RRAP REEF RESTORATION & ADAPTATION PROGRAM

Developing, implementing and testing fine scale hydrodynamical models in the context of larval supply and restoration– Standard Operating Procedure

Nov 2024

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REVISION HISTORY			
Version	**Date**	**Commentary [section/s updated]**	**Author [incl. ORCID ID]**
1.0	April 2024	First draft	C. Langlais [0000-0002-6423-7678]
1.0	Nov 2024	Second draft – all sections	C. Langlais
1.0	Nov 2024	Second draft – edit, comments – all sections	C. Doropoulos [0000-0001-8038-2771]
1.0	Nov 2024	Third draft – extra section 5	C. Langlais R. Mason [0000-0002-2725-2449] R. Thomson [0000-0002-1922-8051]

This report should be cited as

Langlais, C. et al. (2024) Reef Restoration and Adaptation Program – **Developing, implementing and testing fine scale hydrodynamical models in the context of larval supply and restoration** – Standard Operating Procedure. (23 pp).

Acknowledgement

This work was undertaken for the Reef Restoration and Adaptation Program (RRAP). Funded by the partnership between the Australian Government's Reef Trust and the Great Barrier Reef Foundation, partners include: the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Foundation, Southern Cross University, the University of Queensland, Queensland University of Technology and James Cook University.

The RRAP partners acknowledge Aboriginal and Torres Strait Islander Peoples as the first marine scientists and carers of Country. We acknowledge the Traditional Owners of the places where RRAP works, both on land and in sea Country. We pay our respects to elders; past, present, and future; and their continuing culture, knowledge, beliefs, and spiritual connections to land and sea Country.

We specifically acknowledge and thank the following Traditional Owners of sea country that this report relates to:

Location	**Traditional Owner Group**
Palm Islands	Manbarra
Capricorn Bunkers	Bailai, Gurang, Gooreng Gooreng, Taribelang Bunda

Table of Contents

List of Figures

1 Executive Summary/Abstract

Hydrodynamic and particle connectivity models have the potential to support the operationalisation of coral reef restoration and conservation. Restoration tools such as direct larval seeding onto reefs have the potential to manage the spatial footprint of larval releases by using natural hydrodynamics of a reef to retain or disperse larvae to previously unprecedented scales of coral reef restoration. Spatial conservation of reef networks such as the Great Barrier Reef relies on understanding metapopulation dynamics and connectivity among reefs, which occurs through larval movements. However, there is a need to demonstrate that the dynamical models that support these decisions can adequately forecast the spatial variability of larval connectivity, retention and supply at the scales relevant to restoration – i.e., 100's m to 1-10's km.

Here, we describe how to develop, implement, and validate hydrodynamical models and Lagrangian particle tracking models that can inform reef restoration and conservation activities.

A major challenge is configuring the hydrodynamical models to capture multiple spatial scales while maintaining model performance that can inform daily intervention decision planning. Potential larval sources can stretch 10's to 100's of kilometres, while potential larval sinks, self-retention and small-scale convergence and retention zones stretch 100's of metres to 1's kilometres. Such multi-scale models require special consideration to high powered computing capability, run times, and data management.

Comparisons of models with *in-situ*, empirical observations for validation is an important step that should not be overlooked. Validation processes highlight the performance and limitations of a model. Some best-practise Eulerian and Lagrangian comparison techniques are described in this document.

2 Background

Marine dispersal patterns are central to the mode of reproduction of marine species with pelagic larvae (Cowen and Sponaugle, 2009). once competent. Ocean currents allow reefs to connect at various spatial ranges, from 10’s of m to 100’s of km (Wolanski and Kingsford, 2024). Knowledge about highly connected and poorly connected reefs is key for targeting restoration planning of degraded reefs and optimising resource allocation for restoration efforts (Mumby et al., 2011; Hock et al., 2017).

Due to the extent of the Great Barrier Reef (GBR) and the scale of potential dispersal, the use of hydrodynamic models and larval dispersal models are central to identify sources and sinks of larvae. Whilst hydrodynamic models are mature and can represent the distant connectivity at the scale of the GBR (Gurdek-Bas et al., 2022; Condie et al., 2021; Hock et al., 2019), the current models developed for the GBR do not characterise local retention nor local connections adequately (Bode et al., 2019 ; Riginos et al., 2019) Moreover, connectivity models do not capture well the natural variance in larval supply at the scale of the reef.

Local retention, local connections and reef scale larval supply operate at the spatial scale most relevant for early recovery, as well as at the scale of restoration activities (Doropoulos and Babcock, 2018 ; Gouezo et al., 2021; Gouezo et al., 2024). These are also the scales at which natural fluxes of larval supply are observed and documented (Oliver at al., 1992; Gilmour et al., 2009; Mason et al., Under Review).

One objective the RRAPs Ecological Intelligence for Reef Restoration (EcoRRAP) Subprogram was to refine and validate connectivity models on the GBR. For that purpose, coral dispersal was measured and modelled using high intensity spatial and temporal sampling of coral larvae and high resolution hydrodynamical models in the inshore Palm Island reefs (2022) (Mason et al., In prep) and offshore Capricorn Group reefs (2021-2023) (Mason et al., In prep). This document describes the procedure to deploy new hydrodynamical model configurations, with the objective of representing the natural supply of larvae to the reefs and comparing it with *in-situ* observations.

