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Distribution patterns of migrating humpback whales (*Megaptera novaeangliae*) in Jervis Bay, Australia: A spatial analysis using geographical citizen science data

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A B S T R A C T

Increases in east Australian humpback whale populations, specifically in areas where sightings were previously infrequent, highlight the importance of understanding the usage patterns and habitat preferences for resting grounds along migration pathways. This study investigates the spatio-temporal distribution of humpback whales in Jervis Bay, Australia, based on pod composition, providing insight on the role of this shallow coastal embayment for mother-calf pods during the southern migration to polar feeding grounds. Geographical citizen science-based sighting data, collected from a commercial whale-watch platform during the 2007–2010 migration seasons, were used to examine variations in bay usage and pod composition. Differences in the distribution patterns of mother-calf and non-calf pod sightings were examined using spatial cluster analysis. The impact of sampling bias, introduced through non-specialist volunteer collected data, on spatial cluster detection was simulated. Observation error and spatial sampling bias may affect local spatial cluster detection. Sampling processes with potential to contribute to this bias should be recorded in the survey design of geographical citizen science based data collection programmes. Mother-calf pods showed a significant preference for the shallow waters of Jervis Bay during October and November, indicating the bay may function as a preferred resting location during their southern migration with important marine management implications.

Introduction

Following near-extinction in the 1950s and early 1960s due to whaling, there has been a significant increase in the east Australian humpback whale population. Land-based surveys conducted at Point Lookout, south-eastern Queensland over the last 25 years have shown a strong, long-term rate of population growth in the east Australian humpback whale population (Noad, Dunlop, Paton, & Cato, 2011). Estimated growth rates are predicted as one of the highest for any mammalian population, and are close to the theoretical reproductive limit of the species (Noad et al., 2011; Paterson, Paterson, & Cato, 1989; Paterson, Paterson, & Cato, 2001).

Southern hemisphere humpback whales undertake extensive annual migrations between high latitude feeding grounds where they spend the austral summers, and the low latitude breeding grounds where they spend the austral winter, a distance of approximately 5000 km (Baker et al., 1986; Clapham, 2000; Valsecchi, Hale, Corkeron, & Amos, 2002). Humpback whales display high site fidelity; returning year after year to the same breeding and feeding grounds (Clapham, 2000; Stevick et al., 2003). These migrations predominantly follow near-shore migration corridors, providing protection from rough seas, predators and conspecifics (Bryden, 1985; Mattila & Clapham, 1989). Some individuals have been observed moving into sheltered coastal embayments where they rest and socialise before completing their migration (Corkeron, Brown, Slade, & Bryden, 1994). There is limited understanding of the migratory stages of humpback whales, particularly regarding the social interactions and habitat constraints that may be exhibited (Valsecchi et al., 2002).

Humpback whale calves are born in the warm, sheltered waters of the winter breeding grounds (Smultea, 1994). From there, the calf

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travels south with its mother to the rich feeding grounds in the high latitudes and are rarely observed travelling in large groups or associated with other mother-calf pairs, generally preferring to travel with one additional whale, an 'escort whale' that may assist with care, as well as protecting against predation or harassment by conspecifics (Brown & Corkeron, 1995; Herman & Antinoja, 1977). During a calf's first southern migration, the mother is the primary provider of food and protection, as well as teaching (Clapham, 2000). Humpback whales exhibit high levels of maternally directed philopatry and the foraging success of an individual may depend on its exposure to a variety of foraging habitats as a calf (Weinrich, 1998).

Studies examining habitat preferences of mother-calf pairs in humpback whale breeding grounds worldwide have shown that mother-calf pairs prefer shallow, calm waters; hugging the shoreline while migrating or resting in protected embayments or coastal waters (Ersts & Rosenbaum, 2003; Rasmussen et al., 2007). Distribution by depth is a function of social organisation, with mothers and calves showing a strong preference for shallower water compared to all other pod types (Ersts & Rosenbaum, 2003). Ersts and Rosenbaum (2003) observed that 95% of mother-calf pairs sighted in Antongil Bay Madagascar, were within 7 km of the shore and 20% of those pairs were found within 1 km of the shore, a statistically significant percentage in comparison to other group types (adult or sub-adult competitive groups). Escorted and non-escorted mother-calf pairs showed a slightly different preference for water depth with non-escorted pairs found in shallower waters. In a breeding ground off the coast of the Santa Elena Peninsula in south-central Ecuador, Félix and Botero-Acosta (2011) found that the majority of humpback whale groups sighted within a 9 km radius of the peninsula tip were in water less than 50 m depth. Mother-calf pairs exhibited significant preference for shallower depths relative to other group types, with escorted pairs found at mid-depths.

In eastern Australia, an increase in whale abundance and sighting frequency has been observed in two main shallow coastal embayments: Hervey Bay, Queensland (Corkeron et al., 1994) and more recently, in Jervis Bay on the south coast of New South Wales. Increases in the number of whale sightings within Hervey Bay over a 14-year study period strongly suggests that this area provides a suitable stopover for mother-calf pairs during their southern migration (Franklin et al., 2011). In Jervis Bay, there has been limited research on humpback whales and their habitat usage patterns, primarily as their presence had been infrequently documented prior to 2000. However, the increased occurrence of humpback whales in more recent years may suggest that Jervis Bay could provide another resting area for southern migrating whales. Jervis Bay is a multiple use marine park which provides for commercial and recreational uses; therefore, there is potential for anthropogenic interaction.

The current study investigates the spatio-temporal distribution of humpback whales in Jervis Bay, based on pod composition. This study provides insight on the role of this shallow coastal embayment for mother-calf groups during the southern migration to polar feeding grounds. In the absence of systematic observational surveys, citizen science based non-specialist volunteer collected sighting data were used to examine distributional trends over a four year period. The specific objectives were to: (1) establish whether mother-calf groups are observed at higher rates within Jervis Bay relative to other whale pods during mid to late austral spring; (2) determine whether there were distinctly different spatial clusters of mother-calf pods and non-calf pods; (3) examine differences in preference for depth and coastal exposure between different pod compositions; and (4) examine the impact of potential sampling bias associated with volunteer collected whale observation data on measures of spatial clustering. Detailed studies of the spatial patterns observed in humpback whale distributions, can provide an understanding of the significant environmental components for this species (Vigness-Raposa, Kenney, & Gonzalez, 2010) and spatial cluster analysis (Haworth, Bruce, & Iveson, 2013) may assist in establishing habitat usage patterns within the bay.

The role of geographical citizen science and VGI

The intent of this study was to examine mother-calf pod preference for the shallow protected waters of Jervis Bay. This involved the use of citizen science data collected onboard a commercial whale-watching vessel to establish the spatio-temporal distribution of whale observations and examine the influence of depth and ocean exposure on distribution. Analysis of broad scale species distribution patterns, in particular the movements of migratory species, requires extensive monitoring data (Bonney et al., 2009), the collection of which is often challenged by logistical constraints (Theberge & Dearden, 2006). Citizen science, defined here as engaging non-specialist volunteers in the collection of data for scientific enquiry (Bhattacharjee, 2005; Silvertown, 2009), provides a practical tool to achieve the geographical reach needed to address spatial ecological questions at scales relevant to species migration patterns (Dickinson, Zuckerberg, & Bonter, 2010). Citizen science involving the collection of explicit geographic information falls within the definition of Volunteered Geographic Information (VGI) and the term geographical citizen science is used to refer to projects in which the collection of locational information is integral to the study (Elwood, Goodchild, & Sui, 2012; Haklay, 2013). The VGI phenomenon involves the acquisition and dissemination of geographic information through the voluntary activity of individuals or groups (Elwood et al., 2012; Goodchild, 2007) and encompasses geotagged photographs shared through sites such as Flickr and Wikimapia to focused web-enabled crowdsourcing for improving the reliability of nautical charts (Sedaghat, Hersey, & McGuire, 2013). The scientific protocols required in the collection and analysis of data, the focus on recording observations rather than community perception and the scientific intent or motivation distinguishes geographical citizen science from other VGI and participatory mapping activities (Haklay, 2013). The emergent VGI literature offers important contributions on the challenges associated with the use of non-specialist volunteered data in addressing scientific questions. Brunsdon and Comber (2012) demonstrate the research implications of unexpected changes in geographical citizen science based data collection programmes resulting from the ending of public funding, the loss of a key organizing individual or involvement of new participants. These issues are particularly relevant to long-term marine species monitoring programmes reliant on commercial whale-watching and other wildlife tourism activities in which events such as operator ownership changes may disrupt continuity of record or overrepresentation in tourist frequented areas result in spatial sampling bias.

