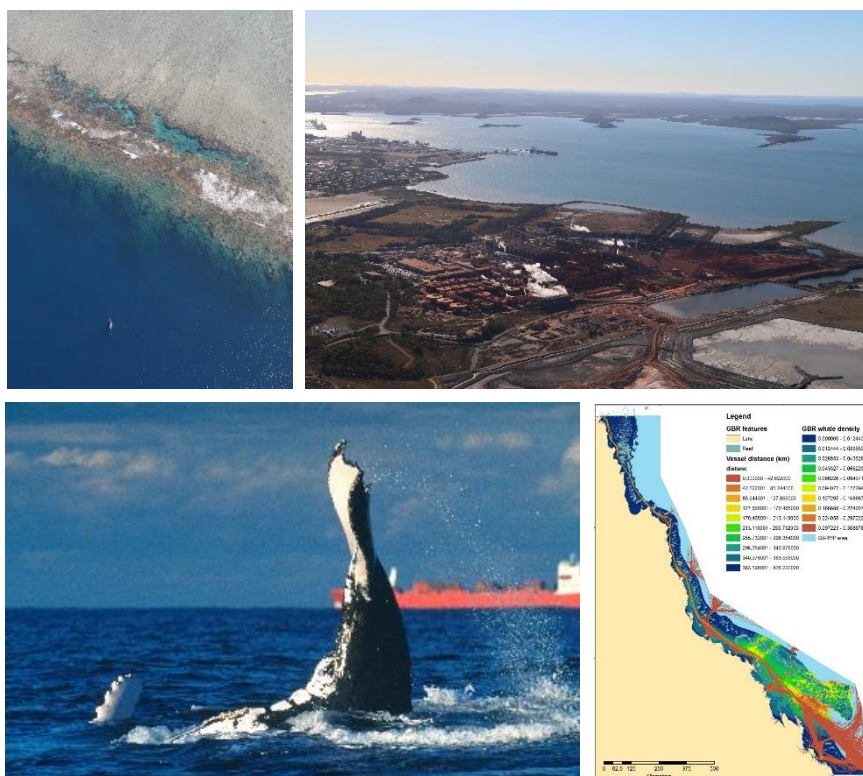# Quantitative assessment of relative ship strike risk to humpback whales (*Megaptera novaeangliae*) in the Great Barrier Reef World Heritage Area



**Final report to Maritime Safety Queensland**

**July 2019**

**Joshua Smith[1], David Peel[2] and Natalie Kelly[3]**

Please address any queries to Joshua Smith joshua.smith@uqconnect.edu.au
Author affiliations:
1 Aquatic Megafauna Research Unit, Centre for Sustainable Aquatic Ecosystems, Harry Butler Institute, Murdoch University, Perth, Australia
2 Data61, CSIRO, Hobart, Australia
3 Australian Antarctic Division, Hobart, Australia

**Preferred Citation**

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**Acknowledgement**

# Executive summary

The Australian east coast population of humpback whales (E1 sub-population) annually migrate to the Great Barrier Reef for mating and calving. Recent improvements in our understanding of the distribution of humpback whales on their breeding ground in the Great Barrier Reef World Heritage Area (GBRWHA) indicate the main breeding aggregation (highest density area) is in offshore waters of the southern GBR, in close proximity to coastal areas undergoing significant port development. The core breeding area overlaps the inner shipping route that services all ports on the Qld coast. A quantitative assessment of relative ship strike risk (ships > 80m) to humpback whales in the GBRWHA was recently undertaken. However, it was not possible to model the Capricorn Bunker Group due to limited humpback whale distribution data. This Capricorn Bunker Group is an area of significant shipping activity and represents a significant information gap on relative risk of ship strike to humpback whales in the GBR. This report presents data on the distribution of humpback whales in the Capricorn Bunker Group area from an aerial survey undertaken in July 2018. This data enabled a quantitative assessment of relative ship strike risk for this area and a re-assessment of risk in the extended GBRWHA when integrated with existing aerial survey data.

To quantify relative risk of ship strike in the Capricorn Bunker Group and wider GBRWHA, we calculated the Relative Risk of a Fatal Collision between a whale and a ship. This metric incorporates the co-occurrence of a whale and ship in a given grid cell, vessel width and an estimate of the probability of a lethal whale strike given vessel speed. This approach is very similar to the approach to estimate absolute risk, although provides a simplified risk calculation in that any parameter that is constant across the population can be ignored, even if unknown. As such, it does not provide an indication of the magnitude of the risk or any indication of the true frequency of vessel collisions with humpback whales. We do not currently have adequate information on some of the parameters necessary for absolute risk estimates (e.g. behavioural response of whales to approaching vessels), and we know less about their variability, making it difficult to propagate error and provide a robust measure of uncertainty/error on absolute risk measures. Relative risk can predict where a collision is more likely to occur and identify priority areas for further research to ascertain the magnitude of the issue.

There is a relatively uniform overlap of the GBR inner shipping route with humpback whale distribution and the risk of ship strike in the GBR closely conforms to the distribution and density of whales. Therefore, in areas of high whale density where there is little variation in

shipping traffic, the abundance of whales is a good proxy for risk of ship strike. The predicted distribution of whales in the Capricorn Bunker Group region showed a relatively distinct pattern, similar across all of the three whale categories modelled ('all whales', 'non-calf groups' and 'calf groups') and consistent to the movements of satellite tagged whales. Humpback whales occurred offshore and east of the Capricorn Bunker Group of islands and reefs, with the southern area displaying a restricted distribution of whales along a narrow continental shelf and a more dispersed distribution of whales in the north near the Swains Reef Complex. Due to less overlap of whales with the shipping lanes in the south, the area of highest relative risk (≥ 70 % risk) to 'all whale' groups is the central and northern area of the shipping lane.

Incorporation of the 2018 humpback whale sighting data with existing data has enabled predictions of humpback whale density throughout most of the GBR between latitudes 15.5°S to 24.5°S. There is a clear core aggregation area of high densities (≥ 80%) of whales covering a range in latitude between 19.5°S to 21.5°S, encompassing the offshore area of the Whitsundays in the north and south to east of Mackay. Within this range, 'non-calf groups' have a higher predicted density (≥ 90 %) of whales and greater relative risk of ship strike risk offshore of Mackay, whereas the greatest risk for 'calf groups' is the offshore Whitsunday region. There is lower relative risk of ship strike (≤ 48%) in the Capricorn Bunker Group compared to the rest of the GBRWHA, however reduced survey effort in this region means relative ship strike risk is likely underestimated in the Capricorn Bunker Group.

The ship strike risk quantified in this report is a relative risk metric. The relative risk maps can provide information to identify priority areas for further research and obtain data to address knowledge and information gaps that could improve the relative risk metric used in this study and/or aid estimates of absolute risk or ship strike mortality. The rapidly increasing abundance of this humpback whale population suggests ship strike is unlikely to have a population level effect on the whales. However, the spatial overlap between whales and the shipping lanes and projected increases in shipping and whale population size could result in welfare issues to the whales from non-fatal injuries. Relative high-risk areas of ship strike to humpback whales will require further consideration for targeted applied research and assessment of potential management action. Fundamentally, quantifying uncertainty is an integral factor to improving estimates of ship strike risk and informing spatial decisions to manage risk. To improve estimates of relative and absolute ship strike risk, two key parameters that require further work and data are on variability in the humpback whale distribution models and the behavioural response of the whales to ships.

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# 1. Project background and significance

The global shipping industry is extremely important to world economic trade, with over 80% of current global trade by volume and more than 70% of its value undertaken by ocean shipping (UNCTAD 2017). The world shipping fleet has been continuously growing since the 1990's and has doubled in number over the last 12 years, with ships increasing in both size and designed speed capacity to accommodate this trade growth (UNCTAD 2017). Additionally, there has been increased use of smaller commercial vessels in growing marine tourism industries and increased numbers of recreational vessels worldwide. This, combined with variable recovery rates of whale species' from commercial whaling over the last century, has resulted in increased interactions between whales and ships and a growing increase in the apparent rate of vessel strikes in some parts of the world, particularly areas in the Mediterranean and United States (Cates *et al.* 2017). 'High risk' areas occur where there are high volumes of shipping (i.e., shipping lanes or port areas) and whales or conversely high numbers of whales (i.e., known aggregation areas for feeding or breeding and areas of critical habitat) and shipping (Cates *et al.* 2017). Direct reports of ship strikes will never provide accurate estimates of the numbers of whales involved because ship strikes involving large vessels can often go unnoticed and so there is a need for estimates based on an understanding of risk, and relating this to densities of ships and whales.

The International Whaling Commission (IWC) is addressing the problem of vessel strikes of whales through its Scientific and Conservation Committees and has established a Ship Strike Working Group, of which Australia is a member. In accordance with the International Maritime Organization's Circular MEPC.1/Circ.674 that provides guidance for minimizing the risk of ship strikes with cetaceans, the Australian Maritime Safety Authority have produced the Marine Notice 15/2016 for an Australian context. In 2017, the Australia federal government released a *National Strategy for Reducing Vessel Strike on Cetaceans and Other Marine Megafauna* to provide guidance on understanding and reducing the risk of vessel collisions and the impacts they may have on marine megafauna in Australia (Department 2017). Quantifying the population level extent of vessel strike mortality on whales, however, is notoriously difficult due to inherent reporting biases and because collisions with large vessels are frequently unnoticed and consequently go unreported (Laist *et al.* 2001; Panigada *et al.* 2006; Vanderlaan & Taggart 2006; Peel, Smith & Childerhouse 2018).

## 1.1 Risk of ship strike to humpback whales in Australia

In Australia, humpback whales were historically, and are presently, the most frequently reported whale species involved in vessel collisions (Peel, Smith & Childerhouse 2018). The Great Barrier Reef (GBR) is an area identified as having a high co-occurrence of shipping traffic and numbers of whales (Peel *et al.* 2015). This is due to Australia being one of the largest exporters of natural resources and the GBR inner shipping route servicing several large natural resource export ports. Additionally, the breeding ground of the east coast population of humpback whales (E1 population; IWC) is located in the GBR, which is a population undergoing a rapid rate of recovery from commercial whaling at an estimated 11% increase per year (Smith *et al.* 2012; Noad *et al.* 2016). There have been recent improvements in our understanding of the distribution of humpback whales on their breeding ground in the GBR World Heritage Area (GBRWHA) using spatial habitat models of opportunistic sightings validated from satellite tagged humpback whale data (Smith *et al.* 2012), and subsequent dedicated aerial surveys in 2012 and 2014 (Peel *et al.* 2015; Smith, Kelly & Renner 2019). The main breeding aggregation of highest whale density in the GBRWHA is situated in offshore waters of the southern GBR close to coastal areas (e.g. Mackay) undergoing significant port development. This core breeding aggregation overlaps with the inner shipping route that services all the ports on the Queensland (Qld.) coast (Fig. 1A).
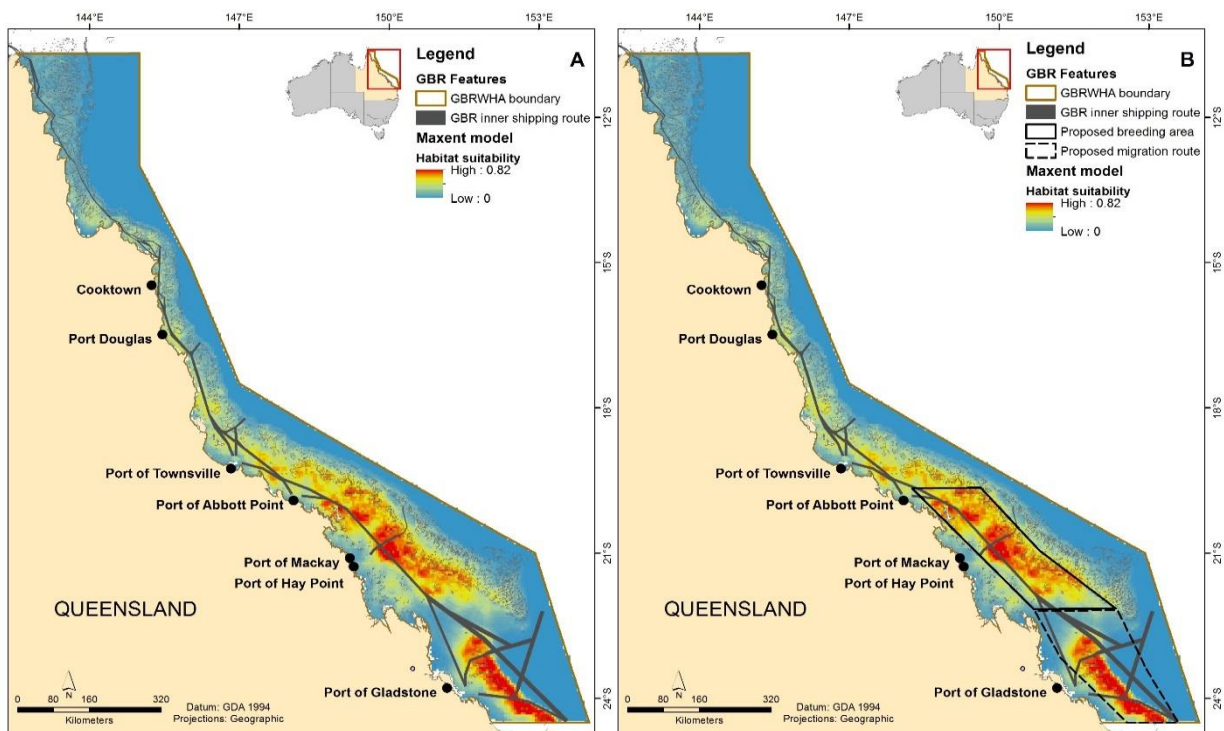