3 Objectives and Scope

Hydrodynamic and particle connectivity models have the potential to support the operationalisation of coral reef restoration and conservation. However, at the scale of restoration that typically occur at 10-100's of metres, we need to demonstrate that models can adequately forecast the spatial variability of larval arrival rates to reefs.

The objective of this document is to describe how to develop and implement the hydrodynamical models and their testing for monitoring restoration intervention activities and efficacy.

The document describes:

1. How to set-up hydrodynamical models for restoration purpose
2. Particle tracking models and protocol for coral larvae
3. How to validate the hydrodynamical model
4. Model details and limitations

4 Procedure – model implementation

To simulate larval dispersal, numerical hydrodynamical models are used to provide three-dimensional ocean currents. These models simulate hourly ocean currents and physical processes at the scale of their grid resolution. The challenge is to set-up and validate these models across spatial scales of interest for restoration activities. Thus, the models need to capture:

- The scale of influence: distant and close connections between reefs, which can stretch from 1's to 100's of km
- The scale of the reef: within reef connections and fine scale convergence and divergence patterns stretching 100's m to 1's km.

The challenge is finding the optimal balance between domain size and resolution, and model performance.

Domain size – scale of influence around the target reef

The domain size needs to cover the cluster of all potential source reefs. At the scale of the GBR World Heritage Area, the eReefs (http://ereefs.org.au) hydrodynamical models (Steven et al, 2019) are regularly used to understand inter-reef connections (Gurdek-Bas et al., 2022; Condie et al., 2021; Hock et al., 2019). To select the domain, we use the GBR connectivity simulations of coral mass spawning based on eReefs GBR4 (~4 kilometre grid resolution model of the GBR) from Hock et al. (2019). Analysing the connectivity matrix from Hock et al. (2019) allows us to identify source reefs that supply ~90% of particles to the identified target reefs (Mason et al., In prep; Mason et al., Under Review).

Examples of domain implementation:

For the Capricorn Bunker area, the target reefs for model validation of larval supply and settlement were: One Tree Reef, Heron Reef, Wistari Reef and Sykes Reef (Mason et al., Under Review). Between 2008 and 2016, most source reefs were restricted to the Capricorn and Bunker Groups. Only in 2014, the Swains reefs contributed as a demographically relevant source to the target reefs. The chosen domain covers the Capricorn Group of 17 reefs: Heron, Wistari, Sykes, One Tree, Irving, Polmaise, Masthead, Erskine, North, Tryon, North West, Broomfield, Wilson, Wreck, Lamont, Fitzroy and Llewellyn. Lady Musgrave, Boult, Hoskyn and Fairfax Reefs, all immediately to the south, were not included in the model domain (Fig. 1).

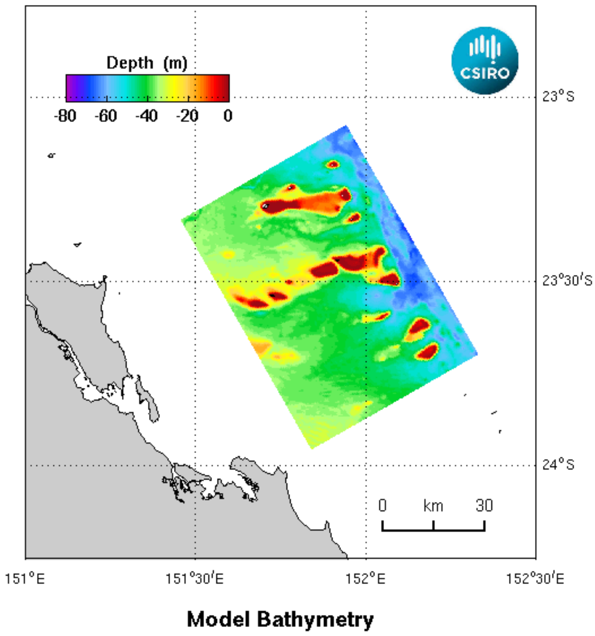

Figure 1: Domain extent and bathymetry for the Capricorn Bunker area capturing the major sources of modelled larval supply to Wistari, Heron, Sykes, and One Tree Island reefs.

For the Palm Island group, larval supply validation to Orpheus, Pelorus, and Fantome Islands' reefs were targeted. Results from Hock et al. (2019) show a very large zone of potential reef sources in the Central GBR (Fig. 2), which is unsurprising given the more complex reef network compared to the Capricorn-Bunker reefs. The final domain encompasses the outer reefs from Cairns to Townsville (Fig.3).

