There is also strong interannual variability in the connectivity patterns. In general, the difference between two models run for the same year is larger than the difference between two different years for the same model, highlighting the significant influence of hydrodynamic model choice. While it is difficult to pinpoint the exact reason, be it the bathymetry dataset interpolation over the grid cell, 2D vs 3D, different forcing datasets or model parameterisation, this result demonstrates that equivalent hydrodynamic models modelled slightly different circulation at reef scale.

Table 4. Summary difference statistics ($\Delta_{t_1 t_2}^{mn}$) for reef-to-reef connectivity between hydrodynamic models m and n in years t_1 and t_2 . Values range between zero (where the two models make identical predictions for all larvae) and one (where the models disagree entirely). Cells are coloured from most similar to least similar (blue – green – yellow – red).

		GBR1			GBRL			SLIM		
		2019	2020	2021	2019	2020	2021	2019	2020	2021
GBR1	2019	0	0.71	0.64	0.86	0.89	0.87	0.81	0.85	0.82
	2020		0	0.64	0.84	0.84	0.83	0.79	0.78	0.78
	2021			0	0.84	0.85	0.84	0.79	0.80	0.78
GBRL	2019				0	0.56	0.41	0.69	0.71	0.70
	2020					0	0.41	0.74	0.70	0.73
	2021						0	0.69	0.69	0.69
SLIM	2019							0	0.38	0.30
	2020								0	0.31
	2021									0

The comparisons in **Figure 6** and **Table 4** summarise the results across the whole GBR. When we focused on smaller regions (**Figure 7**), the divergence between the predictions of the different hydrodynamic models became more apparent. **Figure 7** shows spatial connectivity patterns from a single year (2018), visualised as graphs, for three different regions of the GBR. In each region, the predictions of the three different hydrodynamic models varied considerably. Many connections between reefs only occurred in a single model. The general patterns created were also different. One model predicted large amounts of connectivity, while another predicted fewer, weaker connections. These exemplars are not unusual among locations on the GBR and demonstrate the influence of the hydrodynamic model choice on local-scale connectivity.

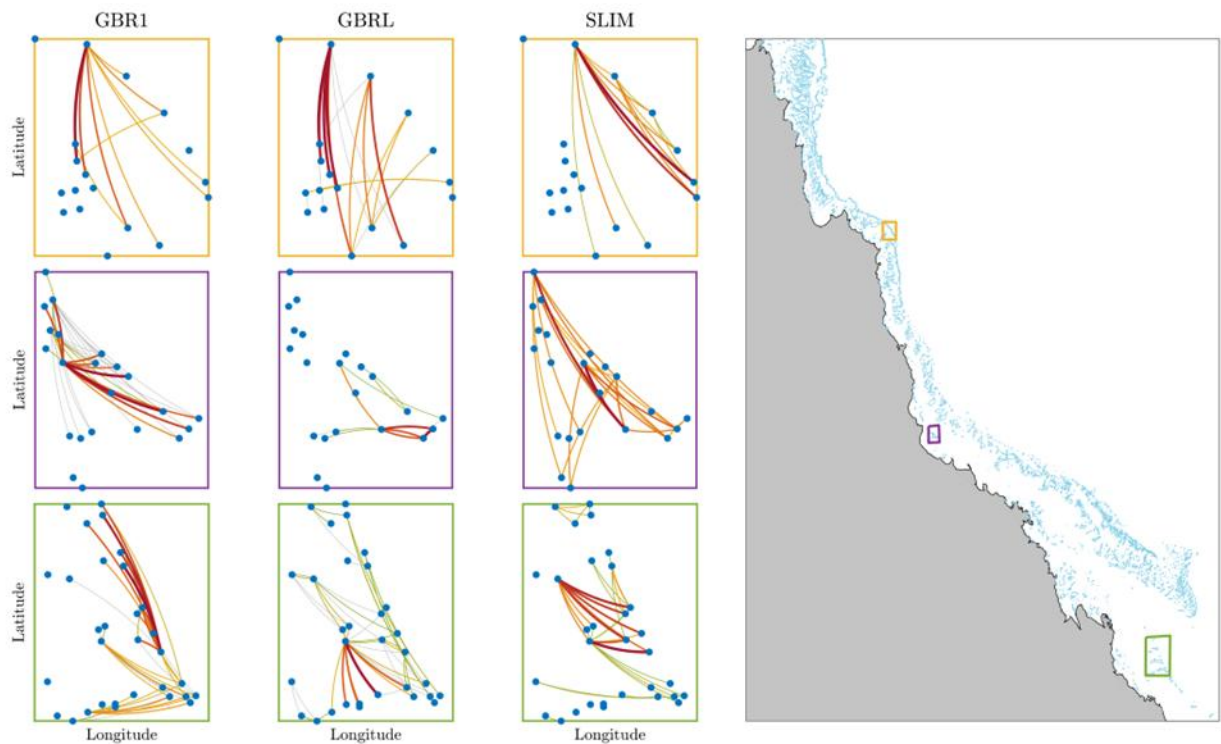


Figure 7. Local-scale connectivity patterns among three groups of reefs, for each of the three biophysical models. Top row shows connections among 18 reefs in the northern section; middle row shows connections among 22 reefs in the central section; bottom row shows connections among 31 reefs in the southern Capricorn Bunkers region. Lines show the strongest 10% of connections in each location, with colours showing the relative strength from red (strongest) to green (weakest).

Aggregating connectivity differences with increasing radii (**Comparison 4, Equation 9**) confirmed that model disagreement decreases as the spatial scale of aggregation increases (**Figure 8**), consistent with the coarser-scale agreement observed in **Figure 6** and the finer-scale divergence observed in **Figure 7**.

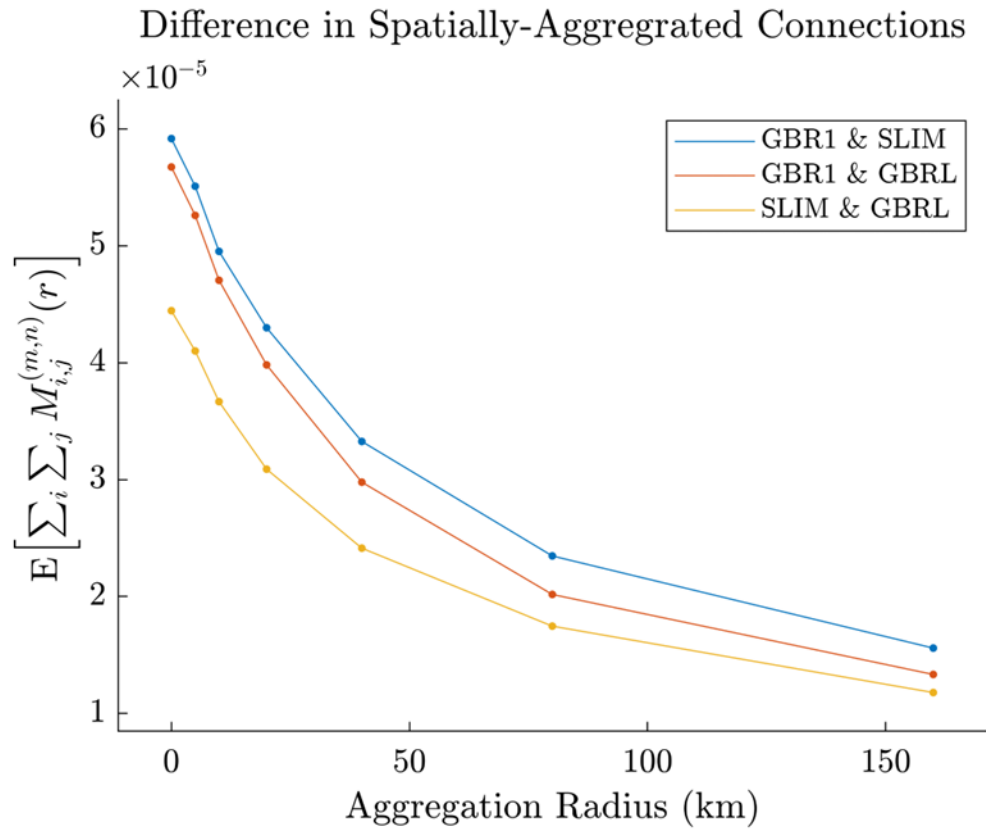


Figure 8. Evolution of difference metric $M_{i,j}^{(m,n)}(r)$ for varying radii of aggregation (see **Equation 9**). $M_{i,j}^{(m,n)}(r)$ is used to measure the difference in connectivity matrix values between models m and n , when values are aggregated within a radius of r km of reefs i and j . Values are averaged across all possible connections in the system.

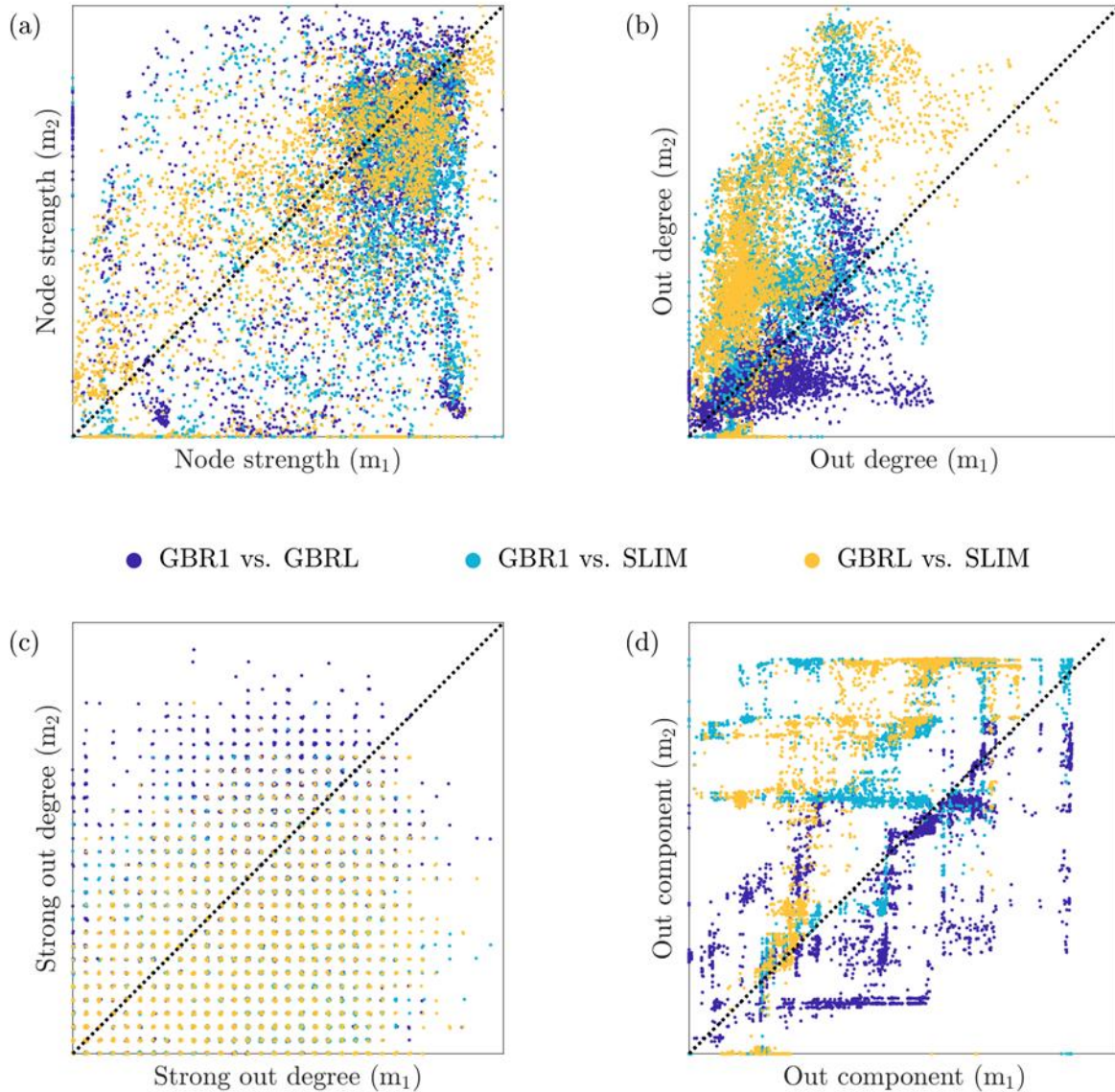


Figure 9. Each point in these panels shows a network metric calculated for an individual reef on the GBR, compared between two different hydrodynamic models. The three different colours show pairwise comparisons between the three hydrodynamic models. Panel (a) compares node strengths. Panel (b) compares node out degrees. Panel (c) compares node strong out degrees. Panel (d) compares the size of each node's out component.

When we calculated the network metrics for each reef on the GBR, we observed a similarly low amount of agreement between the predictions of the three models (**Table 5** and **Figure 9**). The rank correlation between the different network metrics is low to moderate; as with the reef-to-reef connections. However, in this case, the similarity is not always greatest between GBRL and SLIM. When we use these metrics to predict priority reefs, following the median

threshold of Hock et al. (2017), we observe only limited overlap between the priority sets – generally between 30% and 40% of the reefs are classified as priorities by both models. This value is larger than random expectation (25%, with 95% confidence bounds of 24–26%), but not considerably larger.

Table 5. Blue columns show the rank correlation between the network metrics calculated for each reef in the GBR, according to different hydrodynamic models. As a general guide, rank correlations below 0.3 are typically considered weak, 0.3–0.6 moderate, and above 0.6 strong. Green columns show the fractional overlap between priority sets calculated based on different hydrodynamic models. Both values are relatively low.

	Rank correlation		Overlap percentage	
	GBRL	SLIM	GBRL	SLIM
<i>Node Out Degree</i>				
GBR1	0.30	0.28	0.30	0.30
GBRL		0.52		0.35
<i>Node Out Strength</i>				
GBR1	0.63	0.59	0.36	0.33
GBRL		0.61		0.34
<i>Node Out Component</i>				
GBR1	0.70	0.62	0.40	0.37
GBRL		0.78		0.46

While the different hydrodynamic models predict diverse individual reef-to-reef connections at the whole GBR scale (Section 3.2), similarities between models begin to emerge when connectivity patterns are examined at a regional scale. We compared the model predictions at a regional scale by identifying strongly connected communities from among the GBR reefs. **Figure 10** shows the communities identified by an analysis of the connectivity matrices, for each of the three different biophysical dispersal models in 2019–2020. The regional connectivity clusters displayed similar characteristics of size and location across the three hydrodynamic models. This result highlights how coherent regional circulation patterns are across the hydrodynamic models.

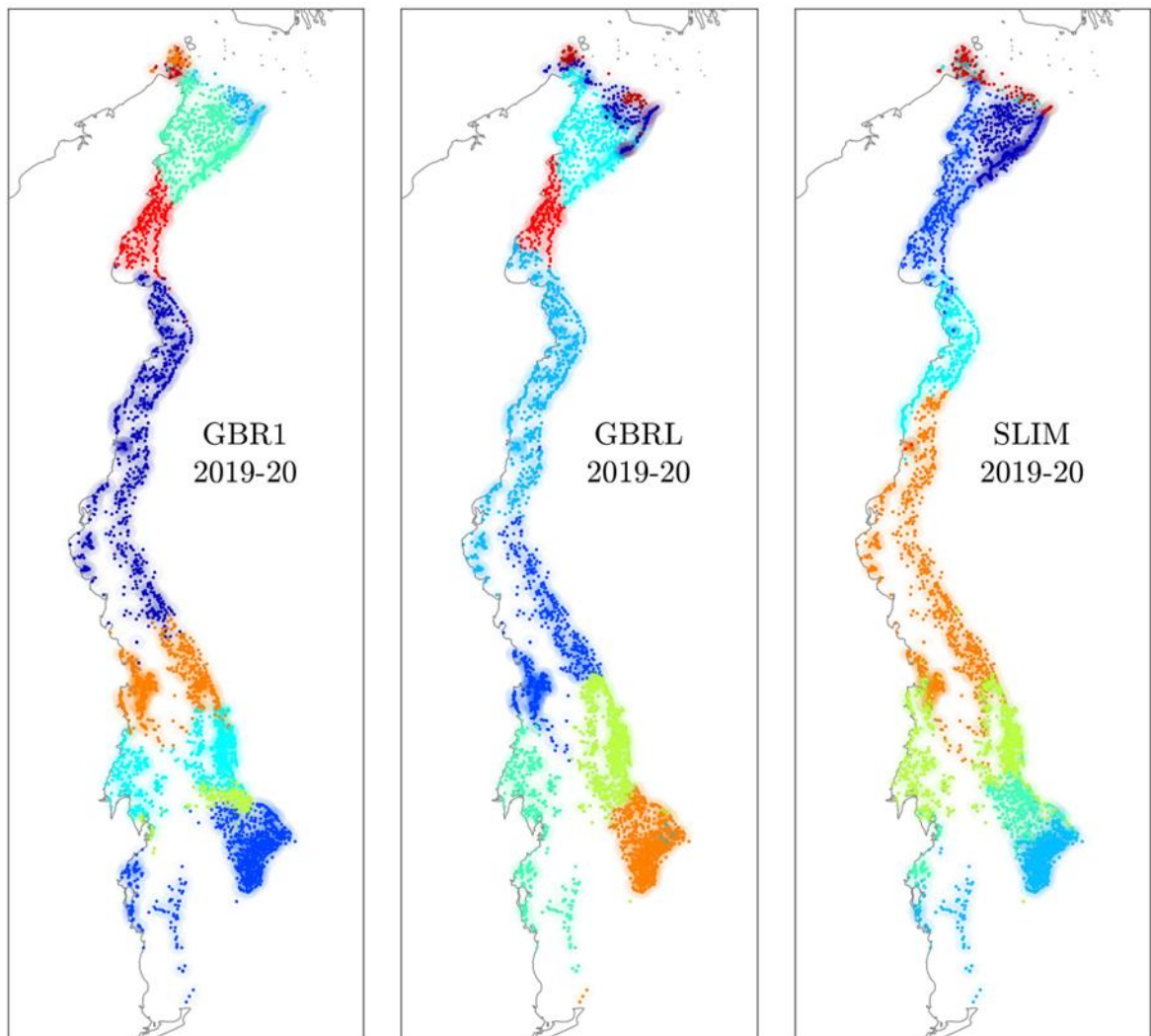


Figure 10. Dispersal communities in the GBR with high modularity. Reefs with the same colour belong to the same community within each hydrodynamic model's results (colours are not matched across models). Results are compared for GBR1, GBRL, and SLIM.