**Figure 1.** (A) Modelled humpback whale habitat suitability (Jul/Aug. 2003-2007), and (B) the proposed core breeding area and migration route in the Great Barrier Reef World Heritage Area

In contrast to our knowledge of humpback whale distribution on their breeding grounds within the GBRWHA, little data exists on their distribution past the Capricorn Bunker Group of islands and reefs, offshore of Gladstone. Opportunistic sighting data and satellite tag data suggests that the movement of whales through this region is still migratory behaviour (Smith et al. 2012) (Fig. 1B). This is an area of significant shipping activity due to it being the southern entrance to the GBR inner route and its proximity to the significant multi-commodity port of Gladstone. A recent quantitative assessment of relative ship strike risk to humpback whales in the GBRWHA from large ships (>80m) was undertaken, highlighting the shipping area near the Whitsunday Islands and offshore of Mackay as areas of highest relative risk (Peel et al. 2015). However, it was not been possible to undertake this assessment in the Capricorn Bunker Group region due to the lack of dedicated whale sighting data (Fig. 2). The Capricorn Bunker Group region is likely to exhibit a level of ship strike risk comparable to other high-risk areas already identified due to; (i) the apparent restricted movement of whales through this region and (ii) the overlap of the inner shipping route running parallel (north-south) to, and bisecting across, the migration path.
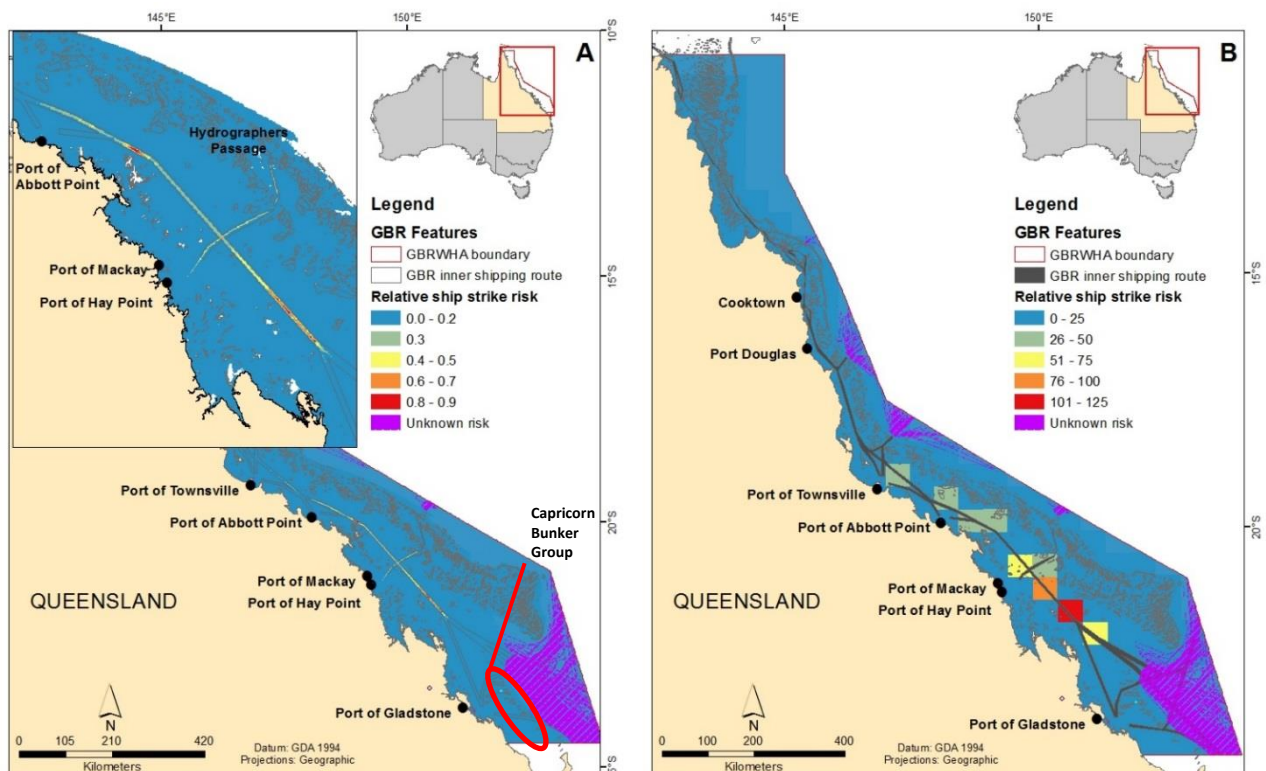


**Figure 2** Modelled densities of humpback whale groups throughout the Great Barrier Reef during Aug. 2012 in relation to the inner shipping route at a (A) 1 x 1 km and (B) 50 x 50 km resolution

## 1.1 Project objectives

The primary objective of the study was to evaluate the relative risk of ship strike to humpback whales in the Capricorn Bunker Group. To do this, it is necessary to understand the broad-scale distribution of humpback whales in this area before localised studies can occur. The aims of this project are to:

1. Undertake a dedicated humpback whale aerial survey in the Capricorn Bunker Group region to better understand the level of spatial overlap with shipping
2. Refine our understanding of the whale migration path and width in this region
3. Quantify the relative risk of ship strike to humpback whales in the Capricorn Bunker Group region and integrate with existing data to develop a GBR-wide risk model.

# 2. Methods

## 2.1 Humpback whale aerial surveys

The GBRWHA is an expansive area, which has made systematic surveys of the entire area prohibitively costly. Consequently, much of our earlier knowledge of the distribution of humpback whales in the GBRWHA was from incidental aerial and vessel sightings (Simmons & Marsh 1986; Chaloupka & Osmond 1999). There have been recent improvements in our understanding of the distribution of humpback whales on their breeding ground in the GBRWHA, using spatial habitat models of opportunistic sightings validated from satellite tagged whale data (Smith *et al.* 2012) and subsequent dedicated aerial surveys in 2012 and 2014 (Peel *et al.* 2015; Smith, Kelly & Renner 2019). These aerial surveys had different objectives and sub-sampled the GBR within specific regions of whales' breeding ground in the GBRWHA. Further details of the survey methodology are found in Peel et al. (2015). In brief, the 2012 aerial survey was undertaken in three main areas of the GBR in early August, between latitudes 15.5°S to 22°S and extending offshore to the outer reef whereas the 2014 aerial survey was undertaken in one main area on August/September between latitudes 19.5°S to 24°S.

The aerial survey data presented in this report consists of a targeted, dedicated aerial survey of humpback whales undertaken on their northward migration past the Capricorn Bunker Group offshore of Gladstone, Qld in July 2018 (latitudes 21.8°S to 24.7°S). Knowledge of whale distribution from previous humpback whale aerial surveys undertaken in 2012 and 2014 informed the 2018 survey design. The Capricorn Bunker Group is an area of limited knowledge on the distribution of humpback whales (Fig. 2A), although opportunistic sighting data from Border Protection Command and a small sample of satellite tagged whales (N = 12) (Gales *et al.* 2010) suggests that the movement of whales through this region constitutes migratory behaviour (Smith *et al.* 2012).

Combined, the 2012, 2014 and current 2018 aerial surveys have subsampled along the majority of the latitudinal gradient of the GBR and Qld. coast (15.5°S to 24.5°S). Based on the 2012 and 2014 aerial survey data, a quantitative assessment of relative ship strike risk to humpback whales in the GBRWHA was undertaken. In this assessment, it was not possible to model the Capricorn Bunker Group area due to limited humpback whale distribution data. Consequently, data from this aerial survey will enable a quantitative assessment of relative ship strike risk for this area, and a re-assessment of risk in the extended GBRWHA.

## 2.1.1 Aerial survey methodology

The 2018 aerial survey was undertaken using a Partenavia P-68B six-seater, twin engine, high-wing aircraft. Surveys were conducted in passing mode at a height of 1000 feet to improve the ability to identify calves and a ground speed of 100 knots. Transects were spaced 40km apart and orientated approximately 30 degrees from the coastline to survey across the depth gradient, extending offshore from the coastline past the continental slope to offshore waters up to 3,155m depth (Fig.3). Humpback whales were the primary focus of this survey and the survey was designed to maximise detection of this species. Other species of marine megafauna, including other whales, dolphins, dugongs and sharks, were recorded when humpback whales were not present.
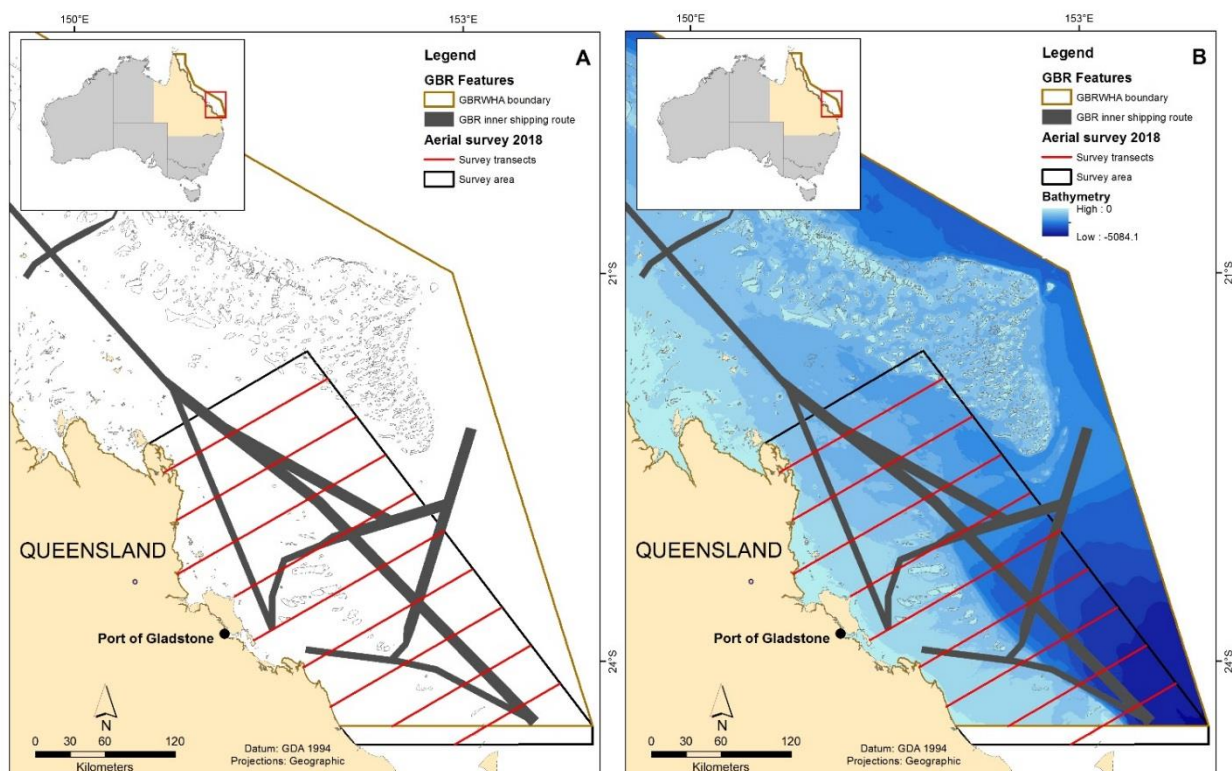
**Figure 3** (A) Map of the survey area and transects that were flown during the 2018 aerial survey and (B) overlayed with depth

The survey team consisted of four dedicated observers and a survey leader, constituting a double platform observer configuration. This allowed the sightings of the two observers on each side of the aircraft to be independent and perception bias to be calculated, whereby observers fail to detect animals even though they are available for detection (Pollock *et al.* 2006). The two primary observers were in the middle seats and the two secondary observers in the rear seats.

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The survey leader was in the front seat next to the pilot and entered all sightings called by the primary observers into a Getac PS336 handheld computer using a specialised program developed for humpback whale aerial surveys. The observers and the survey leader communicated via David Clark aviation headsets connected to two portable Aviall intercoms. Each intercom connected to a separate track of a two-track Zoom H4N digital voice recorder to record the flight audio. During survey mode when 'on effort', the flight leader is in audio contact only with the two primary observers and the secondary observers are acoustically and visually (a black curtain) isolated from the primary observers.



**Figure 4** A photograph of the aerial survey team with the Partenavia P-68B.
Aerial survey team consisted of (left to right) Josh Smith (survey leader), Matt Wedge (pilot), Nicola Ransome, Louise Bennett, Elisa Girola and Jennifer Allen.

For each flight the survey leader recorded environmental conditions at the beginning of each flight, periodic intervals during the flight and whenever conditions changed. Observer effort was concentrated ahead and as close to the track line as possible. For each group sighted the total number of animals, number of calves, vertical and horizontal angles and sighting cue were recorded. A clinometer (Suunto PM-5/360PC) measured vertical angles to the whale for declination and an angle board (protractor) was used for horizontal angles. Whales were identified to species where possible by observers along with a category of reliability (certain, probable or guess) in relation how sure they were of the species.