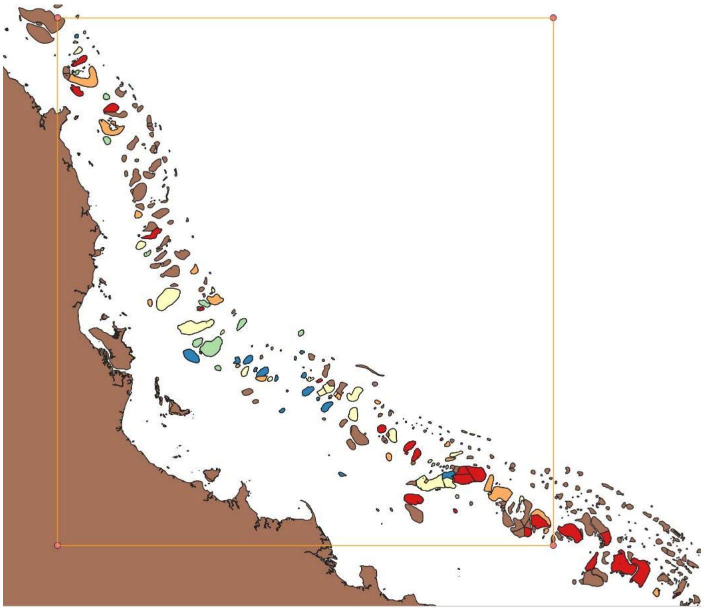

Figure 2: Potential source reefs for Palm Island (Mason et al., Under Review).

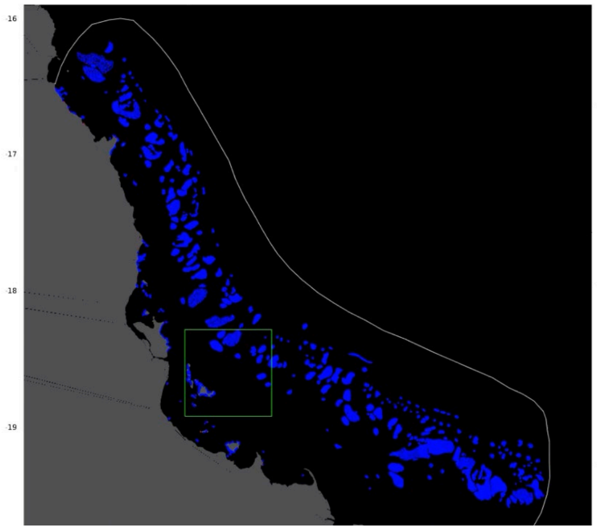

Figure 3 Domain extent (white contour) and reefs (blue) for the Palm Island model.

Model resolution

The model resolution needs to be sufficient to represent the circulation features responsible for the fine scale high and low larval fluxes at the chosen reef area. Expert knowledge is used to select a resolution between 10's to 100's of metres. A pilot model is developed, and qualitative behaviours are assessed to validate and/or refine the choice of resolution. In particular, attention is given to the simulation and representation of Lagrangian coherent structures creating small-scale convergence and retention zones (Bertin et al., 2024 ; Matuszak et al., 2024).

Examples of resolution choices:

For the Capricorn Bunker area, we used a geographic grid of 200 metres resolution, allowing us to represent the tidal and wind-induced circulation, and the channelling of ocean currents in-between the reefs (see Fig. 4). At that resolution, the behaviour of the semi-enclosed lagoons is also well represented.

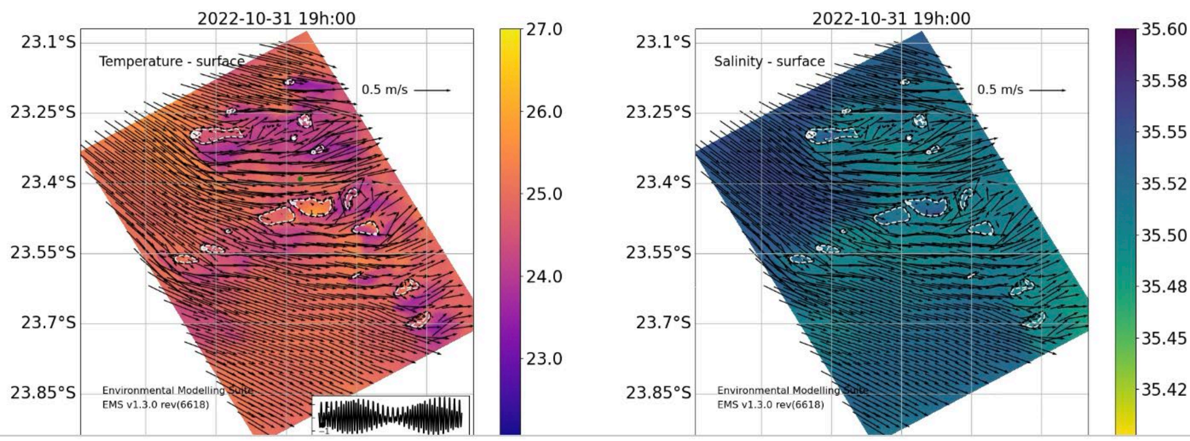

Figure 4 Surface currents, temperature and salinity

For the Palm Islands, due to the size of the domain, a geographic grid could not be used. Instead, an unstructured model grid was used, allowing for a resolution of ~100 metres near the target reefs and a resolution of 1 kilometre at the boundary of the unstructured Palm Island grid (Fig. 5). The model is then extended to the domain limit described in Fig. 3 by merging the model data with eReefs GBR1 (~1kilometre grid resolution model).