3.3 Sensitivity analysis

Having examined the sensitivity of dispersal predictions to the choice of hydrodynamic model (Section 3.2), the sensitivity of these predictions to key biological modelling assumptions is now explored: the depth at which larvae disperse (Section 3.3.1), the settlement radius applied around each reef (Section 3.3.2), and the survivorship and competency curves used to model larval mortality (Section 3.3.3). Unlike the three-model comparison in Section 3.2, this analysis includes all four hydrodynamic ensemble members, since comparing GBRL Up and GBRL Deep directly is central to testing dispersal depth sensitivity.

3.3.1 Depth of dispersal

The GBRL particle tracking model's capability to represent larvae at different depths in the water column as they develop (see Appendix B for full technical detail) was used to test dispersal sensitivity to more complex phases of larvae development. This allowed us to compare two depth scenarios (GBRL Deep and GBRL Up, Section 2.2) directly against each other, as well as against the two other models (GBR1 and SLIM), which do not represent this depth-dependent behaviour.

We also computed the distance of dispersal kernels for the two other models. A dispersal kernel describes the probability of a larva travelling a given distance from its source reef before settling. Depth of dispersal refers to a larva's vertical position in the water column, which is distinct from dispersal distance which is the horizontal distance a larva travels before settling. Across all models, irrespective of depth, most dispersal took place within 50 km of the source reef, with the potential for dispersal becoming low beyond 150 km (**Figure 11**). However, depth of dispersal did affect the distance to settlement. The GBRL Deep dispersal model had the shortest dispersal distance to settlement, followed by GBRL Up, SLIM and GBR1, in order of increasing distance.

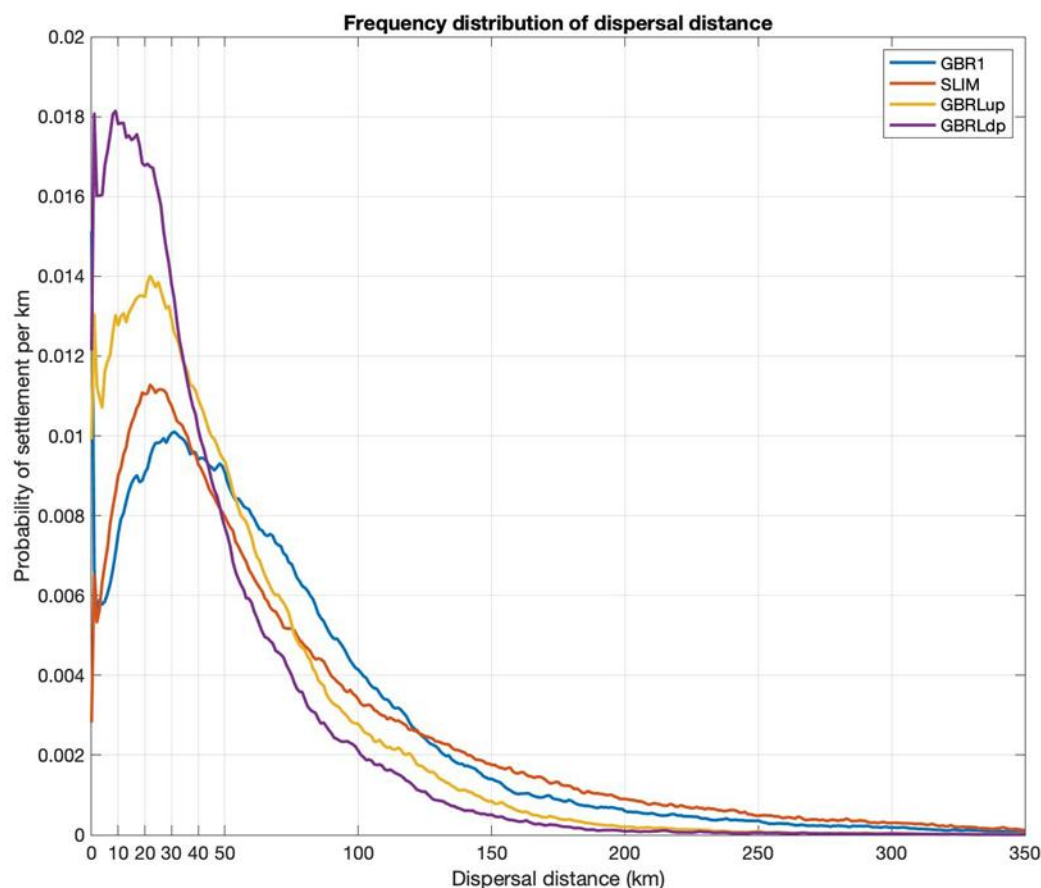


Figure 11. Comparison of dispersal distance kernels summarised over the five year spawning season.

The local retention, self-recruitment and settlement rates were computed from the annual connectivity matrices for each model and are summarised in **Figure 12**. The settlement rate was highest with GBR1 COTS dispersal with a median value of 16.29% and lowest with SLIM at 12.57%. However, GBR1 also had the lowest self-recruitment rate and local retention rate of the four models. Our results indicate that the deeper the dispersal the higher the rate of self-recruitment and local retention. Indeed, GBRL Deep had the highest rate for both self-recruitment and local retention with a median value of 0.6% and 1.1% respectively.

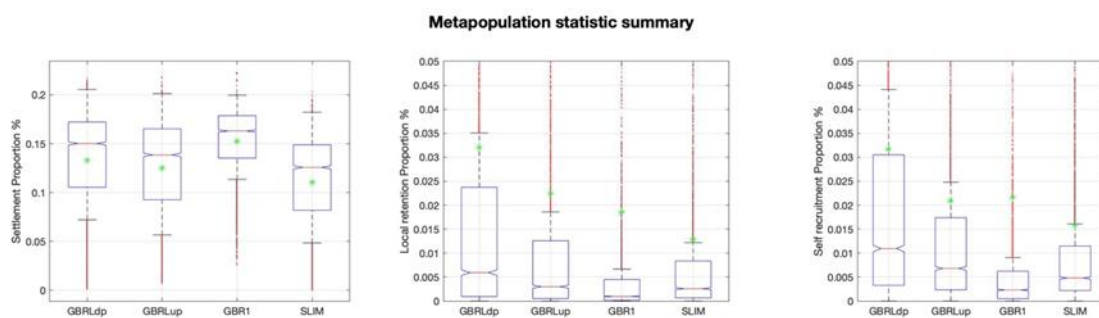


Figure 12. Comparison of the metapopulation statistic metrics using a boxplot representing the median (red line) and 25% and 75% quantiles (represented by the blue box) for settlement, local retention and self-recruitment rate for GBRL Deep, GBRL Up, GBR1 and SLIM.

3.3.2 Impact of Settlement Radius

As expected, increases in settlement radius resulted in higher settlement probabilities in the GBR1 and GBRL models examined (see **Figure 13** and **Appendix A**). Across all hydrodynamic models, as the settlement radius increases, the distribution of settlement probabilities shifts upward, evident in mean and median values. In terms of the impact of settlement radius on out degree, the same hierarchical relationship between models emerged, albeit less pronounced (see **Figure 14** and **Appendix A**). While it is visually difficult to discern changes in the distribution of out degrees across the varying settlement radii, both median and mean values exhibit slight upward shifts as the settlement radius increases.

Impact of Settlement Radius on Settlement Probability GBRLUp, averaged across survival and competency models

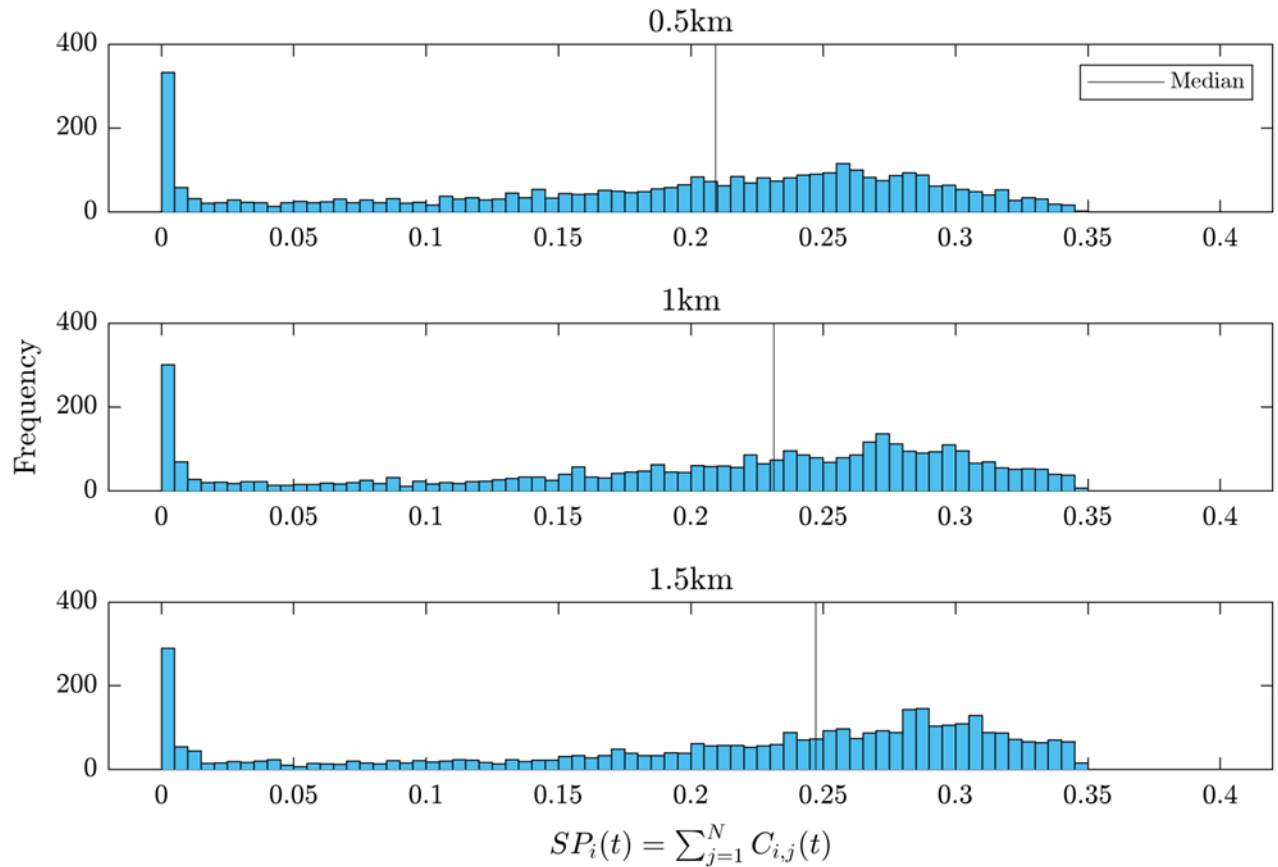


Figure 13. Impact of settlement radius on settlement probability for the GBRL Up hydrodynamic model (representing larvae distributed in the shallower portion of the water column). The settlement probabilities for each reef are averaged across the three component models that use the same settlement radius but varying survival and competency curves, with their distribution represented by a histogram.

Impact of Settlement Radius on Out Degree GBRLUp, averaged across survival and competency models

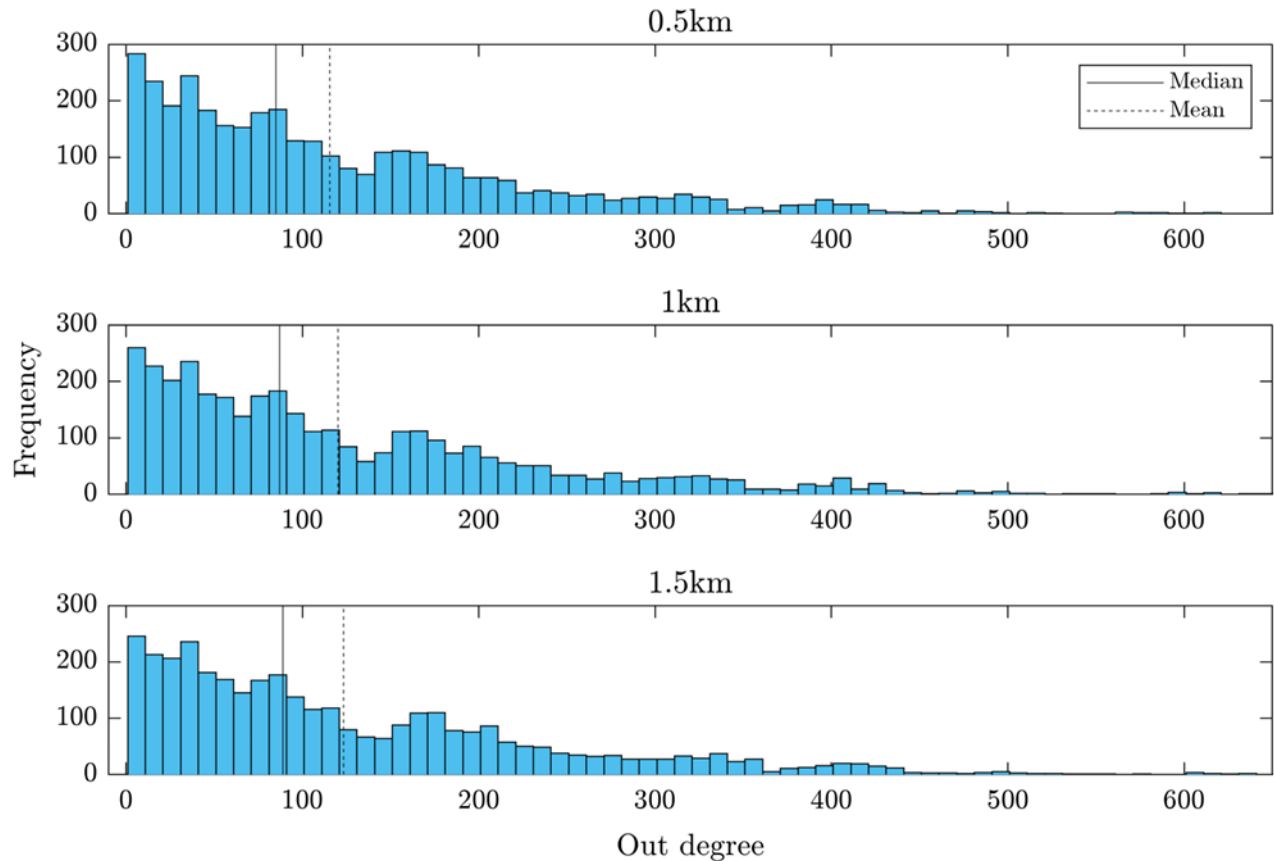


Figure 14. Impact of settlement radius on out degree for the GBRL Up hydrodynamic model (representing larvae distributed in the shallower portion of the water column). The out degrees for each reef are averaged across the three component models that use the same settlement radius but varying survival and competency curves, with their distribution represented by a histogram.

3.3.3 Impact of Survivorship and Competency Curves

Similar outcomes were evident when examining the impact of survivorship and competency models on both settlement probability and out degree. The distributions of settlement probabilities exhibited marked shifts upward as models moved from being fit to the bottom 50% of data, to all data, to only the top 50% of data (see **Figure 15**, and **Appendix A**). This hierarchical relationship was mirrored on inspection of the distribution of out degrees, with distributions shifting upwards in the same manner as settlement probabilities. While these shifts were less pronounced than those observed for settlement probabilities, they were nonetheless evidenced by increases to median and mean values.

Impact of Survival and Competency Model on Settlement Probability GBR1, averaged settlement radii

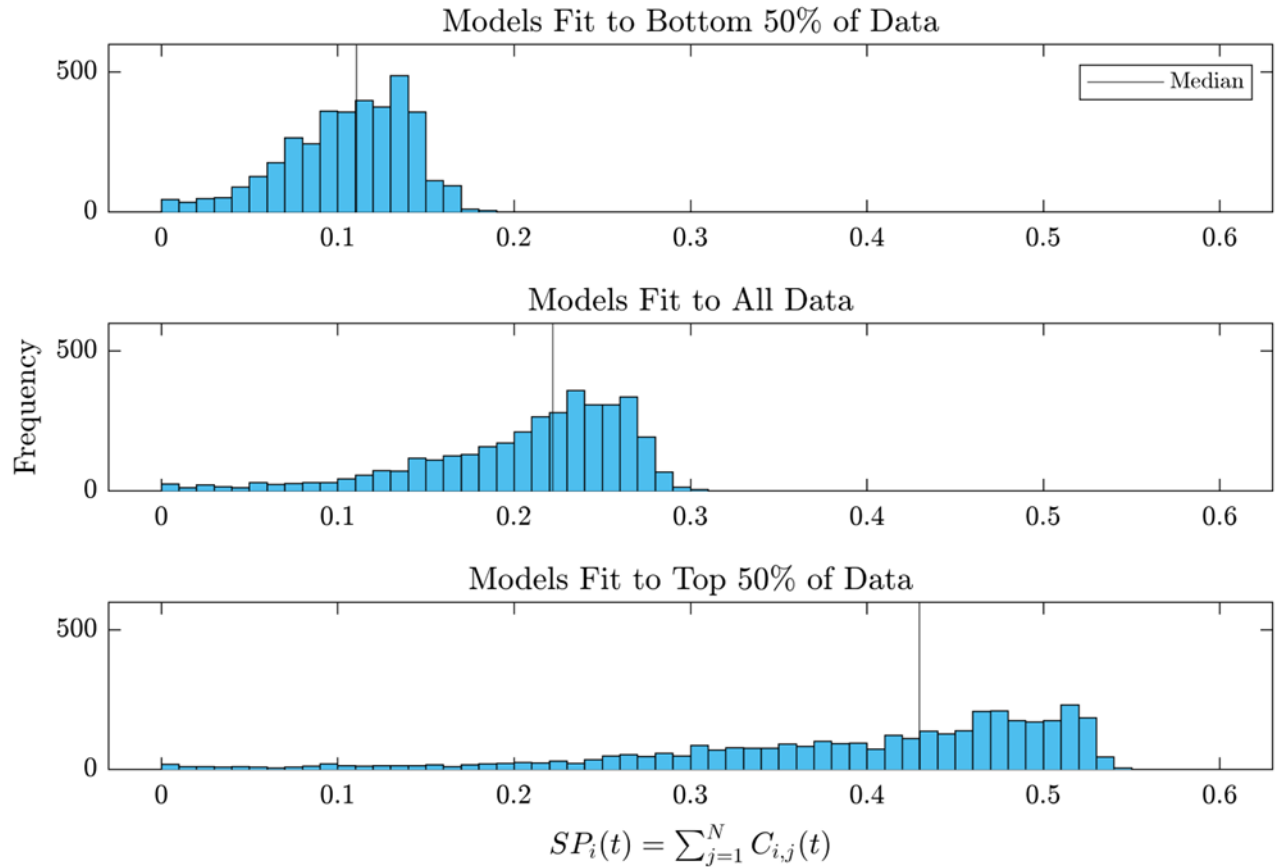


Figure 15. Impact of competency and survivorship models on settlement probability for the GBR1 hydrodynamic model. The settlement probabilities for each reef are averaged across the three component models that use the same competency and survivorship models but varying settlement radii, with their distribution represented by a histogram.

