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Regional oceanography affects humpback whale entanglements in set fishing gear

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Abstract

Humpback whales *Megaptera novaengliae* undertake annual migrations along eastern Australia, where they can be susceptible to entanglement in set fishing gear. This can potentially result in both sublethal and fatal outcomes for the whales, and financial losses for the fishing industry, including loss of gear and catch. Interannual fluctuations in entanglement records suggest that dynamic oceanographic features may be associated with the whales' migration path, and therefore, risk of entanglement. Using records of demersal fish traps off the coast of New South Wales (NSW), we identify two areas of high fishing pressure and entanglement risk overlap. Within each area, we combine entanglement observations with metrics associated with the East Australian Current (EAC) and climate (i.e., southern oscillation index). We show that the strength and position of the EAC was associated with the likelihood of entanglement in set fishing gear. In northern NSW (30.3° S), entanglement risk was highest between July and October when the EAC is relatively close to the coast. In contrast, there was no evidence suggesting that oceanography further south in the separation zone of the EAC (33.8° S) was associated with risk of entanglement. In the years following a strongly negative SOI (i.e., El Niño events), entanglement risk was also reduced. While we provide clear linkages with regional oceanographic dynamics and entanglement risk off NSW, if a dynamic ocean management approach to reducing entanglements is to be realized, further research into the fine-scale movements of humpback whales is needed.

KEYWORDS

bycatch, dynamic ocean management, east Australian current, fish traps, fisher-wildlife interactions, *Megaptera novaengliae*, migration

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1 | INTRODUCTION

Baleen whales within the Southern Ocean were heavily targeted in the 20th century by commercial whalers. It is estimated by Clapham and Baker (2018) that over two million whales from the Southern Hemisphere were killed as part of commercial whaling, including 200,000 humpback whales (*Megaptera novaeangliae*) and 36,000 blue whales (*Balaenoptera musculus*). Despite this exploitation of Southern Ocean whales (in some cases by 99%), many species appear to be recovering due to reduced whaling (Best, 1993; Clapham & Baker, 2018). In particular, the southwest Pacific humpback whales off eastern Australia (E1 breeding stock) have shown high rates of population growth (>10% per annum) since the late 1900s (Paterson & Paterson, 1989; Pirotta et al., 2020), and have potentially returned to estimated pre-exploitation numbers (Noad et al., 2019).

Due to their high consumption rates (Savoca et al., 2021), whales have substantial impact on ecosystems via nutrient cycling (Roman et al., 2014; Roman & McCarthy, 2010) and ecosystem stabilization (Roman et al., 2014). Unfortunately, while the rebounding populations may have significant positive ecosystem outcomes, there are also increased anthropogenic interactions, both positive and negative. Increased whale abundances may present the opportunity to grow or sustain a whale-watching or 'ecotourism' industry (Cisneros-Montemayor et al., 2010) but may also present a potential issue for shipping (Kelley et al., 2021) and fishing industries (Knowlton et al., 2012), where an interaction may not only be detrimental or fatal for the whale but the industry can experience significant financial costs. Entanglement in trap fishing gear frequently results in loss of trap hardware, broken off in efforts by the whale to rid itself of the encumbrance, inclusive of lost catch that may already be in the trap, and lost fishing opportunity while trap hardware is replaced.

For fisheries and wildlife managers to make effective decisions for both conservation and fisheries management objectives, there is a need to balance the conflict between maximizing conservation through mitigation and maintaining economic viability of fisheries (How et al., 2021). One such area of management concern regarding the interaction between fishing and increasing whale abundances is the forementioned southwest Pacific breeding stock of humpback whales that seasonally migrate along the east coast of Australia. Here, they undertake long-distance migrations during austral winter from high-latitude feeding grounds to low-latitude breeding grounds. Under the Australian Environment Protection and Biodiversity Conservation Act 1999, injury and fatality to vertebrate marine life caused by entanglement is listed nationally as a Key Threatening Process and there are increasing concerns around humpback whales interacting with commercial fishing gear as the rate of reported entanglements increases (Oceanwatch Australia, 2019). Growth in the whale watching industry, due to increased whale abundances (Cisneros-Montemayor et al., 2010), combined with whale watching operations frequently engaging with social media, can mean that observations of injured whales often rapidly become headline news to a wide audience, including conservation groups, tourism audiences, international seafood markets and consumers. Not only are these interactions with fisheries detrimental to the whales but negative publicity such as this can result in the loss of social license (Pavitt, 2012), potentially jeopardizing public recognition of the commercial fisheries environmental stewardship and, may result in significant economic loss through reduced market access or fishery closures.

During their annual migration, southwest Pacific humpback whales rely on sustained body reserves from the previous summer feeding period (Corkeron & Connor, 1999), although there is now some evidence of supplementary feeding in southern Australian waters (Eisenmann et al., 2016; Pirotta et al., 2021; Stamation et al., 2007). Additionally, there is interannual variation in the number of humpback whales that migrate each year. For example, not all mature females participate in migration or they delay their migration in response to feeding success (Corkeron & Brown, 1995; Druskat et al., 2019). Recent research is consistent with these previous findings and has found that members of this population may experience increased feeding success and spend more time at higher-latitude foraging areas following El Niño events compared to reduced success in years following La Niñas (Dedden & Rogers, 2022). If the numbers of migrating whales differ interannually, then the risk of interactions with fisheries will vary with both the annual abundance of whales in temperate regions and potential variations to their migration path.

Regional oceanographic features have been found to influence migratory behavior of humpbacks through both the timing of their migration and fine-scale variations in route choice. In the North Atlantic, fin and humpback whales shifted their arrival date (to summer feeding grounds) earlier, particularly in accordance to earlier ice break-up, increasing sea surface temperature and an increase in primary productivity (Ramp et al., 2015). Humpback whales from the southwest Pacific tend to use cooler waters and areas of strong temperature gradients (Reinke et al., 2016). It was suggested these coastal fronts provide a navigational tool as well as areas for opportunistic feeding along the humpback's southward migration route. The use of dynamic oceanographic features as navigation aids was also recently highlighted as a contributing cause to entanglements of whales in shark-control nets in subtropical Australia (Bolin et al., 2020).