The recent emergence of spatially enabling technologies including Web 2.0, burgeoning user generated content disseminated via the internet and proliferation of locational-acquisition devices (such as GPS-enabled smart phones) is altering the way geographic information is produced and shared. This has important implications and new opportunities for understanding spatial distribution patterns of marine and coastal species. While facilitating large-scale citizen science initiatives, data generated from these new information sources also challenge traditional scientific practices (Connors, Lei, & Kelly, 2012).

The use of data collected by non-specialist volunteers has received growing interest in marine conservation (Bird et al., 2014; Darwall & Dulvy, 1996; Davies, Stevens, Meekan, Struve, &

Rowcliffe, 2013; Foster-Smith & Evans, 2003; Marshall, Kleine, & Dean, 2012; Monk, Ierodiaconou, Bellgrove, & Laurenson, 2008; Theberge & Dearden, 2006). However, despite the recognized value and impact of geographical citizen science and VGI, its acceptance within the scientific community is dependent on an understanding of the inherent biases within these data. Concerns include the robustness of volunteer-collected data (Foody et al., 2013), lack of standardized collection procedures (Underwood & Chapman, 2002) and inadequate evaluation of the validity of these data for the intended study (Boudreau & Yan, 2004; Delaney, Sperling, Adams, & Leung, 2008). This is particularly relevant for geographic citizen science initiatives that involve surveillance, rather than targeted, monitoring and opportunistic sampling methods often adopted in volunteer-tourism based marine surveys, such as those conducted in Jervis Bay. This study will examine the impact of potential error and bias introduced through non-specialist volunteer collected data.

Variation in observer quality, which refers to inter-observer differences in the ability to collect data between different participants and expert field researchers, may introduce bias in survey results (Dickinson et al., 2010; Foody et al., 2013). This was minimized in the current study through personalized in-field training of volunteers and the weekly involvement, during the migration season, of a marine mammal observer with over 10 years' experience in cetacean identification and data collection. Adequate volunteer training and volunteers, accompanied by experienced observers, have shown to improve observer quality (Fitzpatrick, Preisser, Ellison, & Elkinton, 2009) and observer bias will generally decrease as observers become more experienced over time (Delaney et al., 2008).

Standardization of sampling effort can be difficult in geographical citizen science initiatives particularly if survey design requires flexibility. VGI projects are often unable to meet the conventional data collection requirements for scientific research, such as random sampling (Elwood et al., 2012). This necessitates recording of expended effort (eg. survey days) and spatial coverage (transect location and observation viewing field) to ensure observed patterns represent true geographical or biological trends rather than variation in survey effort (Dickinson et al., 2010). In addition, certain attributes will be more difficult to measure or distinguish than others. For example, adult whales may be undoubtedly sighted, but the erroneous observation of a calf, as a young juvenile, may result in the underestimation of mother-calf pod types. Calf presence, within an observed whale pod, is a key variable in this study. For this reason it was important to understand whether misinterpretation of pod composition will impact on analysis results.

The potential for bias inherent in geographical citizen science data highlights the need for spatial analysis approaches that provide an understanding of data uncertainty and insight on the reliability of results used to inform marine management decisions. The effect of survey bias or sampling error on the detection of spatial clusters of whale pods may vary depending on the form of inaccuracy (for example, positional error or observer misinterpretation) and the spatial statistic applied. Burra, Jerrett, Burnett, and Anderson (2002) found that the G_i^* statistic was robust to location errors but recognise that this may reflect the relatively large search window (lag distance) rather than the stability of the statistic. There is a need for further research on how local metrics of spatial association are affected by sampling inaccuracies (Malizia, 2013).

Methods

Study site

Jervis Bay is a semi-enclosed embayment situated along the New South Wales (NSW) coastline, approximately 180 km south of Sydney and approximately 115 km^2 in area (Fig. 1). The area was declared a marine park by the NSW Government in 1998 based on natural and cultural values. The sea floor of Jervis Bay is gently sloped, averaging 15–20 m in depth, reaching a maximum depth of 40 m near the entrance. Extending out from the mouth of the bay, the continental shelf is narrow (20 km wide) and sharply descends to depths below 100 m within 5 km of the mouth (Holloway, 1995; Ward, 1995). The high cliffs and narrow opening of Jervis Bay protect the bay from most ocean swells and sea winds.

Data and preprocessing

In the absence of systematic surveys of humpback whales within Jervis Bay and surrounding ocean environs, sighting data were collected by a commercial whale-watch operator. Dolphin Watch Cruises (DWC) collected detailed records of humpback whale sightings from an 18 m whale-watching vessel (observation height = 6 m). Data collected included sighting date and time, location (using differentially corrected GPS, Simrad CX44), direction of travel, group size, group composition (adults, non-adults and calves), as well as predominant surface behaviour (greater than 50% of whales displaying behaviour). Sightings were recorded during daylight hours between 06:00 and 17:00. These data were collected by DWC crew and trained volunteers from the Marine Mammal Research Unit (MMR), based in Jervis Bay. Although some of these observers had considerable field experience in cetacean sightings, the term 'non-specialist volunteer' is used here to refer to all data collectors without scientific expertise in marine mammal

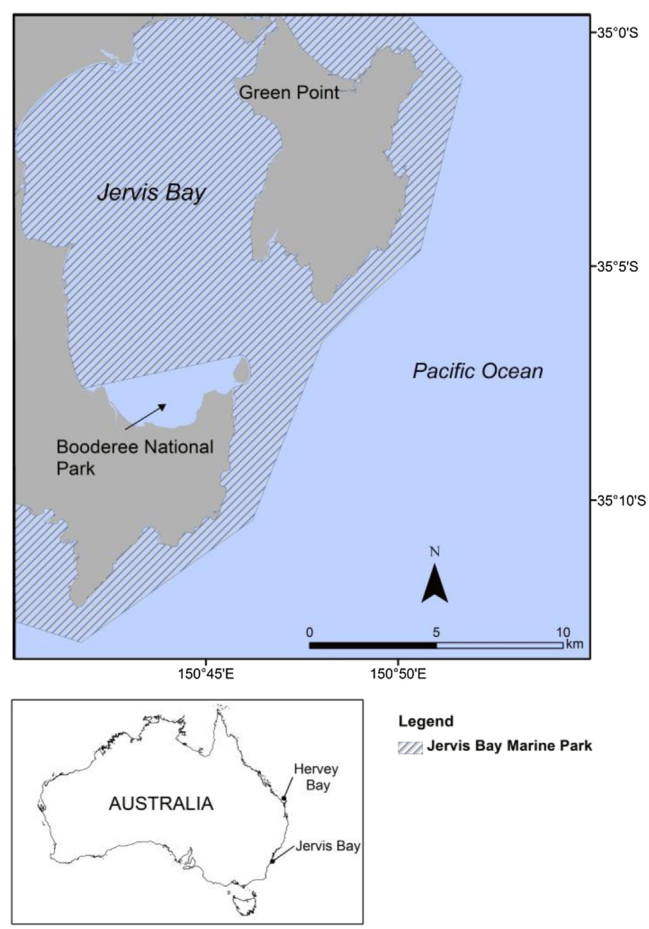

Fig. 1. The location of Jervis Bay on the south eastern Australian coast. Source: Marine Parks Authority (2009)

survey and identification. Training of non-specialist volunteers involved a field training day, supervised by an experienced marine mammal observer, during which survey protocol was introduced through photographs, identification sheets and training on observational techniques. Survey protocol was designed by a marine mammal ecologist, in regular communication with volunteers during survey months.