## 2.1.2 Analysis of aerial survey data

Exploratory data analysis of the aerial double platform data was undertaken in Distance v6.0 release 2. This enabled an examination of the data to determine whether the sighting data

distances needed to be truncated to increase the robustness of detection model fitting. A double platform model was developed which incorporates two components; **1)** a detection function of unique observations which models how detectability varies with perpendicular distance and other covariates, and **2)** a mark-recapture analysis of the capture history data using at least perpendicular distance and potentially other covariates. In addition to perpendicular distance the other covariates examined were: school size; sea state; cloud cover; cue type and turbidity.

Detection probabilities, and corrections for perception bias, were estimated using Mark-Recapture Distance Sampling models as described in Laake & Borchers (2004) and Burt et al. (2014) using the MRDS package (Laake *et al.* 2015) in R (R 2015). To improve detection function fit, perpendicular sighting distances were truncated and sightings of uncertain species identification were excluded from the analyses. A final detection function was selected by minimising the Akaike Information Criterion (AIC) and examining model diagnostics.

### 2.1.3 Spatial modelling of whale distribution

Spatial models were fitted to the 2018 and combined 2012/2018 aerial line transect data, to produce models of humpback whale density and distribution in the Capricorn Bunker Group and majority of the GBRWHA, respectively. The 2014 whale sighting data was not used to fit the spatial models of humpback whale distribution because it was conducted later in the breeding season (late August/early September) and we wanted to confine the modelling to the time of peak whale abundance on the breeding grounds. These models are a two-stage process:

(i) The double-platform data are analysed using a mark-recapture distance sampling model to estimate the 'effective strip width' and level of perception bias, and

(ii) The spatial data are used to develop a detection-adjusted density surface model using generalized additive models (GAM's) to estimate variation in distribution and density and thus predict areas that are important to the species (Hedley & Buckland 2004).

A density surface model was developed using the GAM model. This was done by segmenting track lines into pre-defined lengths of approximately 10 km, summing the numbers of whale groups and total animals (including the presence and number of calves), incorporating the geographic variables of Latitude and Longitude (represented by the midpoint of the segment) and estimating a total effective strip area for each segment. The density surface models were fitted using the dsm package (Miller et al. 2019) and sightings data projected to a 'easting' and 'northing' value (transformed from longitude and latitude using the Albers equal area projection).

The number of whales in each segment, of width twice the right truncation distance, is adjusted by the probability of detection of a sighting in that segment given its sighting conditions. This is accomplished via an offset in the model, equivalent to log (effective area) of each snippet. A Tweedie distribution was used to account for over-dispersion in the counts of groups per segment.

Predictions of whale densities for the Capricorn/Bunker Group region and for the majority of the GBRMP (south of Cooktown) were developed at a 6 x 6 km grid cell resolution. This represents a spatial scale approximately corresponding to the length of a segment x effective search width, or effective search area). Spatial density models were produced for three different whale groups: 1) all whales, 2) groups that contained a calf (hereafter, calf groups) and 3) groups in which a calf was not present (hereafter, non-calf groups). Sightings and modelled distributions of calf groups are used as a proxy to identify likely calving areas and non-calf groups to identify potential mating areas.

## 2.2 Shipping data

Large vessels (≥ 50 m) transiting through the GBRWHA are identified and monitored by an automatic identification system (AIS) by the Great Barrier Reef and Torres Strait Vessel Traffic Service (REEFVTS), with ships only permitted to transit through Designated Shipping Areas. In December 2014, the International Maritime Organization formalised a two-way shipping route in the GBR that extends from the Torres Strait in the north and terminates at the southern boundary of the GBRMP (Fig. 1). The two-way shipping route follows pre-existing traffic patterns through the GBR and now encourages shipping to follow well-defined northbound and southbound lanes.

The Australian Maritime Safety Authority (AMSA) provided AIS data in the form of their craft tracking system (CTS) product, which provides processed ship locational data sampled to a five-minute frequency. AIS data was analysed for 2015 and was restricted to commercial vessels ≥ 50 m in length for three months of the humpback whale breeding season (July, August, and September). Only vessels ≥ 50 m were included for the following reasons: it is mandatory for vessels ≥ 50 m to report to REEF VTS, vessels of this size and larger predominantly inflict fatal or severe injuries (Laist *et al.* 2001), larger vessels traverse predictable routes and AIS data provides relatively accurate ship positional data. Navigational status of the vessel provides information on whether vessels are underway or not (e.g. anchored), although was not available in the AIS data. A filter of > 0.4 knots was applied to the data to remove stationary/anchored vessels less than this speed, which would have limited risk for ship strike.

## 2.3 Risk assessment framework

There are two types of vessel strike risk: relative and absolute risk. The following briefly outlines the differences between the two types of risk and a more detailed discussion on the relative risk framework that is the risk metric used in this study. While there are several different approaches to quantifying relative risk (e.g. co-occurrence, relative risk of a collision), the relative risk metric used in this study is the relative risk of a fatal collision with a ship (discussed in section 2.3.2). This approach is detailed in Peel *et al.* (2015) and is very similar to the approach to estimate absolute risk concurrently developed by Martin *et al.* (2016). Although it is possible to estimate absolute risk, achieving a useable absolute probability of fatal vessel strike is extremely difficult in most applications (and in some cases potentially misleading) and we therefore consider the derived relative risk estimates as a conservative estimate of absolute risk. Essentially, there are several parameters necessary for estimating absolute risk of ship strike for humpback whales for which there is no data and the degree of uncertainty in the parameters that are used often result in ineffective estimates of absolute risk. Given we do not currently have adequate information on some of the parameters and even less is known about their variability, it is difficult to propagate error and provide a robust measure of uncertainty/error on absolute risk measures. Discussion on the benefits and limitations of both absolute and relative risk is outlined in section 2.3.1.

## 2.3.1 Relative versus absolute risk

Relative risk can predict where a collision is more likely to occur, but not how many collisions are likely to occur. Relative risk will therefore not provide an indication of the magnitude of the risk or any indication of the true frequency of collisions to compare to strike rates in other countries, but rather provides a unit-less measure that compares risk between different areas or times within a given area. For example, relative risk may indicate that the risk of collision is higher in area A than area B, or the risk of collision is 2.5 times higher in area A than area B but not how many whales are likely to be involved in fatal collisions with ships. The estimate of the relative risk of a fatal collision is proportional to the true expected probability of fatal vessel strike. The advantage to the use of relative risk is that parameters integral to the estimation of absolute risk (e.g. surface availability, behavioural response of avoidance/attraction to vessels) which might be unknown can be ignored if they are reasonably constant across cells and thereby allows risk to be compared across spatial locations. The main assumptions involved in relative risk are:

- The various parameters that can possibly affect the risk of collision are constant spatially and across the population age groups and are therefore ignored (e.g. behavioural response of attraction/avoidance, surface availability).

- All vessels have the same risk of collision (i.e., the design or type of vessel does not significantly affect the risk of a collision). While this is potentially untrue, without specific information/data we must make this assumption.

Absolute risk quantifies the actual probability of a collision occurring in a defined geographical area and given timeframe. For example, area A has a 20 per cent chance of an individual and a vessel colliding over a specified duration. The advantage of absolute risk is that it enables an estimation of the expected number of animals likely to be involved in a collision and hence an indication of the magnitude of the problem that ship strike poses to a species, although does not provide the actual mortality rate. Consequently, it is possible to estimate population level impacts from ship strike and compare estimated ship strike rates between different species and countries. The biggest limitation to estimating absolute risk is the variance involved in the parameters used to calculate it, which relates to the uncertainties in each parameter used in the calculation process. Significant knowledge is required on the reliability of the parameters used in the absolute risk estimate and uncertainty/error need to be minimal or at least known. If these uncertainties (variance) are substantial and propagated in the estimation of absolute risk, it could result in confidence intervals around any absolute estimates large enough to render the estimates meaningless. The sources of uncertainty involved in the parameters necessary for estimating absolute risk are outlined in Table 1.

**Table 1** Sources of uncertainty/variation in the estimation of absolute risk.

| Source of Uncertainty | Description |
|---|---|
| Animal density | - Detection probability of animals during surveys<br>- Temporal variation of animals within a breeding season<br>- Spatial variation within a breeding season (intra-annual) and between years (inter-annual)<br>- Surface availability between different sexes, age and reproductive (calf versus non-calf groups) classes to determine 'availability bias' in species distribution modelling<br>- Species distribution modelling involving model mis-specification, environmental covariate resolution and measurement error and model variable selection<br>- Sampling error related to frequency of sampling (e.g. you are not taking a population census but rather a sample of the population and extrapolating) |

| | | |
|---|---|---|
| Animal dive/surface availability | - | The animal needs to be in the strike zone of the ship by being near the surface, at the depth of the hull/propeller or in close proximity to be drawn into the strike zone. |
| | - | Some species have studies using focal follows or depth tag data to estimate surface availability. A considerable sample size is required to obtain a representative sample of the population. Variation will occur between individuals, sub-groups (e.g. mother calves vs adults) and by location (e.g. migratory corridor vs breeding or feeding areas). Furthermore, there can be sampling bias (i.e. animals that surface a lot and in a certain way are easier to tag and easier to focal follow). |
| | - | Using this information from published studies in a different area is not necessarily representative of the population in question, which can introduce bias/uncertainty. |
| Animal behavioural response | - | Often little data exists about the behavioural response of animals in the presence of ships |
| | - | This avoidance and/or attraction can be on a local scale (e.g. respond to individual oncoming vessels) or broader scale (e.g. shipping routes and potential response due to noise) |
| | - | Most current work assumes zero avoidance, although variation will likely exist among individuals and species |
| Vessel speed | - | Vessel speed is an important factor, which can have variability depending on the way it is calculated (e.g. instantaneous speed reported in the AIS when polled or calculated speed as an average between polls) and the temporal resolution between polled AIS vessel positions. |
| Collision model and the vessel speed/whale lethality relationship | - | In most cases, little data exists for the probability of a whale fatality given the speed of the vessel. |
| | - | For large whales, Conn & Silber (2013) provide a fatality curve based on vessel speed incorporating the latest knowledge. The main limitation of this is that it combines observations from several large whale species and provides little data on risk related to vessel type. It is possible there are individual whale and species differences related to this relationship. |
| | - | There may be unknown mechanisms/processes involved that have not been modelled (e.g. blunt force impacts versus propeller interaction). |
| Vessel draft and characteristics | - | Limited information exists on the hydrodynamic effects of a vessel movement in the immediate proximity of a whale. It is largely unknown whether a whale can be drawn into, or repelled out of, the strike zone and propeller of a ship based on the hydrodynamics effects of water around the vessel. |
| Vessel density | - | A common source of vessel data is AIS that can incorporate uncertainty (e.g. terrestrial vs. satellite receivers), although is likely to have the least amount of uncertainty compared to the other sources. The temporal resolution of polled AIS positions is likely to have an influence on the degree of uncertainty in vessel density. |

## 2.3.2 Quantification of relative risk of a fatal collision with ships

To quantify relative risk of ship strike we calculated the Relative Risk of a Fatal Collision between a whale and a ship. This metric incorporates the co-occurrence of a whale and ship in a given grid cell (Redfern *et al.* 2013), vessel width and the equation from Conn & Silber (2013) to estimate the probability of a lethal whale strike given vessel speed. This approximates the risk of a fatal ship strike more accurately than co-occurrence alone because severity of a ship strike relates to the speed of a vessel. This risk metric does not include parameters such as the behavioural response of whales to approaching vessels, necessary for estimating absolute risk. The main assumption beyond the two outlined for relative risk in section 2.3.1 (e.g. parameters ignored in the risk estimation are spatially constant and all vessels have similar risk) is that the probability of fatality given vessel speed used (e.g., based on the lethality curve by Conn & Silber (Conn & Silber 2013) for large whales) is correct and applicable to humpback whales. Given the curve includes records involving all large whale species and all geographic areas worldwide, there is a degree of unknown validity regarding the application of this assumption.

AIS data is the sampled location of a vessel at a given point in time and is therefore time-based, although the risk assessment uses data based on the distance-traversed by a vessel. To use the AIS data in the risk assessment framework we need to convert the data to distance rather than time. To do this, we created track line data from the five-minute AIS vessel position point data based on a unique ship-related identifier, the Craft-ID which is equivalent to the Maritime Mobile Service Identity (MMSI). Track line data were created by joining contiguous unique point positions of ship locations less than 60 minutes apart that exhibited little course deviation. Data were removed when there was uncertainty of the ship's path of travel to interpolate between positions. This included vessel positions greater than 60 minutes apart and between 30 and 60 minutes apart where there was a change in ship's course over ground greater than five degrees. A 6 x 6 km grid was created over the entire GBRWHA region using the line data, then summarised based on how much line segment is in each grid cell to produce a grid of the cumulative distance travelled by ships. To calculate relative ship strike risk, we multiplied the ship and whale densities with the mean vessel beam and the probability of a lethal whale strike given the mean vessel speed for each 6 x 6 km grid cell. Relative risk was also summarised at a decreased spatial resolution of 50 x 50 km grid cells to identify risk patterns at the broader regional scale.

