Improving certainty in marine ecosystems: a biophysical modelling approach in the remote, data-limited Gulf of Carpentaria

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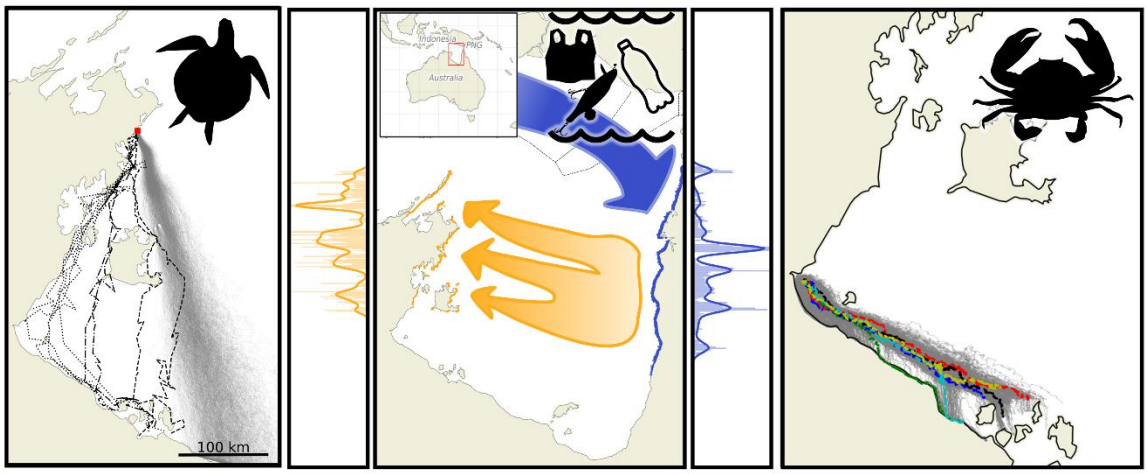
Graphical Abstract



Highlights

- Remote data-limited locations need creative scientific enquiry and participation with Indigenous and commercial communities
- Post-nesting migrating Green turtles swim strongly against currents and use coastal cues to navigate to foraging grounds
- Marine debris in the Gulf of Carpentaria has been underestimated in past studies
- Giant mud crabs (*Scylla serrata*) used selective tidal stream transport to migrate 200 km in 28-35 days
- Biophysical modelling could be adopted globally in remote and data-limited locations to advance ecological knowledge

Abstract

Remote, data-limited marine environments are poorly understood, making conservation and resource management major challenges in the rapidly changing environment. High field data collection costs results in sparse data, which limits the traditional scientific approach to understand the functioning of these remote ecosystems. The Gulf of Carpentaria is a vast,

remote and data-limited region in northern Australia that is vulnerable to rapid changes due to climate change and externally derived marine debris, but extremely difficult and costly to access. This study aimed to test a method of improving certainty in ecological and physical processes in the Gulf of Carpentaria by maximising the use of alternative biophysical data from local Indigenous-owned and managed land and sea country, to elucidate the ecosystem functioning. We investigated the role of currents and wind in previously published Green turtle (*Chelonia mydas*) post-nesting satellite tracking migration data, and found they had no influence on the turtles' migration path. We also found that turtles did not use compass bearing alone to make their migration, rather they seemingly used coastal cues to 'leap-frog' along the coastline until they reached their foraging grounds. Next, we identified the spatio-temporal distribution of floating marine plastics using Indigenous-lead citizen science coastal marine debris surveys, and found that previous studies have underestimated marine debris presence in the region. Finally, biophysical modelling suggests that large migrations (>200 km in 28-35 days) of tagged male Giant mud crabs (*Scylla serrata*) against prevailing winds, currents and tides were possible by using selective tidal stream transport and directional swimming. These case-studies demonstrate the effectiveness of explorative biophysical modelling supported by alternative field data, and improve certainty in ecological processes with significance in culture, conservation and commercial values in the region.

Keywords: Marine debris, Marine turtle ecology, Selective tidal stream transport, Giant mud crabs, Remote oceanography

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1. Introduction

Human influences reach the most remote and untouched marine ecosystems on the planet (Magnan et al. 2021). Socio-economic activities and human-induced changes lead to marine heatwaves, months-long events of mean sea level changes, and increased marine debris (Österblom et al. 2017), resulting in proximate stressors on marine ecology and coastal livelihoods. While much of the research on these effects relate to temperate systems, tropical environments do not escape impacts (Harris et al. 2017; Wolanski et al. 2017). Certainty in foundational ecological knowledge is required for effective management and conservation, however, uncertainty is a major aspect of remote and data-limited locations, where exorbitant field monitoring costs result in sporadic, infrequent, or short-term ecological studies that inadequately identify long-term impacts of environmental stressors. Researchers and managers need alternative methods of preliminary marine ecological investigations so that they can reduce expensive, exploratory fieldwork in very remote locations.

Biological-physical modelling ('biophysical modelling') is a low-cost and unobtrusive method of exploring and quantifying the origin, transport paths and fate of animals, particles and objects in the ocean (Critchell et al. 2015; Le Port et al. 2017; Lebreton et al. 2012; Swearer et al. 2019). Biophysical modelling is interdisciplinary, combining computational oceanographic modelling with biology and physics to estimate the movement of animals or objects in the ocean. Biophysical modelling reaches beyond disciplinary boundaries and scales (Little et al. 2017), producing outcomes that can inform connectivity (Godley et al. 2010; Ospina-Alvarez et al. 2020; Treml et al. 2008; Wolanski, 2016), fisheries management (Condie et al. 1999; Kough et al. 2013; Le Port et al. 2017; Thomas et al. 2016), conservation (Hold et al. 2021; Jahnke et al. 2018; Mertens et al. 2018), direct and optimise research (Van der Stocken et al. 2019), and quantify population structures and animal behaviour (Kingsford et al. 2021; Leis 2007; Schlaefer et al. 2021). A major challenge in biophysical modelling is attaining adequate empirical information that is needed for robust outcomes (Swearer et al. 2019). Inadequate data in remote locations

impedes data-led environmental management. Therefore, alternative approaches to gaining knowledge is needed.

Participatory and diverse social contributions to western scientific methodologies and governance in very remote locations are being increasingly adopted (Davies et al. 2020; Jones et al. 2013; Stori et al. 2019), and there is potential for this approach in the field of biophysical modelling. Forging relationships outside of academia enhances interdisciplinary ecological research (Blythe & Cvitanovic 2020; Danielsen et al. 2007; Jones et al. 2013), and is especially relevant in remote marine locations (Caill-Milly et al. 2021). The top thirteen nations with the highest proportion of ocean as a percentage of sovereign area are small, tropical island nations, also referred to as large ocean nations (Degnarin & Stone 2017). These nations do not have the means to undertake long-term and broadscale oceanographic research, despite their populations being disproportionately dependent on the ocean whilst also the most vulnerable to the cumulative impacts of anthropogenic threats such as climate change and marine debris (Boyce et al. 2020; Horton & Barnes 2020).

This study focuses on the very remote and data-limited Gulf of Carpentaria (GoC) in tropical Australia (Figure 1), which is vast, sparsely populated, has a high proportion of Indigenous-owned and managed land, and hosts multiple small-scale commercial fisheries. The GoC is nested in one of the most extensive, environmentally intact regions (e.g. low human footprint) in the world (Jones et al. 2018; Stuart-Smith et al. 2013; Venter et al. 2016). It is a large (~370,000 km^2) and relatively shallow (~60 m average depth) semi-enclosed sea in northern Australia, defined by the 'u-shaped' land boundary of the Queensland and Northern Territory coastlines, and a northern border approximately between the Wessel Islands and Cape York (Patterson, 2019)(Figure 1). Structured and coarse grid hydrodynamic models, with horizontal cell resolutions of ~5 km (Condie, 2011) ~11 km (Ridgway & Godfrey 2015) and 18.53 km in Wolanski (1993) and Oliver and Thompson (2011), have shown that the regional circulation is driven by tides and seasonal wind. A clockwise gyre exists during the southern hemisphere winter (May – October) caused by persistent and strong southeasterly trade winds. The wet season occurs during the southern hemisphere summer (October – April), and active monsoon pulses and troughs set in for weeks to months, resulting in an average of five cyclones annually.

The population along the ~2,500 km long coastline of the GoC is ~14,900 people, spread across 12 coastal towns and the majority are Indigenous Australians (Australian Bureau of Statistics 2016). The GoC has high-value commercial fisheries, notably crustaceans and finfish (Dambacher et al. 2015) and hosts smaller-scale fisheries such as spanish mackerel, pearl oystser, mollusc, aquarium, and mud crab fisheries. The GoC is an internationally significant critical nesting habitat for four of the five marine turtle species inhabiting Australian waters (Department of the Environment and Energy 2017; Pavey et al. 2009).

This study takes a novel approach to reducing marine ecological uncertainties in the GoC, and demonstrates methods that could be adopted in other remote and data-limited locations throughout the world. Here we present three interdisciplinary biophysical modelling case studies that improve certainty in understanding the (1) migratory behaviour of post-nesting Green turtles (*Chelonia mydas*), (2) spatio-temporal distribution of floating marine plastics, and (3) behavioural long-distance (~200 km) movement of male Giant mud crabs (*Scylla serrata*). We utilise alternative data, collected for purposes unrelated to this study and with inherent cultural, conservation and commercial value, and provide focus for future research in the data-limited GoC. This approach is transferable across disciplines and geography in remote and data-limited marine environments worldwide.