Sighting data were collected for each migration period (May to November) between 2007 and 2010 and was imported into ArcGIS 10.2. The sighting of a whale pod was recorded once per trip to avoid multiple sampling of the same pod resulting in artificial inflation of occurrences. Survey effort was determined based on the proportion of survey days in which each whale group composition (mother-calf pair, mother-calf-escort pod and non-calf pod) sighted per month which was averaged across the four survey years (Table 1). Potentially erroneous observations were filtered based on spurious coordinates and absence of pod composition data. Vessel track data were not recorded and the broad survey zones in which the vessel traversed was documented for 24% of sighting observations. In accordance with the *National Parks and Wildlife Amendment (Marine Mammals) Regulation* (NSW) and the *Environment Protection and Biodiversity Conservation Act* 1999, the whale watching vessel remained a minimum distance of 100–300 m from observed whales (300 m if calf was present). The offset between the GPS location of the vessel and true pod(s) location was visually estimated based on approximated sight distance and compass bearing.

The spatial extent of all DWC survey records during the study period was mapped to define the study area boundary. The number of humpback whales sighted per month was estimated by summing the number of whales per sighting, accounting for the number of trips per day, as well as the pod composition within each sighting. Mother-calf pod observation rates within the bay environment relative to other non-calf whale pods during mid to late austral spring was calculated using spatial overlay, the seaward boundary defined as the bay entrance. A chi-square test of independence was performed to examine the association between whale pod composition and observed location within and outside the bay.

Aggregation of sighting data into spatial units of analysis to examine spatial clustering was undertaken using a rectangular celled fishnet and spatial join in ArcGIS 10.2 to generate two 300 m fishnet vector layers containing the sighting frequency of; (1) mother-calf pods and (2) non-calf pods. The 300 m aggregation cell size was determined based on average nearest neighbour distance.

Spatial analysis

The spatial distribution of mother-calf pods and non-calf pods was examined using Global Moran's I to confirm the presence of global patterns and the Getis-Ord G_i^* statistic to provide statistical evidence for the presence of local clusters. Spatial autocorrelation of humpback whale sightings was tested using the Global Moran's I statistic (Getis & Ord, 1992), to evaluate whether the overall pattern expressed is clustered, dispersed or random. The null hypothesis stated that whale sightings were randomly distributed within the study area. The Getis-Ord G_i^* measures the degree of spatial clustering of a local sample relative to the mean (Ord & Getis, 1995). The G_i^* statistic can identify areas where local averages are significantly higher than global averages (Getis & Ord, 1996), detect spatial clusters despite negative tests for global spatial autocorrelation (Jacquez, 2009) and identify features within neighbourhoods of high whale sightings, even if the feature does not differ from the global mean (Braithwaite & Li, 2007), which is particularly relevant in determining local clusters of vagile marine species. The G_i^* test was performed to examine the degree of spatial association between mother-calf pod sighting locations and was repeated for non-calf pod sighting locations (Ord & Getis, 1995). Following Ord and Getis (1995) and Getis and Ord (1996), the statistic is given as:

$$G_i^*(d) = \frac{\sum_j w_{ij}(d)x_j - W_i^*\overline{x}^*}{s^*\sqrt{\frac{(nS_{1i}^*)-W_i^{*2}}{n-1}}}$$

where x_i is the value of feature i, i is the centre of the local neighbourhood, d is the lag distance (bandwidth of sample window) and w_{ij} is the elements of the weight matrix defining the weight assigned to each pair of features x_i, x_j, n is the number of samples in the data set, W_i^* is the sum of weights, S_{1i}^* is the number of samples within d of the central location, $\overline{x}^*$ is the sample mean, and s^* is the standard deviation of the sample (Laffan, 2006; Mueller-Warrant, Whittaker, & Young, 2008). A binary weights case was applied for both the Moran's I and G_i^* statistics using a fixed distance band weighting procedure with row standardization. In a binary weights case, the spatial weights are one if the x_i are within d of the central location and zero if otherwise (Getis & Ord, 1996). A lag distance d (band width) of 2000 m was specified based on ecological considerations and to ensure a reasonable number of j neighbours to support the assumption of normality (Getis & Ord, 1996). The false discovery rate (FDR) criterion was applied to adjust for multiple testing, this procedure controls the average rate that declarations of significance are truly non-significant (Caldas de Castro & Singer, 2006).

The G_i^* is expressed as a 2-tailed z-score with a mean of 0 and standard deviation of 1 (Laffan, 2006), so that positive G_i^* values indicate statistically significant spatial clustering of high values (whale sightings) and negative values indicate statistically significant spatial clustering of low values (samples with few or no whale sightings).

Assessing uncertainty associated with geographic citizen science data

To account for uncertainty associated with non-specialist volunteer collected data it was necessary to consider potential for: (1) sighting location error, (2) volunteer observer error and (3) spatial sampling bias. As the survey design was opportunistic and the observation platform was a commercial operating vessel, it is appropriate to apply conservative thresholds when examining geographical variation between whale pods. Different spatial

Table 1
Humpback whale survey effort based on commercial mammal watch vessel activities in Jervis Bay.

	Study period	Number of boat days per month							Total no. days effort	Total no. days possible	Percent effort
		May	June	July	Aug	Sept	Oct	Nov			
2007	May 26 – Nov 26th	5	11	12	6	12	22	17	85	185	46%
2008	May 19th – Nov 30th	7	16	12	11	11	24	28	111	196	56.6%
2009	May 9th – Nov 23rd	7	22	23	21	20	26	17	136	199	68.3%
2010	May 28th – Nov17th	2	12	16	9	9	16	2	66	174	37.9%

configurations of errors may result in either the underestimation or overestimation of a cluster (Burra et al., 2002). Randomisation tests were performed in which the sample data was randomly rearranged to examine the impact of potential bias on analysis of spatial-autocorrelation (Global Moran's I) and local cluster detection (G_i^*). Randomisation tests performed on the Global Moran's I statistic were reported as mean, standard deviations and ranges of the index. To examine whether theG_i^* analyses were robust to potential survey bias, randomisation tests were iterated. The proportion of rearranged samples whose test value exceeded the original test value was given by

$$P = \frac{1 + \sum_{j=1}^{B} I(x_j \geq X)}{B + 1}$$

where x is the test value (G_i^* statistic), I is the indicator function that takes the value one when its argument is true, and zero when it is false and B is the number of randomisations ($B = 500$) (modified from Ruxton, Neuhäuser, & O'Hara, 2013). The proportion of spatial units of analysis in which the null hypothesis was accepted or rejected, at different confidence limits, was calculated to examine the influence of survey bias on over or underestimation of local clusters.

Vessel movement, distance regulations and approximation of pod offset from the vessel will potentially introduce positional error in the sighting data. To examine whether positional error has a discernible impact, a spatially constrained randomization process was run in which sighting data were offset at distances of 50, 100, 150, 200, 250 and 300 m.

Intensive volunteer training in whale sighting methods ensured consistency in observation and reduced the likelihood of observer error. However, over the four year survey period, it was possible volunteer inexperience may have resulted in misinterpretation of whale pod composition. Error may have sporadically occurred through misidentification of young juveniles as calves or the reverse. The impact of this form of observer error on spatial association estimates was assessed by randomly rearranging pod description assigned to samples in a defined subset of the total samples. This was repeated for different subset sizes to examine the influence of varying levels of observer error.