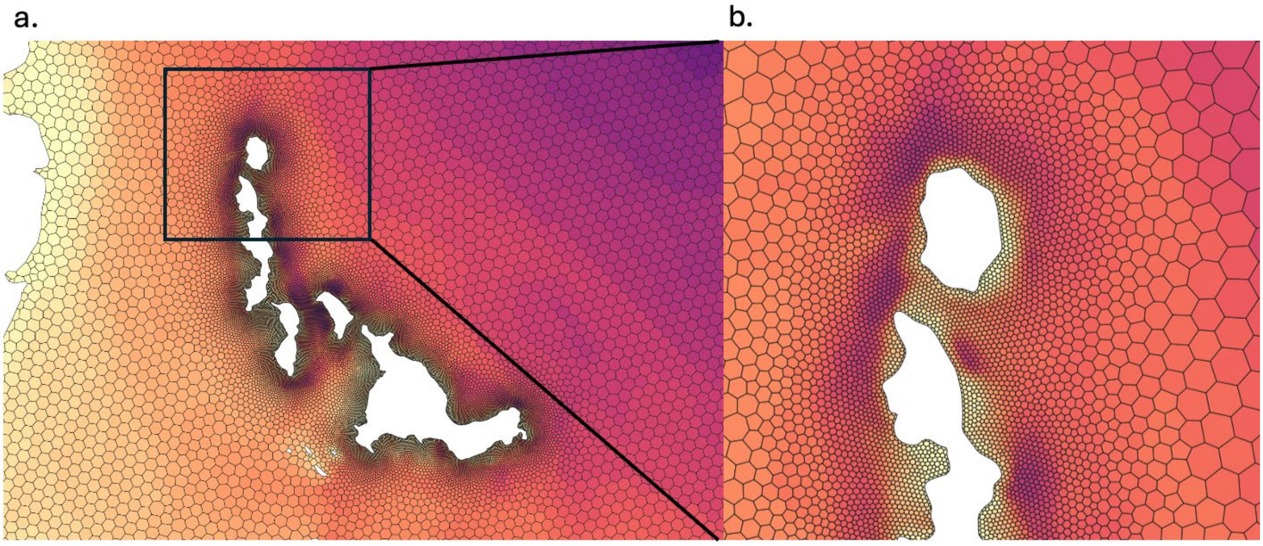

Figure 5: Palm Island unstructured grid: high resolution grid around Palm Island (a), zoom over the northern islands (b)

This unstructured grid has the advantage of representing the physical processes responsible for offshore advection and inter-reef connections (wind-driven circulation and tidal circulation), as well as sub-mesoscale circulation patterns like wake eddies that developed in-between islands (Fig. 6).

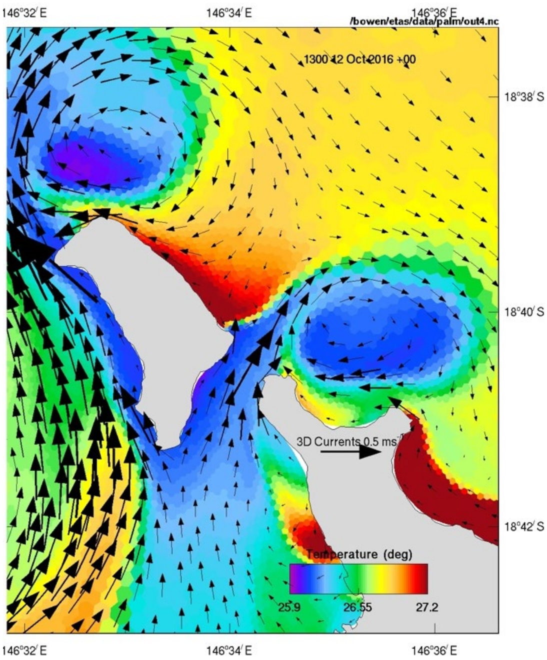

Figure 6: Wake eddy forming between the islands

5 Procedure – particle tracking

Particle tracking is a powerful tool for understanding the movement and dispersion of particles within marine environments. It is widely used in applications ranging from predicting oil spill trajectories (Liu et al., 2023) and plastic debris transport (Alosairi et al., 2020) to studying larval dispersal and connectivity in marine ecosystems (Hock et al., 2017).

The velocities of hydrodynamic models are used to simulate the trajectories of virtual particles, enabling precise insights into the pathways and fate of particles under the influence of ocean currents, winds, and other environmental forces.

This approach plays a crucial role in environmental management, conservation planning, and the development of effective response strategies for marine pollution and ecological challenges.

Particle tracking techniques

Particles are seeded using an initial spatial distribution of particles at a specified release period. They are subsequently tracked individually using a 4th-order Runge-Kutta numerical technique for solving ordinary differential equations. This technique linearly interpolates in time and space to find the horizontal velocity at the required depth and time.