1.1. Environmental risks in the Gulf of Carpentaria

Risks to the broadscale environmental quality in the GoC arise from marine heatwaves and sea level rise associated with climate change and marine debris originating from adjacent seas and neighbouring countries (Patterson, 2019). Shallow, intertidal mudflats can heat to extreme temperatures and the water temperature on an incoming tide can reach at least 44°C (Mounsey 1989). The GoC is particularly vulnerable to climate change due to the shallow waters (max ~80 m), increased evaporation rates and warmer seas (Duke et al. 2017). Marine heatwaves, defined as the exceedance of seasonally varying 90th percentile climatology for at least five consecutive days using daily temperature (Hobday et al. 2016), have increased in intensity and length over the past two decades in this region; while the average annual occurrence is 3.5 times per year, six marine heatwaves occurred in 2016 (Benthuysen et al. 2018). More than 7,400 ha of mangroves were severely damaged in a 2016-17 dieback related to marine heatwaves (Duke et al. 2017).

Most of the marine debris in the GoC comprises derelict fishing nets, or 'ghost nets' (measured by weight), and floating plastics (measured by count), amongst other materials (Gacutan et al. 2022). The marine debris washing up on shorelines around the GoC is seemingly relentless and pervasive. The population density is far too low for the marine debris to originate locally, and local communities are not resourced to provide adequate clean-up or political interventions. There have been no overarching studies to describe the marine debris spatio-temporal distribution or quantify the effects of marine plastic debris to the communities or ecosystems within the GoC.

2. Methods

2.1.1. Study Objectives

The objective of this study was to utilise unconventional data sets to address ecological questions in a very remote and data-limited location that is subjected to the effects of climate change and anthropogenic threats. We utilise existing data sets (Table 1) to support the development and calibration of biophysical modelling for three locally-relevant case studies. The use of unconventional and un-tailored field data is an important factor in the potential technological transfer of these methods to other very remote and data-limited locations, where field-based data collection may be too expensive. The case studies developed in this study broadly address values in culture, conservation and commercial fisheries (Table 1).

Table 1: Summary of the three biophysical modelling case study objectives, research questions, and the original datasets that were utilised in this study and their value in the Gulf of Carpentaria.

Case Study	Biophysical model objective	Research questions	Existing data utilised in this study	Driver of existing data collection	*VALUE*
(1) Post-nesting migrating green turtles	Investigate the role of currents and wind in the migration patterns of female post-nesting Green (*Chelonia Mydas*) turtles	*What drives turtle migrations? Are migration routes vulnerable to environmental change?*	GPS tracking of post-nesting marine turtles during peak of nesting season (Kennett et al. 2004)	Indigenous land and sea managers and owners in Northeast Arnhem Land sought to understand the migratory routes of Green turtles nesting on a local beach	***CULTURAL***

(2) Spatio-temporal distribution of floating marine plastics	Describe the temporal and spatial distribution of floating marine plastics in the GoC	*Can the spatio-temporal persistence and coverage of marine debris be quantified using biophysical models and beach clean-up data?*	Indigenous ranger-led marine debris beach surveys: counting and categorisation in two different Indigenous communities (unpublished)	Marine debris washes up on the eastern and western sides of the GoC, causing habitat degradation	***CONSERVATION***
(3) Anomalous male Giant mud crab migrations	Investigate the movement mechanisms of anomalous male Giant mud crab (*Scylla serrata*) migrations	*What were the possible movement mechanisms used by the mud crabs to migrate ~200 km in under 31 days?*	Government-led tagging study of Giant mud crabs with participating commercial fishers, returning two tagged crabs with anomalously long migration distances (unpublished)	Very low commercial catch rates of Giant mud crab (*Scylla serrata)* in 2016, indicated in commercial fisher logbooks	***COMMERCIAL***

2.2. Hydrodynamic model description, governing equations and calibration

The water circulation was modelled as a 2-D barotropic model using the Second-generation Louvain la Neuve Ice-ocean Model (SLIM; www.climate.be/slim)(Deleersnijder et al. 2009). SLIM is a discontinuous Galerkin finite element model which solves the shallow water equations to calculate water elevation (η) and the current velocity (u):

$$\frac{\partial \eta}{\partial t} + \nabla . (\eta u) = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + (u\nabla) . u = -f e_z . u - g\nabla\eta - C_D|u|u + \frac{\tau}{\rho H} + \frac{1}{H}\nabla . [Hv(\nabla u)] \quad (2)$$

Where H is the water column depth, f is the Coriolis factor, e_z is a unit vector pointing vertically upwards, C_D is the bottom stress coefficient calculated using $C_D = \eta^{(1/6)}/n$, and n is the manning's n coefficient (0.0025 $m^{-1/3}s$), τ is the surface wind stress, g is the gravitational acceleration, ρ is the water density and v is the horizontal eddy viscosity as described in Lambrechts et al. (2008) and Thomas et al. (2014).

The unstructured, triangular model grid varies in size from approximately 400 m near the coastlines and archipelagos to approximately 10 km offshore (Figure 1 C), which is an improvement in horizontal resolution from the previous models (Condie, 2011; Lambrechts et al. 2008; Oliver & Thompson 2011; Ridgway & Godfrey 2015), and similar to another contemporary SLIM model in the region (Schlaefer et al. 2022). The modelled and reconstructed tides were validated at six locations around the GoC and the root mean square error (RMSE) ranged between 0.1 and 0.16 m (Figure 1 B). The hydrodynamics were verified by comparing modelled tidal ellipses with field tidal ellipses from Wolanski (1993)(Figure 1 D and E), described in more detail in S1.

An implicit, second-order Runge-Kutter scheme was used to account for stability in the time step, reduce computational cost and allow for a wetting and drying regime, described in Le et al. (2020). The model geometry was derived from the 250 m Geoscience Australia (2009) bathymetry, and surface wind reanalysis at 12.5 km resolution and hourly time steps were applied across the model domain (Su et al. 2019). The open boundary conditions were forced at five points along the ocean boundaries; two on the western boundary and three on the eastern boundary. Four of the tidal boundary conditions were derived using AusTides tidal predictions

from the Australian Hydrographic Office. The tidal constituents at False Cape (Figure 1 A) were derived from a hydrodynamic model calibration in Condie et al. (1999). The tides were assumed to vary linearly along the open boundary.

The model is depth-integrated, which we consider appropriate for the applications described in this paper as they focus on surface waters (case studies 1 and 2: turtles and marine debris) and shallow, coastal water (case study 3: mud crabs). It is possible that there may be vertical flow velocities that affect horizontal flow at the surface or in shallow, coastal waters, however, there are no contemporary or historical field data to provide model verification or validation for this aspect of the flow. Three hydrodynamic models using identical settings were run over three different time periods; one for each case study (Table 2). Each hydrodynamic model was run for a 'spin-up' period of at least four days to allow the hydrodynamics to stabilise before running the biophysical model, determined by comparing calculated tides with the model sea level as in Figure 1 (B). The duration of each hydrodynamic model differed depending on the modelling methodology of the case studies (Table 2).