In the absence of vessel track data, an assessment of the potential impact of spatial sampling effort bias was examined based on available survey zone data. These data represented 24% of the total sample and were used to derive an estimate of relative spatial sampling effort. This was determined based on the proportion of observation trips during which a zone was traversed. Based on the survey protocol requiring an observer field of view of 2 km and multiple observers, it was assumed survey coverage would extend the entire zone during a traverse. Effort estimates remain approximate as the differing spatial extent of survey zones and lack of records on vessel time spent within each zone limits true comparative analysis. Effort standardization was then applied to determine rate of mother-calf and non-calf pod observation within each zone relative to sampling effort. The randomization test involved removing a random selection of samples within each survey zone, proportional to the sampling effort for each iteration.

Environmental influences

Differences in water depth and exposure preference between; (1) mother-calf pairs and mother-calf-escort pods and (2) calf-pods and non-calf pods were tested using one-way ANOVA. The seabed exposure grid of Jervis Bay was used as a proxy for the level of coastal protection from ocean swell. Seabed exposure was derived using the Simulating Waves Nearshore (SWAN) model, a fine scale hydrodynamic model used to estimate wave propagation (Geoscience Australia, 2010). The influence of water depth and exposure on the distribution of mother-calf groups and non-calf groups was examined using the MaxEnt (Version 3.3.3) species distribution model to derive species response curves. MaxEnt is a maximum entropy model (Elith et al., 2011; Phillips, Anderson, & Schapire, 2006) which has the ability to model presence only data and performs well with small sample sets (Phillips, Dudík, & Schapire, 2004). The model was developed for all mother-calf pod sightings (including mother-calf-escort groups) using 75% ($n = 238$) of the sighting data and tested using 25% ($n = 80$) of the data, with all response functions selected. This was repeated for non-calf pod sightings using 75% ($n = 260$) of the data for training and 25% ($n = 87$) for testing.

Results

Humpback whales migrate north past Jervis Bay between May and July each year. Sightings during this period across all surveyed years, were infrequent and predominantly outside the bay. Southern migration occurs between August and November. During this period, there was an increase in whale sightings and a higher proportion of mother-calf pods inside Jervis Bay. Pod composition was highly variable by season. Sightings of adults and juveniles were highest during the autumn and winter months (May through to August) when few mother-calf pods are sighted. The proportion of sightings of pods with calves in Jervis Bay increased during the spring, along with a significant decrease in the number of adult sightings (Fig. 2).

Results of the Global Moran's I statistic allowed for rejection of the null hypothesis, that sightings of both mother-calf and non-calf pods were randomly distributed within the study area. There was clear geographic variability between the distribution of mother-calf humpback whale pairs and non-calf groups. The relationship between pod composition and observed location within and outside the bay was highly significant, X^2 (1, $N = 665$) $= p = 129.39$, $p = <0.0001$. Mother-calf pods were more likely to be observed within the bay than non-calf pods. The Getis-Ord G_i^* analysis determined a significant cluster of high observation rates of mother-calf pod sightings ('hotspot') within Jervis Bay, extending 1.5 km from the entrance on the seaward side and across most of the bay in waters greater than 12 m in depth (Fig. 3A). There were clusters of low observation rates of mother-calf pod sightings ('cold spots') north and south of Green Point in the northeast corner of Jervis Bay as well as in the deeper ocean waters outside the bay. A significant cluster of high observation rates of non-calf pod sightings ('hotspot') occurred near the bay entrance and extended north and south along the coast adjacent to the entrance (Fig. 3B). Clusters of low observation rates of non-calf pods occur within the bay.

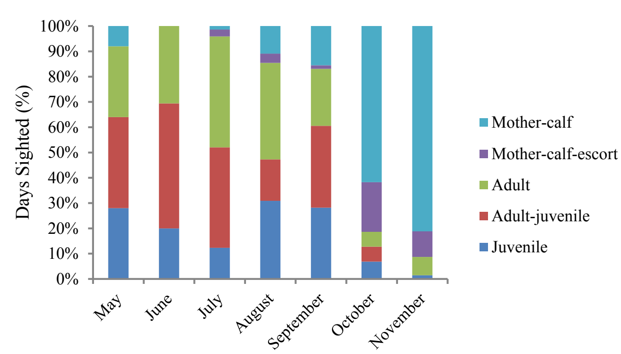

Fig. 2. Proportion of days in which each whale pods composition was sighted per month across the study period.

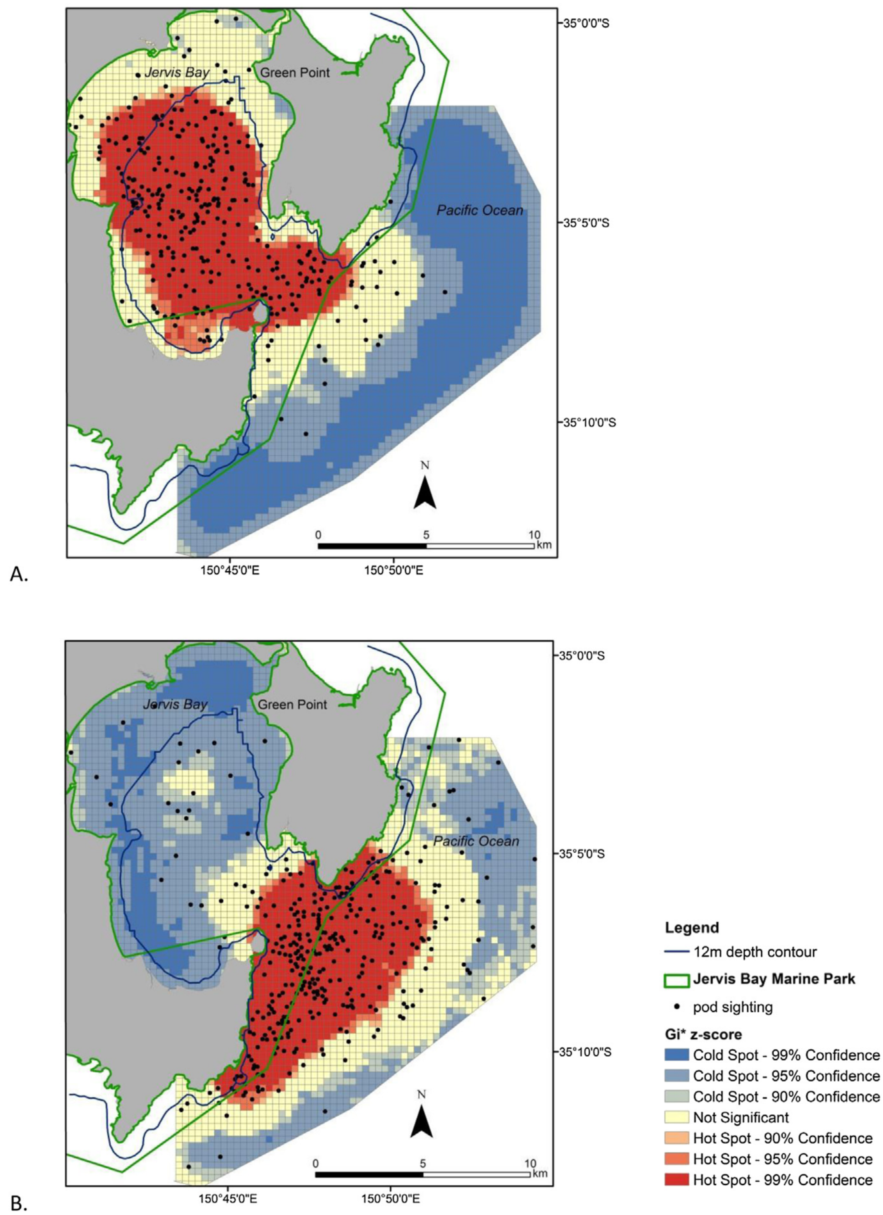

Fig. 3. Spatial clusters of high and low incidences of humpback whale sightings between 2007 and 2010. High Getis-Ord G_i^* *z*-scores depict more intense clustering of high whale sighting frequencies (hotspots or positive clusters), shown in red, and low *z*-scores depict more intense clustering of low whale sighting frequencies, shown in blue (cold spots or negative clusters). A) Areas of high and low frequencies of mother-calf group sightings; B) Areas of high and low frequencies of non-calf group sightings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Similar values of the Global Moran's I statistic were observed for the sighting data that were offset at different distance intervals, suggesting positional error has minimal effect on this global statistic for both calf pod and non-calf pod occurrence (Table 2). The effect of potential errors in pod composition description (observation error) was more apparent for both mother-calf and non-calf pod compositions (Table 2). Analysis of relative sampling effort showed higher rates of sampling in survey zones in the northwest and centre of the bay, and lower rates in the north entrance of the bay. Adjustment for spatial sampling bias resulted in a discernable difference in the Global Moran's I statistic for mother-calf pod distributions but not non-calf pods. Although the null hypothesis for Global Moran's I can be rejected despite uncertainties associated with these volunteer collected data, spatial sampling bias and pod observation errors (affecting as low as 2% of the original data) can impact results.