While there is limited published information regarding fine-scale movements of the southwest Pacific humpback whale migration along the east Australian coast, there is abundant citizen science and anecdotal evidence of interannual variation in migratory pathways and distance from shore, potentially related to oceanography. The ocean dynamics of the subtropical east coast of Australia are dominated by the East Australian Current (EAC). The EAC is a southward flowing western boundary current which flows faster away from the coastline (Archer et al., 2017). The EAC is closest to the coast during winter when it is observed as near as 30 km from the coastline between 28° S and 32° S (Xie et al., 2021). During the annual migration, humpback whales are commonly observed moving north at the end of autumn (May–July) and south in spring (September–November) (Russell et al., 2022). Unfortunately, variations in the precise migration path (e.g., proximity to coast) taken by the humpback whales during their migration are not well understood, however it is clear that the whale's migration path overlaps with set fishing gear which is deployed along the continental shelf of New South Wales (NSW) and reports of entanglements with whales have increased over the last three decades. While this increase in interactions may be driven by a rebounding population of humpback whales or increased reporting due to more whale watching and coastal activities, interannual fluctuations in entanglement observations suggest oceanographic factors may affect the risk of entanglement.

Identified sources of gear associated with entanglements in NSW include configurations used in the demersal fish trap (DFT), spanner crab and demersal setline sectors of the NSW ocean trap and line fishery (OTLF), traps used in NSW and interstate rock lobster fisheries, surface longline gear and shark mitigation gear from NSW and Queensland (NPWS Unpublished Data, Oceanwatch Australia, 2019). However, preliminary results indicate that the level of interaction between the DFT sector of the OTLF and whales is greater than the combined interactions from spanner crab, demersal setline and NSW lobster fishing gear (NPWS Unpublished Data, Oceanwatch Australia, 2019), and hence is the focus of the current study. Current DFT fishing practices involve individual baited traps (e.g., traps not set in fleets or trawls) being set on or near reefs at depths between 20 and 200 m and soaked for 1-to-3 days.

With reference to the NSW DFT fishery, the aims of this paper were therefore to (1) quantify the seasonal and interannual trends in humpback whale entanglements, (2) identify the areas of high fishing intensity (entanglement risk), and (3) investigate the potential oceanographic and climatic effects on observed numbers of entanglements.

2 | METHODS

2.1 | Study site and entanglement data

The EAC is a southward flowing western boundary current which transports oligotrophic warm water from the Coral Sea towards the cooler Tasman Sea (Oke et al., 2019). The EAC typically separates from the coast around 32° S where it then extends to the east (Cetina-Heredia et al., 2014), leaving behind a southward shifting eddy field (Everett et al., 2012; Suthers et al., 2011).

Observations of whale entanglements in NSW, Australia are maintained in a database by NSW National Parks and Wildlife Service. The database records begin in 1994 with the quality and amount of information regarding each record increasing over time. Entanglements are generally observed by the general public before being reported to NSW National Parks and Wildlife Service.

To address our first aim, we restricted the database to humpback whales (that form the E1 breeding stock in the southwest Pacific), excluding a small number of other species and other gear types not being trap related. Each record was scrutinized to remove duplicate records of the same entanglement as a whale moved along the coast by comparing photographs and other recorded details. The earliest record of each interaction was retained. We then subset the dataset to only include interactions that were identified as highly likely to be NSW set fishing gear, removing interactions with gear such as shark nets, resulting in 242 entanglement records (as of February 1, 2022). Not all entanglements were able to be positively identified to a particular gear source, especially when a whale evaded rescue or the gear had already broken off, but where the 'gear source' was not identified in the data, further clarification was sought from the rescue personnel and witnesses at the event. Under the assumption that all entanglements consistent with set fishing gear were DFTs, 242 entanglement records (as of February 1, 2022) were included in analyses. To prepare the final response variable for our analysis, we grouped observations to the monthly level.

To investigate trends in entanglements in DFT gear over time we summed all entanglements within each calendar year to visualize as a line plot. To investigate seasonal trends in entanglements, we calculated the percentage of entanglements that occurred in each month within each calendar year. These monthly percentages were used to calculate the average percentage of entanglements that occur in each month. This information was used to identify key months of interest for entanglements.

The abundance of humpback whales in the southwest Pacific population is estimated to be increasing at approximately 10.9% per year (Noad et al., 2019). To account for this in our study we used the population growth estimate presented in Noad et al. (2019), extrapolated out from 2015 to 2020. This rate also aligns with citizen science estimates (Pirotta et al., 2020; 10% annual increase).

2.2 | Fishing effort data

To address our second aim of identifying areas of high fishing intensity (entanglement risk), DFT fishing effort data was extracted from the NSW DPI Fisheries logbook database as the number of Fisher Days month^{-1}. Fishing effort has been reported in the OTLF with this method since 1997 but in 2009, this changed to more detailed reporting. Recent data (July 2009–June 2020)—daily catches (kg) are reported to a finer spatial scale (0.1° × 0.1°C-square grid) for ocean waters. As fishers are not required to report the date traps were set or the number of days soaked (actual time a trap is in the water) in the OTLF (only the number of trap lifts), the total number of days traps were in the water for each month (Rope Days) was estimated by calculating the mean number of trap lifts per day and multiplying it by number of fishers participating monthly (e.g., submitted >2 logsheet entries in a month) and days in each month. Analyses were completed for each degree of latitude to account for variations in numbers of traps used in different sections of the coast. To investigate long term changes in entanglement risk and fishing effort we plotted the monthly Rope Days over time and the total Rope Days in the months of interest each year.

To quantify the spatial extent of the fishery and therefore identify the areas with the highest concentration of fishing gear/entanglement risk we used the detailed post 2009 daily ‘C-Square’ trap lift data. For each calendar year and for the months of interest, we generated spatial maps of fishing effort (Figure S1). As there was no clear change in the distribution of effort between 2009 and 2020, we combined all years into a single summary figure with which we identified areas of the highest fishing pressure/entanglement risk. Using this high-resolution spatial data we matched each C-Square to latitude, bathymetry and distance from the coastline using the R package ‘remora’ (Jaine et al., 2021), which was used to summarize the distribution of fishing effort.

2.3 | Oceanographic and climate data

Based on the areas of higher fishing pressure we focused our oceanographic analysis around 30.3° S and 33.8° S (centered around Coffs Harbour and Sydney, Figures 1 and S1). At both sites we calculated two oceanographic metrics relevant to our hypotheses. The first variable was the mean southward current speed over the fishing area. The second variable was the monthly mean distance from the coast to the EAC edge. The software R v4.1.2 (R Core Team, 2021) was used for all data handling, manipulation and plotting conducted with the packages ‘tidync’ and ‘tidyverse’ (Wickham et al., 2019).

To calculate the mean monthly southward current speed, we used the IMOS—OceanCurrent—Gridded sea level anomaly Delayed Mode GSLA version 01 dataset. This dataset provides daily gridded (adjusted) sea level anomaly (GSLA), gridded sea level (GSL) and surface geostrophic velocity (UCUR, VCUR) for the Australasian region, derived from satellite altimetry and tidal gauges. For the northern region (30.3° S), we extracted velocity data between 28.4° S and 32.25° S. We then subset to only include the cells closest to the coast (20 km resolution) to best represent the fishing area. The daily gridded data were then averaged by month to produce a monthly mean southward current speed. For the southern region, the same process was followed for the area between 32.25° S and 35° S.