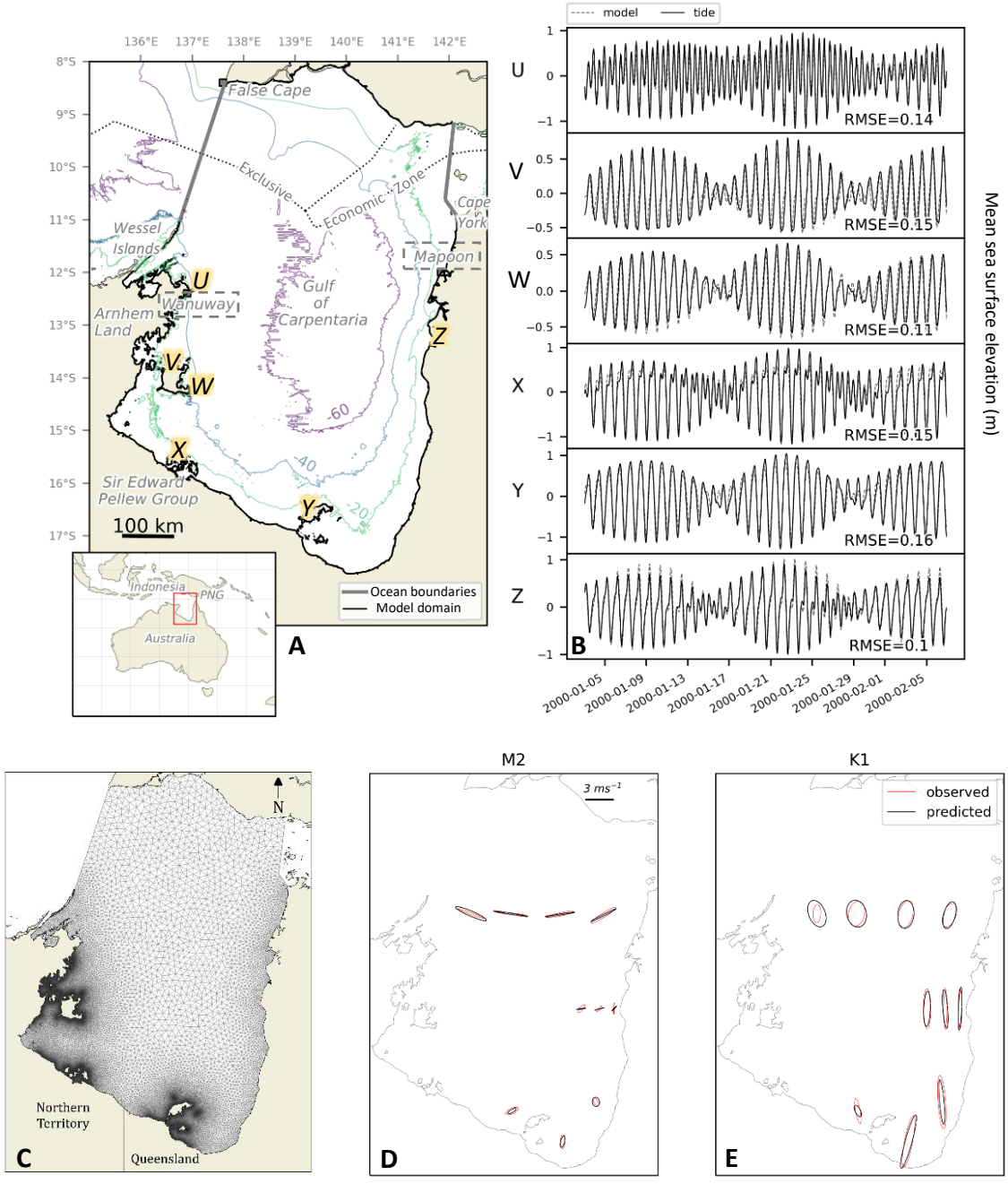

Figure 1: (A) Study area and six locations used for hydrodynamic model calibration along the coast of the Gulf of Carpentaria. (B) The six timeseries plots (U-Z) compare mean sea level (m) model output (dashed) with tidal predictions (solid) and report the root mean square error (RMSE) for each location comparison. (C) The SLIM model mesh, (D and E) the M2 and K1 observed (Wolanski, 1993) and predicted tidal ellipses.

2.1. Biophysical applications

2.1.1. Biophysical model description

An offline Lagrangian advection-diffusion module of SLIM, referred to herein as the 'biophysical model' used the output of the hydrodynamic model to calculate the particle positions between model time steps using a random walk formulation of the 2-D advection-diffusion equations described in Spagnol et al. (2002) and Hunter et al. (1993). The model particles at location X_t are displaced to location X_{t+1} at each time step (t and $t+1$) (eq. 3), where Δt is the time step (900 s), R_n is a horizontal vector of zero-mean random numbers with variance r.

$$X_{t+1} = X_t + v_n \Delta t + \frac{R_n}{\sqrt{r}} \sqrt{2K_h \Delta t} \quad (3)$$

$$v_t = \left(u + C_w u_w + u_s + \frac{K_h}{H} \nabla H + \nabla K_h \right) \Big|_{x_t} \quad (4)$$

The advective velocity of the particle is v_t (eq. 4), where u is the the depth averaged horizontal water velocity, which is an output of the hydrodynamic model, u_w is the wind velocity, C_w is the wind drift coefficient, which represents the proportion of wind that influences the particle movement, u_s is a constant swimming vector, η denotes water depth which is also a hydrodynamic model output, K_h is the horizontal diffusivity coefficient calculated on a sub-element scale for each element using the Okubo (1971) scheme, and H is the water column depth.

We developed an independent formulation of v_t (eq. 4) for each case study, where the particles represent turtles, floating marine plastics and adult male mud crabs, described in detail in the case study methods. We calibrated each biophysical model to previously collected field data to investigate the movement mechanisms of turtles and mud crabs, and the spatiotemporal distribution of marine debris at sea. In every biophysical model, the hydrodynamics are inherently captured in the particle movements, whereby any other movement characteristic applied to the particle (e.g. swim speed) is in addition to its movement caused by the hydrodynamics.

The SLIM biophysical model has two particularly attractive features for use in this study; (1) it is very flexible and bespoke; complex particle movement mechanisms that represent animal movements based on the hydrodynamics can be easily implemented and adapted, and (2) the SLIM model is freely available, making it attractive for projects with little or no project funding. SLIM has been used widely for fine-scale (< 1km mesh size) studies of marine biophysics (Figueiredo et al. 2022; Frys et al. 2020; Hamann et al. 2011; Schlaefer et al. 2022; Wolanski et al. 2017) and of marine debris (Critchell et al. 2015; Critchell & Lambrechts 2016; Li et al. 2018). All particles were released as instantaneous releases to match the real release-time of turtles in case study 1 and mud crabs in case study 3. The marine debris instantaneous release is discussed in 2.3.3 and 3.2.2

Table 2: Biophysical model run times and calibration data

Case Study	Modelling methodology	No. Particles released	Biophysical model start and end date	Biophysical model duration	Particle seeding location	Particle release timing	Particle end timing and location
(1) Post-nesting migrating green turtles	Simulate turtle migration	1,000	15 Nov 1999 – 30 Nov 1999	15 days (longest turtle migration)	Turtle nesting beach	Date turtles started migrating	Date and location turtle reached foraging grounds

(2) Spatio-temporal distribution of floating marine plastics	Simulate 16 months of marine debris movement, capturing two wet seasons and one dry season	14,580	1 Jan 2008 – 1 May 2009	16 months (two wet seasons and one dry season)	Iterative backward calibration using particle end location as points of truth	Iterative backward calibration using known beach clean-up times to the nearest month	Month and location of Ranger marine debris surveys
(3) Anomalous male Giant mud crab migrations	Simulate precise male mud crab migration	1,000	27 May 2016 – 28 June 2016	31 days (longest mud crab migration duration)	Tagged mud crab release location	Date tagged mud crab was released	Date and location mud crab was re-captured

2.1.2. Case Study 1: Post-nesting, migrating green turtles

Green turtles (*Chelonia mydas*) are a circumglobal species with complex life histories. They nest approximately every 2-5 years (Azanza Ricardo et al. 2013; Broderick et al. 2003; van Buskirk & Crowder 1994) and typically migrate from foraging grounds to their natal beach (Limpus et al. 1992), where they nest several times over 3-5 months and then migrate back to their foraging grounds, which can be several hundred to thousands of kilometres away. The physical mechanisms of navigation are thought to be based on a crud internal geomagnetic map and possibly olfactory (e.g. wind) cues near their foraging grounds (Hays et al 2018).

Indigenous land owners in northeast Arnhem Land (Figure 1 A) sought to understand the location of the foraging grounds of the green turtles that nest in their community, so that they could identify connections with other communities, or 'co-managers' (Kennett et al. 2004). For the Yolngu people in Northeast Arnhem Land at the nesting site, and the Yanyuwa people of the Sir Edward Pellew Group at the foraging sites (Figure 1 A), marine turtles are culturally embedded and inseparable in Indigenous law, history, sustenance, spirituality and being, and are manifested in dance, art, songs, dreaming and stories (Bradley 1997; Kelly 2015; Kennett et al. 2004; Munungurritj 1997; Yunupingu 1997). Establishing these co-managers was an important aspect of culture and life.

Researchers worked with traditional land owners and managers to fix satellite tracking tags to 20 post-nesting female Green (*Chelonia mydas*) turtles, during the peak nesting month of November in 1998 (n = 5) and 1999 (n = 15) on a very remote beach in Northeast Arnhem Land. All 20 individuals migrated south relatively short distances ($\overline{x}$ = 364.5 ± 124.4 km) to the Sir Edward Pellew Island Group at average speeds of 0.3 ms^{-1} to 0.7 ms^{-1} (Kennett et al. 2004). We categorised the turtle tracks into three migratory groups by differentiating their movement patterns into coastal, semi-coastal and non-coastal migrations (Figure 3), which were used to guide the biophysical model calibration, a technique also used in Cerritelli et al. (2018).

Biophysical models have been used to investigate the potential role of ocean currents on the movement of hatchlings (Godley et al. 2010; Hamann et al. 2011; Le Gouvello et al. 2020; Lalire & Gaspar 2019) but models are limited due to lack of empirical data on hatchling movement behaviour, such as swim speed and direction. The influence of ocean currents on adult turtle migrations has been investigated (Galli et al. 2012; Luschi et al. 2003) but these typically use low spatial (e.g. 25 x 25 km) and temporal (typically 5 days interval) resolution altimetry data, which is too coarse for the GoC and inappropriate for shallow (<80 m) continental shelf environments such as the GoC.

Here we use the historical satellite turtle tracks and a biophysical model to investigate the role of currents and wind in the turtle migration patterns with the overall aim of investigating the green turtle movement behaviour during their migrations. To test the influence of currents and wind on turtle migrations, we developed biophysical models to test passive drifting, and four combinations of directional swimming and wind drift (Table 4). The models calculated the advective particle velocity for each time step using eq. 4, which added a constant 'swim' speed and direction vector (u_s) to the physical model forcings. The model was calibrated iteratively to swim speed and direction until the model was calibrated to match the satellite tracks in space (Figure 3) and time (S3).