An additional horizontal velocity component can be added to represent the effect of the wind drag when the particles are floating at the surface.

Particle tracking models

For the Capricorn Bunker area, we used Connie 2 (http://www.csiro.au/connie2/) to deploy virtual particles. Connie2 has been developed as a user-friendly online tool capable of generating detailed information on oceanographic dispersal of marine larvae, pollution or objects, for a wide range of research, educational and management applications. Connie only uses 2D velocity fields as input. But vertical migration can also be represented as instantaneous jumps between vertical levels.

For the Palm Islands, due to the unstructured nature of the grid, we used the particle tracking module supported in SHOC/COMPAS (https://research.csiro.au/cem/software/ems/ems-documentation/). This model has the advantage of tracking the particles in 3D. Users have the option to make the particles stay at the surface (positive buoyancy) for a specified period of time, thus being able to incorporate the natural history of spawned coral larvae dynamics.

Particle tracking protocols for coral larvae

Capricorn Bunker area – Connie protocol

- Particles are released inside source polygons defined as coral cover at each source reef in the model domain by the Allen Coral Atlas (https://allencoralatlas.org/)
- At each source reef, 1000 particles are released per hour between 6 pm and 10:59 pm (5000 particles per source reef per evening).
- Evenings of release are chosen from field observations of spawning in the region of the model, made during the same year. In cases where these are not available, the Indo-Pacific coral spawning database is used to infer the likely evenings of spawning (Baird et al. 2021).
- Surface currents are used to advect the particles during the first 12 h, and a wind drag effect (3% of the wind) is superimposed

- After 12 hours, the particles migrate to 2 metre deep and are only advected by the ocean currents from this point on. After a further 12 hours, the particles migrate to 4.5 metre depth for the remainder of the dispersal period.
- Particles are tracked for a period of time appropriate to the range of the pelagic larval duration of the targeted coral species. Whilst this is unknown in most coral species, a 60-day simulation is expected to capture the pelagic period of the majority of larvae (e.g. Randall et al. 2024).

Palm Island area – SHOC/COMPAS protocol

- Particles are released inside source polygons defined as coral cover by the Allen Coral Atlas (https://allencoralatlas.org/)
- Particles are released at the surface and a wind drag effect (3% of the wind) is superimposed for the first 12 hours.
- Particles are tracked for a period of time appropriate to the range of the pelagic larval duration of the targeted coral species. Tracking occurs for 60 days (see above).

Particle tracks analysis

The resulting particle tracks can be analysed to assess the connection between source reefs and the receiving reefs. To assess the incoming larval fluxes at the target reefs, receiving areas are defined as small polygons around the monitoring sites defined around the target reefs. There are several options as to how particles arriving to a target polygon may be accounted for. At both of the Capricorn-Bunker and Palm Islands domains featured in this study, this was accounted for by taking the mean of the number of Lagrangian-tracking timesteps that a particle arriving to a target polygon spent in that polygon.

To estimate the connectivity between reefs, a competency and mortality curve is used to describe the survival and dispersal dynamics of the marine larvae (Connolly and Baird, 2010 ; Moneghetti et al., 2019). These curves can provide insights into the likelihood of an organism reaching a suitable habitat (competency) and the probability of survival over time (mortality). Competency refers to the period when an organism, such as a larva, is physiologically ready to settle and metamorphose into its next life stage (e.g., attaching to a substrate and transitioning from a motile larvae to a sessile, benthic organism). The mortality curve tracks the likelihood of survival over time. In most cases, mortality increases over time due to predation, starvation, or unfavourable environmental conditions. By overlaying these two curves, we gain insights into the window of opportunity for successful settlement.

Several further adjustments are made to the tracked particle data. The amount of particles released every evening at each source reef are weighted by the proportional contribution of each evening to the total spawning effort of that spawning event. During one spawning event, it is common for there to be one or a few major evenings of spawning interspersed with several minor evenings of spawning. These values are determined from recent field observations or from the Indo-Pacific coral spawning database.

The amount of particles released every evening are also weighted by the size of the source reef, taken as the area of coral cover on that source reef in the Allen Coral Atlas.

In addition, it may have been necessary to use receiving polygons whose sizes (areas) varied among the monitoring sites. If this is the case, the amounts of particles captured at receiving polygons are weighted to account for the differences in area among the receiving polygons.

6 Procedure – model validation

Validation of the hydrodynamical models is not only a necessity but also a challenge.

The lack of observations is often the primary difficulty to validate high resolution hydrodynamical model. In the context of larval supply and restoration, the essential ocean variable are the ocean velocities – the components of the current and associated transport. Both Eulerian and Lagrangian approaches can be considered for validation purpose: *in-situ* observations from current meters at moorings, acoustic doppler current profilers (ADCPs), surface drifters or deep floats. In a coastal setting where tidal movements are present, both tidal current and residual large-scale current should be assessed.