To calculate the distance from the coast to the EAC edge, we followed the procedure of Bolin et al. (2020) however we used an updated version of the BLUELINK Reanalysis (BRAN2020 rather than BRAN2015 and BRAN2016). Briefly this method involves specifying latitudes of interest (30.3° S and 33.8° S) and then applying a principal component analysis using the longitudinal gradients of sea-surface temperature, southward velocity and current speed to detect the edge of the EAC. We proceeded only with the 30.3° S region for this variable as the identification of the EAC edge did not perform well in the 33.8° S due to the highly dynamic eddy field (the EAC edge was identified only outside the fishing area, >100 km from coast).

To investigate the effect of climate modes on the variation in entanglements, the monthly southern oscillation index (SOI), which is an indication of the development and intensity of El Niño or La Niña events in the Pacific Ocean (which can influence Australian and Southern Ocean climate), was downloaded from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/enso/soi/). For the year each whale entanglement occurred in, we averaged the SOI index of the previous calendar year, resulting in a 1-year lag. This accounted for potential climate driven changes in resource

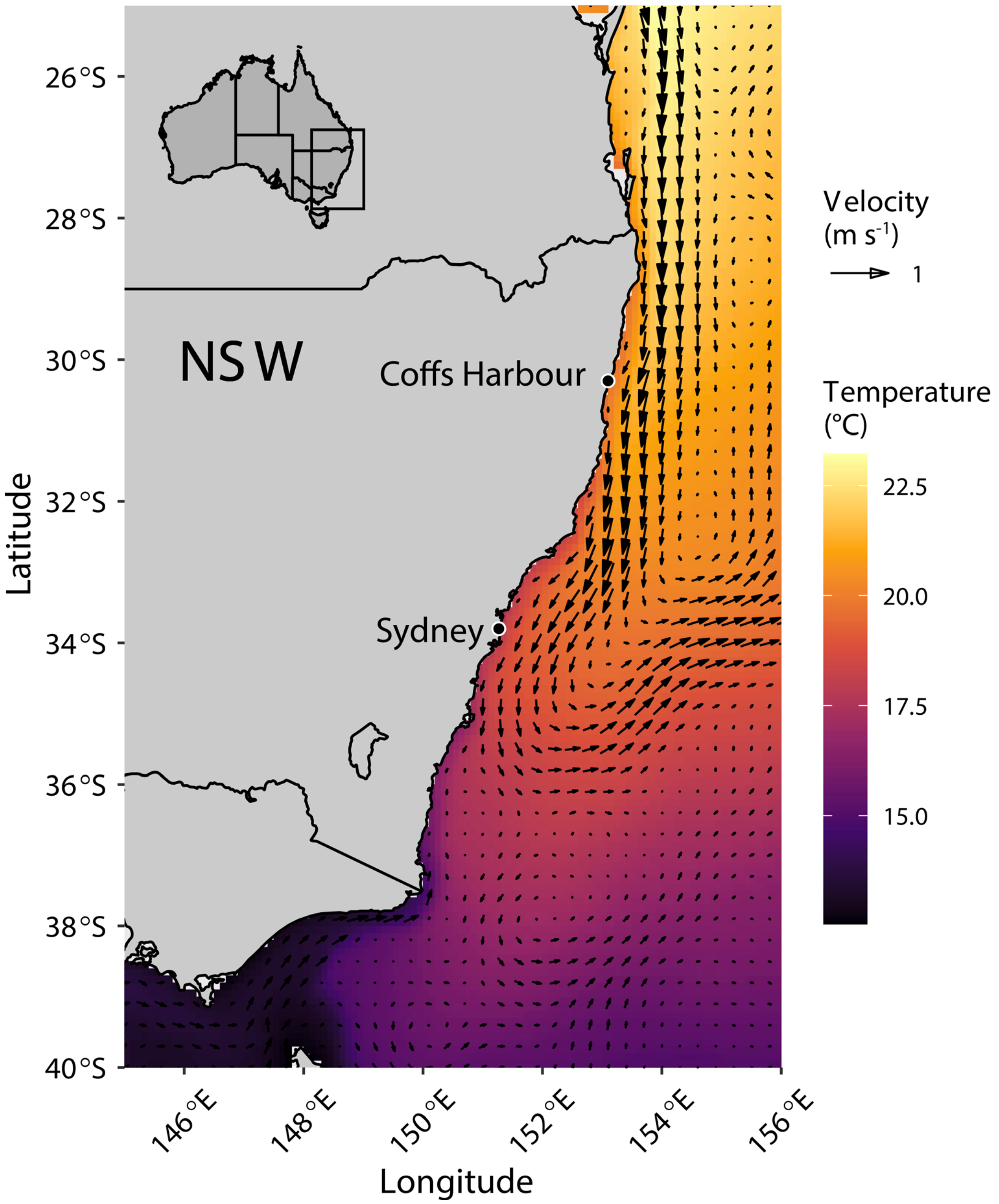

FIGURE 1 Winter (June–October) climatology where the color shows the mean sea-surface temperature (°C), and the arrow size shows the surface velocity (m s^{-1}) and direction along the east coast of Australia. The East Australian Current (EAC) can be seen as the strong southerly current flowing along the coast in the northern area before separating eastward approximately 35° S. Note the cooler slower water inshore of the EAC, demonstrating the edge of the EAC. Data from the BRAN2020 oceanographic model (Chamberlain et al., 2021).

availability within their feeding grounds that occurred the previous year (e.g., feeding period prior to migration) influencing the potential number of migrating whales.

2.4 | Statistical analysis

To investigate the possible influence of oceanographic variables on the number of entanglement observations and address our third aim, we used generalized additive models (GAMs). Since the oceanographic effects could vary in each region, we analyzed each region separately. Both analyses included the variables Month, Mean Southward Current, Distance to the EAC Edge (only in the northern region) and mean SOI lagged 1-year, in addition to an offset accounting for the estimated size of the humpback population each year. The two analyses varied only in the spatial range of the oceanographic parameters and the fact the southern analysis did not include a Distance to the EAC edge variable. All GAMs were parameterized with a negative binomial error distribution due to the overdispersed count nature of the entanglements. Due to the seasonal nature of the humpback whale migration and therefore presence in our fishing area, we modeled both the interactions of month and mean southward current, and month and distance to the EAC edge. Both interactions were modeled with tensor splines where month has a cyclic cubic regression spline while the other variable has a cubic regression spline. These splines allow the variables to follow seasonal cycles while the interaction may vary each month. Initial analyses revealed strong concurvity (>0.8) between the two interaction terms in the northern region and therefore two models were run for the northern region. The final model structure was therefore:

$$E_{i,p} \sim \mathrm{te}\left(\mathrm{Month}_{i,p}, X_{i,p}, k=12\right) + s\left(\mathrm{SOI}_{p-1}, k=5\right) + \mathrm{Offset}\left(\log \mathrm{POP}_p\right)$$

where $E_{i,p}$ is the number of observed entanglements in month i of year p. $\mathrm{te}\left(\mathrm{Month}_{i,p}, X_{i,p}\right)$ represents a tensor spline interaction between Month i of year p and $X_{i,p}$ which represents either the mean southward current of Month i of year p or the distance to the East Australian Current edge of Month i of year p. $s\left(\mathrm{SOI}_{p-1}\right)$ represents the mean SOI during the year $p-1$ smoothed with a cubic regression spline. k represents the number of knots in each smooth term. $\mathrm{Offset}\left(\log \mathrm{POP}_p\right)$ represents an offset term accounting for the population size during year p. The estimated population size was strongly negatively correlated with the fishing effort (winter rope days) so we included only the population size in the model (Figure S2, $r=-0.86$).

The two models from the northern region (differing in the interaction term) were initially fit using maximum likelihood compared using AIC values with the best model refit using REML before interpretation of results. The separation zone did not have competing models, so the single model (containing southward velocity) was fit with REML. All GAMs were fit using the R package 'mgcv' (Wood, 2004) using the 'select' option within the 'gam()' function to apply extra penalties to each term enabling each parameter to be effectively removed from the model if it was not important. Model fits were assessed via a simulation method using the 'DHARMa' package (Figure S3; Hartig, 2019). Significant effects from the GAMs were visualized with the 'gratia' R package and partial predictions were made to visualize the month-specific effects of the oceanographic parameters.

3 | RESULTS

3.1 | Temporal entanglement trends

Consistent with the increasing population size, entanglements of humpback whales in set fishing gear have been rising steadily since the 1990s. In some years such as 2008, 2009 and 2019 entanglements appear to be overrepresented while in some years such as 2016 and 2020 entanglements appear to be under-represented when compared to the population increase (Figures 2a and S4). When the monthly distribution of entanglements were averaged, 89.5% of entanglements were observed between June and October with less than 5% occurring in May and November (Figure 2b,c). We therefore focused our analyses between June and October inclusive. It appeared there may be two modes with a slight decrease in entanglements in August before a second peak in September (Figure 2b).

3.2 | Demersal fish trap effort and entanglement risk

Since 2009, it was revealed that almost all the fishing effort in the DFT fishery is on the continental shelf (Figure 3b), with most traps on the inner half of the shelf (<100 m bathymetry and <30 km from the coastline; Figures 3c,d, S5 and S6). There were two main peaks in the latitudinal distribution of fishing effort, around 30° S and 33° S (Figure 3a), corresponding to the major ports of Coffs Harbour and Sydney respectively. The region around 30° S is located in an area of consistent EAC influence while the area around 33° S is in the highly dynamic separation zone (Cetina-Heredia et al., 2014), and these zones were therefore analyzed separately in terms of oceanographic effects.

Winter fishing effort (June–October) peaked in 1998 with 185,160 Rope Days before a 66% decline to a minimum of 63,072 Rope Days in 2017 (Figure 4). The largest declines occurred between 29° S and 35° S with smaller reductions in effort outside this range (Figure S7).

3.3 | Oceanographic analysis

The GAM suggested that oceanographic and climate variables are influential factors in the numbers of observed whale entanglements. In the northern region, there was no difference between the model including mean southward current speed (AIC = 445.60) and the model including distance to the EAC edge (AIC = 444.69). As the EAC distance model showed better diagnostic plots

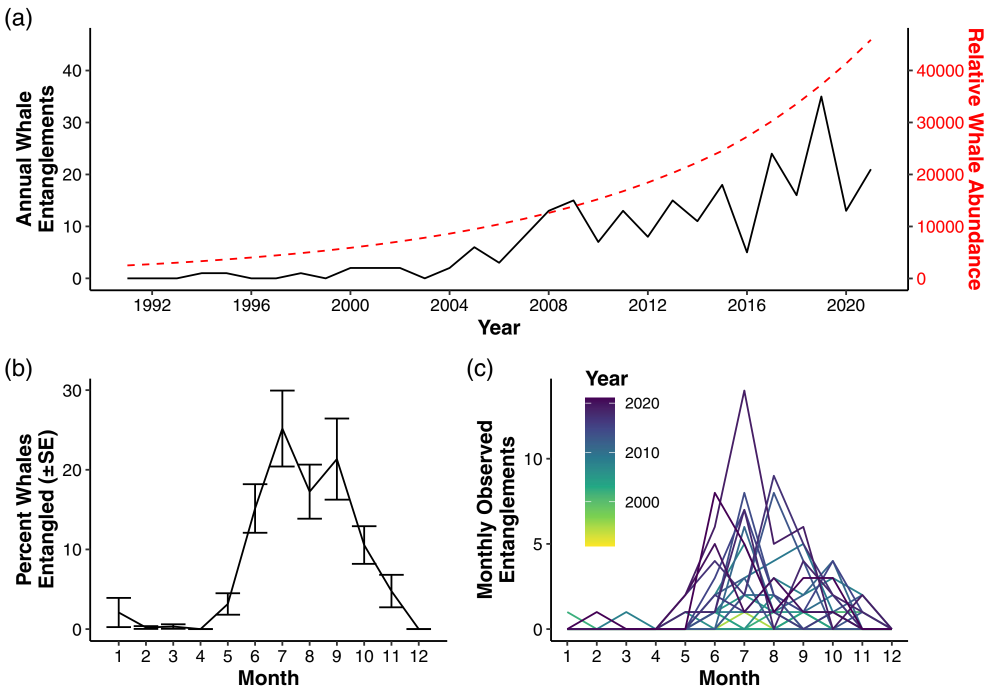

FIGURE 2 Summary of observed humpback whale entanglements in NSW demersal fish traps ($n = 242$). Panel (a) shows the observed entanglements each year in black with the estimated population size in dashed red. Panel (b) shows the average distribution of entanglements by month with standard errors over the entire dataset. Panel (c) shows the actual observations each month colored by year (individual years can be seen in Figure S4).