# 3. Results

## 3.1 Aerial survey sightings data

The project aimed to survey the Capricorn Bunker Group region with 18 survey transects spaced 20km apart. However, due to a prolonged period of bad weather and strong winds survey effort was reduced to nine transects spaced 40km apart. The aerial survey was undertaken successfully over 3 days of effort during 6th to 9th July 2018. The total areal coverage of the survey area was 61,451 km². The amount of flying time (includes transit time to and between transects) and percentage of 'on effort' time spent surveying within different sea states is presented in Table 1.

**Table 2** Summary data of effort and sea state conditions during aerial survey.

| Survey region | Flight time (hrs) | On-effort flight time (hrs) | Beaufort sea state (percentage of on-effort time) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | **0** | **1** | **2** | **3** | **4** | **5** |
| **Capricorn Bunker Group** | 17.4 | 7.5 | 0 | 52 | 34 | 11 | 3 | 0 |

In total, there were 180 sightings (Fig. 5) of whale groups by front and rear observers (includes resight data), of which 134 (74%) sightings were of 'certain' reliability that the whales were humpback whales, 45 (25%) were 'probable'. Of the total 180 whale group sightings, 70 were resights in which the front and rear observers saw the same group. Consequently, there were 110 unique sightings of humpback whale groups during the aerial survey consisting of 184 individual whales, of which 167 were adults and 17 calves. The sightings data show a relationship with the distribution of whales and bathymetry (Fig. 5B), with all sightings on the continental shelf within 500 m depth in an area with a steep continental slope where bathymetry quickly increases from 100 m to 4000 m depth (Fig. 5C). Previously, there was limited survey effort in bathymetric values deeper than 90 m (only 122 km of a total of 6650 km (1.8%) across both 2012 and 2014 survey years). The 2018 aerial survey was designed to overcome this limitation and resulted in 584 km of a total 8031 km (7.2%) of survey effort in bathymetric values greater than 90 m (maximum depth of 3192 m). Observed group sizes ranged from one to six whales, with the most common group sizes sighted during the survey being single whales (49%) and groups of two (40%) (Table 2). However, it should be noted that group size can be underestimated during aerial surveys, due to the limited time to observe an 'available' animal.
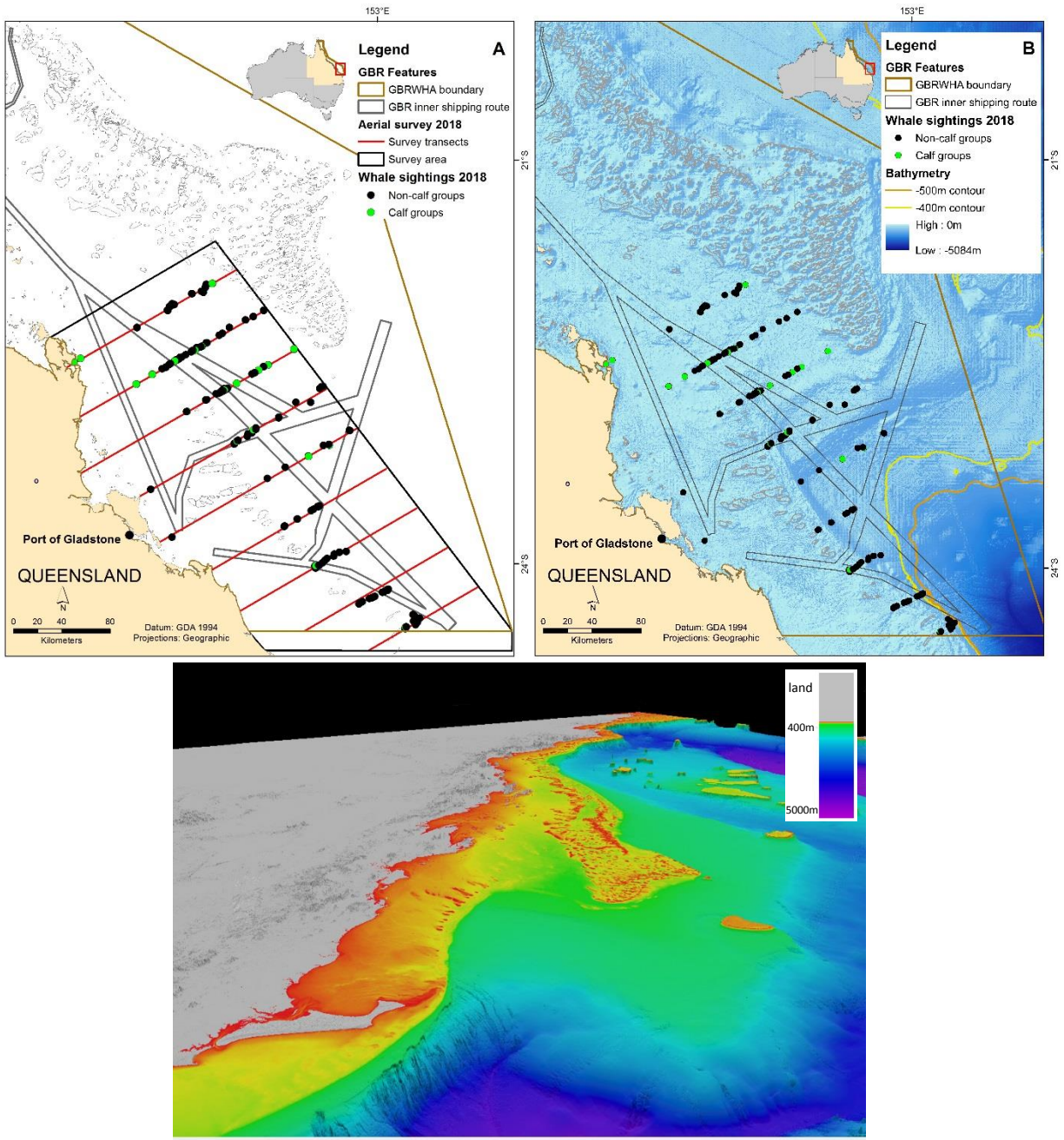
**Figure 5** Map of the sightings of humpback whales (N=180) from the July 2018 aerial survey showing the (A) survey area, (B) depth and (C) a 3D representation of bathymetry

**Table 3** Comparison of group size of humpback whales sighted in the 2018 Capricorn Bunker aerial survey.

| Survey region | | | | Group | size | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Av | Min | Max | 1 | 2 | 3 | 4 | 5 | 6 |
| **Capricorn Bunker Group** | 1.67 | 1 | 6 | 54 | 44 | 8 | 3 | 0 | 1 |

## 3.2 Aerial survey data analysis

Aerial sightings data were left truncated at 0.14 km due to some evidence of missed sightings close to the track line, and were right truncated at 3.7 km in order to improve the robustness of detection model fitting. The fitting of the detection function was based on 105 observations, of which 94 were seen by the front observers and 80 by the rear observers; 69 were duplicate sightings. Figure 6 shows the frequency histograms and fitted detection probability as a function of perpendicular distances for the front and rear observers. Figure 6 shows the conditional detection function plots, which is the probability that one of the observers will see a whale, given that the other observer has seen it. As expected, the duplicate proportions and conditional probabilities are higher for the front observer given that a sighting was made by the rear observer. The open circles represent the actual sightings – these appear segregated because of variation in sea state and school size. These plots showed the expected trends, which were higher probabilities of sighting a whale in calmer seas and with higher group sizes.

The Double platform model assumed point independence because the full independence model showed a lack-of-fit, such that it is assumed detections made by the front and rear observers are independent except for at distance zero (in effect this is at 0.14 km because of the left truncation). The best fitting model was selected for by using AIC and was a perpendicular distance-only model for both the detection and mark-recapture models. Estimated mean group size was 1.69 (SE = 0.5) and the average probability of detection within the surveyed strip was 0.41 with a standard error of 0.052. Hence, the estimated average effective strip half width (uncorrected for $g(0)$) was 1.52 km. Estimated $g(0)$, which is the average probability of at least one platform detecting a group at "zero" distance from the track line, was 0.95 (SE = 0.014). This does not take into account the surface availability of the whales, which is uncorrected for in the density estimation and is simply a measure of the level of perception bias.

**Figure 6** Figures of the frequency histogram of perpendicular distances, along with fitted detection function for the **a)** front observers, **b)** rear observers, **c)** the pooled detections and **d)** duplicate detections.

## 3.3 Spatial modelling of whale distribution

### 3.3.1 Spatial modelling of whale density in the Capricorn/Bunker Group

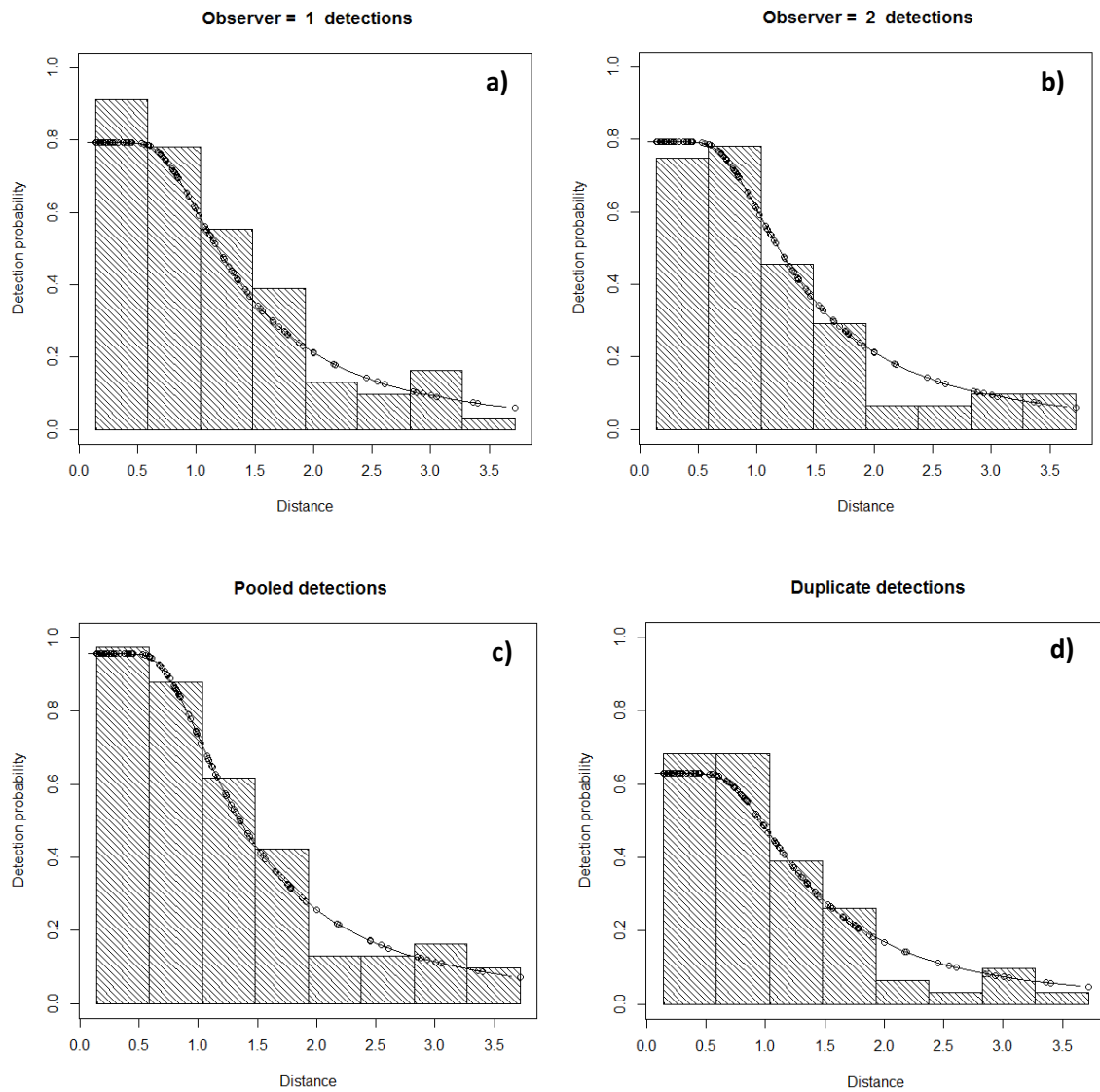The predicted distribution of whale densities within the Capricorn Bunker Group region showed relatively consistent patterns across all of the three whale categories modelled; 'all whales', 'non-calf groups' and 'calf groups'. The majority of sightings on the whales northward migration occur offshore (to the east) of the Capricorn Bunker Group of islands and reefs, with only a few (N = 4) sighted close (< 15 km) to the coast (Fig. 7C). The 'all whale' (Fig. 7C) and 'non-calf' (Fig. 7A) density models show a very constricted movement of whales in the most southern part of the GBRWHA, offshore of the reef, which broadens in width from the area east of Heron Island up to the Swains Reef complex. This is supported by the satellite tagging data (N = 12 whales), which shows the same constricted movement of whales in the most southern region of the Capricorn Bunker Group and a broader distribution in the northern study area (Fig. 7D).