Eulerian validation

Current meters at moorings, ADCPs or tiltmeters can be used to conduct timeseries analysis and direct comparison between observed and modelled northward and eastward velocity components (Fig. 7). Figure 7 shows the comparison between ADCP velocities averaged over 0-10 m water depth and modelled velocities averaged over 0-10 m water depth south of Heron Island in December 2021 (from Mason et al., 2024, *Under Review*).

We use 4 skill metrics: the root-mean-square error (RMSE), the mean absolute error (MAE), correlation coefficient (cc), model bias, and model skill described by Willmott (1981). The model skill is used to validate model performance. It is a dimensionless index between 0 and 1 that weights the model errors relative to the known amplitude of local variability. It is computed as the difference between the model and observation anomalies relative to the time-average observations, divided by the sum of observed anomalies relative to the time-average observations.

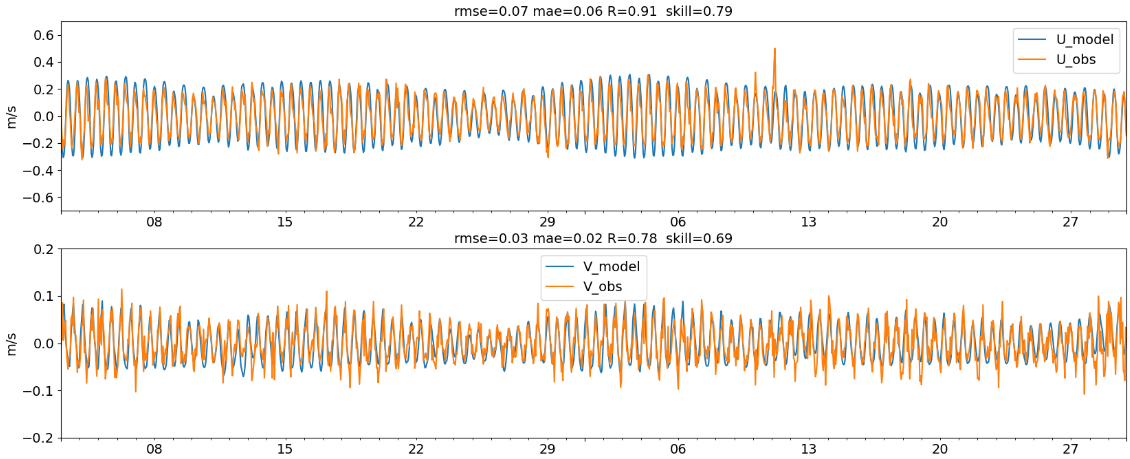

Figure 7: Eulerian time series comparison between observed and modelled eastward and northward velocities in December 2021 at south Heron Island (Mason et al., 2024, Under Review).

The use of tidal analysis allows us to separate the tidal signal from the residual signal. The top 2 panels in Figure 8 shows the tidal signal using the height major tidal constituents:

- K1: A diurnal constituent with a period of 23.93 hours
- O1: A diurnal constituent with a period of 25.82 hours
- P1: A diurnal constituent with a period of 24.07 hours
- Q1: A diurnal constituent with a period of 26.87 hours
- S1: A diurnal constituent with a period of 24.00 hours

- M2: A semidiurnal constituent with a period of 12.42 hours
- S2: A semidiurnal constituent with a period of 12.00 hours
- N2: A semidiurnal constituent with a period of 12.66 hours

The bottom 2 panels in Figure 8 show the residual current or low frequency current comparison for 2 different depths: 0-10 m and surface.