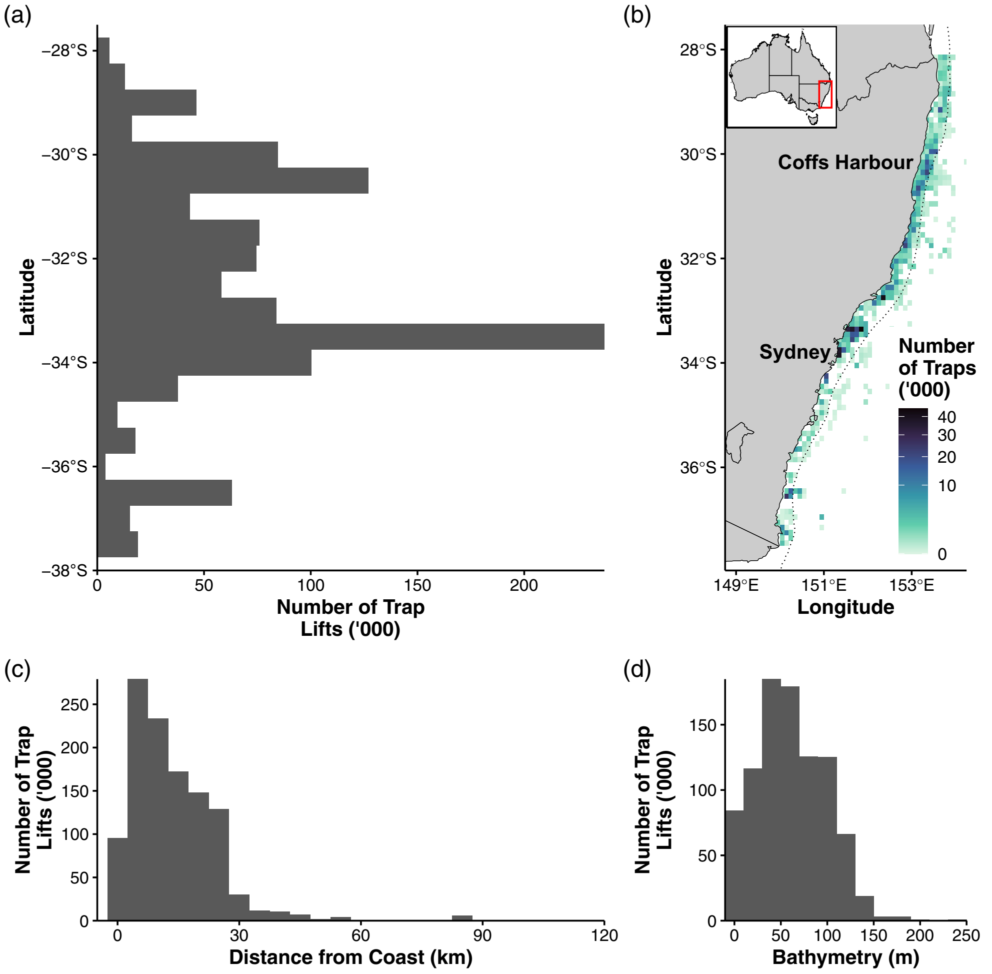

FIGURE 3 Spatial distribution of winter (June–October) fishing effort in the NSW demersal fish trap fishery between 2009 and 2021. Effort is recorded as the number of trap lifts in each C-square per day and was summed by C-square for our analysis. Panel (a) shows the distribution of effort by latitude. Panel (b) shows the spatial distribution of demersal fish traps. Panel (c) shows the distribution of traps by distance from the coast. '000 represents thousand trap lifts. Panel (d) shows the distribution of traps by bathymetry.

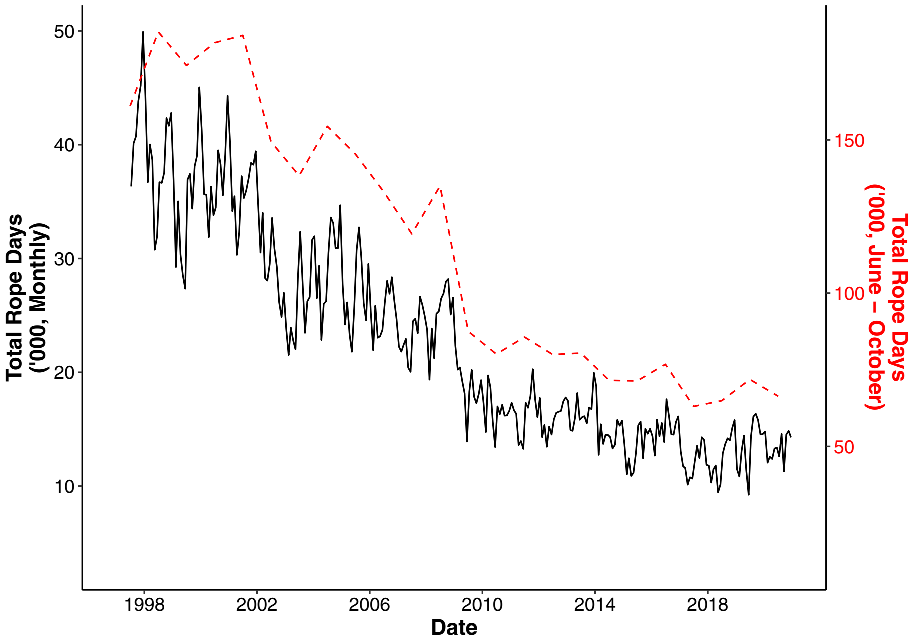

FIGURE 4 Fishing effort (Rope Days) over time in the NSW demersal fish trap fishery. The black line shows the total monthly effort (Fisher Days) for each month. The red dashed line shows the summed winter (June–October) fishing effort (Rope Days) for each year. For a breakdown by latitude see Figure S7.

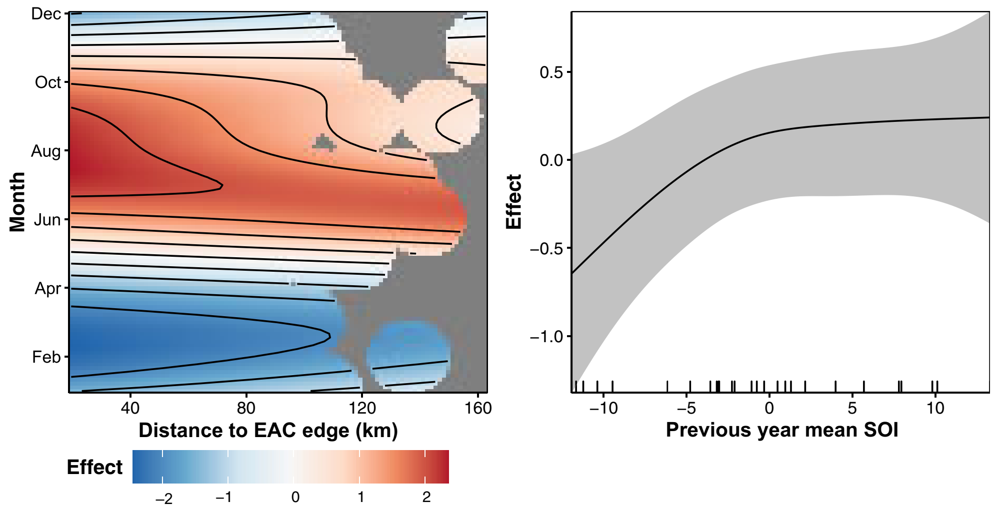

FIGURE 5 Estimated terms from the fitted GAM for the northern region (30.3° S) for the number of observed whale entanglements. The left panel shows the interactive effect of Distance to the EAC edge (km) and Month with black lines connecting areas of equal estimates. The gray areas represent interaction combinations with no data. A different way of visualizing this interaction is provided in Figure 6. The right panel shows the effect of SOI in the previous year with the black lines showing the mean effect with gray ribbons indicating the 95% confidence intervals. Similar results were seen for the southward velocity model (Figures S8).