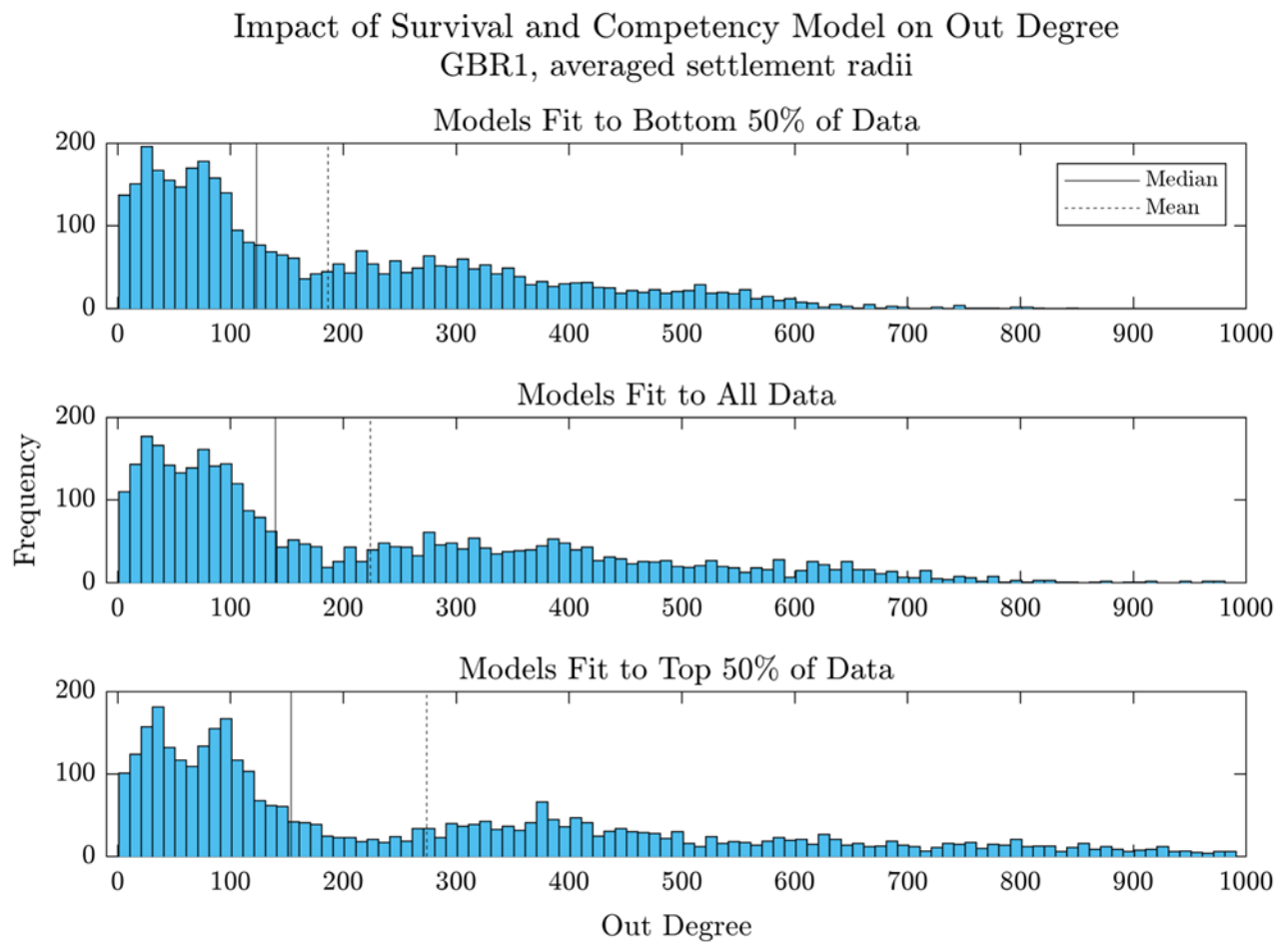


Figure 16. Impact of competency and survivorship models on out degree for the GBR1 hydrodynamic model. The out degrees for each reef are averaged across the three component models that use the same competency and survivorship models but varying settlement radii, with their distribution represented by a histogram.

3.4 Application to management

As summarised in **Figure 1**, our project has a direct input into the annual reef prioritisation process as one of five metrics used to calculate the ecological value of a reef. We have also provided our code to compute the competency and mortality curve that has been used to post-processed ‘coral connectivity’ now available on RRAP (<https://data.mds.gbrrestoration.org/datasets>) to the COTS Control Program. Our project has also provided an indirect input into resilience and recovery potential, through providing ecological models with improved estimates of COTS dispersal for the last five spawning seasons (CCIP-R-01 Information Infrastructure: Fletcher & Rezvani, 2026, CCIP-R-04 Regional Modelling: Skinner et al., 2025, CCIP-R-10 Fish predator conservation for biocontrol: Ceccarelli et al., 2025). Our collaboration with CCIP-P-04 (Pre-outbreak monitoring, Pratchett et al., 2025) is also another indirect input to a third metric ‘COTS outbreak history’ by helping interpret the oceanographic conditions associated with detected outbreak locations.

4. DISCUSSION AND OUTPUTS

Our project has developed a novel approach to accounting for uncertainties at both the physical and biological level when estimating larval dispersal. By developing an ensemble of biophysical models, the project has focused on identifying and incorporating the uncertainties in each of the steps involved in estimating COTS dispersal in the GBR. This approach has focused on enhancing the accuracy, robustness, and applicability of dispersal predictions to support effective reef management and conservation efforts. The improved dispersal predictions generated by the hydrodynamic ensemble will be key to understanding reef organism dynamics and underpinning effective management strategies to preserve and restore this vital ecosystem. A further 33-model biophysical ensemble, quantifying uncertainty across a wider range of biological assumptions, is still being processed and will be reported separately once complete.

In collaboration with key experts in COTS larval biology, hydrodynamic and biophysical modellers, and COTS Control Program managers, we have updated the COTS modelling framework described in Hock et al. (2017). We have done so by integrating higher resolution flow fields, updated and broadened biological parameterisations, and developed sensitivity analyses to address remaining gaps. The project successfully generated advanced larval connectivity matrices for COTS across the GBR from 2018 to 2023 using three distinct hydrodynamic models: SLIM COTS, CSIRO eReefs GBR1, and GBRL.

4.1 Hydrodynamic Models

Our project explored the impact of the hydrodynamic models' resolution on predicting COTS larval dispersal among the GBR reefs. Estimating the circulation in the GBR remains a trade-off between higher horizontal resolution, 2D vs 3D and baroclinic vs barotropic.

This study has significantly enhanced the predictive accuracy of COTS dispersal within the GBR by employing hydrodynamic models with substantially higher horizontal grid resolution (4 to 20 times greater) than the previous 4 km models. While a 4 km resolution is sufficient to resolve the circulation in most shelf environments, it is inadequate in the GBR and directly impacts the circulation in dense reef areas (St Amand et al., 2023). This improvement has enabled the resolution of more intricate processes and better captures the complex circulation patterns within the GBR.

The initial step in generating the ensemble involved evaluating the hydrodynamic models against *in situ* observations of currents within the GBR and comparing the models with each other. It was observed that, at the IMOS mooring sites, located away from the reef matrix, the models exhibited equivalent skill in resolving circulation. Although all three hydrodynamic models were specifically developed and calibrated to resolve circulation within the GBR, they also demonstrated distinct characteristics in dispersal pathways. This study has clearly demonstrated that the choice of hydrodynamic model impacts the reef-to-reef connectivity outcomes. As discussed in St Amand et al (2023), open ocean validation can be misleading, and not an accurate way to estimate how well a model will perform in a dense reef matrix. When the bathymetry dataset is integrated in the hydrodynamic model, it is re-interpolated, or smoothed to match the grid resolution. If the model resolution is coarser than a channel

between reefs, this discrepancy would directly affect transport through the channel and subsequently impact dispersal pathways (Marmorino, 2022). The higher resolutions employed across all three models in this project (**Table 1**) go some way to mitigating this issue relative to the 4 km models used previously, however even SLIM's finest resolution (250 m) and GBRL's (1 nautical mile) remain coarser than many reef channels, meaning this source of uncertainty is reduced, but not eliminated, by this project's modelling improvements.

While the importance of spatial resolution is obvious when modelling complex reef structures, the influence of 3D circulation and baroclinic physics cannot be overlooked. Incorporating 3D flow fields was essential for testing specific biological traits of COTS and their influence on dispersal.

To mitigate the uncertainties in circulation patterns, using an ensemble of hydrodynamic models is justified. The comparison presented in Sections 3.1 and 3.2 represent this ensemble approach in its current, comparison-based form. By characterising where and how much the three models disagree, this work identifies the reef-to-reef scale at which single-model predictions cannot be relied upon in isolation, and establishes the groundwork for the combined ensemble product to further improve predictive accuracy in the future.

4.2 Particle tracking models

Our project also increased the complexity and improved the accuracy of the COTS larval biology used in the biophysical models. Faced with a high degree of uncertainty in the timing of COTS spawning, previous work made simplified choices or chose parameterisations that were known to be incorrect for the species (e.g., allowing larval settlement within 12 hours of egg release, rather than the 11+ days observed). Here, we tested the impact of these choices.

In the particle tracking component of dispersal modelling, the spawning window of adult COTS and the developmental phases of their larvae constitute significant data gaps resulting in uncertainties. Enhancements were made to the particle tracking methodology of Hock et al. (2017) by increasing the frequency of release dates throughout the spawning season. This adjustment was designed to better capture the dispersal pathways, during the monsoon season when the GBR lagoon circulation can be highly variable. Additionally, the release times were extended to include both nocturnal and diurnal periods, based on recommendations from COTS larval biologists. Sensitivity analyses were conducted to examine the effects of vertical dispersal within the water column during specific ontogenetic phases, as suggested by experts in COTS larvae. These methodological changes represent a substantive departure from previous practice which assumed near-instantaneous larval settlement and a narrow, fixed release window. By contrast, our results show that dispersal distance is sensitive to depth-related behaviour, and our broader hydrodynamic comparisons show that release timing materially affects predicted connectivity. Together, these findings indicate that earlier COT dispersal estimates, which did not account for this variability, likely understated the true range of plausible dispersal outcomes, highlighting the value of employing an ensemble approach.

This project has tested and generated a total of 286 trajectory datasets, each representing the simulated release and tracking of thousands of individual larvae from a single reef on a single date, across three models over five spawning seasons, a substantial increase from the previous 10 datasets generated in previous work (Hock et al., 2017). This order of magnitude increase in the volume and temporal resolution of simulated release events enabled the sensitivity analysis in Section 3.3.

Since many COTS larval behavioural dynamics remain unclear, the project has approached this uncertainty using the same ensemble approach as with the hydrodynamics.

The 286 trajectory datasets encompass a broad range of potential dispersal scenarios, thus providing a more comprehensive ensemble description of possible COTS larval dispersal patterns.

4.3 Post processing

The post-processing component of the project applied a suite of decisions and probabilities to generate the connectivity matrices from the 286 trajectory datasets. To begin with, we investigated habitat suitability for settlement, by testing three settlement radii ranging from 500 m to 1.5 km around the reef outline. The radius is usually set to the horizontal grid cell resolution of the hydrodynamic model (GBR1=1 km radius, Ceccarelli et al., 2025), and accounts for reef scale processes that may facilitate settlement but are not resolved. Secondly, using observations of COTS larval mortality and settlement rates during the pelagic phase, we have developed competency and mortality functions based on Wilmes et al. (2018) and Pratchett et al. (2017). These mortality and settlement probabilities for COTS larvae during the pelagic phase are greatly influenced by ecosystem drivers, such as temperature, salinity and food availability (Caballes et al., 2017; Pratchett et al., 2017). To capture this variability, we tested three pairs of functions for the mortality and competency of larvae respectively, fit to the upper and lower portions of the datasets, alongside the entire dataset.

4.4 Ensemble comparisons

4.4.1 Subsurface dispersal models comparison

At the scale of the entire GBR, different biophysical models show broad agreement, and predict similar overall dispersal patterns. Connections are strongest between reefs in the same region (i.e., within a few hundred kilometres of each other), and the reefs in the northern GBR are connected at greater distances than those in the southern GBR (**Figure 6**). However, at smaller scales, the strength of different dispersal pathways, and the extent to which the relative dispersal strength of individual reefs varies between models (**Figure 7**), are substantially different.

Model agreement is not uniform across metrics or comparisons. For instance, GBR1 shows a higher rank correlation with GBRL than with SLIM according to some network metrics (**Table 5**), despite GBRL and SLIM sharing the same 24 h release window. Moreover, our comparisons show that agreement is higher when comparing models across different years,

than when comparing different models in the same year. These results suggest that model parameterisation and structure, not just release timing, are also contributing to variability in these predictions.

While dispersal patterns appear similar between models when viewed at the scale of the GBR, their strength differs substantially, which is to be expected where flow in the complex matrix may vary greatly among hydrodynamic models. At the smaller scale that is most relevant to managers, the models predicted very different dispersal patterns (**Figure 8**). Reef managers decisions are more likely to be affected by differences at this scale, in the immediate vicinity of their actions. Our three models also disagree on which reefs should be prioritised for COTS control actions according to network metrics (**Figure 9; Table 5**). For any single metric, rank correlations were between 0.3 and 0.4, which is better than random chance, but insufficient on their own to give COTS decision-makers confidence in prioritising individual reefs based on a single model's predictions. This underscores the value of the ensemble approach, rather than relying on any one hydrodynamic model's priority reef predictions. Once completed, the biophysical ensemble will allow managers to identify reefs that are consistently prioritised across models, and treat as higher uncertainty any reef whose priority status depends heavily on which model is used.

These results represent the first in-depth comparison between biophysical models that are based on different hydrodynamic models of the same coastal marine ecosystem. It is not impossible that more agreement would be observed between models of other marine ecosystems, even in other coral reef systems. The GBR is characterised by high-volume tidal flows across a wide continental shelf, whose drainage is complicated by shallow-water reefs separated by high-velocity channels. These unique dynamics may amplify the differences between the model predictions. Moreover, the differences we observed are primarily at the reef-to-reef scale; from a sufficient distance, the models produce quite similar dispersal patterns (**Figure 6**). Our findings therefore specifically caution against using single models to make decisions about individual reefs. The completed biophysical ensemble will help address this limitation directly, by providing a combined estimate alongside a quantified measure of confidence. Until that ensemble is available, decision-makers should treat single model, reef-scale connectivity predictions with appropriate caution, while whole-GBR-scale patterns can be relied upon with greater confidence.

The final outputs of this project include:

- Developed a mortality and competency model of COTS larvae based on observations and integrated in the post-processing analysis to derive connectivity matrices.
- Developed new parameters and metrics for connectivity including reef-level network metrics (node out-degree, node strength, and out component (Section 2.4) and regional dispersal communities through modularity-based clustering, providing new tools for identifying influential reefs and coherent regional grouping for management purposes.
- Dataset of connectivity matrices from the three-model hydrodynamic ensemble (2018–2023), quantifying the degree of agreement and disagreement in predicted dispersal pathways. A more complete accounting of uncertainty, incorporating

variation in biological assumptions, will be available once the 33-model biophysical ensemble is processed.

- Current meter dataset deployed over two summers in the Far Northern GBR, supporting hydrodynamic model validation in this data sparse region.
- Identification of knowledge gaps in larval biology and sensitivity analysis to inform future research directions.
- **Journal article:** Choukroun S, Stewart OB, Mason LB, Bode M (2024) Larval dispersal predictions are highly sensitive to hydrodynamic modelling choices. *Coral Reefs* 44: 1–13.

5. RESEARCH SYNERGIES AND NEXT STEPS

The research conducted in our project complemented other CCIP projects within the Response and Prediction subprograms.

1. **CCIP-R-02 Empirical decision support (Fletcher et al., 2026a):** Data sharing and novel strategies based on COTS dispersal data to inform on-water operation and development.
2. **CCIP-R-07 Multi Criteria Decision Analysis (MCDA) for reef prioritisation (Fletcher et al., 2026b):** Results from our project feed directly into the MCDA. The two projects have presented their results jointly at the COTS Program Planning Workshop (Reef Authority) and the Connectivity Community of Practice (RRAP).
3. **CCIP-P-04 Pre-outbreak monitoring (Pratchett et al., 2025):** Our project has worked closely in evaluating the potential for the Far Northern GBR outbreak to initiate further to the south. This project has supported our project by deploying current meters over two spawning seasons in the vicinity of their monitored sites.
4. **CCIP-R-04 Regional modelling (Skinner et al., 2025):** Our project has delivered improved connectivity matrices to be implemented in ReefMod.
5. **CCIP-R-10 Fish predator conservation for biocontrol (Ceccarelli et al., 2025):** Connectivity predictions used in CoCoNet were updated based on the results from our program, specifically around dispersal trajectories and connectivity matrices.
6. **The Reef Restoration and Adaptation Program (RRAP):** Our project has contributed to RRAP and Reef Integrated Monitoring and Reporting Program (RIMReP) by providing mortality and competency models to represent coral and COTS larvae. These models have been implemented by the CSIRO eReefs researchers and resulting connectivity matrices have been made available on the RRAP Modelling & Decision Support data portal.
7. **AIMS Long-Term Monitoring Program (LTMP):** Data on COTS density was provided by the LTMP.