In tests of the G_i^* statistic, the proportion of spatial units of analysis in which the null hypothesis is rejected increased with observation error, for both mother-calf and non-calf pod distributions (Table 3). This suggests that a true null hypothesis may be incorrectly rejected due to observation error (misidentification of pod composition) resulting in the potential overestimation of local clusters. Positional error <300 m had limited effect on the G_i^* statistic and adjusting for spatial sampling effort resulted in a slight increase in the proportion of spatial units of analysis in which the null hypothesis was accepted for mother-calf pod distributions (Table 3). The proportion of spatial units of analysis recording positive or negative clusters at the 99% confidence level decreased

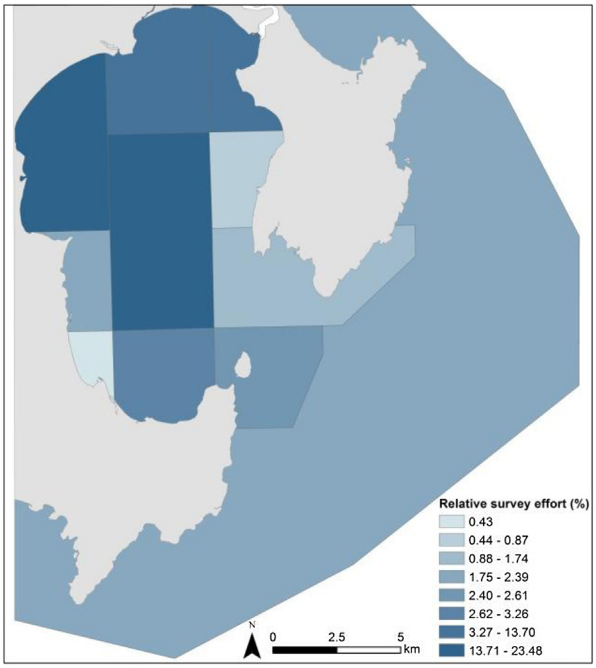

Fig. 4. Map showing relative sampling effort based on the proportion of observation trips during which a zone was traversed.

with increased observation error and was lower in tests using data adjusted for spatial sampling effort. The spatial expression of the effect of adjusting for spatial sampling effort on the G_i^* statistic is shown in Fig. 5. Bias in spatial sampling effort may result in the underestimation of positive clusters (high observation rates) of mother-calf pods near the bay entrance and the southern area of the bay. This bias may cause underestimation of positive clusters (high observation rates) of non-calf pods further seaward of the bay entrance and negative clusters (low observation rates) inside the bay.

The average depth and seabed exposure (Fig. 6) for the different whale pod compositions is shown in Table 4. Depth preference was

Table 2
Comparative global Moran's *I* results for mother-calf pod and non-calf pod sightings using data randomly adjusted for spatial sampling, positional offset and pod composition observation error (100 random samples).

	Non-calf groups			Mother-calf groups		
	Moran's I	STD	p value	Moran's I	STD	p value
Unadjusted	0.1793		<0.001	0.1401		<0.001
Adjusted for spatial sampling effort	0.1797	0.0012	<0.001	0.1148	0.0029	<0.001
Offset distance						
50 m	0.1787	0.0028	<0.001	0.1376	0.0029	<0.001
100 m	0.1740	0.0049	<0.001	0.1399	0.0028	<0.001
150 m	0.1712	0.0062	<0.001	0.1400	0.0033	<0.001
200 m	0.1682	0.0049	<0.001	0.1387	0.0043	<0.001
250 m	0.1651	0.0058	<0.001	0.1364	0.0052	<0.001
300 m	0.1636	0.0061	<0.001	0.1380	0.0046	<0.001
Observation error						
2%	0.1732	0.0034	<0.001	0.1350	0.030	<0.001
5%	0.1654	0.0058	<0.001	0.1286	0.040	<0.001
10%	0.1503	0.0071	<0.001	0.1168	0.062	<0.001
15%	0.1377	0.0083	<0.001	0.1072	0.0057	<0.001
20%	0.1264	0.0084	<0.001	0.0983	0.0061	<0.001
25%	0.1146	0.0095	<0.001	0.0928	0.0065	<0.001

significant between all calf pods and non-calf pods ($n = 664$; $F(1, 663) = 395.1$; $p < 0.001$). There was no significant difference in depth preference between mother-calf pairs and mother-calf-escort pods ($n = 317$; F (1, 316) $= 2.99$; $p = 0.08$). Significant difference was not shown in exposure preference between calf pods and non-calf pods ($n = 664$; $F(1, 663) = 1$; $p = 0.317$) and between mother-calf pairs and mother-calf-escort pods ($n = 317$; $F(1, 316) = 4.08$; $p = 0.044$).

Response curves for calf pods indicate a preference for water depths between 5 and 50 m and exposure levels between 0 and 0.5 (Fig. 7 A and B). Response curves for non-calf pods indicate a preference for deeper water greater than 40 m but do not indicate a clear pattern characterizing the relationship between the probability of non-calf pod occurrence and level of exposure (Fig. 7 C and D).

Discussion

Current literature suggests that whale distribution patterns are influenced by a combination of long-term maternally directed fidelity along migratory pathways, in combination with ecological and oceanographic aspects, which may influence habitat preference and behaviour. As the eastern Australian humpback whale populations continue to increase, it appears that their range has begun to expand beyond their traditional migratory routes, moving away from more densely populated areas and shifting into coastal embayments where sightings were previously infrequent or negligible. This 'spill over' into new regions is particularly important for mother-calf pairs, who are migrating to the polar feeding grounds for the first time and are in need of suitable habitats for protection against the elements or harassment from predators or conspecifics. These changing habitat usage trends have important coastal management implications.

Geographic variability was observed between mother-calf humpback whale pods and non-calf pods during the southern migration period with mother-calf pods indicating higher usage of the coastal embayment of Jervis Bay, on the south eastern Australian coast. Several studies undertaken in humpback whale breeding grounds have concluded that mother-calf pairs show a significant preference for warm, shallow water, relative to other group types (Craig, Herman, Gabriele, & Pack, 2003; Ersts & Rosenbaum, 2003; Martins et al., 2001; Smultea, 1994). The current study demonstrated similar findings, with mother-calf pairs displaying a significant preference for the protected shallow waters inside Jervis Bay during the southern migration period, in particular during October and November.

Temporal trends

During the southern migration, there was a significant shift in the composition of groups sighted in Jervis Bay (Fig. 2). From the beginning of September continuing through to November, mother-calf pairs were the most commonly observed pod type within the bay. Fewer competitive pods consisting of adults and juveniles were observed at this time, with the majority of sightings recorded within the bounds of the Jervis Bay Marine Park. This temporal trend is consistent with findings from research conducted on humpback whales in Hervey Bay, a major southbound stopover site for migrating humpback whales located approximately 1325 km (coastal distance) north of Jervis Bay. Chaloupka, Osmond, and Kaufman (1999) found that sightings in Hervey Bay peaked between August and October, one month earlier then sightings in Jervis Bay. Franklin et al. (2011) identified a similar shift in group composition at Hervey Bay during the southern migration period, with a greater number of adults and juveniles sighted early to mid-

Table 3
Testing of the G_i^* statistic with sample data adjusted for potential bias in sampling effort, observer error and positional offset (100 random samples). The proportion of spatial sampling units in which the null hypothesis was accepted or rejected is presented as a percentage.