(Figure S3), we therefore present this model in the results and the southward velocity results in the supplementary. There was strong evidence that the interaction between month and the distance of the EAC from the coast contributed heavily towards variations in entanglements (edf = 7.919, $\chi^2 = 101.139$, $P < .001$; Figure 5a) and moderate evidence that the SOI of the previous year weakly influenced entanglements (edf = 1.840, $\chi^2 = 6.752$, $P = .016$; Figure 5b). Following El Niño years (low SOI), the chance of entanglements is reduced (Figure 5b). During the winter months (June–October) the likelihood of entanglements is higher but the effect of distance to the EAC edge is variable. During May and June there is a weak trend for increased entanglements as the EAC is further from shore (Figure 6). In contrast, July through to October show more definite patterns with entanglements increasing when the EAC is close to shore (Figure 6). As reduced EAC distance to the shore is related to increased southward velocity, the velocity model shows similar results (Figures S8 and S9).

In the separation zone to the south, there was strong evidence that the month by southward velocity model

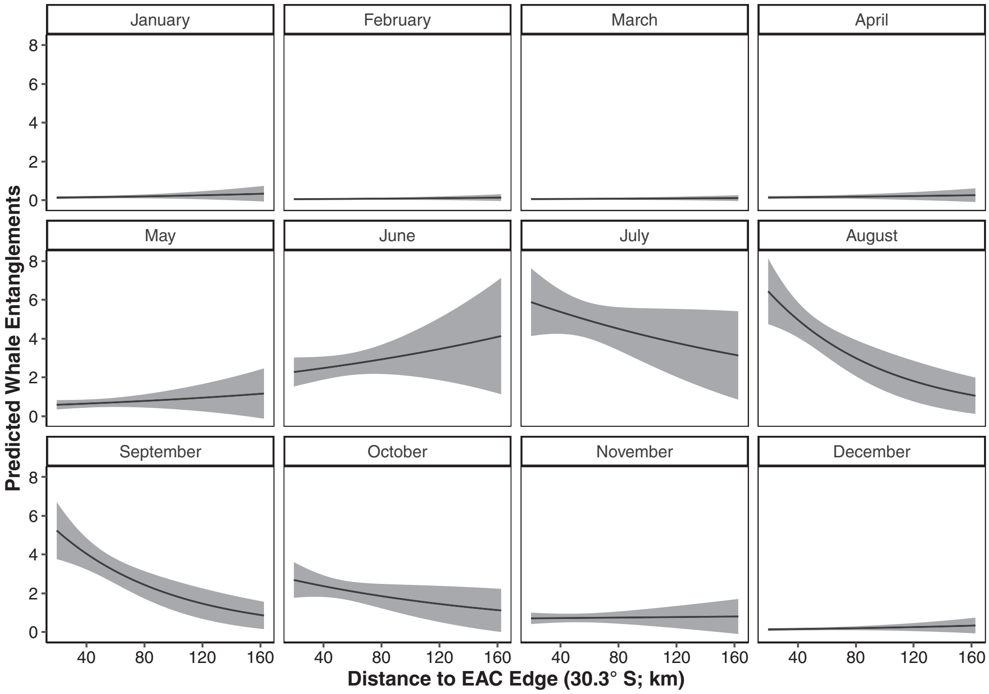

FIGURE 6 Predicted entanglements based on distance to the EAC edge from the coast (km) in the northern coastal region by month. Black lines show the mean prediction (while holding the past SOI value at the median observed value). The gray shading shows ±1 standard error. A similar plot for southward velocity can be seen in Figure S9.

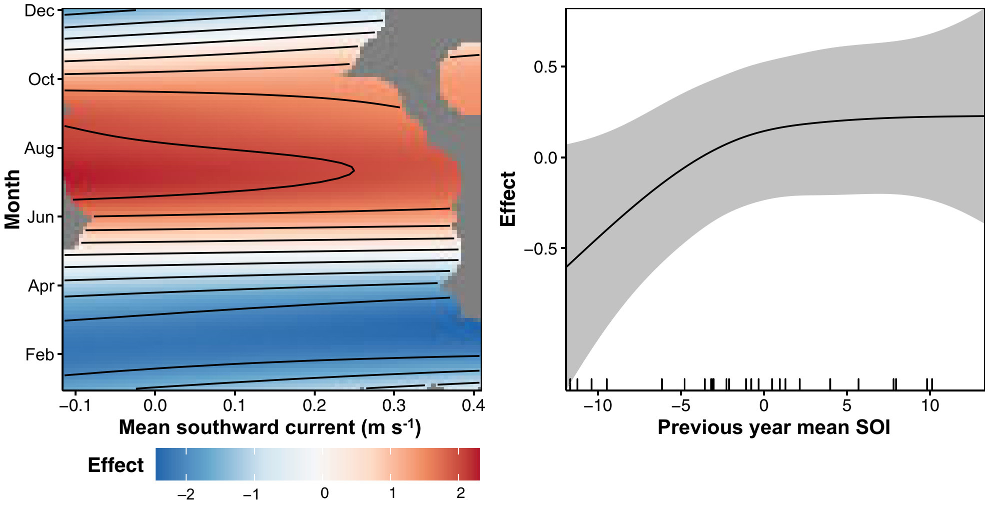

FIGURE 7 Estimated terms in the fitted GAM for the separation zone region (32.25–35° S) for the number of observed whale entanglements. The left panel show the interactive mean southward current with Month with black lines connecting areas of equal estimates and gray areas representing combinations with no data. A different way of visualizing this interaction is provided in Figure 8. The right panel shows the effect of SOI in the previous year with the black lines showing the mean effect with gray ribbons indicating the 95% confidence intervals.

strongly influenced observed entanglements (edf $= 7.984$, $\chi^2 = 95.713$, $P < .001$; Figure 7), while there was moderate evidence that the mean SOI of the previous year had a smaller effect compared to the month by southward velocity effect (edf $= 1.751$, $\chi^2 = 5.753$, $P = .027$; Figure 7).