The modelled distribution of 'calf groups' shows a similar pattern to the 'all whale' and 'non-calf group' models, although there is a broader distribution and greater longitudinal spread of calf group sightings in the northern region of the study area. There were significantly fewer sightings of calf groups compared to non-calf groups and a greater number of calf group sightings closer to the coastline (Fig. 7A & 7C). Furthermore, there were particularly fewer sightings of calf groups in the southern region of the study area, which results in an apparent discontinuous distribution of whales. This is likely an artefact of a low sampling effort for the lower abundance of calf groups. A higher sampling effort of calf groups would likely result in a more continuous latitudinal distribution of calf group sightings similar to non-calf groups.

### 3.3.2 Spatial modelling of whale density in the GBRWHA

Previous humpback whale distribution models based on 2012 and 2014 aerial survey data had not been able to predict whale density within most of the Capricorn Bunker Group region. This was due to only a small amount of survey effort in bathymetric values of 90 m and deeper. The addition of the 2018 aerial survey data has enabled predictions of density throughout most of the GBR between latitudes 15.5°S to 24.5°S, from the southern GBRWHA boundary extending to Cooktown in the north. Predictions do not extend further north of Cooktown because the whale density model is based on geographic variables of Latitude and Longitude and given there is no survey effort in that region the predictions would be unreliable.

Based on the predicted distribution of whale densities for 'all whale' groups, there is a clear core aggregation area of high densities of whales (≥ 75%) covering a range in latitude between 19.5°S to 21.5°S (Fig. 8A). This area encompasses the offshore area of the Whitsundays near Hook Reef in the north and extends south to approximately 90 km east of Mackay near Paul Reef (approximately a 250 km x 50 km area). There is also a second area of high whale density (≤ 70 %), situated in the northern area of the Capricorn Group of reefs offshore of Gladstone. There is a similar predicted distribution for 'non-calf' groups (Fig. 8B) compared to 'all whales' predominantly due to a greater abundance of 'non-calf groups' compared to 'calf groups' (79% vs 21%, combined 2012 and 2018 surveys) observed during the aerial surveys and therefore a greater representation of these groups in the 'all whale' model. Within the predicted distribution range of 'non-calf' groups, there is a higher predicted density (≥ 90 %) in the area offshore of Mackay compared to the Whitsundays. In contrast to 'non-calf' groups, 'calf groups' have a more restricted range with their highest predicted density (≥ 90 %) situated in the Whitsundays region (Fig. 8C). A second area of higher predicted 'calf group' densities is located between Port Douglas and Cooktown in the northern GBR.
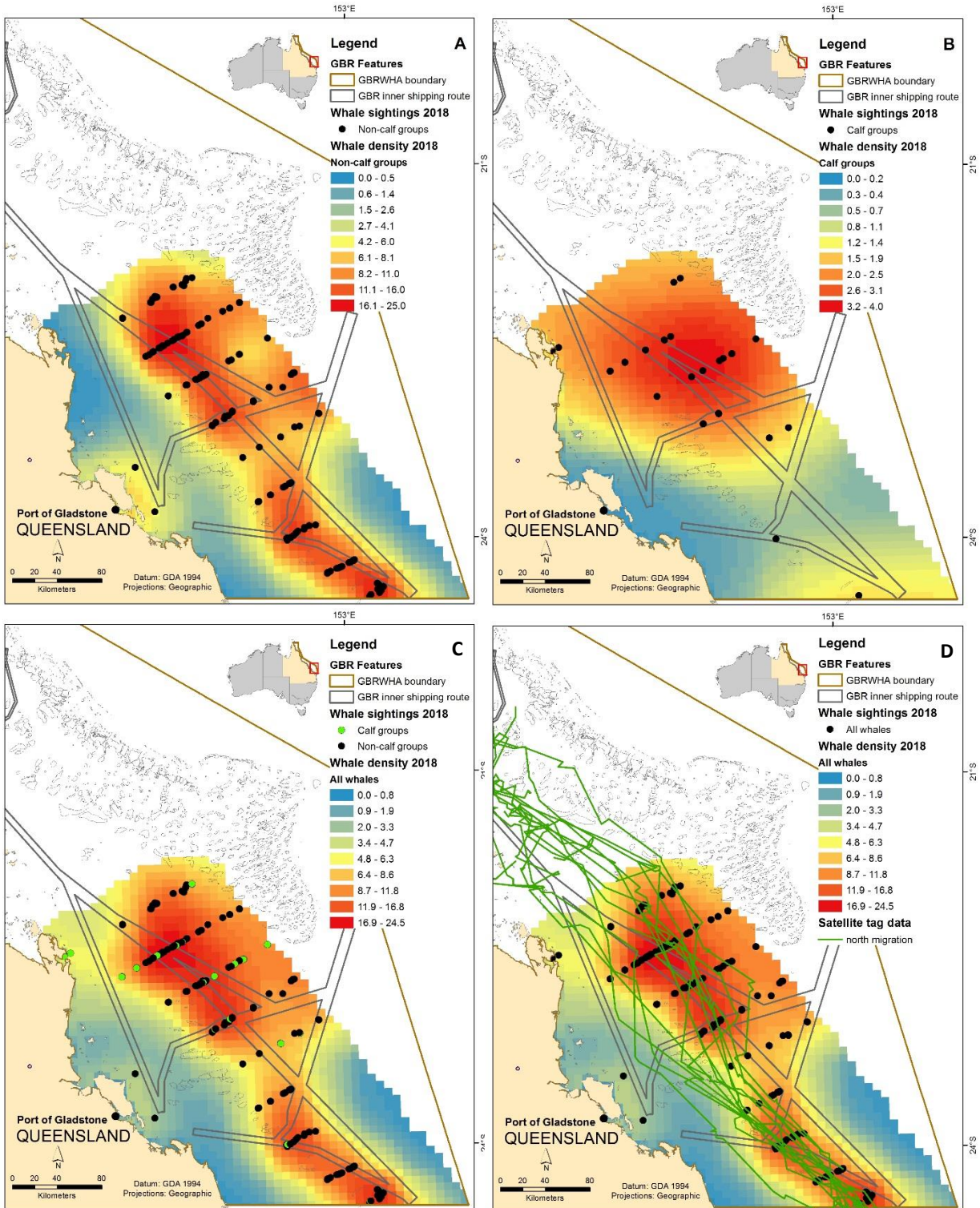
**Figure 7** Map of the humpback whale density surface model and 2018 aerial survey sightings for (A) 'non-calf' groups, (B) 'calf' groups, (C) 'all whales' and (D) 'all whale' groups with overlayed 2009 satellite tagged data (N = 12 whales) in relation to the GBR inner shipping route. The distribution of sightings and satellite tag data provide a form of model validation.
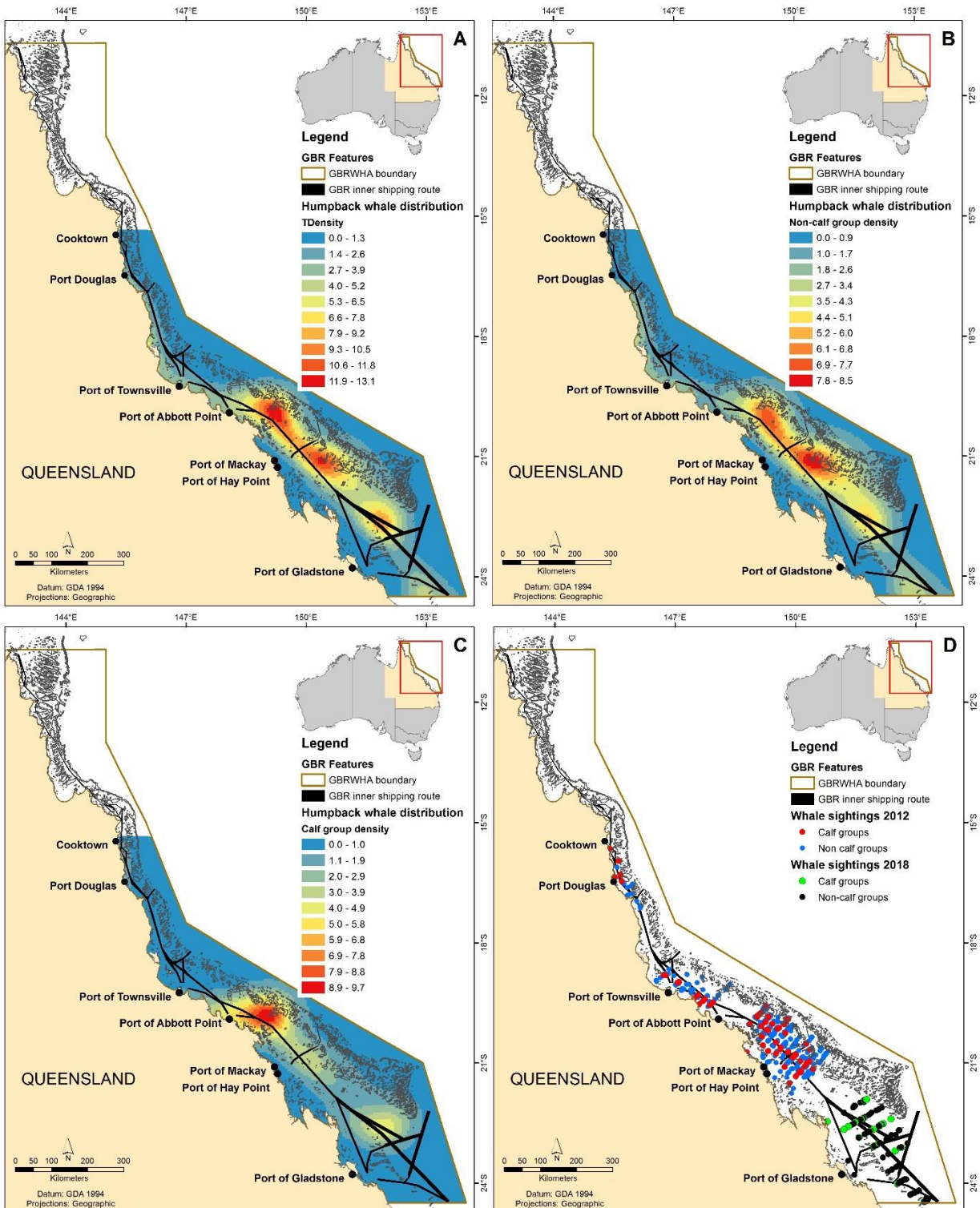
**Figure 8** Map of the humpback whale density surface model for (A) 'all whales', (B) 'non-calf groups' and (C) 'calf groups' based on combined sightings of the (D) 2012 and 2018 aerial survey data, overlayed with the GBR inner shipping route.

## 3.3 Quantitative ship strike risk assessment

### 3.3.1 Ship strike risk to humpback whales in the Capricorn/Bunker Group

The area of highest relative risk to 'all whale' groups of humpback whales in the Capricorn Bunker Group region is the central and northern area of the shipping lane, offshore of the Capricorn Bunker reefs where the central north-south and east-west shipping lanes intersect and to the north along the central lane (Fig. 9A & 9B). This area accounts for ≥ 70 % of the risk of ship strike to humpback whales in this region (Fig. 9B) and was a consistently high-risk area on both the 6 x 6 km (Fig. 9A) and 50 x 50 km (Fig. 9B) resolution and for non-calf and calf groups. The relative risk of ship strike to humpback whales in the southern half of the shipping lane is less than the northern section, predominantly due to a more restricted distribution of whales resulting in a narrower migration width and less overlap with the shipping lanes (Fig. 7C). Given the survey targeted the northward migration of the humpback whales and the greater number of sightings were of 'non-calf groups' (91%) compared to 'calf groups' (9%), the risk map for 'non-calf' groups closely reflects the 'all whale' risk map (Fig. 10). The area of higher (≥ 70 %) relative risk of ship strike to 'calf groups' is predominantly in the northern section of the central shipping lane in the Capricorn Bunker Group region (Fig. 11).



**Figure 9** Map of relative ship strike risk to humpback whale 'all whale' groups at (A) 6 x 6 km and (B) 50 x 50 km resolution based on vessels ≥ 50 m in length and 2018 whale model.

**Figure 10** Map of relative ship strike risk to humpback whale 'non-calf groups' at (A) 6 x 6 km and (B) 50 x 50 km resolution based on vessels ≥ 50 m in length and 2018 whale model.



**Figure 11** Map of relative ship strike risk to humpback whale 'calf groups' at (A) 6 x 6 km and (B) 50 x 50 km resolution based on vessels ≥ 50 m in length and 2018 whale model.

### 3.3.2 Ship strike risk to humpback whales in the GBRWHA

There is predominantly one area of higher relative risk to 'all whale' groups of humpback whales in the GBRWHA, situated offshore of Abbott Point and extending south to offshore waters of Mackay, near the intersection of the central north-south shipping lane and the east-west Hydrographers Passage (Fig. 12). Within this range, the area of highest (≥ 80%) relative risk is between the Whitsunday Islands and outer reef south to offshore of Mackay (Fig. 12B). The relative risk of ship strike in the Capricorn Bunker Group is lower (≤ 48%) compared to the rest of the GBRWHA. The risk to 'non-calf' groups shows a similar pattern to the risk to 'all whale' groups (Fig. 13), predominantly due to there being a greater proportion of non-calf to calf groups. The area of highest relative risk (≥ 75%) for non-calf groups is between the Whitsunday Islands and outer reef south to offshore of Mackay (Fig. 13B). The risk of ship strike to calf groups shows two predominant areas between the 1) Whitsunday region south to offshore of Mackay and 2) Cooktown to Port Douglas (Fig. 14A & 14B). The highest risk (≥ 70 %) to calf groups is the area situated offshore of Abbott Point south to offshore of Mackay at the 50 x 50 km resolution (Fig. 15B). The northerly area between Cooktown and Port Douglas has a considerably lower ship strike risk (≤ 30%).