Pod	Unadjusted (%)	Adjusted for sampling effort (%)	Observer error (%)						Positional offset (%)					
			2%	5%	10%	15%	20%	25%	50 m	100 m	150 m	200 m	250 m	300 m
Mother-calf (N = 3548)														
G_i^*														
Accept null	25.6	27.3	23.9	25.1	27.0	28.4	29.5	30.0	25.7	25.4	25.4	25.5	25.8	25.6
Reject null	74.4	72.7	76.1	74.9	73.0	71.6	70.5	70.0	74.3	74.6	74.6	74.5	74.2	74.4
Positive cluster – 99% CL	23.0	22.7	23.9	23.5	23.0	22.6	22.3	22.2	23.0	23.1	23.0	23.0	22.7	22.9
Positive cluster – 95% CL	3.3	3.6	2.9	3.0	3.0	3.2	3.4	3.7	3.2	3.2	3.2	3.2	3.3	3.2
Positive cluster – 90% CL	1.4	1.4	1.2	1.5	1.7	1.9	2.0	2.1	1.4	1.4	1.4	1.3	1.4	1.4
Negative cluster – 99% CL	25.0	17.7	31.5	30.1	27.5	25.7	23.4	22.4	24.5	25.8	25.4	24.9	23.5	24.0
Negative cluster – 95% CL	18.7	23.1	12.4	12.6	13.1	13.3	14.4	14.4	18.9	17.8	18.3	18.7	19.9	19.6
Negative cluster – 90% CL	3.0	4.2	4.1	4.3	4.6	4.8	5.1	5.2	3.3	3.3	3.3	3.3	3.3	3.3
Non-calf (N = 3548)														
G_i^*														
Accept null	21.1	21.0	23.6	26.5	32.4	36.9	40.7	42.5	21.7	22.4	22.7	23.0	23.5	23.7
Reject null	78.9	79.0	76.4	73.5	67.6	63.1	59.3	57.5	78.3	77.6	77.3	77.0	76.5	76.3
Positive cluster – 99% CL	19.4	19.4	19.0	18.5	17.7	17.0	16.3	15.8	19.1	18.9	18.7	18.6	18.6	18.5
Positive cluster – 95% CL	2.1	2.2	2.3	2.4	2.5	2.5	2.6	3.0	2.3	2.4	2.6	2.5	2.5	2.5
Positive cluster – 90% CL	1.0	1.1	1.0	1.0	1.1	1.3	1.6	2.0	0.9	0.9	1.0	1.1	1.1	1.1
Negative cluster – 99% CL	10.6	10.6	6.2	4.3	2.6	2.1	1.6	1.3	8.4	6.0	5.3	4.3	3.6	3.2
Negative cluster – 95% CL	35.0	36.6	36.4	34.0	28.2	24.6	22.6	21.4	36.6	36.8	36.0	35.3	35.2	35.2
Negative cluster – 90% CL	10.8	9.2	11.6	13.2	15.5	15.7	14.7	14.1	10.9	12.6	13.6	15.2	15.6	15.8

season and mother-calf pairs and mother-calf-escort pods sighted mid-to-late season. The delay in peak between the two sites is expected, as the whales must initially migrate past Hervey Bay before travelling southwards to Jervis Bay, on route to polar feeding regions.

Influence of depth

Studies of migrating humpback whales have demonstrated that escort whales are primarily males (Baker & Herman, 1984; Clapham, 2000). Shallower water depths limit the movements of courting males within the water column which may explain observed depth preference of mother-calf pods as they attempt to avoid harassment by male conspecifics in deeper waters (Ersts & Rosenbaum, 2003; Félix & Botero-Acosta, 2011; Smultea, 1994). It would appear that maternal females may prefer shallower water to avoid harassment and injury to calves by sexually active males, turbulent offshore or deep sea conditions and predators (Smultea, 1994).

In the current study mother-calf pairs and mother-calf-escort pods were found in relatively shallow water compared to competitive pods without calves. Distinct differences in the shape

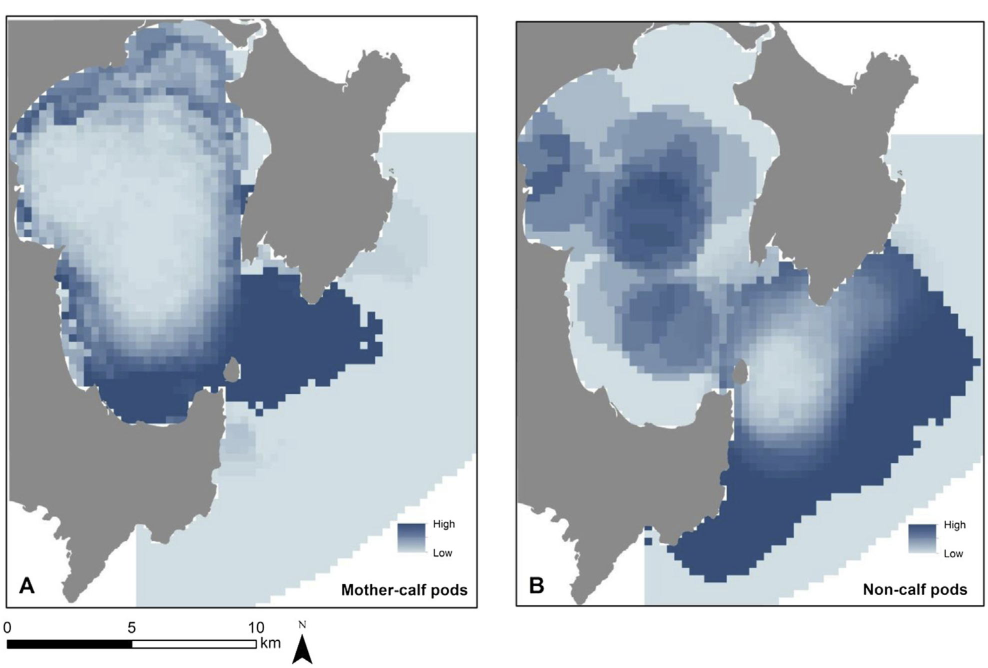

Fig. 5. The proportion of rearranged samples whose test values exceeded the original test value (G_i^* statistic) for (A) mother-calf pods and (B) non-calf pods. Samples were randomly adjusted for spatial sampling bias. Darker shading indicates areas in which clusters of high observation rates or clusters of low observation rates are potentially underestimated due to spatial sampling bias.