Similar to the northern region, in the southern region the likelihood of entanglements reduced following El Niño years (low SOI) (Figure 7). The influence of the EAC represented by velocity appeared to be negligible with all substantial variation driven by month, although there is a weak trend of fewer entanglements in July–September during stronger southward currents. Like the northern region, the overall chance of entanglements was higher in winter (June–October; Figures 7 and 8).

Overall, in both the northern and southern region, it is clear from the effect sizes and visualizations (Figures 5 and 7), the variable with the strongest relationship to

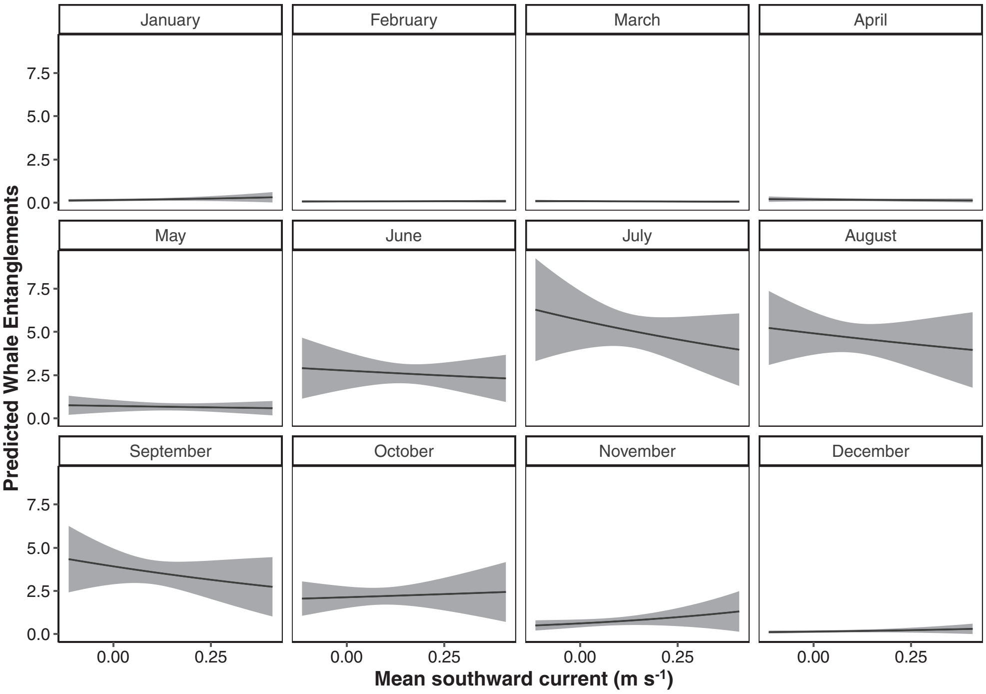

FIGURE 8 Predicted entanglements based upon mean southward current in the separation zone region (32.25–35° S) by month. Black lines show the mean prediction (while holding the past SOI value at the median observed value). The gray shading shows ±1 standard error.

entanglements is the interaction between Month and the oceanographic variables. The largest magnitude of change within this interaction is the effect of month (effect size range > 4) while the range of effect sizes within the oceanographic variables when month is held constant is ≈1. The effect of lagged SOI is the smallest with an effect size range of ≈0.5.

4 | DISCUSSION

Dynamic oceanographic features such as boundary currents may affect the migratory routes taken by marine mammals, in turn influencing the occurrence of human–whale interactions. Our modeling showed that humpback whale entanglement numbers in set fishing gear in eastern Australia vary with changes in oceanographic and climatic variables. While there were effects from oceanographic features north and south of the separation zone, differences in effects were evident reflecting the vastly different oceanographic regions with the largest increases in risk evident in the north when the EAC was close to shore. As the southwest Pacific population of humpback whales continues to increase in abundance, our findings demonstrate that it may be possible in the future to incorporate oceanographic features into fisheries management strategies as part of a dynamic ocean management approach. It may be possible to modify fishing gear or avoid fishing in zones identified as high risk of entanglements based upon the oceanographic conditions, leading to reduced entanglements and reduced financial and social impacts on the fisheries.

4.1 | Oceanographic effects on entanglements

As the dominant oceanographic feature, particularly in the northern area of our study, variations in the EAC (distance to the EAC edge and southward current strength) appears to influence variations in humpback whale entanglements. There are two mechanisms which may be contributing to this relationship. The first being the use of the EAC edge as a navigation aid during the northward migration as suggested in Bolin et al. (2020). Our results showed that in the northern region, between July and October, when the EAC edge is closer to coast the likelihood of entanglements increases, consistent with the idea that whales may be migrating along the EAC edge as it interacts with the coastal fishing area. This contrasted with the findings from the separation zone where no real influence of the EAC was detected. This may be due to the reduced influence of the EAC in this area as it often separates to the north of this zone (Cetina-Heredia et al., 2014), creating a large zone of eddies (Everett et al., 2012), which may alter whale navigation.

The second mechanism which may explain the influence of the EAC on entanglement numbers is that from a bioenergetics perspective. Swimming north will be most efficient if the whales avoid the strong southward flow of the EAC, while their southern migration would be more efficient in the flowing current. In the northern region where the EAC is most coherent and close to the coast, in August and September the likelihood of entanglements increased dramatically when the southerly flow along the continental shelf strengthened. This suggests that for their southern migration, when the EAC is flowing over the continental shelf (i.e., closer to the shelf), the whales follow inwards, potentially to reduce energy expenditure by swimming within the flowing EAC. Thus, they increase their spatial overlap with the fishing areas on the inner half of the continental shelf.

However, in this northern region, there was a weak opposite trend in June, showing a reduced risk of entanglement alongside a strengthened EAC. In the northern regions, June generally marks the start of the northern migration, consisting of predominantly lactating females and immature whales who are the first to leave Antarctic feeding grounds (Chittleborough, 1965; Dawbin, 1966). Therefore, it is possible that this trend is primarily driven by early migrators who behave differently to the rest of the population that join later, and potentially prefer the shallow, protected waters close to the coast that are occupied by fish traps, regardless of the EAC strength and position.

While not a direct oceanographic influence, the SOI from the previous year (1-year lag) was found to alter the number of humpback whale entanglements in both the northern and southern regions. Following El Niño years (negative SOI), the likelihood of entanglements decreased. A similar relationship between SOI and humpback whale strandings is reported for Queensland, north of our study site (Meynecke & Meager, 2016). As recently identified, whales of this population may encounter increased feeding success and spend greater times at higher latitude feeding grounds following years of El Niño (Dedden & Rogers, 2022). Therefore, it is possible whales may delay or not migrate in response to improved feeding opportunities, as suggested for mature females of the same population (Druskat et al., 2019). If portions of the population are not migrating, then the risk of entanglement is lower, consistent with our findings.