**Figure 12** Map of relative ship strike risk to 'all whale' humpback whale groups at (A) 6 x 6 km and (B) 50 x 50 km resolution based on vessels ≥ 50 m in length and combined 2012/2018 whale model.

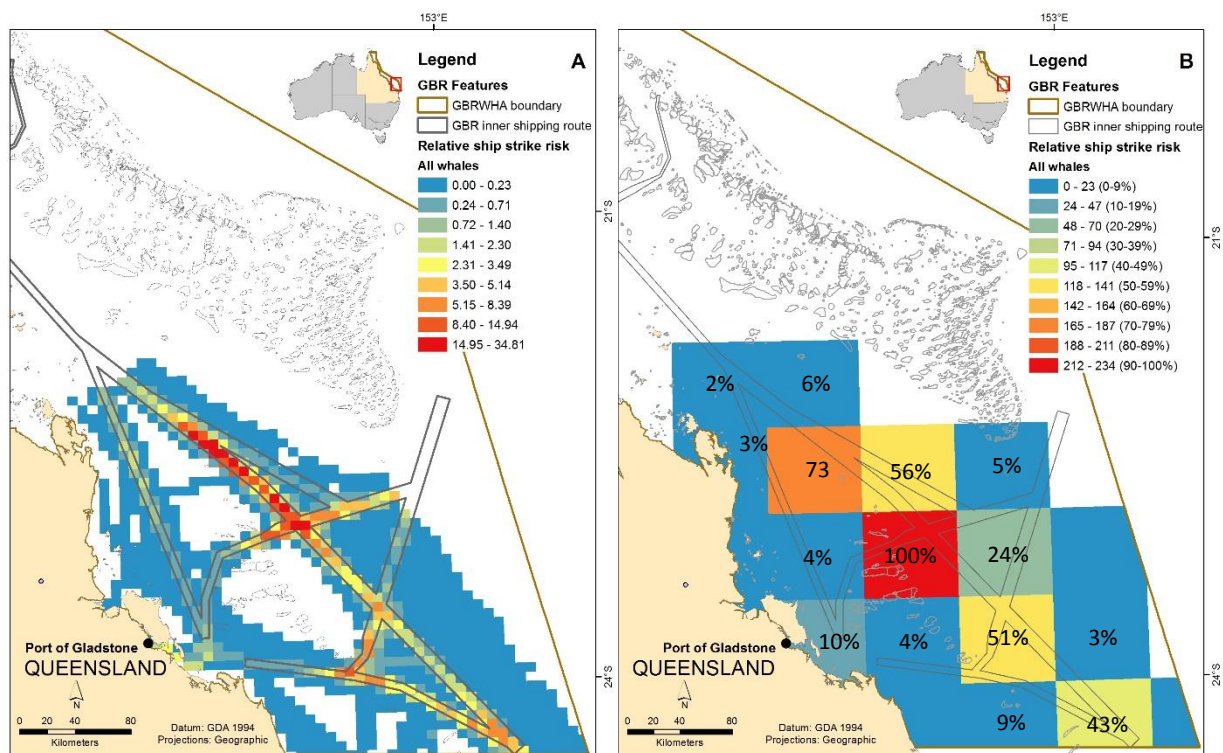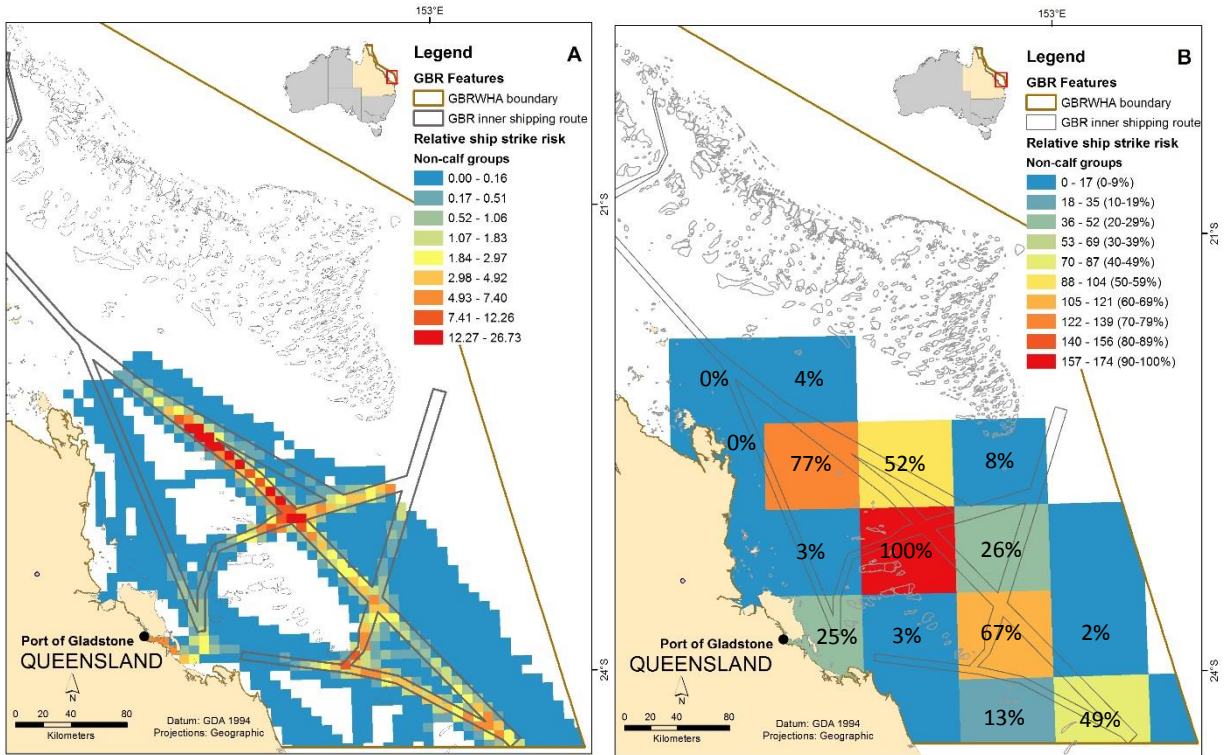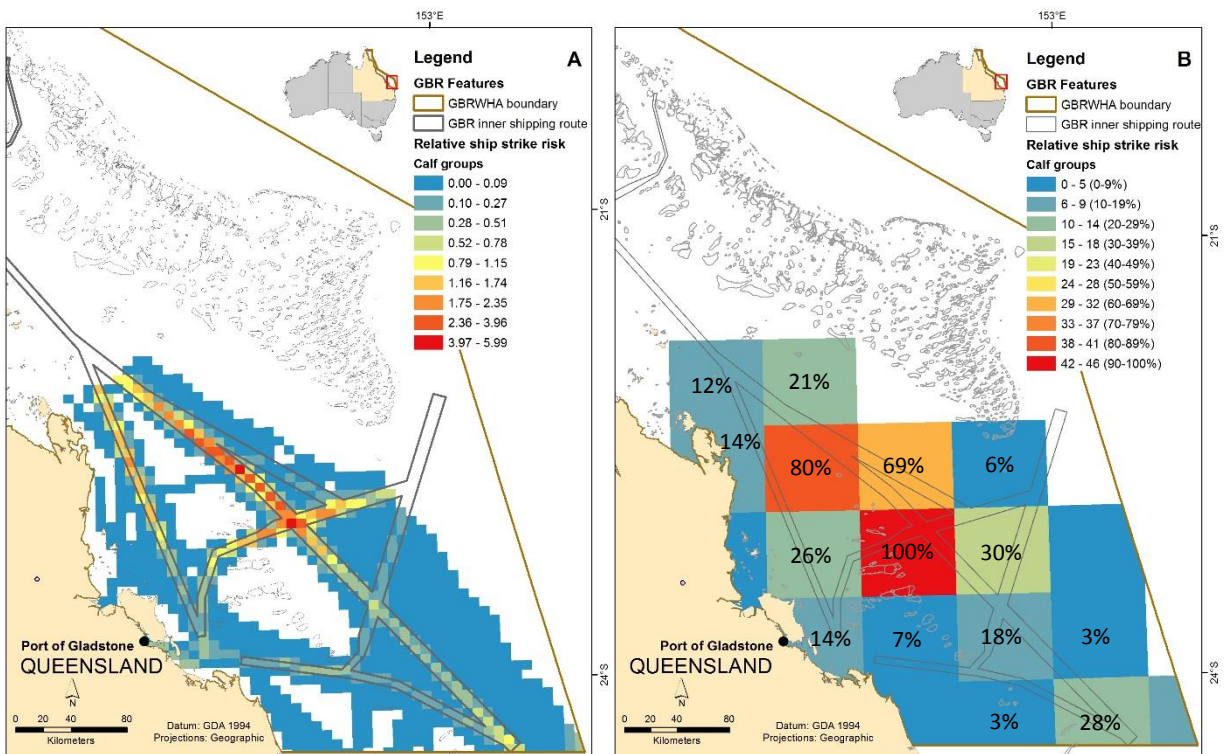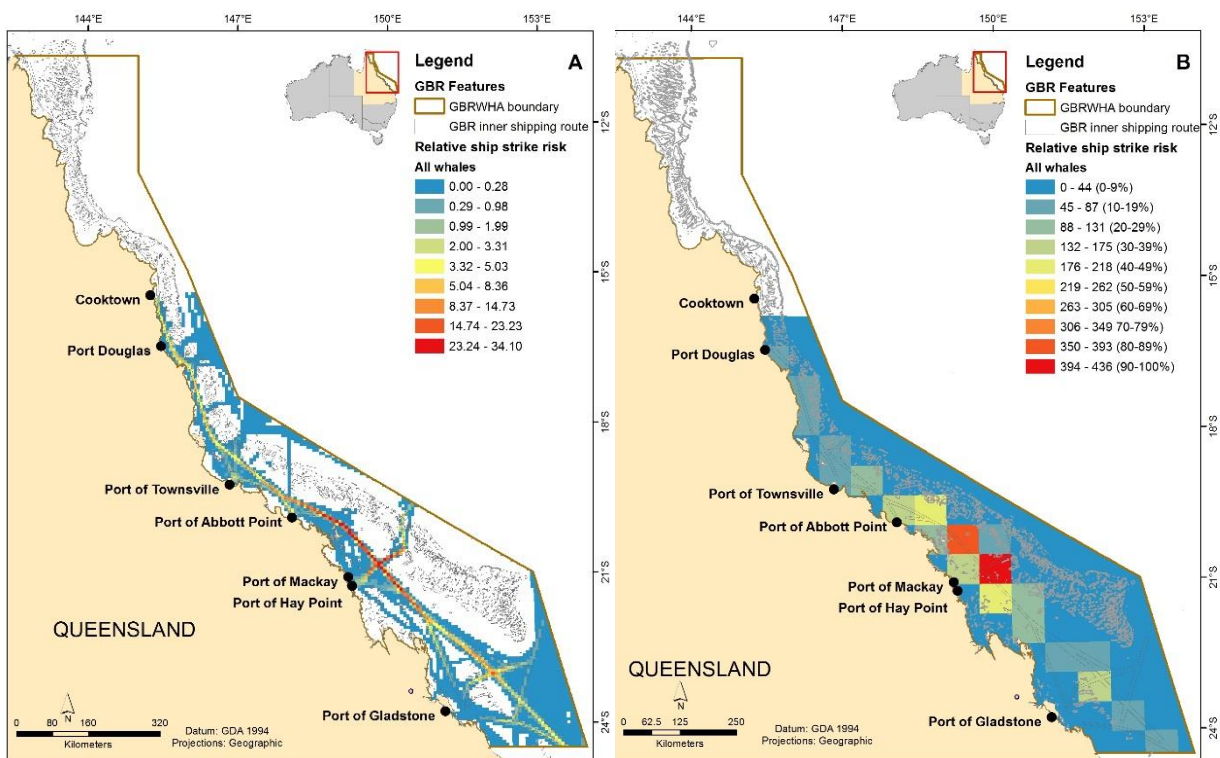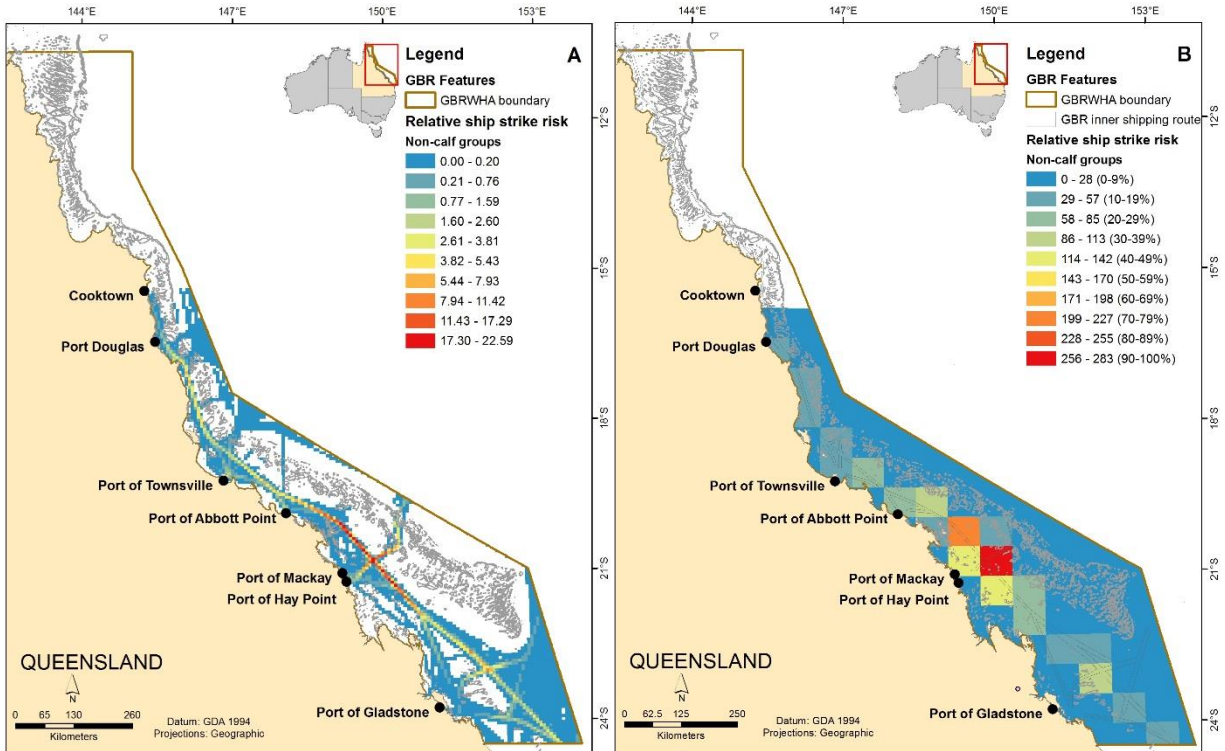**Figure 13** Map of relative ship strike risk to non-calf humpback whale groups at (A) 6 x 6 km and (B) 50 x 50 km resolution based on vessels ≥ 50 m in length and combined 2012/2018 whale model.
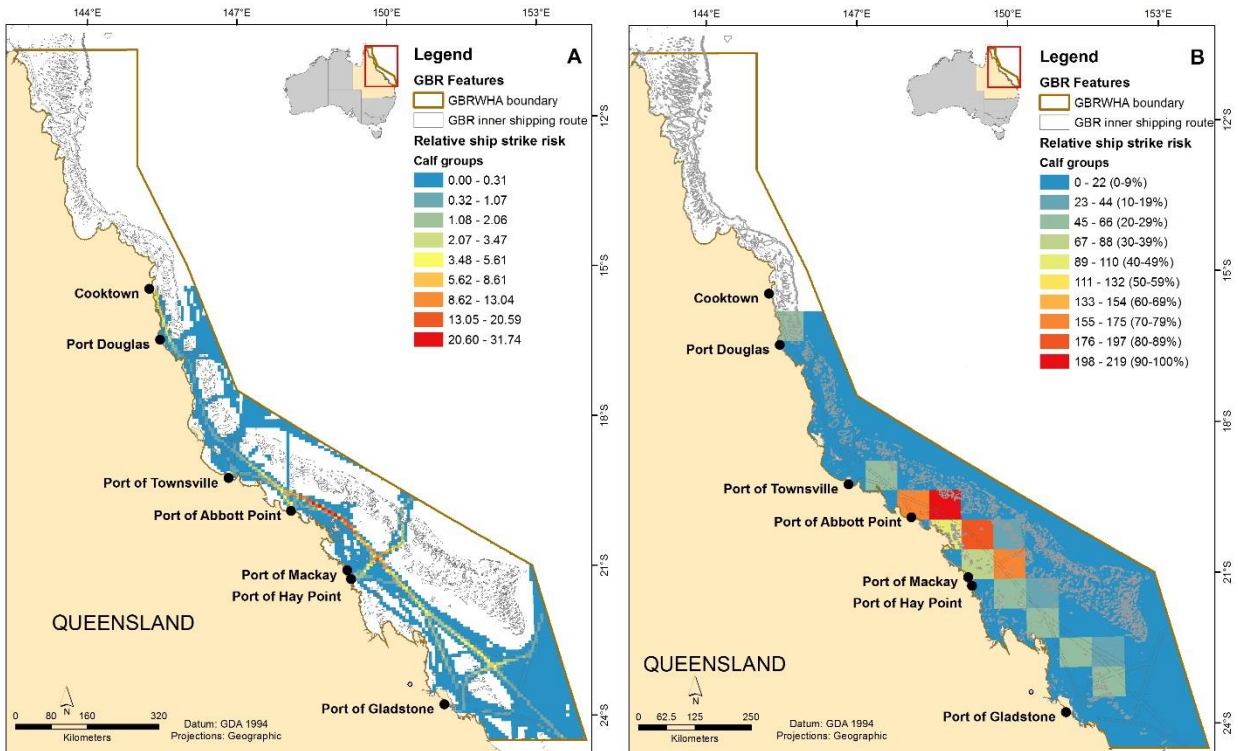