8. **RIMReP:** Mortality and competency models have been implemented in Reef scale modelling. RIMReP is interested in data collected in Far North GBR especially current meter dataset.

The following future research priorities have been identified by our project:

- **Research priority 1:** Hydrodynamic modelling investment is required to answer management at reef scale. Some effort in downscaling to inform reef scale intervention has been made by downscaling regional models using eReefs RECOM and COMPASS down to ~200 m, however these models require calibration and do not represent wave transport.
- **Research priority 2:** COTS larval biology knowledge is very limited. Our competency and mortality modelling for COTS larvae, while an improvement on past effort, was limited to one dataset, focusing on food availability. The sensitivity analysis on depth of dispersal was based on personal communication with experts. There is no dataset that can be used to validate our prediction beside from monitoring of presence/absence and density of COTS population.
- **Research priority 3:** Further work with a multi-disciplinary approach is required to resolve spatio-temporal variability in COTS populations and identification of primary outbreak (see also Pratchett et al., 2024).
- **Research priority 4:** The implementation of a successful restoration program in the GBR requires an intricate understanding of connectivity, particularly concerning corals and COTS. These ecosystems are interconnected through ecological processes like larval dispersal, essential for coral population maintenance and recovery. Knowledge of coral and COTS dispersal can support reef prioritisation, helping identify critical areas for conservation and intervention. Our framework can be easily applicable to identify key reef clusters in the GBR for restoration.

6. MANAGEMENT IMPLICATIONS AND IMPACT

Understanding and predicting COTS larval dispersal is crucial for developing effective reef management strategies. In a complex environment such as the GBR, where physical and biological data sources and models have limitations, addressing the gaps and uncertainties are paramount. Comparing model predictions has provided deeper insight into the ecology and oceanographic processes that drives COTS dispersal. Our project has created datasets, tools and knowledge that have been shared within CCIP, RRAP and RIMReP. The framework can be refined as new data becomes available and adapted to other species with a pelagic larval phase. By applying an ensemble approach, the project has captured a wider range of potential dispersal, thus reducing the uncertainties in the prediction. These more precise and reliable predictions have assisted reef managers in identifying critical areas for COTS control measures, through the annual reef prioritisation process.

Governance, Engagement and Communications

Engagement with stakeholders was undertaken from the inception of the project and throughout the project duration. Datasets were shared with the COTS Control Program within the first year of the project.

COTS Strategic Management Framework

Results from this project have significantly enhanced the understanding of COTS dispersal patterns. The integration of the connectivity matrices into the reef prioritisation process has been a key outcome. A consequent benefit of our project is the preservation of coral reef health and the reduction of COTS populations.

Annual Reef Prioritisation Process

As presented in **Figure 1**, the project has contributed directly and indirectly to four out of the five parameters utilised in the annual reef prioritisation process.

Integrated Pest Management (IPM) Framework

Our project contributes directly to the IPM framework as part of the prevention and control and the advanced modelling to estimate dispersal.

7. ACKNOWLEDGEMENTS

We acknowledge the Traditional Owners as the first scientists of the Land and Sea Country on which we work, and pay our respects to their leaders, past present and emerging. We thank Sven Uthicke, Morgan Pratchett, Peter Doll, Bethany Lang, Ciemon Caballes, Josie Chandler and Maria Byrne for their input into the biological parametrisation and their help in designing the depth experiment. We thank the JCU High Performance Computer personnel, Whitney Mallet, for their support and help during the project.

8. DATA ACCESSIBILITY

The CCIP-R-05 model and outputs have been uploaded into the COTS Information Catalogue. The current meter data are available from the Research Data JCU (<https://researchdata.jcu.edu.au/published/45ba3e009b9211f1a4c2235f17345359/>).

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APPENDIX A: ADDITIONAL FIGURES

Biophysical Ensemble Validation

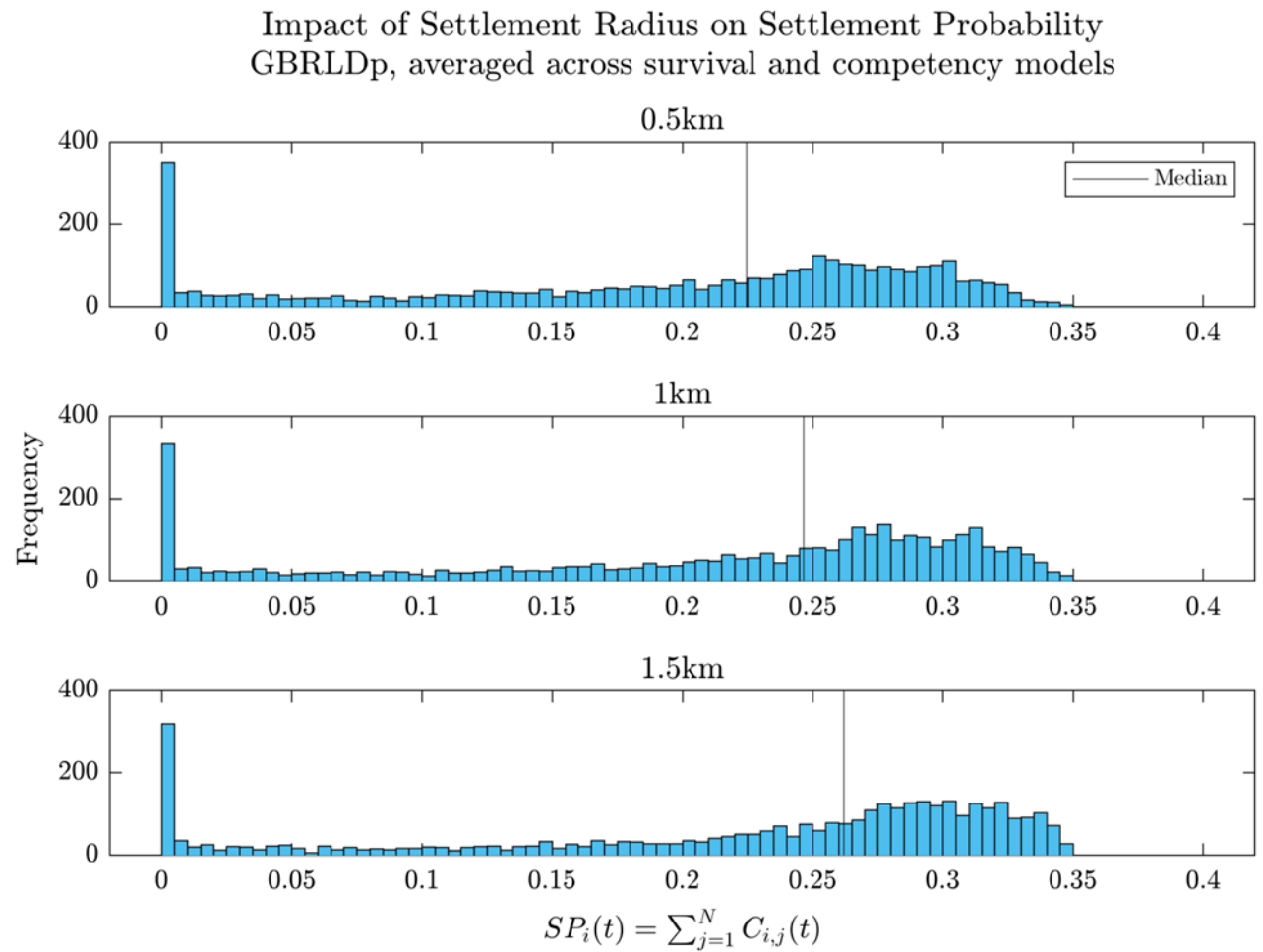


Figure S1. Impact of settlement radius on settlement probability for the GBRL hydrodynamic model with the lowest depth distribution for larvae. The settlement probabilities for each reef are averaged across the three component models that use the same settlement radius but varying survival and competency curves, with their distribution represented by a histogram.

Impact of Settlement Radius on Settlement Probability GBR1, averaged across survival and competency models

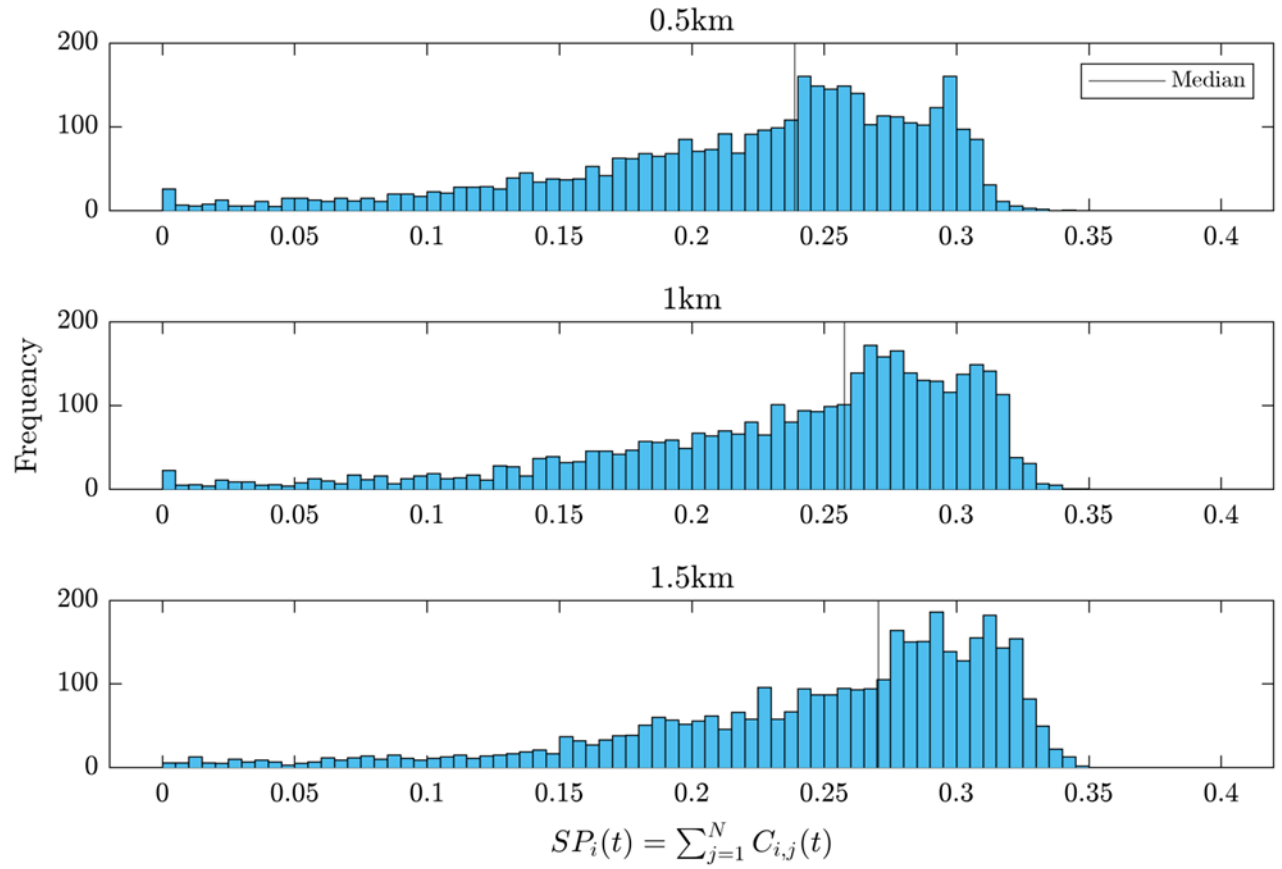


Figure S2. Impact of settlement radius on settlement probability for the GBR1 hydrodynamic model. The settlement probabilities for each reef are averaged across the three component models that use the same settlement radius but varying survival and competency curves, with their distribution represented by a histogram.

Impact of Settlement Radius on Out Degree GBRLDp, averaged across survival and competency models

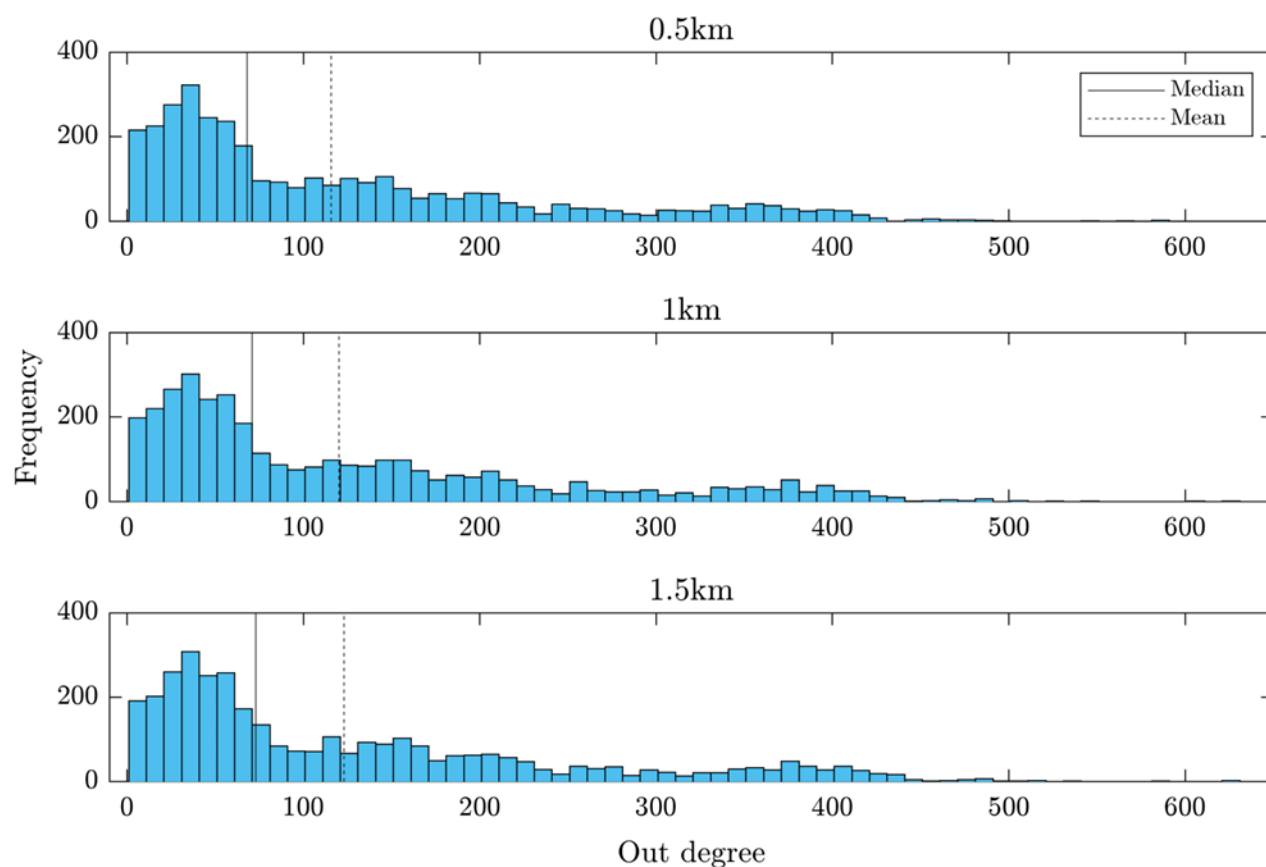


Figure S3. Impact of settlement radius on out degree for the GBRL hydrodynamic model with the lowest depth distribution for larvae. The out degrees for each reef are averaged across the three component models that use the same settlement radius but varying survival and competency curves, with their distribution represented by a histogram.

Impact of Settlement Radius on Out Degree GBR1, averaged across survival and competency models

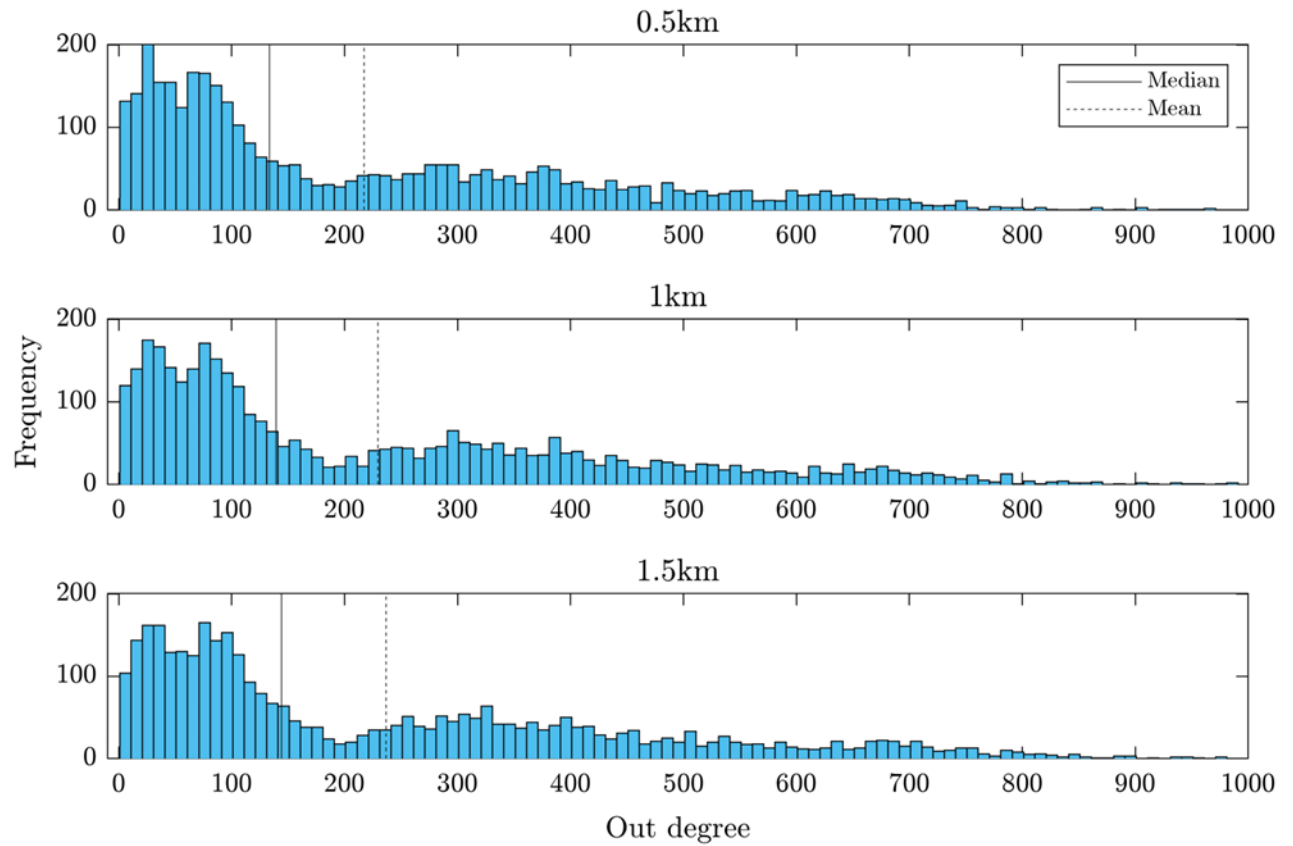


Figure S4. Impact of settlement radius on out degree for the GBR1 hydrodynamic model. The out degrees for each reef are averaged across the three component models that use the same settlement radius but varying survival and competency curves, with their distribution represented by a histogram.