Turtle swim speeds from publications provided a rough guide for determining the modelled swim speeds, however, published studies tend to present calculated speeds using total distance over time, and seldom account for currents that influence true migration velocity (Luschi et al. 2003). Therefore, the modelled swim speeds were expected to be different to published swim speeds. There was no algorithm to deter particles from reaching the coastline and getting trapped because the mechanisms for turtles moving to and from the coastline are unknown.

Surface wind drift may be a mechanism by which turtles move to save energy, but is difficult to test in the field. Surface wind drift is simple to test in a biophysical model using wind drift coefficients. Wind drift studies from deceased turtle carcasses found wind drift coefficients between 1.14 – 3.59% (Nero et al. 2013; Santos et al. 2018). Migrating green turtles are known to remain at the surface most of the time but regularly dive during migrations (Hays et al. 2001; Rice & Balazs, 2008) and hence are not constantly exposed to surface winds. Therefore we tested a wind drift coefficient of 1%, which is slightly lower than the minimum coefficient for a constantly floating turtle carcass (Santos et al. 2018).

2.1.3. Case Study 2: Spatiotemporal distribution of floating marine plastics

Understanding the spatio-temporal distribution of marine debris and its impact on marine animals is a global research priority (Nelms et al. 2016; Provencher et al. 2017; Vegter et al. 2014). At least 12 of the 17 United Nations Sustainable Development Goals (United Nations 2015) are impacted by plastic pollution, and establishing and reaching clean-up targets are a significant global challenge (Walker 2021). Juvenile seabirds and sea turtles are at greater risk of plastic ingestion than in other life-stages (Acampora et al. 2014; Nelms et al. 2016; Schuyler et al. 2016), and plastic ingestion contributes to a higher likelihood of death. For example, a study found a 50% probability of mortality once a turtle had ingested at least 14 pieces of plastic (Wilcox et al. 2018). Accumulated plastics on beaches can obstruct nesting sea turtles and hatchlings (Triessnig et al. 2012), and increase incubation temperatures (Carson et al. 2011) leading to higher proportions of female turtles. Plastic ingestion by sea turtles is most likely to occur in the ocean (Schuyler et al. 2016). A first step to assessing the risk of plastic ingestion to marine megafauna is to map its spatiotemporal movement in the ocean.

Marine debris has been a persistent problem in the GoC since at least 1997 (Yunupingu 1997), however there have been no studies to broadly describe the spatio-temporal extent and movement of the debris, except for those focussing on derelict fishing gear ('ghost nets') and their potential impact on marine species (Edyvane & Penny 2017; Hardesty et al. 2021; Wilcox et al. 2013). The beached marine debris in the GoC has previously been dominated by derelict fishing gear (Edyvane & Penny 2017), however, in the past decade, indigenous land and sea rangers, tourists and the media have reported that marine debris appears to be mostly foreign domestic waste.

Land and sea ranger groups have been conducting annual coastal marine debris clean-ups on two stretches of beach in the GoC for at least a decade and have recorded the type, quantity

and location of beached marine debris at specific times of the year. The Dhimurru Rangers undertake their clean-up at Wanuway (Figure 1 - northwestern GoC, and Figure 2), and the Mapoon Land and Sea Rangers undertake their clean-up at Mapoon (Figure 1 - northeastern GoC). Although the indigenous-led clean-up data have not been explicitly collected for scientific investigation, the citizen science data is appropriate for this investigation, because they include quantity, quality, location and timing.

Although it has never been explicitly documented, several lines of evidence suggest that marine debris in the GoC originates from neighbouring countries to the north: (1) the extremely low population density throughout the GoC where mismanaged waste is very low (Jambeck et al. 2015), (2) the extremely high population density in Southeast Asia where mismanaged waste is very high (Jambeck et al. 2015; Lebreton et al. 2017), (3) prevailing ocean winds from Indonesia in the northwest matching the timing of beached rubbish on the eastern side of the GoC, (4) notes taken during the ranger and community clean-ups that many of the waste products have Indonesian labelling, and (5) supporting literature (Lebreton et al. 2019; Lebreton et al. 2012; Purba et al. 2021; Schmidt et al. 2017). Establishing the precise origin of the marine debris is an essential step towards its mitigation.

Figure 2: Example of the access road to the Wanyuway marine debris clean-up site in July 2022. Photo credit: Ruth Patterson.

First we assessed marine debris clean-up data from Mapoon and Wanuway beaches to determine whether there were any differences in marine debris accumulation on the opposite-facing beaches. Both ranger groups do a 'clean sweep' of a recorded beach length each year, sorting and counting debris into categories following different methodologies. Mapoon used the Australian Marine Debris Initiative (AMDI) methodology (Australian Marine Debris Initiative 2018), facilitated by Tangaroa Blue Foundation staff and volunteers. This methodology involves sorting the debris into categories (123 options) and then counting and weighing each category. The Wanuway group uses a methodology developed in-house over the past two decades, which involves sorting the debris into categories (60 options), weighing all the categories, and counting

some categories in some years. The Mapoon data was sought from the Tangaroa Blue Australian Marine Debris Database and delivered in an excel spreadsheet. The Wanuway data was sought directly from the Dhimurru Rangers, delivered in the form of annual internal (not publicly available) marine debris reports. We digitised the information from the Wanuway reports into a spreadsheet format. The Dhimurru Rangers surveyed a set length of beach at Wanuway (3.5 km), while the Mapoon Land and Sea Rangers surveyed varying beach lengths (mean = 8.65 km, st.dev = 2.4). We converted the marine debris to count per km of surveyed beach for both beaches. The objective of assessing the marine debris data was to explore any differences between categorical patterns between the two opposite-facing beaches on either side of the GoC. We used python (v. 3.8.10) to plot the results.

Next, we used a biophysical model and evidence from the two surveyed beaches to determine the likely origin of the marine debris and map its spatiotemporal distribution in the ocean. The spatio-temporal distribution is essential for finding patterns that can help to elucidate its origins and transport pathways, assess its risk to wildlife in the open-ocean, and help local communities bring global awareness of the marine debris (Figure 2) on their remote and previously pristine shorelines. A marine debris model was adapted from (Critchell & Lambrechts 2016) which simulated the dispersal of surface particles. A wind drift coefficient of 3% was applied to the model particles, matching previous studies for similar types of floating rubbish; 0-5% (Maximenko et al. 2018) and 1-4% (Critchell & Lambrechts 2016). Evidence from the ranger surveys suggested a net zero accumulation of marine debris may occur in the GoC due to seasonal winds, meaning that opposing seasonal winds shift marine debris from the coastline to the sea during one season, and the sea to the coastline during the opposite season resulting in net zero accumulation on an annual scale. Turrell (2018) describes this as 'Variable Wind and Water Level Interactions', which we represented in the model using a deposition, resuspension and burial algorithm at the model shoreline, determined by the tide level (eq. 6-8) and particle trajectory towards the coastline, which is influenced by the wind (eq. 4).

Deposition: $$P_{water} \rightarrow P_{coast}\ if\ \eta''(x_1) < 0 \quad (6)$$

Resuspension: $$P_{coast} \rightarrow P_{water}\ if\ \eta(x_2) > H(x_1)\ and\ \eta''(x_2) < 0 \quad (7)$$

Burial: $$P_{buried} = K_B P_{coast} \quad (8)$$

where $\eta''(x_2) < 0$ is high tide and K_B is a burial coefficient set to 5%.

The marine debris model was seeded at the edge of the model domain (Figure 5 A) and the 14,580 particles were released instantaneously with 10 particles evenly spaced by 100 m. The presence and absence of marine debris on beaches is known on approximately monthly time resolutions in two different locations (pers comm. Mapoon Land and Sea Rangers; pers comm. Luke Playford, Dhimurru Rangers) and has been observed for decades (Edyvane & Penny 2017). To determine the model seed locations, we used an iterative, backward calibration to determine the possible origin of particles within the model domain. This involved running scores of models to determine seeding locations resulting in beached particles that matched the Ranger observations on the two opposite-facing beaches at different times of the year. A past study that modelled ghost nets in the GoC used a random seeding algorithm (Wilcox et al. 2013), which may be appropriate for slow-moving ghost nets. However, using evidence from the rangers that the marine debris came in seasonal waves, we used an instantaneous release method because it was useful in its simplicity for tracking a temporal unit of marine debris.

2.1.4. Case Study 3: Anomalous male Giant mud crab (*Scylla serrata*) migrations

The Giant Mud Crab (*Scylla serrata*; infraorder Brachyura, family Portunidae, referred to herein as 'mud crab') is a highly exploited commercial species and the most widely distributed species

within the genus *Scylla*, occurring throughout the Western Indian Ocean through to Japan, northern Australia and the Pacific Islands (Brown 1993; Le Vay 2001).