**Figure 14** Map of relative ship strike risk to humpback whale groups containing a calf at (A) 6 x 6 km and (B) 50 x 50 km resolution based on vessels ≥ 50 m in length and combined 2012/2018 whale model.

# 4. Discussion

A humpback whale aerial survey was undertaken in July 2018 within the Capricorn Bunker Group region of the GBRWHA during the whales' northward migration to enable an assessment of relative ship strike risk. Previous humpback whale distribution models based on 2012 and 2014 aerial survey data (Peel *et al.* 2015; Smith, Kelly & Renner 2019) had not been able to predict whale density within most of this region. This was due to a limited number of humpback whale sightings and a small amount of survey effort in bathymetric values deeper than 90 m. The 2018 aerial survey has overcome these limitations, enabling predictions of humpback whale density in the Capricorn Bunker Group and subsequently an assessment of relative ship strike risk to humpback whales from large (≥ 50m) AIS equipped vessels. In combination with the 2012 aerial survey data, it has enabled predicted whale distribution throughout most of the GBRWHA (between latitudes 15.5°S to 24.5°S) and a re-assessment of relative ship strike risk throughout this broader region of the World Heritage Area.

## 4.1 Humpback whale distribution in the Capricorn and Bunker Group

The E1 population of humpback whales annually migrate to the GBR for mating and calving during June to September (Chittleborough 1965; Simmons & Marsh 1986; Chaloupka & Osmond 1999; Smith *et al.* 2012). The 2018 aerial survey was conducted in early July during the whales' northward migration to their breeding grounds, which is reflected by the majority of whale sightings consisting of groups that did not contain a calf (91%). Although calves can be born further south than 24°S, the majority of calving occurs in GBR waters (Chittleborough 1965; Dawbin 1966). There have been recent improvements in our understanding of the distribution of humpback whales on their breeding grounds in the GBR (Smith *et al.* 2012; Peel *et al.* 2015; Smith, Kelly & Renner 2019). However, in the Capricorn Bunker Group and southern area of the GBRWHA there has been limited data on humpback whale distribution, consisting of opportunistic sighting data and a small dataset of satellite tagged whales (Simmons & Marsh 1986; Chaloupka & Osmond 1999; Gales *et al.* 2010; Smith *et al.* 2012). Specifically, the satellite tagging data (N = 12 whales) suggests that the movement of whales through this region is still migratory behaviour, based primarily on the whales' speed and direction of travel (Gales *et al.* 2010; Smith *et al.* 2012). The speed of whales in this region is similar to the swimming speeds of migrating humpback whales from other satellite tagging studies, which estimate an average migration speed of 4.0 km h−1 (N = 4; (Lagerquist *et al.* 2008)) and 4.3 km h−1 (N = 16; (Horton *et al.* 2011)). The whales also display a highly directed movement of travel through the Capricorn

and Bunker Group, similar to the directional precision in the movement of travel characteristic of migratory behaviour demonstrated by humpback whales in other satellite tag studies (Mate, Gisiner & Mobley 1998; Zerbini *et al.* 2006; Horton *et al.* 2011). The migration path widens and speed of travel slows near the Capricorn Group, with this area likely to be the terminus of the migration off the east coast of Australia.

Based on the 2018 aerial survey data, the predicted distribution of whale densities within the Capricorn Bunker Group region showed relatively similar patterns across all of the three whale categories ('all whales', 'non-calf groups' and 'calf groups') modelled (Fig. 7A, 7B & 7C). This whale distribution was consistent with the movements of satellite tagged whales through this region (N = 12 whales) in 2009 (Fig. 7D). The majority of sightings occur offshore and to the east of the Capricorn Bunker Group of islands and reefs, with clear differences in the distribution of whales in the north compared to the south, possibly influenced by bathymetry (Fig. 5). In the southern-most part of the Capricorn Bunker Group there is a restricted distribution of whales, with all sightings on a narrow continental shelf, in a depth ≤ 500 m and close to a steep continental slope where bathymetry quickly increases from 100 m to 4000 m (Fig. 5). It is predominantly due to the restricted distribution of whales and narrower migration width in the south compared to the north, that there is less overlap with the shipping lanes in the southern part of the survey area. This results in approximately ≤ 50% of relative ship strike risk in the southern half of the Capricorn Bunker Group compared to the northern half for 'all whale' groups (Fig. 9B). In the southern region there was a greater risk for 'non-calf groups' (≤ 67%, Fig. 10B) compared to 'calf groups' (≤ 28%, Fig. 11B), predominantly due to fewer sightings of calf groups in the south (Fig. 7B). A low abundance of calf groups at the beginning of the breeding season on the whales' northward migration is expected. However, the low number of calf group sightings compared to non-calf groups is a likely result of insufficient sampling effort for the already expected lower abundance of calf groups. Consequently, it is likely the risk of ship strike to calf groups in the southern area of the Capricorn Bunker Group is significantly under-represented. This lower sighting rate of calf groups gives an appearance of a discontinuous distribution of whales when modelling the predicted distribution (Fig. 7B). Given the Capricorn Bunker Group is a migratory route for humpback whales, the distribution of calf groups in this area is more likely to be a continuous distribution similar to non-calf groups.

The area of highest relative risk to 'all whale' groups of humpback whales in the Capricorn Bunker Group region is the northern area of the shipping lane, offshore of the Capricorn Bunker reefs where the central north-south and east-west shipping lanes intersect and north along the

central lane (Fig. 9). This equates to ≤ 70% of the relative risk of ship strike for 'all whale' groups (Fig. 9A & 9B) and is predominantly due to a more dispersed distribution of whales and broadening of the migration corridor from the area east of Heron Island up to the Swains Reef complex (Fig. 7C). The northern region of the study area was a consistently relative high-risk area for both calf and non-calf groups, highlighted at both the 6 x 6 km and 50 x 50 km data resolution (Fig. 10 & 11). This broadening of whale distribution in the north of the Capricorn Bunker Group is particularly evident for calf groups, which had a greater number of sightings closer to the coastline (Fig. 7C). Whale groups consisting of females with a calf tend to have a more coastal distribution on their breeding grounds (Félix & Botero-Acosta 2011; Craig *et al.* 2014; Guidino *et al.* 2014; Pack *et al.* 2018). Due to the spatial overlap of whales with the inner shipping route, the relative risk of ship strike for calf groups conformed to the spatial pattern in whale distribution, with a greater spatial extent of relative risk in the north compared to non-calf groups. However, their lower relative abundance resulted in less overall risk compared to non-calf groups. It should be noted, this measure of relative risk of ship strike does not incorporate any behavioural response or surface availability data. It is therefore uncertain whether calf groups have a higher probability of exposure to vessels due to more time spent near the surface water and hence higher risk of ship strike. Incorporating whale behaviour and surface availability into the risk framework will greatly enhance risk assessment of ship strike to whales in the future.

## 4.2 Humpback whale distribution in the GBRWHA

There have been recent improvements in our understanding of the distribution of humpback whales on their breeding grounds in the Great Barrier Reef due to systematic and dedicated aerial surveys. Specifically, the combined 2012, 2014 (Peel *et al.* 2015) and current 2018 aerial surveys have enabled predictions of humpback whale density throughout most of the GBR between latitudes 15.5°S to 24.5°S, from the southern GBRWHA boundary extending to Cooktown in the north (Fig. 8D). However, these are also the only systematic surveys for humpback whales on their breeding ground and conducted once at different times of the year. In the GBR, there is relatively uniform overlap of the GBR inner shipping route with humpback whale distribution and consequently, the relative risk of ship strike to whales depends more on the distribution and density of whales rather than the density of ships. Therefore, in areas of high whale density where there is little variation in shipping traffic, whale abundance is a good proxy for the relative risk of ship strike.