Impact of Survival and Competency Model on Settlement Probability GBRLUp, averaged settlement radii

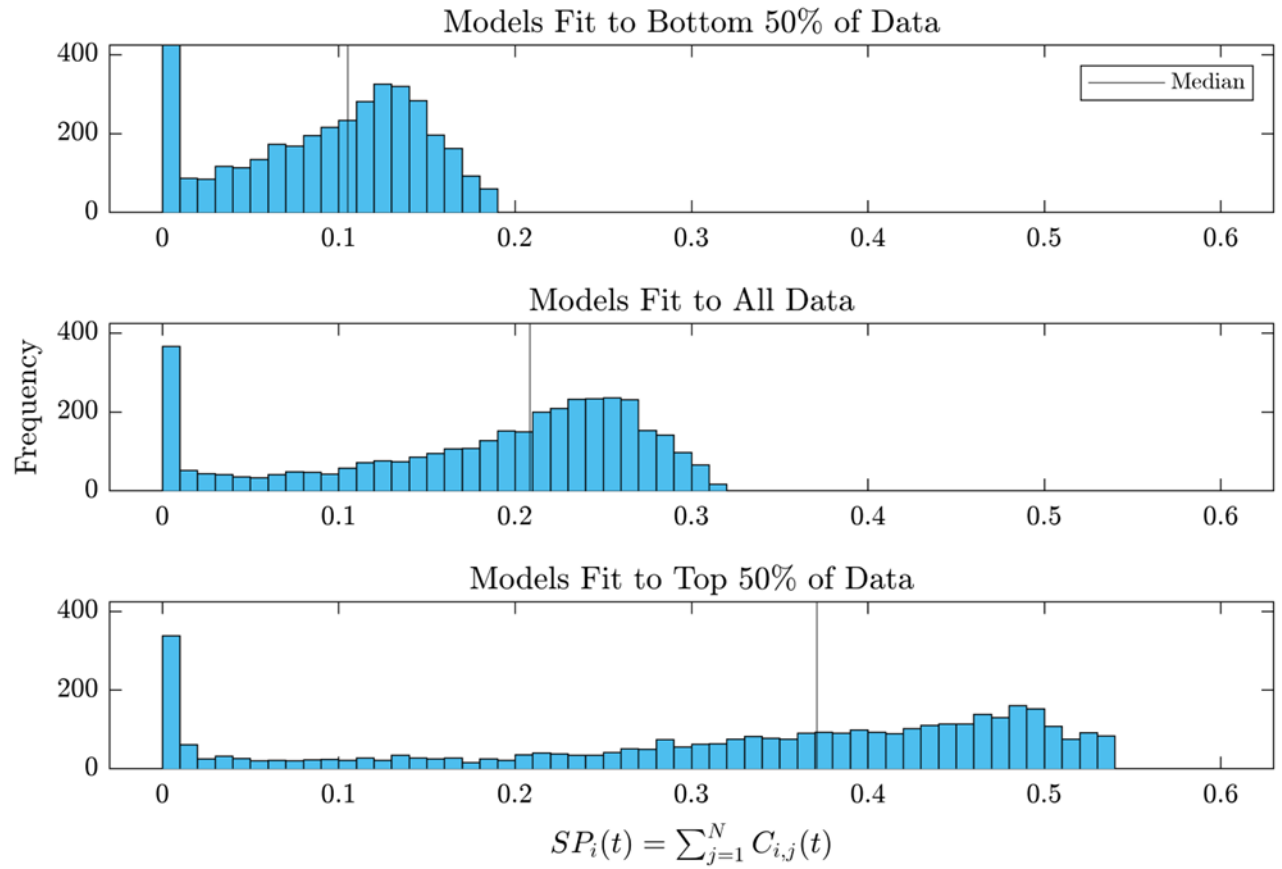


Figure S5. Impact of competency and survivorship models on settlement probability for the GBRL hydrodynamic model with the highest depth distribution for larvae. The settlement probabilities for each reef are averaged across the three component models that use the same competency and survivorship models but varying settlement radii, with their distribution represented by a histogram.

Impact of Survival and Competency Model on Settlement Probability GBRLDp, averaged settlement radii

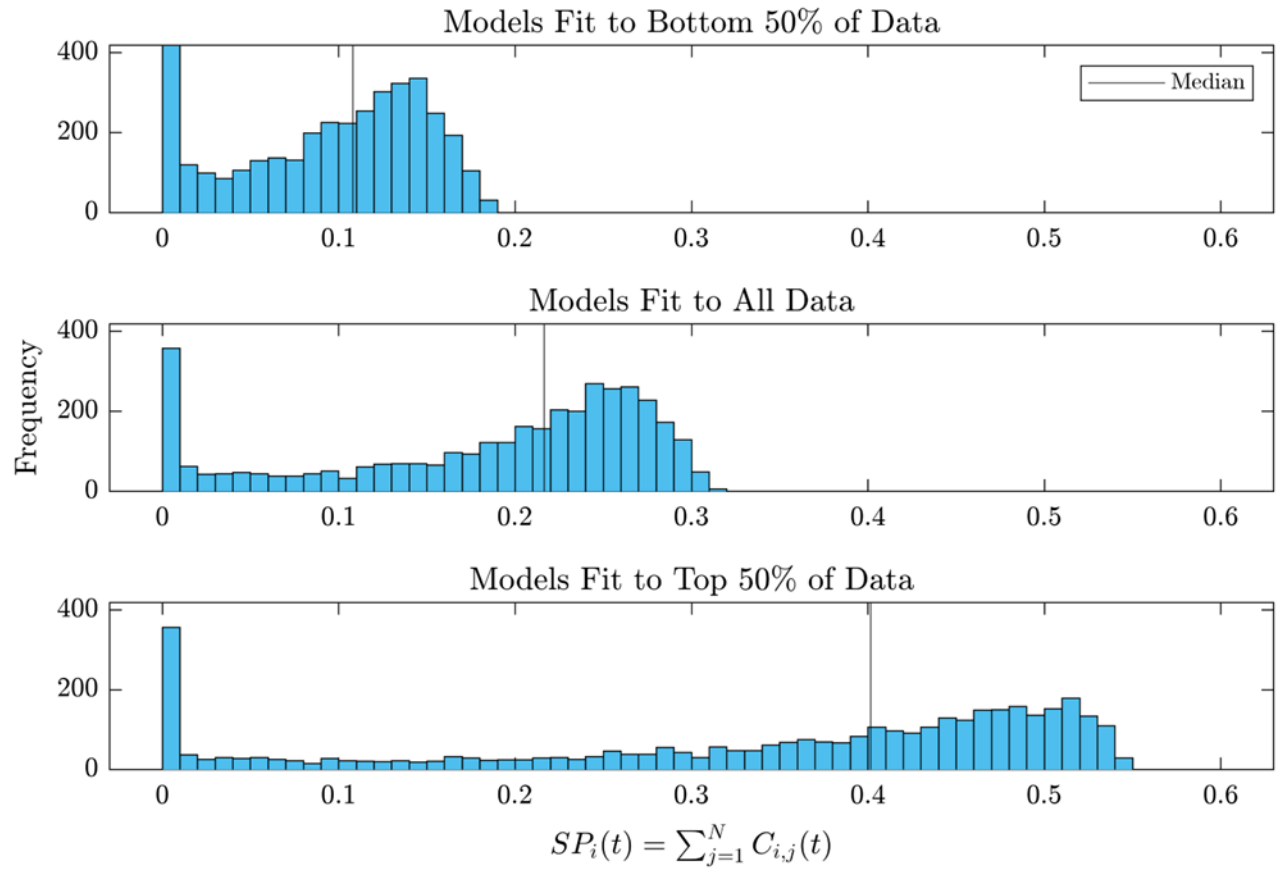


Figure S6. Impact of competency and survivorship models on settlement probability for the GBRL hydrodynamic model with the lowest depth distribution for larvae. The settlement probabilities for each reef are averaged across the three component models that use the same competency and survivorship models but varying settlement radii, with their distribution represented by a histogram.

Impact of Survival and Competency Model on Out Degree GBRLUp, averaged settlement radii

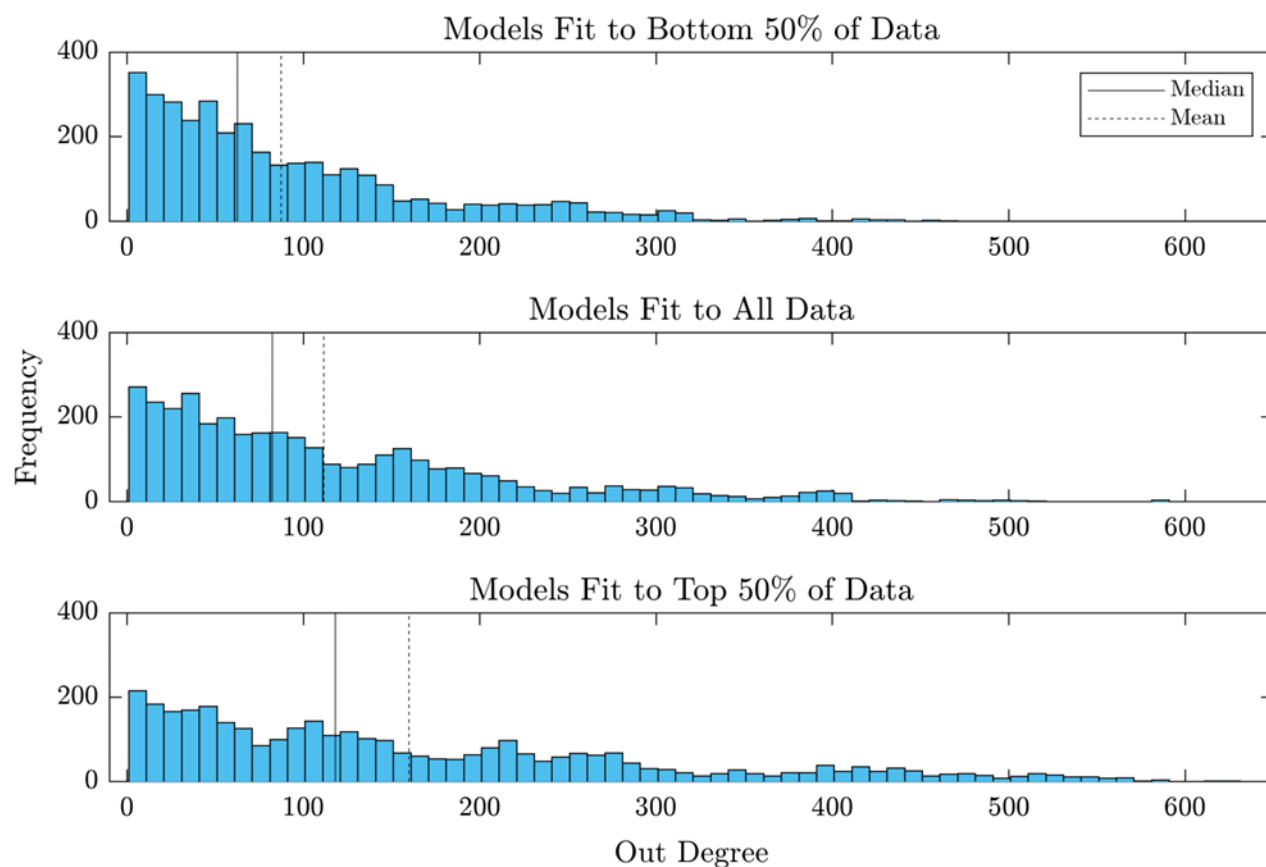


Figure S7. Impact of competency and survivorship models on out degree for the GBRL hydrodynamic model with the highest depth distribution for larvae. The out degrees for each reef are averaged across the three component models that use the same competency and survivorship models but varying settlement radii, with their distribution represented by a histogram.

Impact of Survival and Competency Model on Out Degree GBRLDp, averaged settlement radii

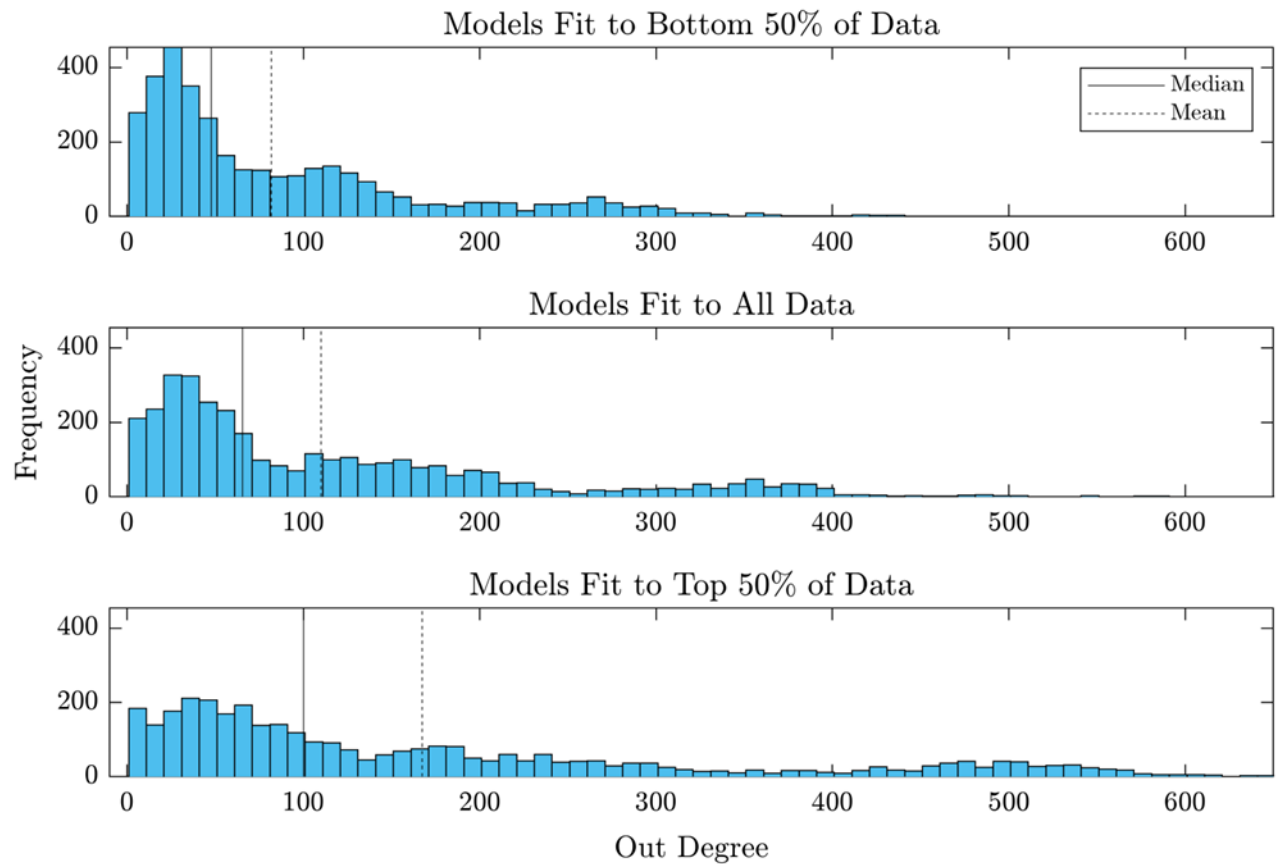


Figure S8. Impact of competency and survivorship models on out degree for the GBRL hydrodynamic model with the lowest depth distribution for larvae. The out degrees for each reef are averaged across the three component models that use the same competency and survivorship models but varying settlement radii, with their distribution represented by a histogram.

APPENDIX B: ONTOGENY PHASE IMPLEMENTATION IN GBRL

The GBRL particle transport model was developed to allow the representation of complex behaviour during the pelagic larval duration. As discussed during the Australian Research Council Centre of Excellence for Coral Reef Studies workshop, COTS spawning can be divided in three stages:

1. Fertilisation: egg and sperm released in the water column. Egg sinks to the bottom then gets fertilised and becomes more buoyant again 0–24h “buoyagespd”
2. Pelagic larvae duration 1: “preferred sigma layer”.
3. Pelagic larvae duration 2: larvae moving to the bottom

Table S1. Summary table of GBRL particle transport model parametrisation for COTS larvae ontogenetic phases utilised to run sensitivity tests.