Adult male mud crabs are poorly studied, although their overall movement characteristics are are thought to be small-scale, with home ranges of ~1 km in mangroves and estuarine environments (Alberts-Hubatsch et al. 2016), 3.7 – 6.6 km in open muddy environments (Hyland et al. 1984; Tait et al. 1985), and have been found not to exhibit homing (Alberts-Hubatsch et al. 2016). Female adult mud crabs migrate offshore to spawn, cued by temperature and salinity changes (Hewitt et al. 2022) and have been recorded to migrate distances of up to 40 km in less than a week (Hewitt et al. 2022). Migrating these long distances are made possible through tidal and hydrological patterns throughout their life-cycles, employed by mud crabs and other marine invertebrates (Alberts-Hubatsch et al. 2016; Devries et al. 1994; Epifanio & Cohen 2016; Pineda et al. 2007). Selective Tidal Stream Transport (STST) is a horizontal movement mechanism adopted by marine animals, including mud crabs, to travel efficiently in one direction, using either flood or ebb tides. Marine animals implement STST by moving vertically into the water column when there is either shoreward (flood tide transport) or seaward (ebb tide transport) movement, and moving through the water column to the seabed when the tide reverses. Acoustic tracking studies have indicated that female mud crabs use STST as a migratory movement mechanism to move from rivers towards the ocean (Alberts-Hubatsch 2015; Hewitt et al. 2022). There have been no tagging studies on adult male mud crabs, although Tait et al. (1985) anecdotally documented a 42 km migration within three months by a male mud crab on the east coast of Australia.

In the GoC, commercial mud crab catch rates declined significantly from 2009 to 2016 in the Northern Territory and from 2013 to 2016 in Queensland, despite different harvest strategies between the jurisdictions; the former harvests both male and female whereas the latter only harvests males (Robins et al. 2020). The lowest annual harvest occurred in 2016, coinciding with a suite of other environmental factors comprising low freshwater runoff leading to high salinity, significant mangrove dieback, high sea surface temperatures and marine heatwaves (Benthuysen et al. 2018). Uncertainties due to data limitations were a major challenge for investigating the decline in the commercial catch in the region (Robins et al. 2020). The low commercial catches of mud crab in the GoC in the first quarter of 2016 prompted a tagging study to determine the harvest rate of this species. A total of 899 crabs of both sexes were tagged with yellow, Hallprint T-bar tags near the entrance to the Roper River (denoted RR in Figure 7 A) between April and July 2016. Only crabs of 120 mm carapace width or above were tagged, with the tag inserted at the rear of the carapace, where it joins the abdominal flap, and offset to the right to avoid internal organs.

Several dozen tagged mud crabs (specific numbers were not available) were recaptured by commercial fishers, recreational fishers and research scientists in subsequent weeks, usually within a couple of kilometres of RR. However, two male mud crabs, tagged on the 27th of May 2016 moved approximately 200 km in a southeasterly direction from RR, one to BB after 28 days at liberty and the other to WI after 31 days at liberty (see Figure 7 A for locations). The precise time of day of the mud crab recaptures were not recorded.

We used biophysical modelling to investigate how the two tagged mud crabs could have migrated 200 km within 31 days. Previous studies that investigated long-term female mud crab movements measured overall movement speed, however, did not measure current speed so true swimming speeds are unknown (Alberts-Hubatsch 2015; Hewitt et al. 2022). True swimming velocities of mud crabs have not been described in any life stages, and experiments on other portunid crabs tend to focuses on early life stage vertical swimming behaviour (Caracappa & Munroe 2019) .

Since long-distance adult male mud crab movement mechanisms have not been described in the literature, we investigated six different movement mechanisms to investigate what behaviour would result in model particles undertaking the 200 km migration within 31 days. The scenarios were: MS1 passive dispersion, MS2 wind drift, MS3 constant directional swimming at 0.07 ms^{-1}, MS4 Selective Tidal Stream Transport (STST) with no swimming, MS5 STST with intermittent swimming toward the southeast on ebbing tide at 0.12 ms^{-1}, and MS6 STST with intermittent swimming only when water velocities moved in a southeasterly direction, which could occur during either ebb or flood at 0.12 ms^{-1} (equations given in Table 3). The speeds for constant directional swimming (0.07 ms^{-1}) and intermittent directional swimming (0.12 ms^{-1}) represent the minimum speeds the crab would have to swim to reach the recapture locations within 31 days, which was evaluated by trial and error in a series of preliminary model runs. Freshwater outflow from RR was not included for a range of reasons: the rivers are not gauged, seasonal flow during May and June was likely to be low, and 2016 was reported as a particularly dry year. We assumed there were negligible effects of the river discharge on the coastal flow dynamics for the distance between the mark and recapture sites. If there was any residual freshwater flow not accounted for in the model, the river discharge was likely to follow the net water movement, which was opposite to the mud crab movements.

Table 3: Modelling scenarios used to determine male mud crab movement behaviour, where C_w is the wind drift coefficient, u_s is the mud crab swim velocity, u is the water velocity, η_t refers to sea surface height at timestep t, and $u_{(x)}$ and $u_{(y)}$ refer to the horizontal water velocity components, where $+u_{(x)}$ is eastward and $+u_{(y)}$ is northward.

Model Scenario	Modelled movement mechanism
MS1	Passive dispersion (eq. 4) where $C_w = 0$ and $u_s = 0$
MS2	Wind drift (eq. 4) where $u_s = 0$
MS3	Constant directional swimming (eq. 4)
MS4	STST on an ebbing tide with no swimming (eq. 4) where $C_w = 0$, $u_s = 0$ and $u > 0$ if $\eta_{t+1} < \eta_t$
MS5	STST and intermittent swimming toward the south east on an ebbing tide (eq. 4) where $C_w = 0$ and $\begin{Bmatrix} u \\ u_s \end{Bmatrix} > 0$ if $\eta_{t+1} < \eta_t$
MS6	STST and intermittent swimming with south easterly ebbing or flooding tide (eq. 4) where $C_w = 0$ and $\begin{Bmatrix} u \\ u_s \end{Bmatrix} > 0$ if $\begin{Bmatrix} u_{(x)} > 0 \\ u_{(y)} < 0 \end{Bmatrix}$

3. Results and Discussion

3.1. Case study 1

We used eleven of the twenty satellite turtle tracks available from the original study; six had no time of day associated with the GPS fixes, and three had few or no GPS fixes between the start and end of the migration (Kennett et al. 2004). The tracked turtles were coastal (n=7), semi-coastal (n=2) and non-coastal (n=2) migrators (Figure 3), nesting from the 4th – 7th of November, 1999, and began migrations from the 6th of November until the 6th of December, with migrations lasting 7 – 15 days. The non-coastal and semi-coastal migrators were on average faster (mean = 0.59 ms^{-1}, s.d. = 0.03) than the coastal migrators (mean = 0.42 ms^{-1}, s.d. = 0.03), however, this calculated movement speed does not take into account any physical processes such as currents.

The model captured the faster, non-coastal turtle migrations and the slower, coastal turtle migrations. The passive biophysical model trial, TMS1, showed the particles move in the opposite direction to the turtles (Figure 3 A). Therefore, the turtles did not migrate using currents. The two models that best described the turtle tracks using only constant swim speed and direction were semi-coastal (TMS2) and non-coastal (TMS4) with swim speeds of 0.35 ms^{-1}

and 0.55 ms^{-1}, roughly agreeing with the migration speeds of 0.42 ms^{-1} and 0.59 ms^{-1}. The swim speeds used in the model agree with green turtle migration speeds of ~0.46 ms^{-1} in northern Australia (Ferreira et al. 2021), 0.24 - 0.82 ms^{-1} in the Indian Ocean (Pelletier et al. 2003) and smaller, Hawksbill turtles for shallow (0.22 ms^{-1}) and deep water (0.66 ms^{-1})(Hays et al. 2022) also roughly agree.

Table 4: Green turtle migration modelling scenarios

	Modelled movement mechanism	Swim speed (ms^{-1})	Swim Direction (°T)	Swim behaviour	Wind drift (%)
TMS1	passive dispersion	0	0	-	0
TMS2	coastal, semi-coastal	0.35	196	direct	0
TMS3	coastal, semi-coastal	0.35	196	direct	1
TMS4	non-coastal	0.55	163	direct	0
TMS5	non-coastal	0.55	163	direct	1

TMS2 roughly matched the semi-coastal migrators, passing through the eastern side of the channel between the mainland and Groote Eylandt (Figure 3, B). The non-coastal model particles moved toward the foraging grounds on the eastern side of Groote Eylandt, but the modelled tracks did not match the satellite tracks (Figure 3, C), instead taking a direct path. We expected the wind drift to influence the turtles by carrying them closer to land in some locations, however, the model simulations that included the 1% wind drift did not affect the particle movements because the swim speed was so strong (TMS3, TMS5 not shown).