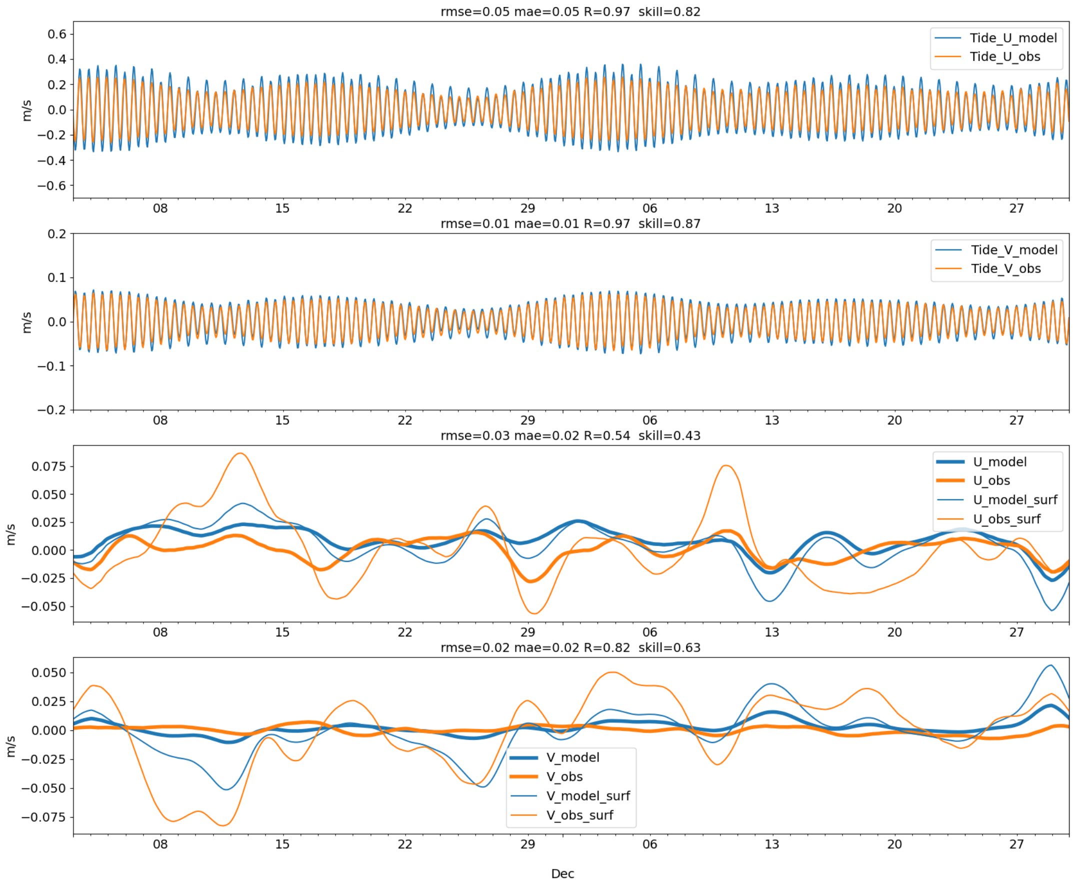

Figure 8: comparison between ADCP velocities averaged over 0-10 m and modelled velocities averaged over 0-10 m south of Heron Island in December 2021 (from Mason et al., 2024, Under Review). Top two panels show tidal current and bottom two panels show the residual current.

Lagrangian validation:

Surface drifters are oceanographic device floating on the surface and enabling the measure of ocean currents by tracking their location. The drifters are designed to follow the ocean currents at a specific depth (surface or a few meters deep) by using drag to minimize the direct wind effect.

Ocean drifter tracks can be compared to numerical drifter tracks, by releasing particles in Lagrangian particle tracking models which are using the hydrodynamical model ocean velocities as forcings.

Figure 9 shows a surface drifter analysis performed at Lizard Island to validate a 50 metre resolution model of the reef area around the island and lagoon (from Gouezo et al., 2024)