Ontogeny phase window		
0–24h	Egg and sperm release + fertilisation	“buoyagespd” = 0.00149. slightly positive between 0 to 24h
1.1 day to 15 days		“buoyagespd”=0 neutral between 1 to 45 “Agesigmadepthlimits”= 3 scenarios: 0<depth<-0.5 -0.25<depth<-0.75 -0.5<depth<-1
15-21 days		All deeper mu=.75, sigma=0.1

In this instance, we are using two of the modules, the “Buoyancy speed” and the “preferred edges sigma”. During the first 24h, the egg and sperm are positively buoyant and the fertilisation takes place at the surface. Between 1.1 and 15 days, we use the “preferred sigma module” and run three experiments. This module allows the user to represent the preferred location of larvae in the water column, as a function of age (ontogeny phase). The module uses a cumulative distribution function (CDF) to represent the probability of finding a larvae in a specific location at a specific time of the day and during a specific period of their development.

The CDF is based on a normal distribution, with mean values of $-0.25 \times \text{depth}$, $-0.5 \times \text{depth}$ and $-0.75 \times \text{depth}$ and a sigma value of 0.1, for scenario upper water column distribution, mid column distribution and deep water column distribution, with the depth being the bathymetry depth at the position of the particle at time t. Only upper and deep water column were presented in the report.

Between 1.1 day to 15 days, the larvae are represented as passive, neutrally buoyant and located in a specific portion of the water column.

From day 15 to 21, particles position in the water column are slowly migrated deeper, following a linear interpolation between scenario upper, middle, deep to deep. At 21 days, the particles remain at the bottom of the water column until 45 days.

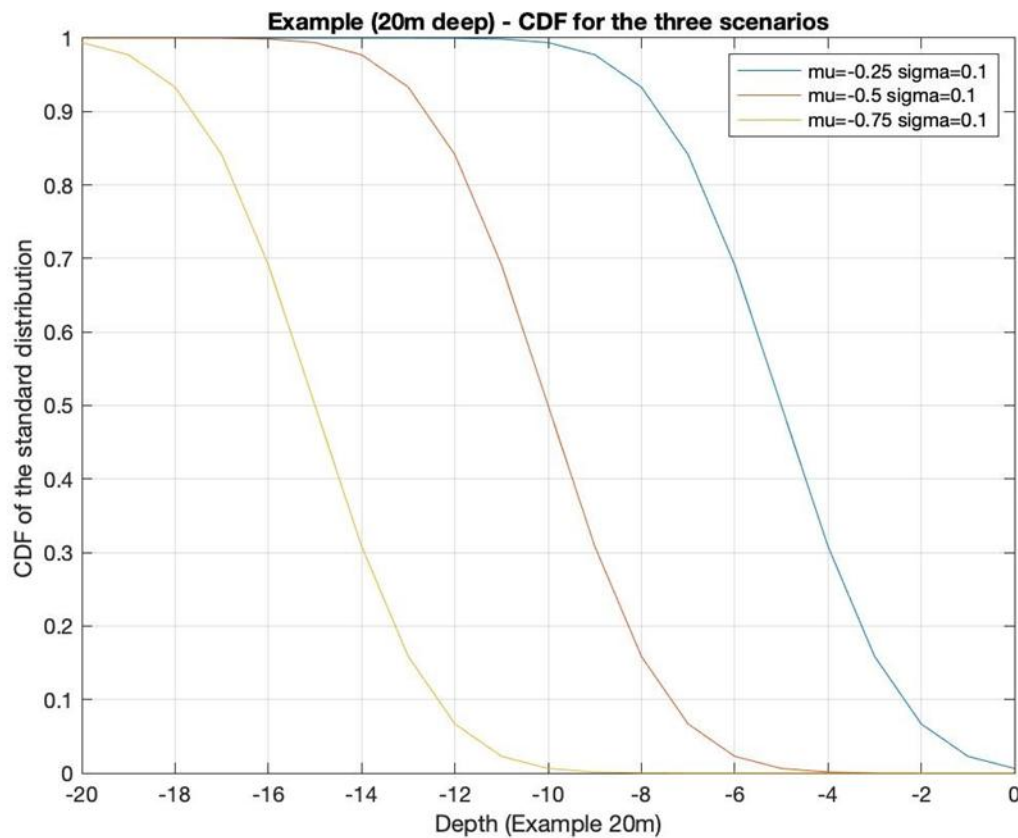


Figure S9. Cumulative density function values for scenario upper (blue), middle (red), deeper (yellow) larval distribution in the water column, represented for a depth of 20 m.

The dispersal of larvae was modelled by applying the velocity field obtained from GBRL. The position of each particle was saved hourly.

APPENDIX C: VALIDATION

The hydrodynamic models were validated against *in situ* measurements of velocity and sea surface elevation at sites occupied by IMOS long-term oceanographic moorings across the GBR, operated by AIMS. ADCP data were downloaded from the IMOS portal for the summer period matching the hydrodynamic runs. Velocity and elevation data were extracted from the flow fields of GBRL, GBR1, and SLIM models and compared to the observed data. Various statistical measures were used to evaluate the performance of the hydrodynamic models.

To compare the models against each other, a Taylor diagram (Taylor, 2001) was utilised, providing a statistical summary of model performance (**Figure S10**). The results indicated that the models performed relatively similarly to each other and accurately predicted circulation on the shelf. However, the performance decreased for ADCPs deployed off the shelf, such as at Myrmidon and Lizard Slope (MYR and LSL).

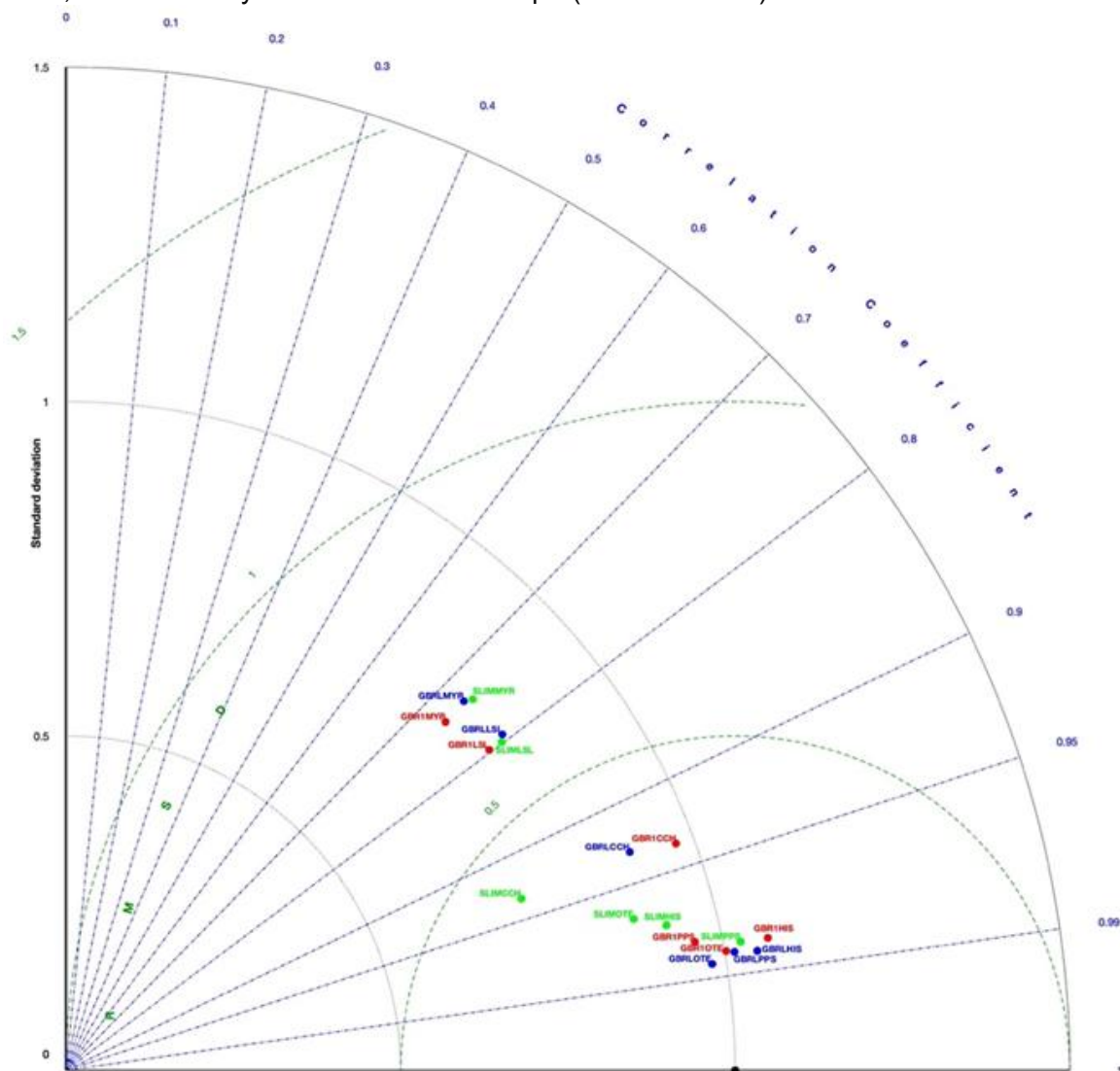


Figure S10. Taylor diagram: Comparison of hydrodynamic model performance for sea surface elevation at sites occupied by IMOS moorings.

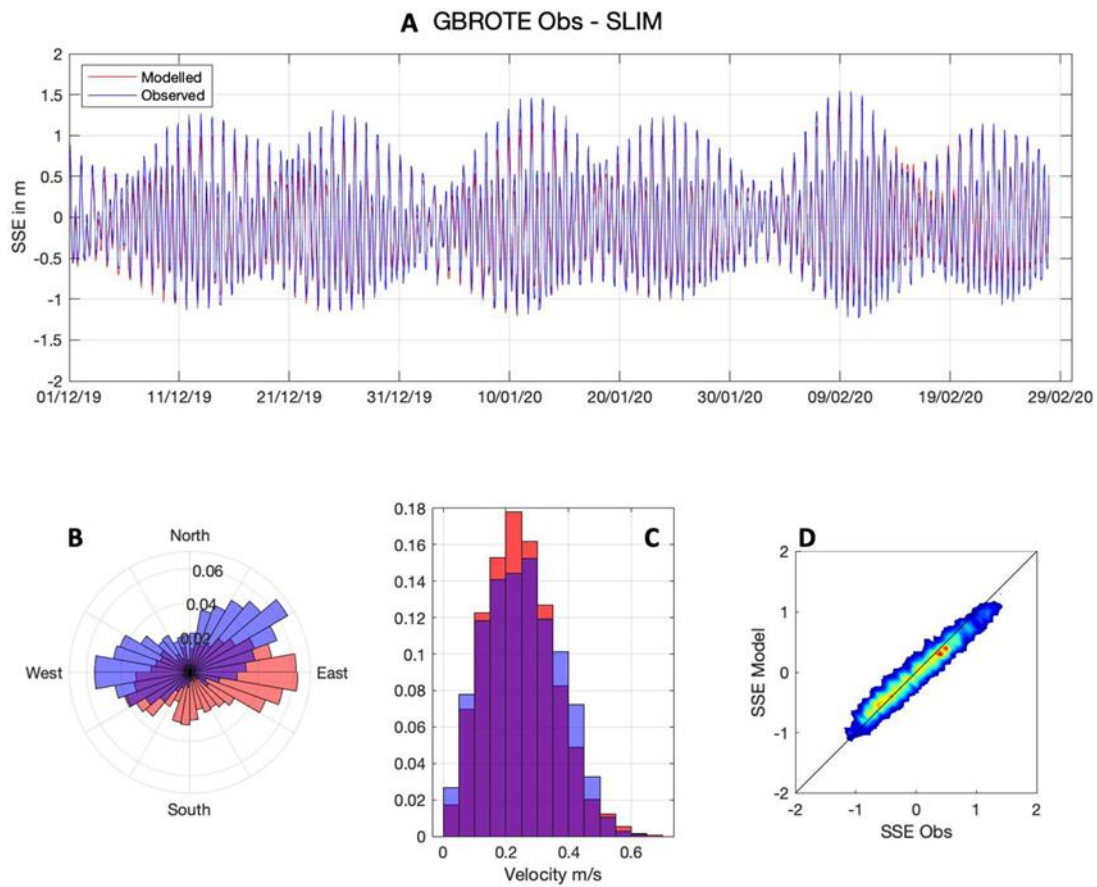


Figure S11. Comparison of the observed and simulated with SLIM sea surface elevation and the simulated currents at One Tree Island mooring. The mean value of the time series was subtracted from all measures to obtain a signal with a zero mean in both cases. **A** Observed and simulated sea surface elevation time series. **B** Histogram of hourly current direction. **C** Histogram of the hourly current amplitude. **D** Density plot of hourly observed and simulated sea surface elevation for the entire simulated period.

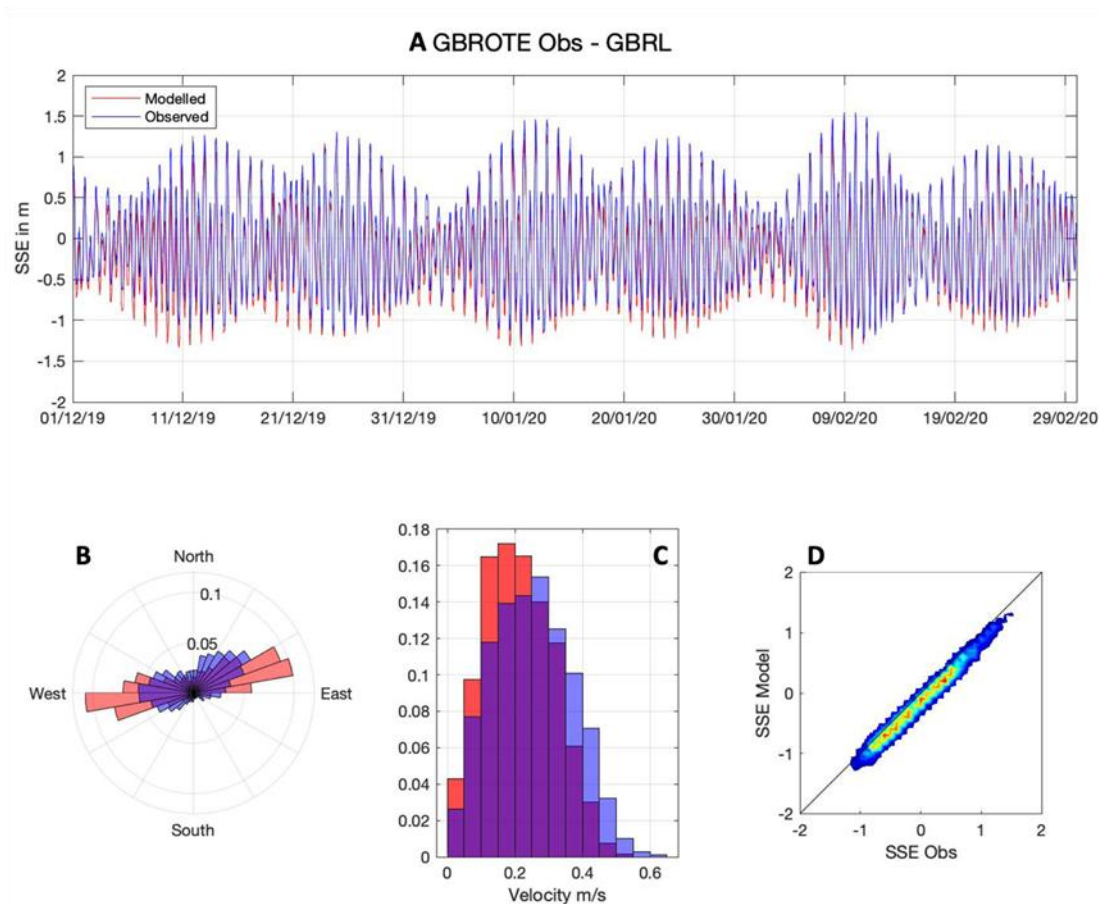


Figure S12. Comparison of the observed and simulated with GBRL sea surface elevation and the simulated currents at One Tree Island mooring. The mean value of the time series was subtracted from all measures to obtain a signal with a zero mean in both cases. **A** Observed and simulated sea surface elevation time series. **B** Histogram of hourly current direction. **C** Histogram of the hourly current amplitude. **D** Density plot of hourly observed and simulated sea surface elevation for the entire simulated period.

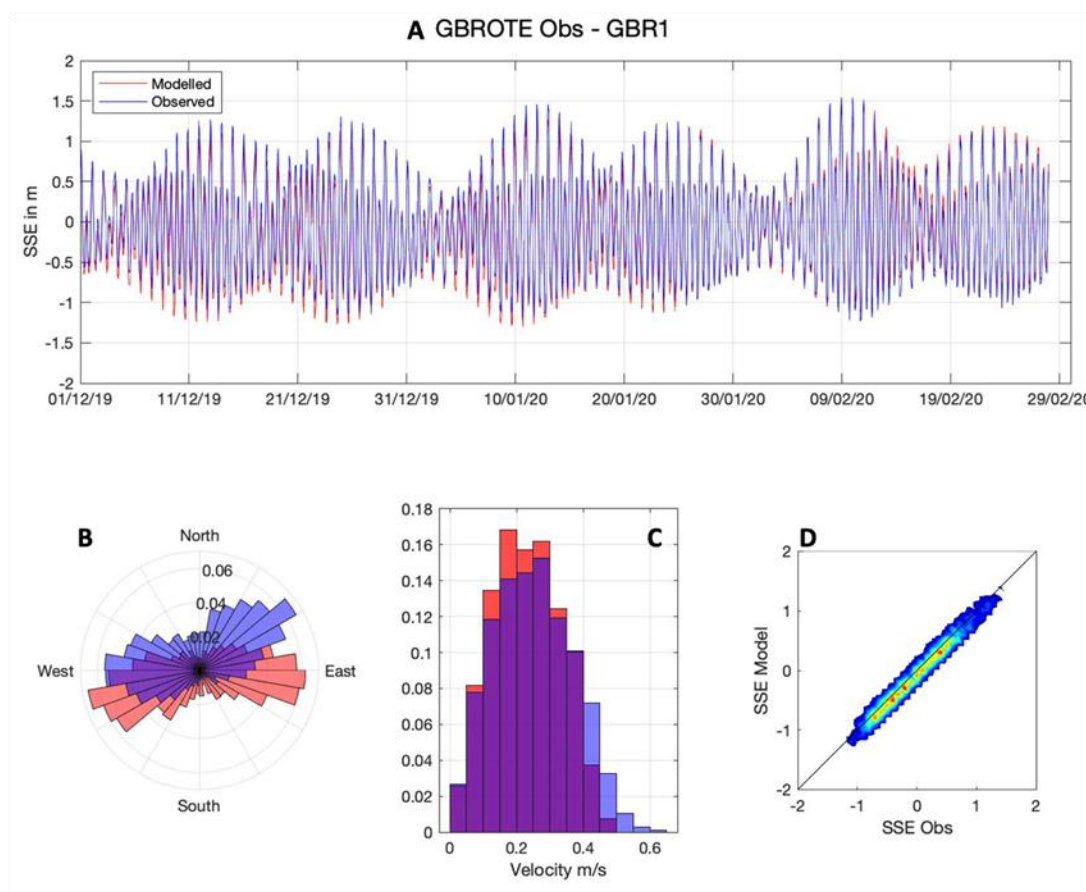


Figure S13. Comparison of the observed and simulated with GBR1 sea surface elevation and the simulated currents at One Tree Island mooring. The mean value of the time series was subtracted from all measures to obtain a signal with a zero mean in both cases. **A** Observed and simulated sea surface elevation time series. **B** Histogram of hourly current direction. **C** Histogram of the hourly current amplitude. **D** Density plot of hourly observed and simulated sea surface elevation for the entire simulated period.