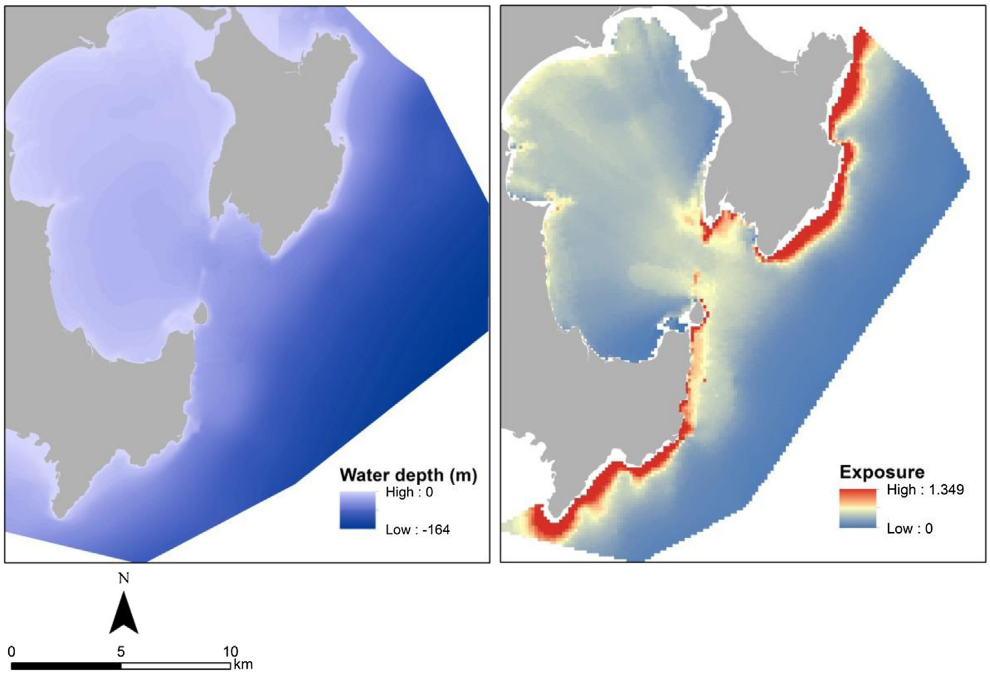

Fig. 6. Map of water depth (A) and estimated seabed exposure (B) for the Jervis Bay study area.
Data sources include Australian Hydrographic Service and Geoscience Australia (2010).

of the response curves for depth between mother-calf pods and non-calf pods were estimated, with low probability of presence predicted to be approached at depths greater than 50 m for mother-calf pods (Fig. 7 A and B). This is concordant with other studies including humpback whale groups wintering off Abrolhos Bank in Brazil (Martins et al., 2001) and the Santa Elena Peninsula in south-central Ecuador (Félix & Botero-Acosta, 2011). Difference in depth preference between mother-calf pods and mother-calf-escort pods was not observed in the current study. This differs from other studies in which escorted pods were found in mid-depth waters (Ersts & Rosenbaum, 2003; Félix & Botero-Acosta, 2011). The observed similarity in depth preference between mother-calf pods and mother-calf-escort pods in the current study needs to be considered with caution as it may reflect spatial survey bias rather than the protective advantage of escorts, due to lower levels of survey effort in mid-depth waters outside the bay (Fig. 4). If whales are present within the bay, the Dolphin Watch Cruises vessel is less likely to travel beyond the entrance to sight whales. Spatial inconsistency in sighting effort between seasons, with effort concentrated outside the bay during the autumn and winter and inside the bay during the spring, further highlights the potential limitations of these geographical citizen science data. Recording of sampling effort needs to be prioritized in future volunteer surveys to ensure distributional trends are considered within the underlying spatial pattern of survey effort (Vigness-Raposa et al., 2010).

Table 4
Summary of depth and seabed exposure for each observed pod composition.

Pod composition	Depth			Exposure		
	Avg	STD	SE	Avg	STD	SE
Mother-calf pair	−25.58	18.99	1.137	0.1701	0.0664	0.004
Mother-calf-escort pod	−31.38	23.74	3.802	0.1467	0.0780	0.013
All mother-calf pods	−26.29	19.69	1.104	0.1673	0.0683	0.004
Non-calf pods	−65.88	37.11	1.777	0.1576	0.15924	0.009

Influence of exposure

Preference for areas of higher coastal protection was examined using seabed exposure data. A significant difference in exposure preference between mother-calf and non-calf pods was not established. However, the response curves for exposure (Fig. 7C and D) show the probability of presence for mother-calf pods was predicted to approach zero at exposure levels of approximately 1.3. Coastal areas sheltered from ocean swell that provide shelter to mother-calf pods during rough seas may be conducive to lower energy consumption (Elwen & Best, 2004). Although the SWAN model used to derive seabed exposure accounts for refraction of swell waves, shoaling, diffraction, dissipation and random waves, model parameterization does not include local wind generated waves (Geoscience Australia, 2010). Exclusion of wind waves in estimations of coastal exposure may limit these data as a proxy for coastal shelter.

Challenges of geographical citizen science data in marine research

The role of volunteer-collected data is much debated by geographers and ecologists (Riesch & Potter, 2014). In the marine environment, non-specialist volunteer observers using a research platform, such as Dolphin Watch Cruises, are able to contribute to extensive longitudinal studies over a wide geographic region otherwise unavailable due to logistical constraints of standardized scientific surveys (Hauser, Vanblaricom, Holmes, & Osborne, 2006). If appropriately selected and trained, volunteers can significantly contribute to the acquisition of experiential scientific data (Elwood et al., 2012). Sighting data collected from whale-watch vessels have been used in studies of mother-calf interactions (Sardi, Weinrich, & Connor, 2005), social grouping patterns (Hamilton & Mayo, 1990; Weinrich, 1991) and feeding behaviours (Weinrich, Schilling, & Belt, 1992). In recognizing that acceptance and adoption of geographical citizen science in species distribution studies requires appropriate data validation (Bonter & Cooper, 2012), the constraints

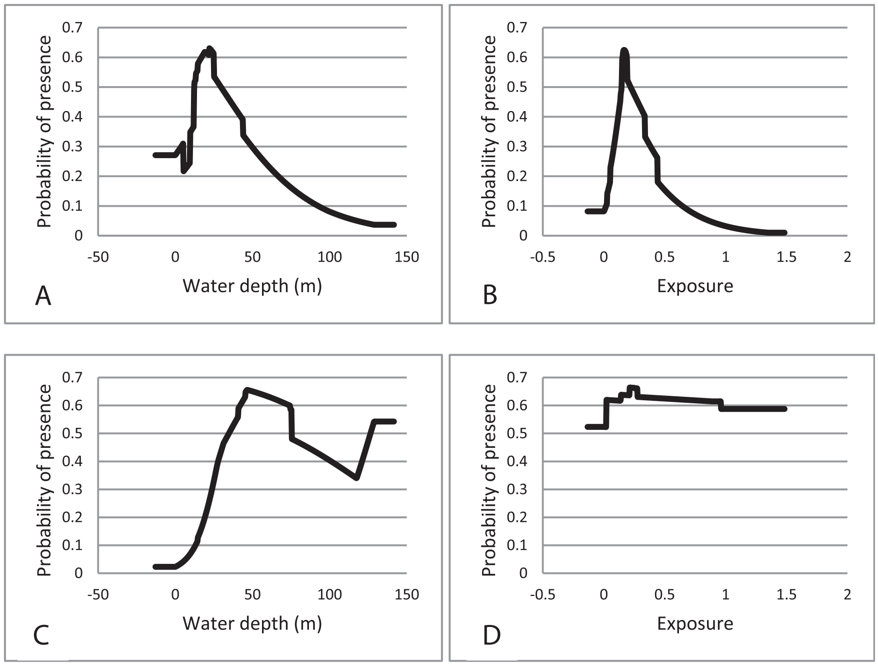

Fig. 7. Response curves showing the relationship between probability of calf-pod occurrence and depth (A) and exposure (B), and non-calf pod and depth (C) and exposure (D). The shape of the curve shows change in logistic prediction for each variable while the other variable is kept at the mean sample value.

of these platforms of survey opportunity need to be considered in the context of introduced bias. Observer bias can be minimized through in-field volunteer training, observer experience and broad spatial coverage (Dickinson et al., 2010; Fitzpatrick et al., 2009; Hauser et al., 2006). In the current study, intensive field training in survey protocol, volunteer continuity provided by involvement of vessel crew and the relative ease of visual recognition in the variable being recorded (pod composition) is favourable to reducing observer bias. The majority of within-bay observations occurred during the late-season migration period of October and November which, when accounting for the temporal lag, corresponds with the peak mother-calf pod migration observed in Hervey Bay studies (Chaloupka et al., 1999; Franklin et al., 2011). During this period, concentrated sampling effort within the bay may result in under-representation of mother-calf pods observed outside the bay preventing robust analysis of the differences in depth preferences between mother-calf and mother-calf-escort pods. Further work is required to evaluate the spatial survey bias implicit in these sighting data (Hauser et al., 2006; Vigness-Raposa et al., 2010).