Based on the predicted distribution of whale densities for 'all whale' groups using 2012 and 2018 whale sightings data, there is a clear core aggregation area of high densities (≥ 80%) of humpback whales covering a range in latitude between 19.5°S to 21.5°S (Fig. 8A). This area (approximately a 250 km x 50 km area) encompasses the offshore area of the Whitsundays (near Hook Reef) in the north and extends south to approximately 90 km east of Mackay (near Paul Reef). It is important to consider the significant temporal component that influences the distribution of whales in the GBRWHA, such that the whales will be migrating through the Capricorn Bunker Group in early July and then peak abundance will occur in mid-late July and August and this is what the 2018 and 2012 aerial surveys capture, respectively. This temporal component to the whales' distribution is consequently reflected in the species distribution model (Fig. 8), given the model is based on these years of sighting data.

The area of highest relative risk of ship strike to humpback whales in the GBRWHA is the area situated offshore of Abbott Point and extending south to offshore waters of Mackay (Fig. 12). Within this range, the area of higher (≥ 80%) relative risk is between the Whitsunday Islands east to the outer reef and extending south to offshore waters of Mackay (Fig. 12B). Within this area of highest relative ship strike risk identified for 'all whale' groups, there is a spatial difference in risk between 'calf" and 'non-calf' groups. Non-calf groups had a higher predicted density (≥ 90 %) in offshore waters of Mackay compared to the Whitsundays region (Fig. 8B) and consequently this is the area of highest relative risk of ship strike for this group is offshore of Mackay compared to the Whitsundays (Fig. 13B). In contrast, calf groups had their highest predicted density (≥ 90 %) situated in the Whitsundays region (Fig. 8C), which was consequently the area of highest relative risk of ship strike in the GBRWHA for these groups (Fig. 14B). For calf group, there was also a second area of lower predicted densities located between Port Douglas and Cooktown in the northern GBR and represented a lower relative risk of ship strike (≤ 30%) compared to the Whitsundays. This area represented a greater relative risk of ship strike to calf groups compared to non-calf groups. This is due to a higher ratio of calves to adults in the northern GBR offshore of Cairns (1:4) compared to the southern GBR offshore of Mackay (1:7.9) (Smith, Kelly & Renner 2019).

There is lower relative risk of ship strike (≤ 48%) in the Capricorn Bunker Group compared to the rest of the GBRWHA. However, reduced survey effort in the Capricorn Bunker Group compared to the rest of the GBRWHA is likely to under estimate the relative risk of ship strike in this region. Relative ship strike risk to humpback whales is likely to be higher in this region than what the current risk maps indicate. This is due to the overlap of whales with the shipping lanes

(Fig. 7C), the restricted distribution of whales in this area and that the majority of whales of an estimated population size of approximately 37,000 whales (Noad *et al.* 2016) migrate through this region. While the magnitude of the risk is likely to be under-estimated in this region compared to the rest of the GBRWHA, the areas of relative 'high risk' identified in the Capricorn Bunker Group are likely to be accurate. This is due to good consistency in the distribution data of whales in this region between the 2018 aerial survey and other existing datasets, consisting of satellite tagged data (Fig. 7D) and opportunistic sightings data (Simmons & Marsh 1986; Chaloupka & Osmond 1999; Gales *et al.* 2010).

## 4.3 Management implications in the GBRWHA from relative risk estimates

Humpback whales are a protected species in the GBRWHA and listed as Vulnerable under both the *Environment Protection and Biodiversity Conservation Act 1999* and Queensland's *Nature Conservation (Wildlife) Regulation 2006*. An outcome from this assessment of relative risk of ship strike to humpback whales' is the spatial identification of areas of high whale density and relative risk of ship strike and their incorporation into spatial risk frameworks. As outlined in section 2.3, the risk of ship strike to humpback whales in this report is a relative risk metric. As such, it does not provide an indication of the magnitude of the risk or any indication of the true frequency of vessel collisions with humpback whales. It does provide the ability to compare risk spatially and temporally, to determine certain areas or times within the breeding season that humpback whales could be at risk from ship strike. The relative risk maps can therefore provide information to identify priority areas for further research and obtain data to address knowledge and information gaps that could improve the relative risk metric used in this study and/or aid estimates of absolute risk or ship strike mortality.

Some of the benefits of ultimately developing absolute risk estimates include a better understanding of the magnitude of the problem, the ability to estimate population level impacts and to compare between different species. However, the rapidly increasing population size of the E1 humpback whale population suggests ship strike is unlikely to have a population level effect on the whales. For example, in 2019 it would require 372 whale mortalities to affect 1% of the population. Interactions with vessels (large and small) on their breeding ground is likely to increase though based on projected increases in shipping and whale population size, which could result in welfare issues to the whales from non-fatal injuries (Peel, Smith & Childerhouse 2018). Despite the lack of reported incidents involving large ships (one reported case) there are indications (e.g. photographs of live humpback whales, scarring on stranded whales) that collisions between large

ships and humpback whales occur and that the number of reports do not reflect the number of incidents (Peel, Smith & Childerhouse 2018). Consequently, it is recommended that further research effort is given to better understanding this problem in relative high-risk areas.

The Great Barrier Reef Marine Park Authority is the lead agency responsible for the management of the GBRMP and World Heritage Area, particularly human activities within the Marine Park. Humpback whales are a high priority species for management by the GBRMPA and presently the main management tools for the protection of humpback whales in the GBR is a 'Whale Protection Area' or 'Special Management Area'. However, it is unclear whether existing GBRMPA management tools can afford any better protection for humpback whales in the GBR. A 'Whale Protection Area' is the main form of zoning legislative protection for whales within the Marine Park, covering the inshore, sheltered waters of the Whitsunday Group of islands (Fig. 15). It was established (presumably) to manage whale-watching operations, with the aim to minimise disturbance to whales and support protection of calving in this area. It is clear the 'whale protection area' does not cover the main calving and mating areas of humpback whales, however, given the purpose for its establishment it is unclear whether GBRMPA would re-evaluate the geographical extent of this whale protection area.
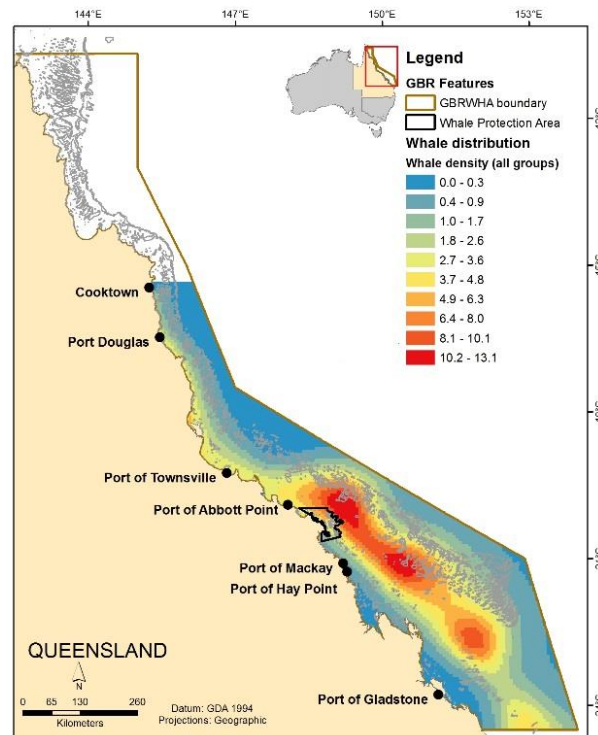


**Figure 15** Map of calving and mating humpback whales in the GBRWHA in relation to the 'Whale Protection Area'.

There are also provisions within the GBRMPA Operational Policy on Whale and Dolphin Conservation 2007 that allows the Authority to develop Special Management Areas (SMA's) for species management. The Operational Policy states the Authority may identify areas in the Marine Park that are considered important habitat (e.g. resting, calving and mating), and/or require special management of human related impacts on whales (e.g. reducing interactions between whales and vessels). Suitable areas could be designated Species Conservation SMA's under the Great Barrier Reef Marine Park Regulations 2019. A Species Conservation (Dugong Protection) SMA currently exists in the GBRMP for dugongs, primarily to regulate fishing activities and the use of nets in these activities in important dugong habitat. There is currently no SMA for whales in the Marine Park, whereas it is possible the establishment of a Species Conservation (Whale Protection Area) SMA in the areas of high whale density and risk of vessel strike could provide better protection to humpback whales in the Marine Park.

Ultimately, the Australian Maritime Safety Authority (AMSA) is responsible for Australia's maritime traffic and safety, including protection of the marine environment. Effective management will require the involvement of all relevant State and Federal government management agencies. The relative risk maps have identified potential hotspots of high interactions between whales and shipping in the GBR. These areas will require further consideration for targeted research and assessment of potential management action. Potential future targeted research is discussed in section 4.4. If mitigation options were considered necessary, vessel routing and speed restrictions have both been shown to reduce the probability and severity of ship strikes (Vanderlaan & Taggart 2006; Vanderlaan & Taggart 2009; Wiley *et al.* 2011; Conn & Silber 2013; Laist, Knowlton & Pendleton 2014). Within the GBRMP, mitigation options are more limited because of the extensive reef structure of the Great Barrier Reef, which constrains ship traffic movement between the reef and the coastline. This significantly limits the viability of re-routing measures and Traffic Separation Scheme's due to the limited space within the Designated Shipping Area. Furthermore, the distribution of whales throughout the breeding season is dynamic with the apparent movement of calf groups from offshore to inshore waters. AMSA in partnership with the International Maritime Organization could impose seasonal speed restrictions in targeted areas to reduce ship strike risk. Speed restrictions could be a viable and cost-effective management option given the evidence that vessel speed reductions of large vessels to ≤ 10 knots significantly reduces the risk of ship strike (Vanderlaan & Taggart 2006). A census of 2016 large vessel traffic (>50 m) show many vessels already travel close to that speed in the GBRMP (74% of vessel transits are between 10 and 15 knots and only 11% > 15 knots).

## 4.4 Recommendations on future research

The risk of ship strike to humpback whales in this report is a relative risk metric, and does not provide an indication of the magnitude of the risk or any indication of the true frequency of vessel collisions with humpback whales. The relative risk maps do identify priority areas for further research to obtain data to address knowledge and information gaps that could improve the relative risk metric used in this study and/or aid estimates of absolute risk or ship strike mortality. This could include applied research and/or an observer-monitoring program to address information gaps on the behaviour of whales around ships.

### 4.4.1 Applied research

Relative risk measures simplify the risk calculations such that any parameter that is constant across the population can be ignored, even if unknown. Fundamentally, quantifying uncertainty is an integral factor to improving estimates of ship strike risk and informing spatial decisions to manage risk, as outlined in Table 1 Section 2.3.1. To improve estimates of relative and absolute ship strike risk, the following key parameters require further work.

Species distribution models

More precise species distribution models are required to resolve substantial uncertainty in the spatial distribution of humpback whales in the GBR. Fundamentally, the distribution of whales and ships is at the core of an assessment of ship strike risk to whales and good, accurate knowledge of both is essential. Specifically, aerial surveys to investigate intra-seasonal (within season) and inter-annual (between years) whale distribution. To date, humpback whale distribution in the GBR consists of only three aerial surveys that represent three samples of the population at any one point in time. Aerial surveys have been conducted in early July 2018, early August 2012 and August/September 2014 and interpretation of whale distribution is based on assumptions of no significant intra- and inter-annual variation in whale distribution. These surveys have had different objectives and been conducted only once at different times of the breeding season and in different years. Intra- and inter-seasonal variability in whale distribution is likely the largest source of uncertainty in this spatial risk assessment and there is little data for which to estimate it. Without additional surveys replicating the coverage of previous ones, this will be difficult to quantify.

Behavioural response of whales to ships

The ship-strike risk framework currently does not incorporate whale behavioural data (e.g. vessel avoidance) that that could differ among age (adults vs. calves) and social class (mother-calf groups vs. non-calf groups). Key parameters include the surface availability (susceptibility) of whales and their response behaviour to vessels. These key parameters could affect estimates of risk, dependent on whether the whales' behaviour makes them more or less susceptible to ship strike. Surface availability of whales relates to the amount of time whales are within the potential strike zone of a ship for a collision to occur and will depend on the species dive behaviour and the vessel characteristics, such as vessel draft and impact on water movement around the vessel. For example, calf groups could be more at risk of ship strike compared to non-calf groups if they have a higher level of exposure to a ships strike zone due to frequent, shallow dives potentially resulting from calves needing to take more frequent breaths at the surface. Little data also exists on the response behaviour of humpback whales in the presence of vessels. Response behaviour by whales to vessels could occur in close proximity to vessels and could result in no behavioural change to clear adjusted dive behaviour and horizontal and/or vertical avoidance of vessels. The best way to address the behavioural response of whales to vessels in close proximity is by the use of short-term tag deployments on whales (e.g. Digital Tags or DTAG's). This could provide information on the horizontal and vertical movements of whales near vessels, quantify any differences in response between calf and non-calf groups and measure the noise exposure of whales to ships at the whales' location.

Collision model and the vessel speed/whale lethality relationship

Little data exists for the probability of a whale fatality given the speed of the vessel, which in reality it is difficult to obtain this data. This predominantly requires opportunistic data that retrospectively analyses AIS data from a known whale mortality.

**4.4.2 Observer monitoring program**

Placing dedicated marine mammals observers on board vessels is a proposed effective method to get information on whale sightings in close proximity to large vessels used in the United States. This involves an observer-monitoring program established within relative high-risk areas to address information gaps on the proximity of whales to large ships, potential rates of near misses and behavioural response of whales to ships.

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