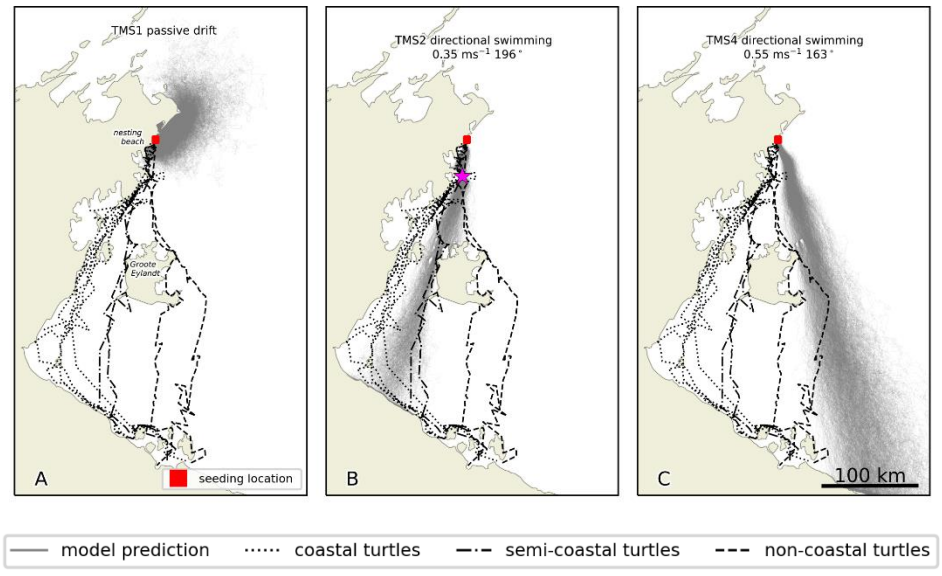

Figure 3: Three biophysical modelling movement scenarios: (A) TMS1 passive drift, (B) TMS2 coastal directional swimming and (C) TMS4 non-coastal directional swimming. Three categories of turtle migratory groups are overlaid on each plot: coastal (black dotted), semi-coastal (black dot-dash) and non-coastal (black dash).

All satellite turtle tracks (Figure 3) exhibited distinct arrivals and departures along the coast during their migrations. The model could not reproduce these coastal contact points suggesting that a navigation behaviour other than swim speed and direction, currents and wind drift influences the turtle movement. If the constant swim speed and direction in the model

represented a true compass bearing, as might be expected for a turtle following geomagnetic cues, then this study shows that compass navigation is not used alone or is very crude. Other studies suggest this type of consistent use of coastlines when nearing the foraging area is part of a 'target searching' navigation behaviour whereby turtles rely on visual or olfactory coastal cues (Hays et al. 2022; Lohmann et al. 2008; Southwood & Avens 2010).

The faster movement of the non-coastal turtles is likely due to less reliance on coastal cues for navigation, and larger intervals between straight non-coastal transits (Hays et al. 2022). Since the coastal, semi-coastal and non-coastal migrations were not correlated with carapace size, it seems that age (perhaps a proxy for experience) does not influence the migratory path.

This case study highlights that these green turtles do not use wind drift or currents to aid their migration either by pushing them toward their target, or toward the coastline. However, frequent coastal arrivals and departures appear to play an important role in their migration, suggesting coastal cues such as landmarks, bathymetry or olfactory are important. It is also possible that their movement is guided by scents from the opposing currents and wind. The effects of climate change such as rapid sea level rise, changing currents, dieback of benthic food sources and coastal scouring may influence the nature of the coastal cues, some of which may occur within the long (2-5 year) remigration intervals.

Migratory keystone species, such as turtles, have high social, cultural and commercial significance globally (Garibaldi & Turner 2004), particularly in large and remote locations such as the pacific (Petro et al. 2007). Geographically separated Indigenous peoples and local communities share custodianship of globally migratory species between very remote locations and have critical knowledge that should be incorporated into global management (Vierros et al. 2020). The modelling methods used here demonstrate an alternative and freely available tool that can be used together with prolific turtle tracking data (Garibaldi & Turner 2004) and local knowledge to help investigate the physical mechanisms of migrational navigation.

3.2. **Case Study 2**

3.2.1. Marine debris clean-ups

The timing of the beach clean-ups on either side of the GoC differed, providing key temporal calibration data for the particle tracking model. In Mapoon (eastern GoC), the clean-ups occurred in July, preceding the annual turtle research and monitoring event in August during the peak turtle nesting season. In Wanuway (western GoC) the clean-ups roughly occurred in October or September, when the beached marine debris was most dense and when the clean-up fit within the rangers' schedule. Both ranger groups expressed that their respective clean-up sites were relatively free of marine debris during opposite times of year (e.g. September in Mapoon and April in Wanuway). In addition, both ranger groups had access difficulties to the sites; tracks are unsealed and often re-routed from year to year due to flood damage during the wet season. The Wanuway site can take up to six hours to reach by four-wheel-drive, depending on track and weather conditions (Figure 2).

The different methodologies between the two locations limited the comparable data to five categories; aluminium cans, plastic bottle tops and lids, cigarette lighters, squid jigs and sandals, over six years (2013-2018). The clean-ups had occurred for at least a decade before 2013, however those data were unable to be used due to inconsistencies in the marine debris categories between years.

Wanuway generally reported more marine debris than Mapoon in bottle tops, cigarette lighters, squid jigs and sandals (Figure 4). Aluminium cans have a different pattern than the other categories (Figure 4). The observed categories are typical of floating marine debris, except for

aluminium cans which are consistently classified as terrestrial in origin in the literature (Pieper et al. 2019). We presume this is because they easily fill with water and sink, and thus do not travel far in the open ocean.

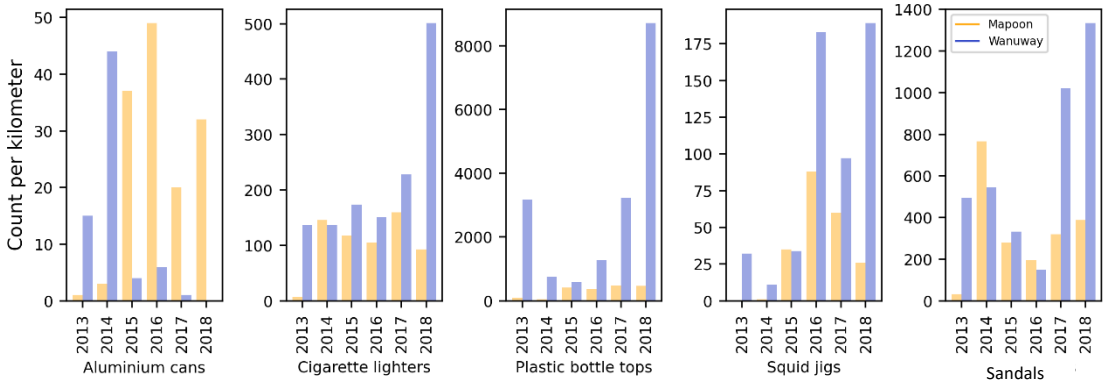

Figure 4: Comparable marine debris categories on the east (Mapoon) and west (Wanuway) coastlines of the Gulf of Carpentaria (note y axis range differs between subplots).

Wanuway's higher marine debris counts may be explained by the late timing of Mapoon's beach clean-up in July, which was after the strongest southeasterly winds of the season, occurring typically in May - June (S4). Therefore, the beached debris was likely blown back into the water and towards Wanuway before the Mapoon clean-up occured. The debris was reported to be collected well above the tide line in the fixed dunes, where it was distributed and trapped in small gullies by the wind or storm surge, confirming the secondary movement of the debris beyond the tideline. An earlier clean-up effort in Mapoon may result in the survey beach remaining cleaner for longer, as well as reduce the amount of debris being transported across the GoC to the western side.

The distribution of aluminium cans, which are typically of local, terrestrial origin, collected over the study years provide an interesting narrative with respect to local recycling laws. The decrease in aluminium cans in Wanuway (Figure 4) after 2014 roughly coincides with Wanuway's jurisdictional implementation of aluminium container refund campaigns, implemented in the years following 2011 (the exact date is not known)(Northern Territory Government 2012). On the other hand, the Mapoon Aluminium can counts after 2014 are larger than prior to 2014, and the same container refund campaigns were not implemented in Mapoon's jurisdiction until 2018 (Queensland Government 2022).

Opposing and asymmetric seasonal winds (S4) and the underlying clockwise circulation of the GoC results in distinct 'marine debris seasons' on either side of the GoC. Dhimurru Rangers confirmed this, reporting that leaving the beach clean-ups too late in the marine debris season resulted in less rubbish to clean up. In Mapoon, the beaches stayed relatively clean from after the annual marine debris clean-up in July, until the following monsoon season. The absolute amount of marine debris is highly variable between years, and it is unknown whether the variability is due to clean-up methodology, timing or factors related to the marine debris origin.

3.2.2. Marine debris model

The objective of the modelling investigation was to provide a high-level overview of the spatiotemporal distribution of marine debris at sea and determine its origin, not to simulate the marine debris from the specific years in the clean-up. As such, the results are generalised by seasons and relevant months because natural variations in the timing of marine debris

accumulation on the coastlines varies between months and years due to natural weather variations.