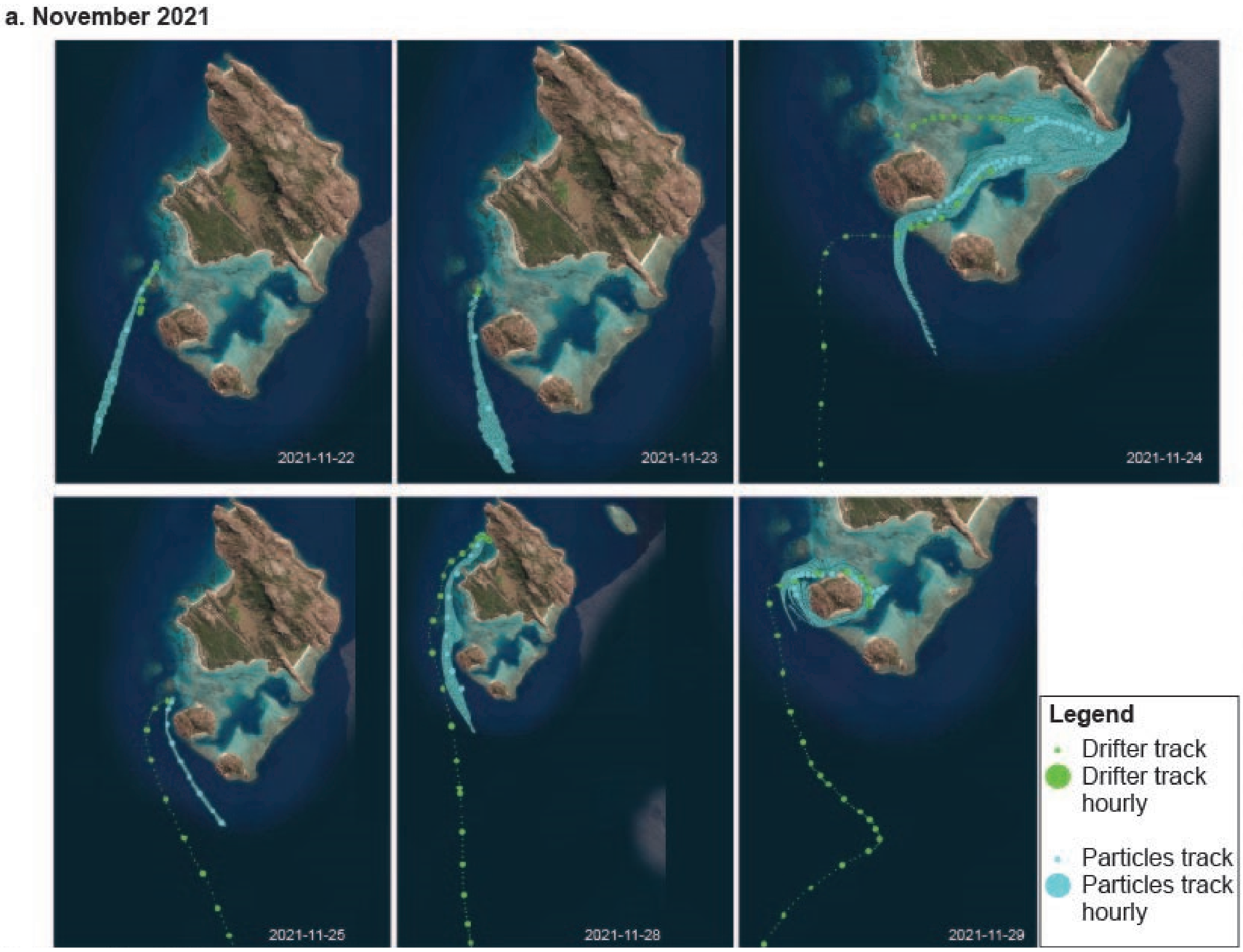

Figure 9: Comparison between modelled particles tracks and observed drifter tracks at Lizard Island in November 2021 (from Gouezo et al., 2024).

7 Hydrodynamical Model: details and limitations

Hydrodynamical model

The Environmental Modelling Suite (EMS) (https://research.csiro.au/cem/software/ems/) was employed for the inshore Palm Island reefs and offshore Capricorn Group reefs. EMS has a dynamical core and also includes libraries for sediment transport, biogeochemistry, waves and tracer statistics.

There are currently two supported dynamic cores for solving hydrodynamic variables:

1.) SHOC – Sparse Hydrodynamic Ocean Model (Herzfeld, 2006); and,

2.) COMPAS – Coastal Ocean Marine Prediction Across Scales.

SHOC is evaluated on an orthogonal curvilinear grid that allow resolution optimization, whilst COMPAS is evaluated on an unstructured mesh.

Both dynamical models are applicable on spatial scales ranging from estuaries to regional ocean domains. They are based on the primitive equations: the equations of momentum, continuity and conservation of heat and salt, employing the hydrostatic and Boussinesq assumptions.

Outputs from the model include three-dimensional distributions of velocity, temperature, salinity, density, passive tracers, mixing coefficients and sea-level. Inputs required by the model include forcing due to wind, atmospheric pressure gradients, surface heat and water fluxes and open-boundary conditions such as tides and low frequency ocean currents

Detailed Science and User Manuals for SHOC and COMPAS can be downloaded from https://research.csiro.au/cem/software/ems/ems-documentation/.

Forcing

The ocean boundary forcing consists of daily average fields of three-dimensional velocities, sea level, temperature and salinity. Open ocean boundary forcing and initial conditions are from the global OceanMAPS model, operated by Bureau of Meteorology (http://www.bom.gov.au/oceanography/forecasts/site-help.shtml) .

Surface atmospheric fluxes (momentum, heat and freshwater) at 1-hour intervals are provided by the Bureau of Meteorology's ACCESS-R atmospheric models with a resolution of ~12 km (http://www.bom.gov.au/australia/charts/about/about_access.shtml).

Limitations

The shallow bays, capes, channels, lagoons and subsurface topographic features can influence the development of dynamical features that can dominate the advection and dispersal of larvae locally. This is why the implementation of 10's to 100's of m resolution models in shallow coastal areas requires bathymetry and coastline products at the same fine scale spatial resolution. In the GBR, we can use the 30 m resolution Beaman bathymetry (Beaman, 2017), but if local high-resolution products are available, they should be used.

At the scale of a reef and a lagoon, the fine scale rugosity of the benthos can impact the boundary layer and turbulence, and modify the propagation of the tidal signal. In the examples described in this SOP, we used a uniform single value bottom friction parameter. Using a 2D spatially variable bottom friction parameter should be investigated in the future, to improve the performance of the hydrodynamical models.

The structurally complex reefs can impact the ocean circulation near and around them, creating areas sheltered from the offshore circulation, where currents are weak. The impact of the reef matrix on the circulation is not represented by the hydrodynamical model. It is also important to note that tiltmeters are often deployed next to target sheltered reefs, and in that case the comparison with the model is difficult.

In coastal settings, the resolution of the atmospheric forcing is also critical. If the sea breeze, the effect of island shadows, and small-scale fronts are not represented in the 12-km atmospheric forcing, the wind-driven ocean circulation will be missing small-scale features.

The interaction of currents and waves as well as waves breaking over reef can modify the local currents (Gourlay and Colleter, 2005) and connectivity patterns (Grimaldi et al., 2022). In the model implementation described in this SOP, the wave impact on current is not accounted for. However, it could be added when using the unstructured grid and the COMPAS dynamical core.

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9 Acronyms

Acoustic doppler current profiler (ADCP)

Correlation coefficient (cc)

Environmental Modelling Suite (EMS)

Great Barrier Reef (GBR)

Mean absolute error (MAE)

Root-mean-square error (RMSE)