Table S2. Table summarising the comparison between the observed Sea Surface Elevation, velocity in the north and east direction observed at eight locations across the GBR, occupied by IMOS moorings against the three hydrodynamic models.

GBRL	Sea surface elevation (m)		U obs (m/s)		Umodel (m/s)		U obs / mod		V obs (m/s)		V model (m/s)		V obs / mod	
Site	Correlation	CRMSD	mean	std	mean	std	Correlation	CRMSD	mean	std	mean	std	correlation	CRMSD
'GBRCCH'	0.982	0.127	0.053	0.220	0.007	0.244	0.932	0.089	-0.068	0.099	0.065	0.097	0.675	0.079
'GBRCCH'	0.984	0.122	-0.012	0.095	0.005	0.243	0.860	0.169	-0.014	0.035	0.066	0.097	0.584	0.081
'GBRHIS'	0.975	0.146	0.027	0.267	0.023	0.280	0.976	0.061	0.009	0.037	0.024	0.054	0.648	0.042
'GBRMYR'	0.894	0.281	0.087	0.116	0.158	0.179	0.067	0.207	-0.074	0.083	-0.059	0.060	0.546	0.071
'GBROTE'	0.954	0.181	-0.040	0.227	-0.032	0.219	0.907	0.096	0.107	0.188	0.087	0.095	0.670	0.143
'GBRPPS'	0.982	0.106	-0.059	0.123	-0.006	0.170	0.538	0.147	-0.009	0.117	0.007	0.170	0.767	0.110
'NRSYON'	0.822	0.365	-0.032	0.151	-0.078	0.154	0.899	0.069	0.032	0.189	0.087	0.204	0.911	0.084
2019														
'GBRCCH'	0.932	0.267	0.072	0.225	0.032	0.242	0.935	0.086	-0.053	0.110	0.053	0.085	0.804	0.066
'GBRHIS'	0.985	0.113	-0.002	0.251	0.017	0.278	0.975	0.065	0.006	0.044	0.031	0.044	0.751	0.031
'GBRLSL'	0.792	0.364	-0.015	0.059	0.043	0.170	-0.124	0.187	0.013	0.024	-0.002	0.069	-0.150	0.077
'GBRMYR'	0.733	0.451	0.172	0.130	0.334	0.174	0.206	0.195	-0.127	0.075	-0.101	0.075	0.379	0.083
'GBROTE'	0.987	0.095	-0.021	0.217	-0.009	0.215	0.921	0.086	0.078	0.151	0.051	0.083	0.625	0.118
'GBRPPS'	NaN	NaN	0.079	0.146	0.050	0.131	0.929	0.054	-0.063	0.156	-0.055	0.167	0.947	0.053
'GBRPPS'	0.985	0.096	-0.026	0.138	0.139	0.140	0.595	0.125	-0.075	0.125	-0.115	0.146	0.785	0.091
'NRSYON'	NaN	NaN	0.079	0.146	0.050	0.131	0.929	0.054	-0.063	0.156	-0.055	0.167	0.947	0.053
GBR1	Sea surface elevation (m)		U obs (m/s)		Umodel (m/s)		U obs / mod		V obs (m/s)		V model (m/s)		V obs / mod	
Site	Correlation	CRMSD	mean	std	mean	std	Correlation	CRMSD	mean	std	mean	std	correlation	CRMSD
GBRCCH	0.990	0.113	0.055	0.220	-0.012	0.251	0.927	0.095	-0.068	0.099	-0.038	0.105	0.825	0.061

GBRL	Sea surface elevation (m)		U obs (m/s)		Umodel (m/s)		U obs / mod		V obs (m/s)		V model (m/s)		V obs / mod	
GBRCCH	0.991	0.106	-0.012	0.095	-0.014	0.250	0.896	0.170	-0.014	0.035	-0.037	0.105	0.745	0.082
GBRHIS	0.988	0.106	0.026	0.268	-0.003	0.304	0.981	0.066	0.009	0.037	0.004	0.046	0.708	0.033
GBRMYR	0.893	0.287	0.087	0.117	0.005	0.136	0.578	0.117	-0.075	0.083	-0.034	0.084	0.604	0.074
GBROTE	0.974	0.137	-0.041	0.227	-0.020	0.232	0.909	0.098	0.108	0.189	-0.045	0.163	0.736	0.130
NRSYON	0.777	0.362	-0.031	0.151	-0.032	0.160	0.778	0.104	0.030	0.190	-0.018	0.171	0.755	0.127
GBRCCH	0.937	0.260	0.070	0.227	0.005	0.248	0.938	0.086	-0.052	0.111	-0.058	0.101	0.852	0.059
GBRHIS	0.983	0.128	-0.003	0.253	0.009	0.301	0.976	0.077	0.006	0.044	0.004	0.035	0.712	0.031
GBRLSL	0.797	0.362	-0.014	0.060	-0.122	0.057	0.052	0.080	0.013	0.024	0.039	0.028	0.019	0.037
GBRMYR	0.736	0.446	0.176	0.129	0.247	0.112	0.485	0.123	-0.127	0.076	-0.161	0.069	0.570	0.068
GBROTE	0.984	0.105	-0.020	0.218	-0.011	0.221	0.914	0.091	0.075	0.151	-0.032	0.116	0.596	0.124
GBRPPS	NaN	NaN	0.079	0.147	0.079	0.120	0.800	0.088	-0.065	0.157	-0.102	0.146	0.700	0.118
GBRPPS	0.980	0.110	-0.021	0.135	0.079	0.120	0.742	0.093	-0.078	0.125	-0.102	0.146	0.775	0.093
NRSYON	NaN	NaN	0.079	0.147	0.065	0.158	0.871	0.078	-0.065	0.157	-0.064	0.149	0.887	0.073
SLIM	Sea surface elevation (m)		U obs (m/s)		Umodel (m/s)		U obs / mod		V obs (m/s)		V model (m/s)		V obs / mod	
Site	Correlation	CRMSD	mean	std	mean	std	Correlation	CRMSD	mean	std	mean	std	correlation	CRMSD
GBRCCH	0.990	0.159	0.055	0.220	0.033	0.247	0.906	0.105	-0.068	0.099	-0.015	0.151	0.801	0.093
GBRCCH	0.991	0.159	-0.012	0.095	0.031	0.246	0.678	0.194	-0.014	0.035	-0.014	0.150	0.684	0.129
GBRHIS	0.981	0.134	0.026	0.268	0.071	0.244	0.914	0.109	0.009	0.037	-0.030	0.077	0.259	0.076
GBRMYR	0.896	0.279	0.087	0.117	0.192	0.129	0.312	0.144	-0.075	0.083	-0.090	0.071	0.272	0.093
GBROTE	0.965	0.169	-0.041	0.227	0.049	0.226	0.881	0.110	0.108	0.189	0.028	0.213	0.704	0.156
GBRPPS	0.988	0.088	-0.059	0.124	0.095	0.167	0.672	0.124	-0.010	0.117	-0.140	0.192	0.696	0.139
NRSYON	0.766	0.396	-0.031	0.151	-0.062	0.293	0.877	0.176	0.030	0.190	0.061	0.280	0.820	0.165

<i>GBRL</i>	<i>Sea surface elevation (m)</i>		<i>U obs (m/s)</i>		<i>Umodel (m/s)</i>		<i>U obs / mod</i>		<i>V obs (m/s)</i>		<i>V model (m/s)</i>		<i>V obs / mod</i>	
<i>GBRCCH</i>	0.935	0.304	0.070	0.227	0.007	0.238	0.923	0.092	-0.052	0.111	0.008	0.147	0.851	0.079
<i>GBRHIS</i>	0.972	0.150	-0.003	0.253	0.039	0.227	0.954	0.077	0.006	0.044	-0.045	0.076	0.192	0.080
<i>GBRLSL</i>	0.798	0.361	-0.014	0.060	-0.003	0.088	0.003	0.106	0.013	0.024	0.004	0.031	0.036	0.038
<i>GBRMYR</i>	0.739	0.448	0.176	0.129	0.238	0.087	0.310	0.131	-0.127	0.076	-0.115	0.052	0.421	0.072
<i>GBROTE</i>	0.966	0.160	-0.020	0.218	0.056	0.215	0.858	0.115	0.075	0.151	-0.018	0.149	0.589	0.136
<i>GBRPPS</i>	NaN	NaN	0.079	0.147	0.195	0.131	0.652	0.117	-0.065	0.157	-0.277	0.144	0.595	0.136
<i>GBRPPS</i>	0.982	0.105	-0.021	0.135	0.195	0.131	0.665	0.109	-0.078	0.125	-0.277	0.144	0.709	0.104
<i>NRSYON</i>	NaN	NaN	0.079	0.147	0.169	0.201	0.840	0.111	-0.065	0.157	-0.141	0.195	0.755	0.128

APPENDIX D: RELEASE TRAJECTORIES VARIABILITY

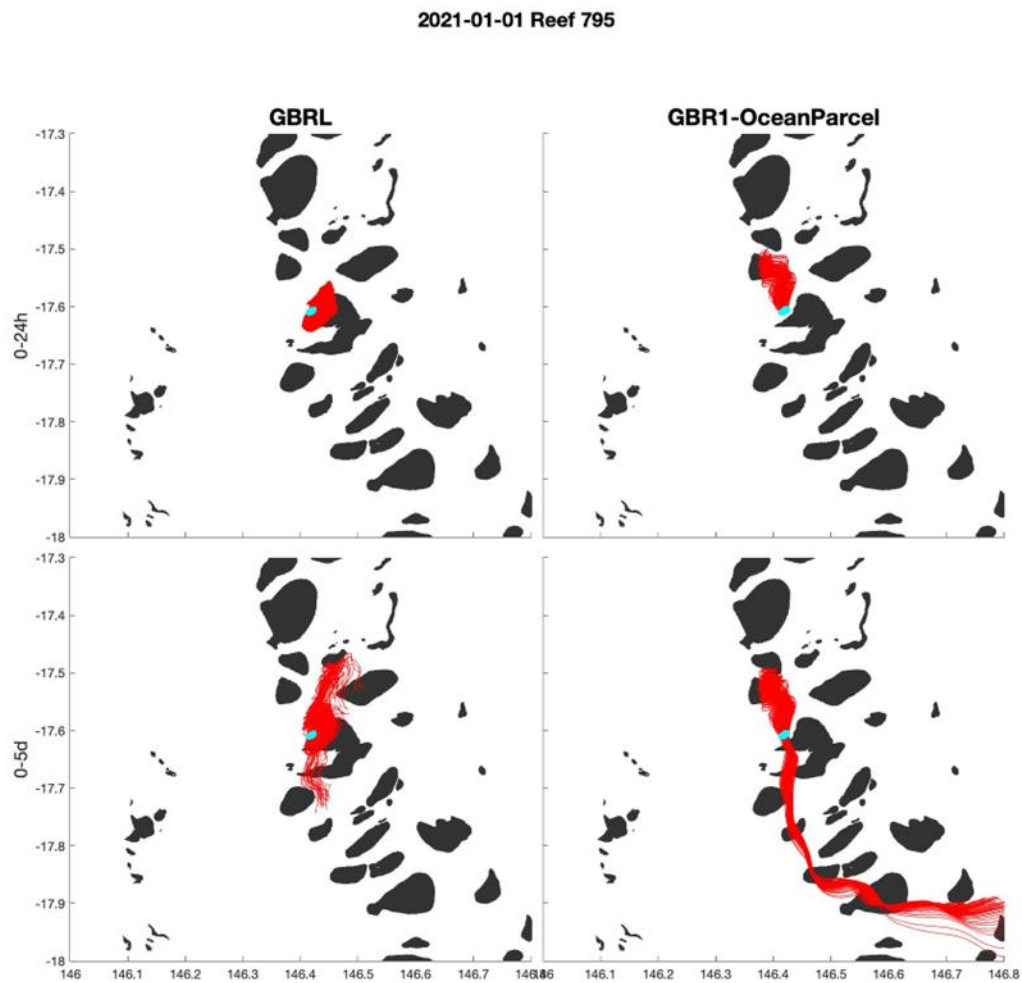


Figure S14. Dispersal trajectory variability over time assessed using GBRL subsurface dispersal and GBR1-Ocean Parcel over 24 h (top two plots) and over 5 days (bottom two plots).

APPENDIX E: DISPERSAL FREQUENCY

The circulation in the Far Northern Great Barrier Reef (FNGBR) is significantly influenced by the prevailing southeasterly winds. These winds generate a mean longshore flow that drives oceanic water from the Coral Sea into the FNGBR. However, during the summer (monsoon), increased variability in wind patterns can alter the dynamics of water movement, potentially affecting the distribution of nutrients and larval dispersal within the reef system (Wolanski and Lambrechts, 2020). To effectively model the transport and dispersal of COTS larvae, the frequency of release needs to capture the variability of the environmental conditions such as the temporal variability of the current in the regions.

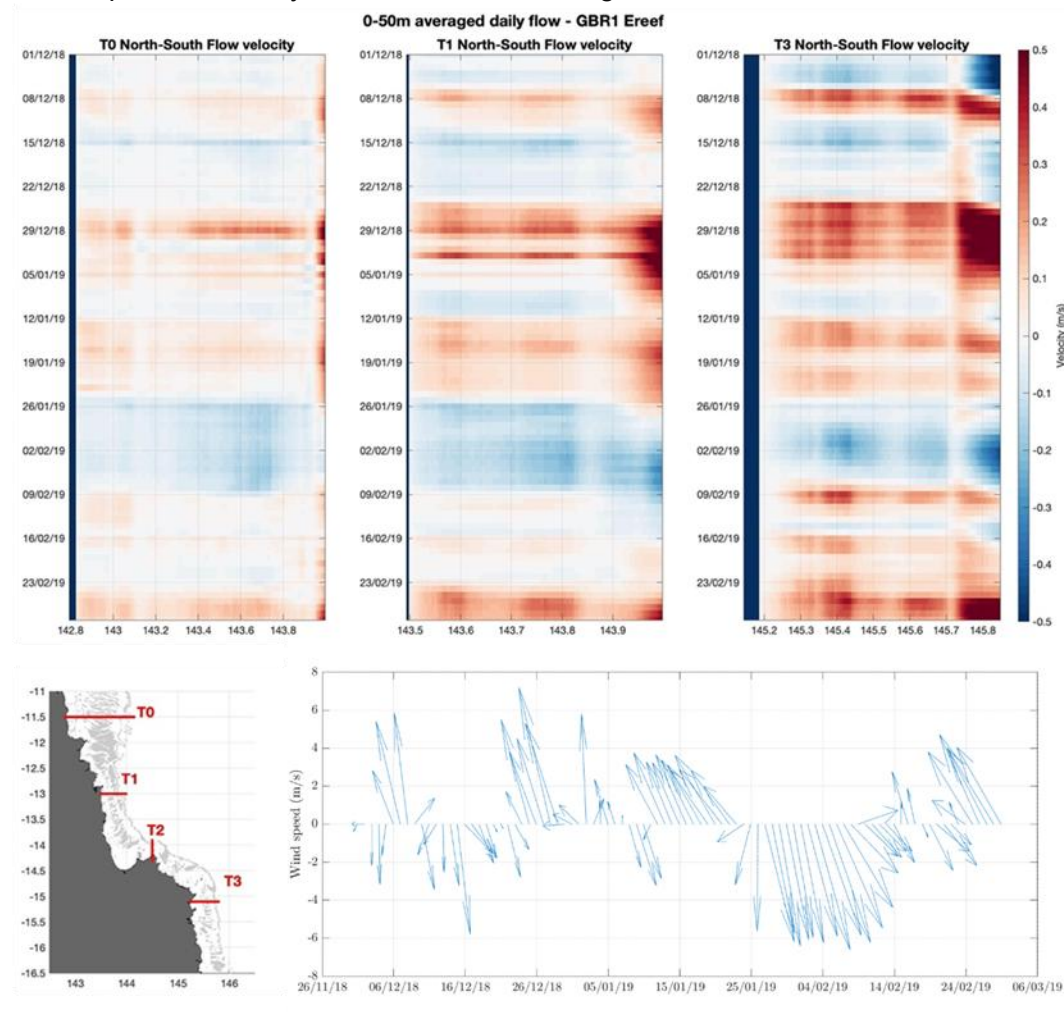


Figure S15. Wind influence on circulation in the Far Northern GBR. The top three panels represent the transport calculated through 2 latitudinal transects T0 (-11.5S) and T1 (-13S), and longitudinal transect T3 (144E). The bottom two panels show the location of the transects (left) and the wind speed and direction over the same period during the 2018/19 summer. We can see that the flow direction is correlated to the wind speed and direction.