Cross-validation of non-specialist volunteer collected data requires an independent survey conducted by scientific observers. In the absence of data accuracy estimates based on such a survey, the impact of potential survey bias on spatial cluster results was simulated. Positional error within 300 m (a distance corresponding to the regulated observational approach zone) had minimal impact on the Global Moran's I and G_i^* statistics producing similar results for the original samples and randomly spatially adjusted samples. Local indicators of spatial clustering measured by the G_i^* statistic were more susceptible to both observational errors and spatial sampling bias. Degraded accuracy due to misidentification of pod composition and spatial variation in sampling effort may result in the incorrect rejection of the null hypothesis and identification of positive and negative clusters at higher confidence levels than would be determined with more accurate data. These errors have potential to influence the spatial extent of strongly defined clusters but for the purposes of this study will not invalidate the estimation of local clusters that clearly differ between pod compositions. The distinct spatial clusters of mother-calf pods within the bay and non-calf pods seaward of the entrance are evident even when potential errors associated with the non-specialist volunteer data are introduced. Increased engagement of non-specialist volunteers in scientific research and the proliferation of VGI based initiatives for use in data collection programmes, prompts the need for methods to evaluate the appropriateness of these data in the context of the research problem for which they are applied.

The inextricable link between geographical citizen science and emerging technologies including smart phone applications, wireless sensor networks and Web2 (Newman et al., 2012) has supported innovative approaches for the collection of non-specialist volunteer data in marine and coastal environments. Although the current study does not involve the use of crowd sourced VGI data and Web 2.0 to facilitate volunteer collaboration on scientific research, these mediums have increasing relevance to marine research as demonstrated in the development of VGI-enabled smart phone applications such as MMR Field App (http://www.marinemammalresearch.com/), Whale Spotter (http://www.pointblue.org/about-pointblue/news-resources/press-releases/scientists-test-whale-tracking-app) and Coastal Walkabout (http://superpod.ml.duke.edu/walkabout/). VGI and geographical citizen science initiatives may encourage public engagement in marine management decision making and policy implementation through fostering of informal knowledge sharing, improving public understanding and facilitating participant knowledge contribution. However, effective and meaningful incorporation of volunteered information in marine and coastal management may require a shift in traditional planning paradigms and decision making practices (Elwood, 2008).

Geographical citizen science necessitate the establishment of alternative approaches to ensure data quality and represent spatial data accuracy in a way that is accessible to the end users (Newman et al., 2010). Collection of data on the sampling process that may influence results and can allow characterization of potential measurement bias should be considered in sampling programme design (Bird et al., 2014).

Connors et al. (2012) argue that in a well-designed geographical citizen science project, data redundancy can provide a form of peer-review that allows for self-correction, with potential improvement in data quality associated with the number of data points for the same occurrence (for example, multiple sightings of the same whale pod). Intrinsic data quality assurance measures based on the number of volunteered data contributions on a given spatial unit or incident (Haklay, Basiouka, Antoniou, & Ather, 2010), combined with methods for evaluating the reliability of non-specialist volunteer collected data presented in this study, allow the fitness of data use to be judged by the end users.

Marine management implications

The Jervis Bay Marine Park Zoning Plan does not currently outline protection for humpback whales when they are in the vicinity. However, park management must adhere to New South Wales and Commonwealth legislation including the *Whale Protection Act* 1980; the *Marine Parks Act* 1982; The *Endangered Species Protection Act* 1994; and the *Environment Protection and Biodiversity Conservation Act* 1999, to ensure their protection from anthropogenic disturbance. Spatial statistical analysis of whale sighting records allows key whale usage areas to be determined and identify potential spatial conflicts associated with exposure to human activities, such as commercial and recreational fishing and naval activities within Jervis Bay. Due to their habitat preference for shallow sheltered waters, mother-calf pods are more exposed to anthropogenic disturbance in the bay than other pod types. Fig. 8 shows the spatial overlap between intense clustering of high mother-calf pod sighting frequencies and the current Habitat Protection Zone, in which selected methods of commercial fishing are permitted (Marine Parks Authority, 2009). Results of this analysis may be used to inform marine spatial planning within the Marine Park and critique of current zone boundaries.

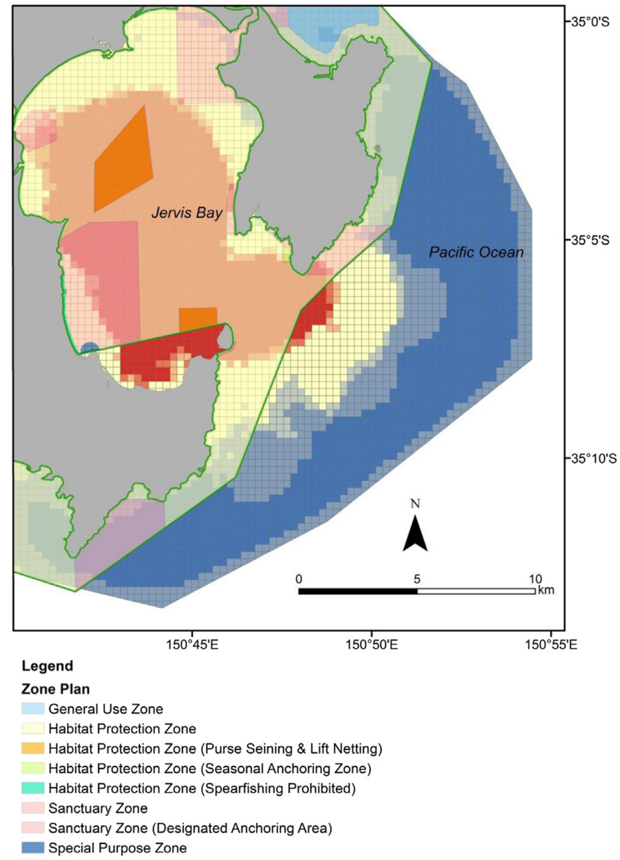

Fig. 8. Map of Jervis Bay showing spatial overlap between clustering of high mother-calf pod sighting frequencies and the current management zones (Marine Parks Authority, 2009).

Further considerations

It is evident that Jervis Bay is an important stop-over for mother-calf pods, but detailed population abundance estimates are needed to estimate the proportion of the east Australian humpback whale population using the bay during the migration period. This requires photo-identification based mark-recapture techniques which, due to the retrospective nature of photo-identification, could potentially involve publically sourced VGI data (Davies et al., 2013). In examining spatial association it is also important to consider edge effects which can result in the exaggeration of similarities or differences near study area boundaries where observation points have fewer neighbours than points in the study area interior (Mueller-Warrant et al., 2008). This is shown in Fig. 3A, where an artificially less significant G_i^* is observed along the seaward boundary of the survey area. Further analysis of the performance of the G_i^* statistic under different spatial configurations of potential error, including consideration of scale and lag distance, is required.

Conclusion

In the absence of systematic long-term surveys of humpback whales, this study used non-specialist volunteer collected data to examine usage patterns of Jervis Bay by mother-calf pods on their southern migration. Geographical citizen science data offers a valuable opportunity to conduct geographical research at multiple spatio-temporal scales (Elwood et al., 2012) and contribute to understanding migratory movements of humpback whales. However, if data sourced from whale watching platforms are to be used in spatial models, methods are needed to evaluate the impact of potential observer bias on measures of spatial clustering and the implications for marine management decisions. Preferential use of the bay environment by mother-calf pods potentially increases their vulnerability to anthropogenic disturbances (Félix & Botero-Acosta, 2011) through greater exposure to tourism, fisheries, shipping and naval activities. The geographic and seasonal variability of humpback whale distribution patterns identified in this study have important conservation considerations and should be incorporated in MPA zone plans designed to both spatially and temporally regulate marine activities.

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