The modelling results demonstrate the marine debris pathways from northwesterly seas reach both coastlines in distinct marine debris seasons, matching the timing of the ranger clean-ups. In the first year, the debris particles took approximately 17 days to reach the shores of Mapoon from the seeding location (Figure 6 A) during a monsoon pulse of northwesterly wind; a relatively short period of time given the distance travelled was 600-700 km. The timing of this marine debris influx was related to the onset of the monsoon from the northwest, which the timing varies from year to year, occurring in early January in the modelled year (2007). The arrival of monsoon pulses between November and April are characterised by strong and persistent northwesterly winds (S4). The instantaneous modelled seed release may exaggerate the 'pulse' of marine debris entering the GoC. In reality, the marine debris is likely to enter the GoC continuously during strong and persistent northwesterly monsoon pulses. On the other hand, if the debris originated from rivers in nearby Southeast Asia, released into the ocean during a rainfall-flushing event related to the same monsoon pulse, then an instantaneous seed release may also be realistic.

Once on the Mapoon shoreline, the marine debris particles remained there during the transition season (March – April), in which a weaker monsoon occurred, pushing the marine debris onto the beach. During this period, a net southern movement of particles occurred (Figure 6 B) until late March, when easterly winds increased in intensity. The debris took roughly one month to cross the GoC under the persistent easterly and southeasterly winds (S4), and remained on the western coastline. Between May and November some debris particles moved along the western coastline from north to south, but predominantly remained beached on the western side of the GoC (see Figure 6). The year two monsoon bursts, starting in November, moved the debris from the western coastline toward the eastern coastline again, however, few particles beached on the eastern side, most of the remaining particles accumulating in the ocean in the southwest of the GoC (see Figure 5 A, March, Year two), which corresponds with an amphidromic point (point of zero tide).

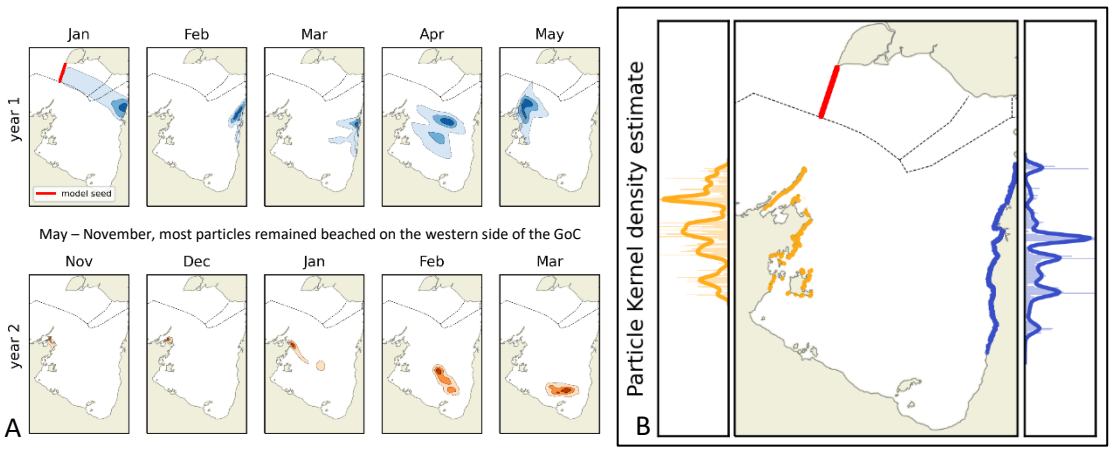

Figure 5: Kernel density estimates of the marine plastics model results of ocean marine plastics (A) and beached plastics (B). Year 1 (blue) shows the first year of entry of marine debris into the Gulf of Carpentaria from international waters. Year 2 (orange) isolates the fate of the first years' marine debris. After March, very little debris hits the eastern coastline. The model captures marine debris beaching on the two opposite-facing sides of the Gulf of Carpentaria (B).

The modelling and clean-up results indicate the GoC is a trap for marine debris, which accumulates on open beaches and coastlines, washing between the eastern and western

coastlines (Figure 6). Seasonal winds and surface currents drive the movement of floating debris that aligns with the observations by Indigenous land managers and the Tangaroa Blue Foundation. Evidence from both the surveys and the model suggests that major rivers in Southeast Asia flush out domestic waste during rainfall associated with an October to January rainfall season (Lebreton et al. 2017), and northwesterly monsoon wind pulses carry the debris rapidly toward the GoC where it washes between the eastern and western coastlines.

The process of determining the marine debris seeding is discussed further in S3, and showed no evidence of its origin coming from the Coral Sea through the Torres Strait. It is possible that given a larger domain, marine debris could originate from the Torres strait during the April – October dry season, travel toward the Arafura Sea in the west and enter the Gulf of Carpentaria in the following wet season from the west. However, the product labelling shows evidence of the marine debris originating from Southeast Asia, and there is a distinct lack of high population density east of the Coral Sea, thus it is very unlikely that the source of the marine debris is from the Coral Sea.

Defining spatial and temporal pathways of persistent marine plastic accumulation in the GoC is crucial for developing ecological risk profiles, especially for seabirds and turtles (Department of the Environment and Energy 2017; Nelms et al. 2016; van Franeker & Law 2015; Van Sebille et al. 2015). Further studies into the effects of marine debris on seabirds and sea turtles in this region should target areas and times of peak debris movement and accumulation during turtle and seabird nesting and migration, and seabird nesting. Quantifying the risk of juvenile sea turtles encountering marine debris in their ocean life-stage could also be assessed using a range of biophysical modelling scenarios similar to the ones presented in this paper and others (Hamann et al. 2011; Wildermann et al. 2017). Extending the model towards the west and north, and trialling the release of marine debris particles from major rivers in those regions during times of monsoon pulses may provide clarity as to the precise origins of the marine debris, although this is also a data-deficient area and has a very complex hydrodynamics.

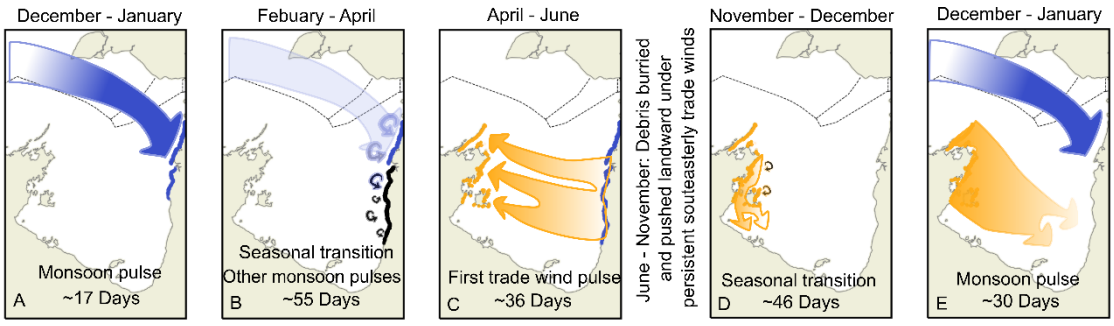

Figure 6: Conceptual, seasonal diagram of marine plastics movement through the Gulf of Carpentaria, descriptions inset.

This study indicates why previous studies may have under-represented the threat of marine debris on coastlines in the GoC; An Australia-wide tow-net study included four surveys on the eastern side of the GoC during late July, reporting a small amount of marine debris in those locations compared with other places in Australia (Cózar et al. 2014; Reisser et al. 2013). However, the present study shows that during late July on the eastern side of the GoC there is likely to be minimal marine debris in the coastal waters. Global modelling studies either omit the GoC due to its relatively small scale (Maximenko et al. 2018), or fail to predict the patterns seen in the ranger clean-up data (Schuyler et al. 2016). Lastly, a continental scale marine debris data analysis classified the marine debris in the GoC as data-deficient, as it calculates accumulation rates on sub-annual scales (Gacutan et al. 2022). These three examples of under-

representing marine debris in the GoC could have been avoided by undertaking consultation with the local communities and ranger land management groups.

The marine debris model used in this study could be improved by implementing freshwater runoff at the major rivers and adding particles with slightly higher and lower wind drift coefficients to account for the different types of marine debris found on the coastline, which could be implemented in future models.

3.3. Case Study 3

The modelled particles reached the island group where the crabs were retrieved in three of the six movement scenarios: MS3, MS5 and MS6 (Table 5). MS6 resulted in the particles reaching the northern part of the island group, where one crab was retrieved within 35 days. In MS5 the particles reached the southern part of the island group, where the other crab was retrieved after 28 days. Thus, MS5 and MS6 are plausible movement strategies for the two male mud crabs. In MS3, the particles also reached the southern part of the island group, and the crab would have to swim constantly at a relatively high speed of 0.07 ms^{-1} and often against the current. This is unlikely given the effort required for continuous swimming for 31 days at most.

Tait et al. (1985) documented a 42 km migration within three months by a male S. *serratta* with on the east coast of Australia, which provides evidence that long migrations made by male individuals occur elsewhere. It is possible that the suite of environmental anomalies (high temperatures and low freshwater runoff) occurring in the GoC during the migration period may have influenced the crabs' movement behaviour.

Uncertainties in the modelling methodology may arise from the fine-scale affects of S. *serrata* transitions between the benthos and the water surface, and the assumption that there are no vertical flow velocities in this coastal region, neither of which were captured in this model. It is unfortunate that there are no verification data on vertical flow velocity, nor any detailed studies on how STST is adopted by mud crabs, highlighting the need for these data in future movement modelling studies. However, this high-level investigation into the possible mud crab movement scenario provides a realistic starting point for field investigations of male movement mechanisms and drivers, which may be relevant to population connectivity between jurisdictions, especially where harvest strategies differ.