APPENDIX F: CONNECTIVITY MATRICES 2018 TO 2023

The resulting connectivity matrices for the project are presented in **Figure 8**. It is important to note that the GBR1-Ocean Parcel trajectories, calculated at a frequency of five times per month, were made available to us only on 22/05/2024. Consequently, these trajectories are not included in this report but will be incorporated into subsequent papers and may improve correlation at the reef scale. Due to the high variability in circulation within our domain, even minor differences in release timing led to significantly different dispersal pathways.

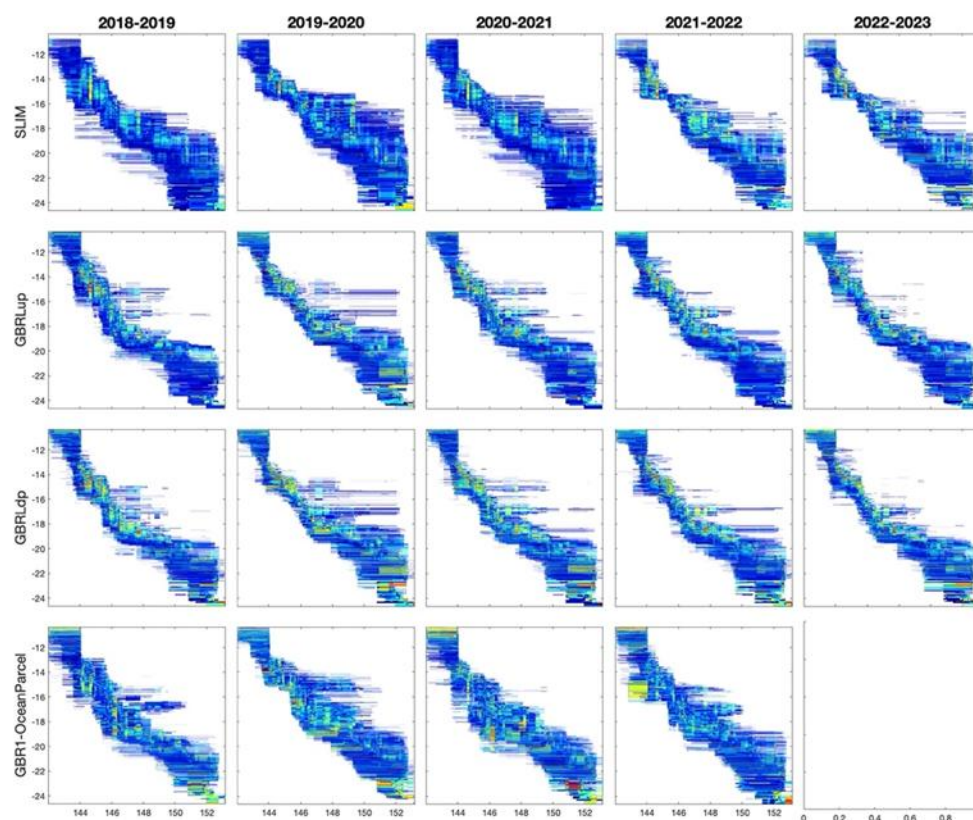


Figure S16. Each row of panels shows connectivity matrices for five different spawning seasons, predicted by one of the hydrodynamic models. Reefs are ordered latitudinally, from north (N) to south (S). The first row shows the SLIM model, the second shows GBRL Up with dispersal limited to the sub-surface, the third row shows the GBRL Deep model with dispersal to the bottom half of the water column and finally GBR1. Each point represents a single nonzero connection, normalised by the number of particles released per reef. GBR1 Ocean Parcel was released twice monthly, while GBRL and SLIM were released five times per month.

APPENDIX G: CURRENT METER DEPLOYMENT SUMMARY

There are very limited observations of oceanographic data in the Far Northern GBR to validate the hydrodynamic models and the current IMOS array doesn't extend past -15°S, off Lizard Island. To remedy this gap, we partnered with CCIP-P-04 (Pratchett et al., 2025) to deploy some Marotte current meters in the vicinity of the Early Detection array of monitoring. The current meters were deployed along transects on the reef slope at shallow and deep sites. Two of the transects were deployed in channel entrances, the Quon Channel and the channel north of Wilson reef to evaluate the exchange of water between the Coral Sea and the GBR lagoon.

The current meter data was downloaded using the MarotteHSConfig software and the velocity was 10 min averaged and saved as csv files. The resulting dataset is available from Research Data JCU

(<https://researchdata.jcu.edu.au/published/45ba3e009b9211f1a4c2235f17345359/>). The datafiles were subsequently processed in matlab, including Principal Component Analysis, tidal analysis using (t_tide from Pavlovich) and low passed using the LP33 filter (this dataset is available upon request).

The velocity in east and north direction was compared to the hydrodynamic model flow fields for the 2022–23 period. Due to the late recovery of the 2023–24 meters, we lacked time to undertake the comparison.

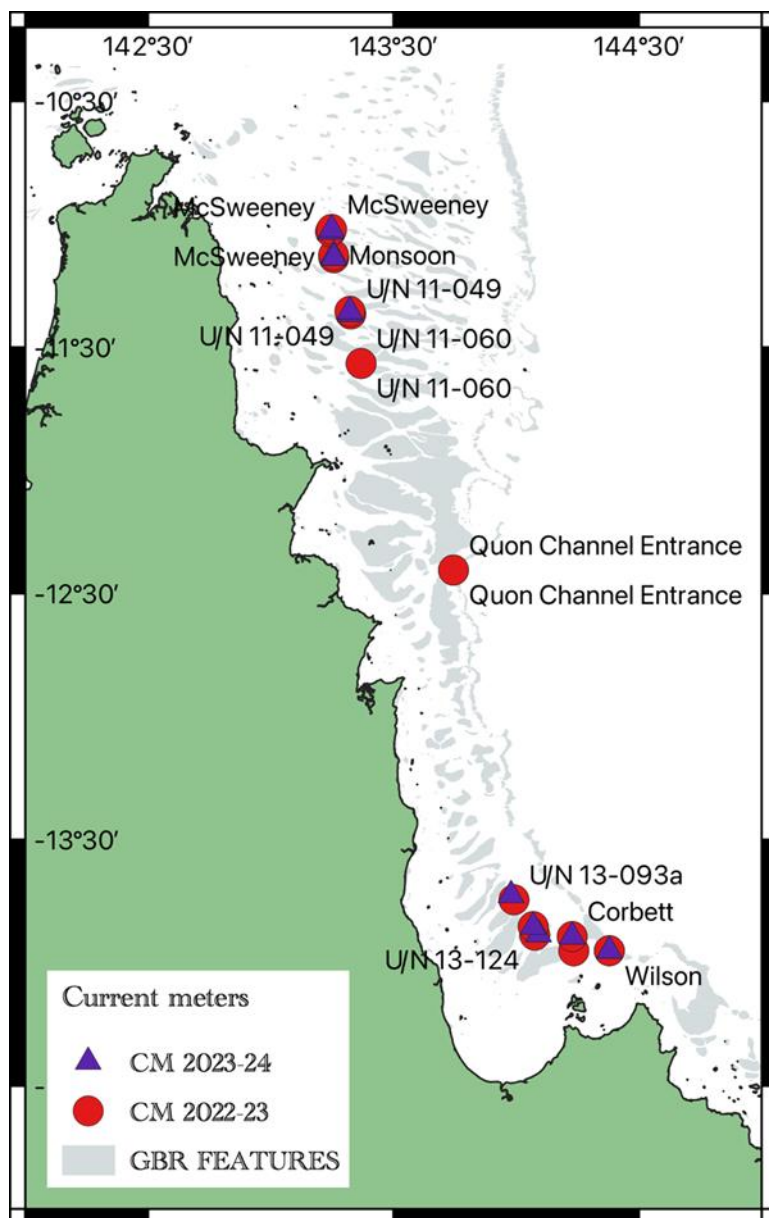


Figure S17. Deployment location of the 30 current meters in 2022-23 and the 20 current meters in 2022-23 in the Far Northern GBR.

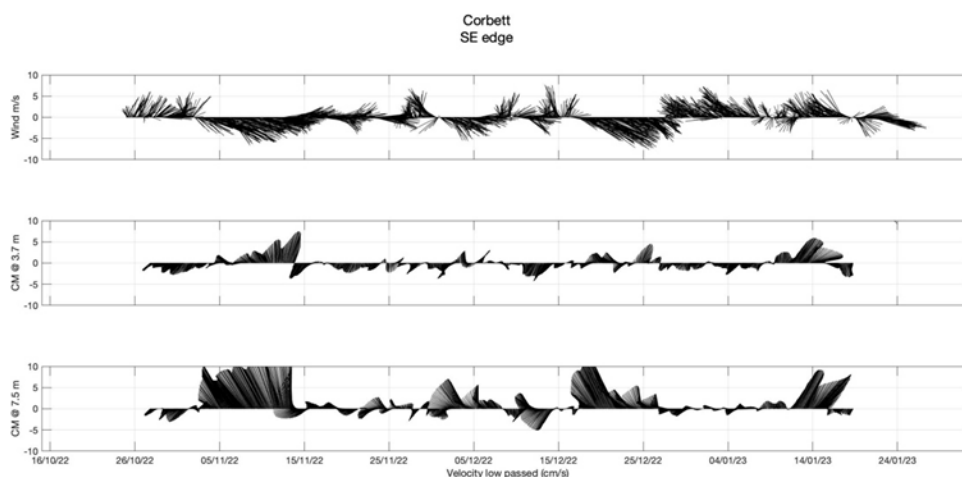


Figure S18. Time series of wind and current velocity vectors recorded by current meters deployed at the Corbett SE Edge site in 3.7 m and 7.5 m depth. Vector orientation indicates current direction, while vector length represents current speed.

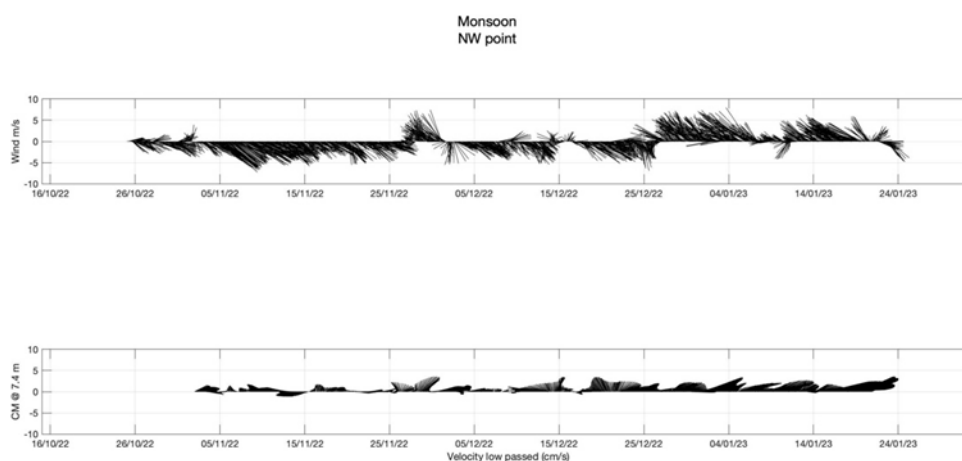


Figure S19. Time series of wind and current velocity vectors recorded by current meter deployed at Monsoon reef site in 7.4 m depth. Vector orientation indicates current direction, while vector length represents current speed.

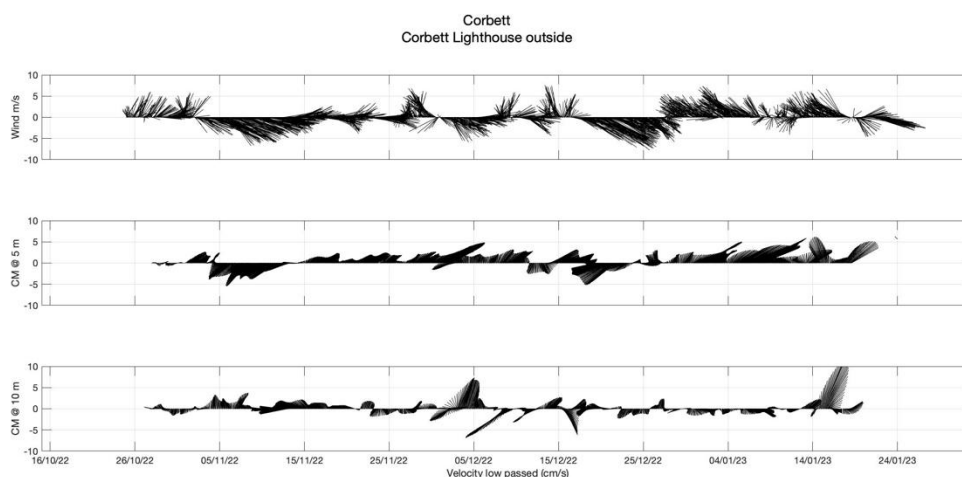


Figure S20. Time series of wind and current velocity vectors recorded by current meters deployed at the Corbett Lighthouse site in 5 m and 10 m depth. Vector orientation indicates current direction, while vector length represents current speed.

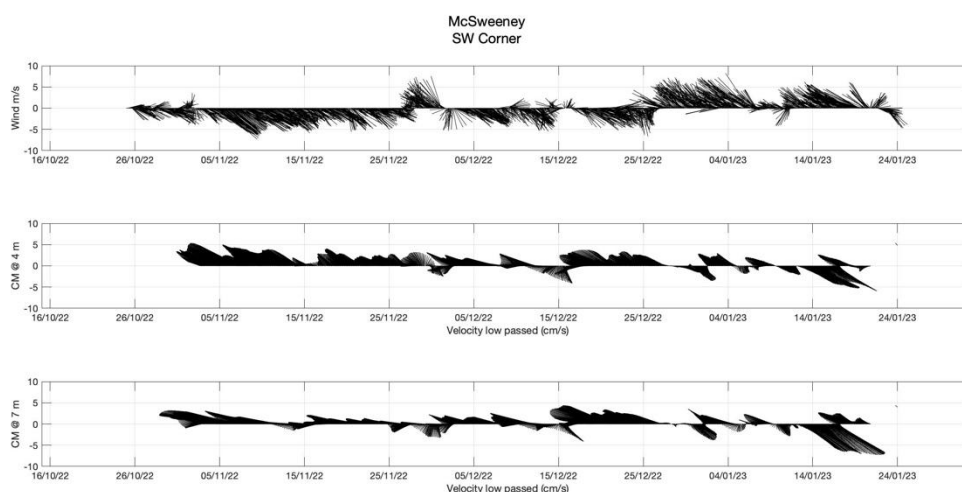


Figure S21. Time series of wind and current velocity vectors recorded by current meters deployed at Mc Sweeney reef in 4 m and 7 m depth. Vector orientation indicates current direction, while vector length represents current speed.

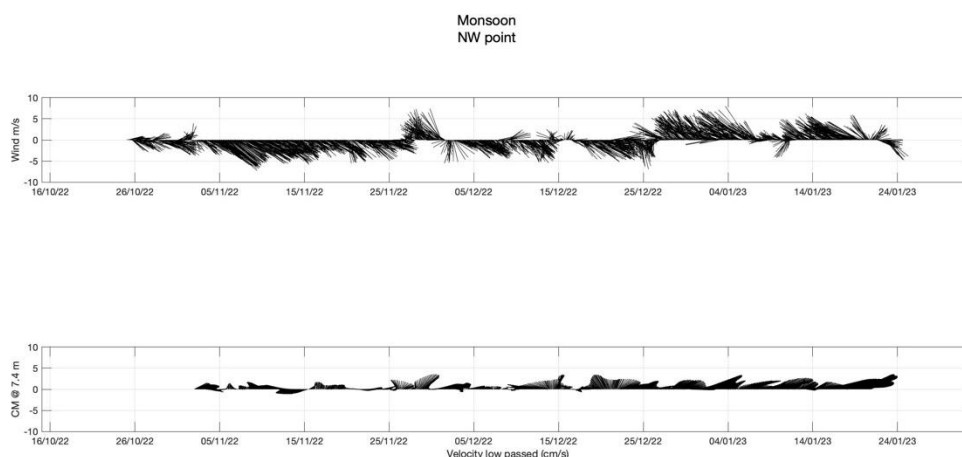


Figure S21. Time series of wind and current velocity vectors recorded by current meter deployed at Monsoon reef, Northwest Site in 7.4 m depth. Vector orientation indicates current direction, while vector length represents current speed.

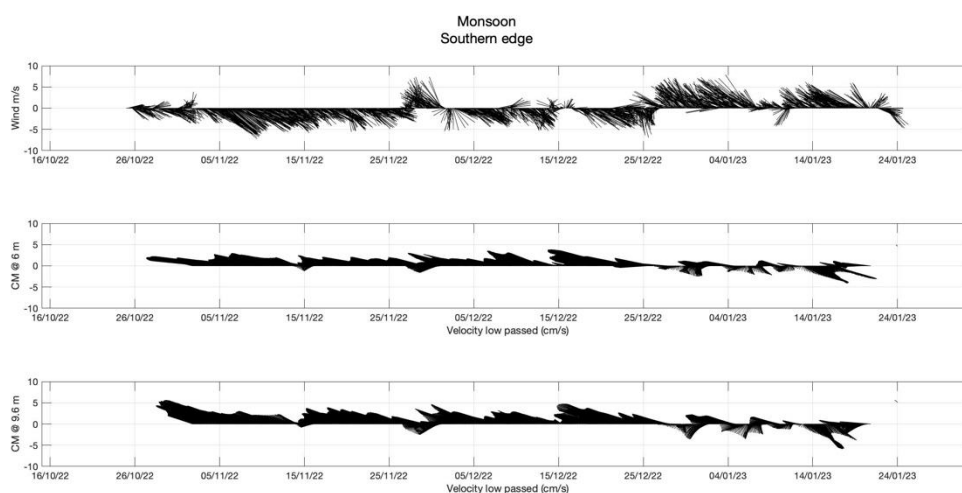


Figure S22. Time series of wind and current velocity vectors recorded by current meters deployed at the Monsoon Reef, Southern edge site in 6 m and 9.6 m depth. Vector orientation indicates current direction, while vector length represents current speed.

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