Table 5: Results for modelling scenarios of mud crab movement

Model Scenario	**Crab swim speed (ms^{-1})**	**Result**	**Reached retrieval point**
MS1	0	Particles dispersed approximately radially around the release point	No
MS2	0	Particles accumulated at the coast north of the starting point (further away from the endpoint)	No
MS3	0.07 ms^{-1} south east	97% of particles moved along the coastline and reached the island group along the southern coastline.	Yes
MS4	0	Particles moved to the northeast and dispersed to the south and western parts of the Groote Eylandt coastline	No
MS5	0.12 ms^{-1} south east	Particles reached the western and southwestern islands in the island group where the second mud crab was retrieved. 12% moved along the coastline, similar to MS3	Yes
MS6	0.12 ms^{-1} south east	Particles moved to the north of the Island group reaching close to the capture point. 48% of the particles moved along the coastline, 42% entered the island group from the north, and 10% swapped from a northerly track to a southerly track to join the coastal particles toward the end of the simulation	Yes

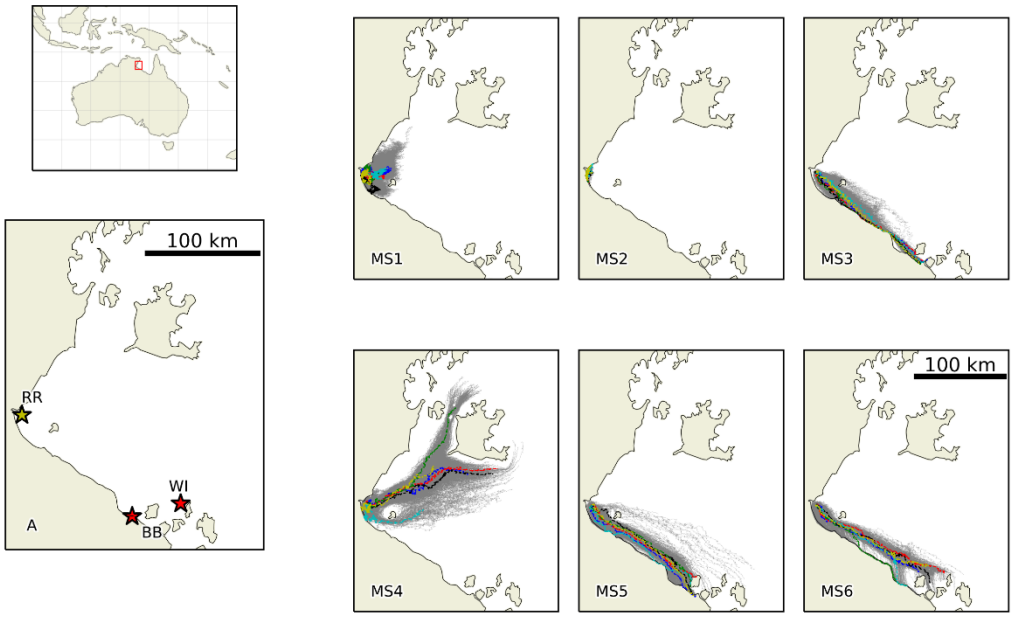

Figure 7: Model results testing six modelling scenarios (MD1 – MS6) for S. serrata movement strategies. The model was seeded at RR (A), the recapture sites were at BB and WI. The model particles are shown as grey lines with six random particles are shown in varying colours for better clarity.

4. Conclusions and recommendations

This study has combined biophysical modelling with existing, locally derrived data sets to improve our knowledge of three ecological case studies in the remote and data-limited GoC. Re-using locally collected information, collected for reasons unrelated to this study, and combining them with biophysical modelling effectively enhanced our understanding of marine ecology and physical processes in this data-limited region without bearing the high costs of exploratory field work. The local data provided three unique opportunities for us to calibrate biophysical models, which are typically unable to be calibrated due to data deficiency (Swearer et al. 2019), and gain a new, locally relevant understanding of the physical movement mechansims of green turtles, marine debris and mud crabs in space and time, producing tangible management recommendations and direction for local planning and future research (Table 6).

Table 6: Outcomes of three case studies as a result of this study

	Conclusions and recommendations	
Case study *Biophysical model investigation*	Local relevance	Global relevance
Post-nesting migrating green turtles *Investigate the role of currents and wind in the migration patterns of female post-nesting Green (Chelonia Mydas) turtles*	• The turtles did not appear to use the currents and wind to aid their migrations during the November migrations • Turtles do not use directional swimming alone to navigate to foraging grounds, but use coastal cues along the migration corridor to guide their navigation to foraging grounds • Further studies should focus on understanding surrounding environmental quality, such as	• Historical satellite tracking data combined with a simple, biophysical model testing basic physical movement drivers was successfully used to enumerate the effects of wind and currents on migrating sea turtles. • Biophysical modelling could be combined with scores of other historical animal tracking data to test basic movement patterns and swim speeds, which is particularly useful in

	benthic habitat, bathymetry, acoustics and seagrass presence, which may identify further movement cues in the movement corridors.	shelf environments where satellite altimetry is innapropriate. • Satellite telemetry of marine megafauna can provide opportunities to test and improve biophysical modelling to better represent animal movement anomalies and cues, providing more evidence to studies limited by the high cost of field observations.
Spatio-temporal distribution of floating marine plastics *Describe the temporal and spatial distribution of floating marine plastics in the Gulf of Carpentaria*	• Past studies have underestimated the amount of marine debris in the GoC. • Marine debris clean-up efforts should use AMDI methodology to record data. • Shorter, more regular clean-ups, including categorisation and counting debris items, should be implemented to enhance the data useability, allowing these locations to be compared with other clean-up locations in Australia. • Marine debris clean-ups should be scheduled when the beached debris load is at its peak, which may mean seeking alternative access to beaches during times of the year that are difficult to access. • Marine debris modelling could be combined with with other ecological data sets such as endangered species (turtles, seabirds) nesting, migration and foraging distributions to assess ecosystem risk.	• Long-term observations from Indigenous coastal land managers provided critical information that was implemented in the model. This is globally relevant where the majority of remote and data-limited locations are indigenous-managed. • The top thirteen nations with the highest proportion of ocean as a percentage of sovereign area are small, tropical island nations (Degnarin & Stone 2017) without the means to undertake significant oceanographic research. Their populations are disproportionately dependent on the ocean and are the most vulnerable to the cumulative impacts of anthropogenic threats such as climate change (Boyce et al. 2020) (Vierros et al. 2020) and marine debris (Horton & Barnes 2020) • Combined with long-term local beach-based observations, biophysical models can provide a relatively cheap tool for investigating the spatio-temporal distribution of marine debris in the ocean, which is the starting point for assessing broader risks to ecosystems.
Anomalous male Giant mud crab movements *Investigate the movement mechanisms of male Giant mud crab (Scylla serrata) migrations*	• Undertake further male and female mud crab tagging studies to determine whether migration is a regular occurrence in this subpopulation • Use biophysical modelling to investigate the sensitivity of population-scale mud crab movements in the GoC, particularly with reference to commercial fisheries licencing blocks.	• Biophysical models can be used with very simple field studies to investigate animal movement behaviour.

Globally, the methods outlined in this study are relevant in developing maritime nations with national livelihoods reliant on marine resources. Creative and unconventional scientific methods need to be embraced to improve our knowledge of remote and data-limited marine regions. Biophysical modelling combined with participation from local communities, Indigenous-managers, and the commercial sector highlight the novel possibilities for advancing ecological knowledge in remote and data-limited locations.

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Author contributions

R.P. developed the hydrodynamic and biophysical model, conceptualised the study, applied the biophysical models, undertook the data analysis, interpretation and visualisations, brokered local knowledge and wrote the manuscript.
E.W. provided supervision, applied the biophysical models, investigated the model and field data, conceptualised the study and critically reviewed the manuscript.
R.G. Participated in the study design, participated in brokering local knowledge, and critically reviewed the manuscript
K.C. developed the marine debris biophysical model, participated in the marine debris data analysis, participated in developing the study conceptualisation and critically reviewed the manuscript.
L.P. collected the marine debris data, participated in developing the study conceptualisation, and provided local knowledge critical for the discussion, conclusion and recommendations
M.G. collected the mud crab data, participated in the study conceptualisation, and critically reviewed the manuscript
R.K. collected and analysed the turtle tracking data, provided local and background knowledge of turtles and culture, and participated in the study conceptualisation.
H.T. participated in collecting the marine debris, provided local knowledge and critically reviewed the manuscript.
V.U. participated in the study conceptualisation, supervised the study and critically reviewed the manuscript
J.L. assisted in developing the hydrodynamic and biophysical models, provided supervision and software, and critically reviewed the manuscript.
Mapoon Land and Sea Rangers provided data and knowledge documented in the manuscript and critically reviewed the manuscript
H.C provided supervision, resources and project administration, and critically reviewed the manuscript
All authors gave final approval for publication and agree to be held accountable for the work performed therein.

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