4.2 | Fisheries management implications

The dichotomy of increasing entanglements yet declining fishing effort highlights the dramatic increase in risk likely driven by the increasing whale population (Figure S2). As the fishing effort in this area has already decreased by almost 70%, further reductions in fishing effort are unlikely to dramatically reduce entanglement risks. In 2018, the NSW government introduced linkages between shares and effort in the DFT with the number of traps each fisher can deploy linked to the number of shares held in the fishery with the goal of providing greater certainty around the viability and sustainability of this fishery. Effort in the DFT fishery is currently below the permitted level and could possibly increase in the future, although unlikely given the recent trends in effort (Oceanwatch Australia, 2019). Based upon population growth estimates, the humpback whale population is likely to reach its carrying capacity this decade (Noad et al., 2019), but it remains likely the population will continue to grow and fluctuate, increasing entanglement risk before the population numbers stabilize and it is prudent to consider management options to mitigate this increasing risk.

Before considering options to reduce the risk of entanglements in fishing gear in the future, it needs to be acknowledged that most of the variation in entanglements is related to month of the year, representing the seasonal presence and abundance of whales along the coast. The variation explained by both oceanographic and climatic variables was smaller and as such any management based upon these variables should ideally be targeted towards specific months and not year-round. Potential mitigation measures include deploying gear avoidance deterrents, modifying fishing gear (How et al., 2021), changing fishing practices or implementing a form of dynamic ocean management. While deterrents have shown some success in humpback whale feeding areas (Basran et al., 2020), investigations into the use of whale alarms as deterrents in the migration route off eastern Australia have shown them to be ineffective in this region so this option is unlikely to be effective for future management (Harcourt et al., 2014; Pirotta et al., 2016). It is also important to highlight that the current observed entanglement rate between whales and fish traps is extremely low, for example in 2020 there were 13 entanglements for 66,400 rope days of winter fishing effort (1 in 5000 rope days or 0.02% interaction rate) and in 2019 there were 37 entanglements for 71,900 winter rope days of effort (1 in 1950 rope days or 0.05% interaction rate). The extremely low rates suggest that if management changes are implemented, it may be difficult to assess their effectiveness. While these numbers are low, it should be recognized they are almost certainly underestimates as not all entanglements will be observed and reported. In 2020 and 2021 our estimates may also suffer from less observation/reporting effort due to COVID-19 restrictions limiting outdoor recreation and social activities.

Dynamic ocean management is gaining rapid popularity as a paradigm to reduce bycatch of marine vertebrates in fishing gear (Hazen et al., 2017; Howell et al., 2008; Thorne et al., 2019). By combining operational oceanography and forecast systems, fishing pressure can be temporally reduced or removed from areas where key species are predicted to be vulnerable. A similar implementation of dynamic ocean management for the reduction of whale moralities is the WhaleWatch program, which uses near-real-time examination of spatio-temporal overlap of blue whales with potentially harmful human activities, such as shipping to reduce harmful ship strikes to whales (Hazen et al., 2017). Within a local context, there is currently limited use of operational dynamic ocean management tools and systems, although it has been used within the Eastern Tuna and Billfish Fishery to set management boundaries to limit capture of southern bluefin tuna (*Thunnus maccoyii*) by non-quota holders up to 4 months in advance (Hobday et al., 2011; Hobday & Hartmann, 2006). To minimize entanglement risk in the future, it is likely that the most effective management strategy would be to combine physical gear modifications (since whales get entangled in the rope and surface buoys, not the actual trap, sunken buoys would reduce this risk) with changed fishing practices and investigate the development of a dynamic management strategy around specific months.

4.3 | Limitations and future research

While this study found strong evidence that oceanography and climatic variables can influence the number of whales becoming entangled in demersal fish traps it does come with several limitations stemming from the available data. The first limitation pertains to the resolution of the entanglement data, as it is unknown where and when each entanglement occurred, rather it is where the entanglement was sighted and reported. Therefore, it is currently not possible to align entanglements with high resolution oceanographic data and we assumed each entanglement occurred during the month it was observed. This means that some of our findings may be biased towards the latter half of the migration season if entanglements occurred earlier but were not observed until later. A possible solution in the future may be to modify gear markings to ensure the source of entanglements is more easily identified, which would also facilitate real-time notifications to allow fishers in areas of higher risk to modify gear and fishing practices. Realtime reporting of trap locations via ropeless fishing apps (e.g., https://www.desertstar.com/page/rope-less-fisher-app) would allow effectiveness of mitigation measures to be accurately quantified when overlaid with detailed observations of whale migration patterns. It is also worth considering the role of reporting as it is possible that over time the likelihood of an entanglement being observed and reported has increased. It has become easier to observe and report whale entanglements because of improvements in telecommunications, boating infrastructure and the increased use of the coastal environment. The lack of high-resolution entanglement data also precludes the use of high-resolution oceanographic data and this study was therefore unable to investigate fine-scale (e.g., daily) variations in oceanography which is likely to be an important influence on whale migration paths.

A key step towards developing dynamic ocean management will be a predictive model of whale movement underpinned by a mechanistic understanding of migratory movement behavior. However, the relationships identified in the current study were correlative in nature, and we are unable to identify exact mechanisms responsible for our findings, and we present hypotheses for further investigations. While the seasonal migration trends are well understood in this area (Chittleborough, 1965; Dawbin, 1966; Russell et al., 2022), the factors that determine the fine-scale route of each whale are not known and the precise timings and routes of each migration ill-defined. Options to gain this information in the future may be through additional satellite tracking technology or perhaps the creation of a high-resolution sightings database which could include whale watching operators or citizen science. Currently only five humpback whales have been satellite tagged off eastern Australia, providing limited data on their southern migration (Andrews-Goff et al., 2018), with previous satellite tagging research focusing on movements around the Southern Ocean (Andrews-Goff et al., 2018; Gales et al., 2009). Citizen science is increasingly appealing with the potential to gather large amount of opportunistic data (Mesaglio & Callaghan, 2021; Pocock et al., 2017). If observations could be obtained with accurate locations, potentially via whale watching operators, it would be possible to align daily observations with high resolution oceanographic conditions.

This study also used a modeled abundance of whales in the E1 population, having both strengths and weaknesses. The modeled population abundance allowed us to detect the effect of SOI through the possible mechanism of reduced migration, but it may have impacted our power to detect the near-real time impact of the oceanographic features which assume no change in abundance. An alternative would be to use actual observations of whales each year such as that from Cape Solander in the separation zone region (Pirotta et al., 2020). This alternate method would instead assume the land-based counts are an accurate representation of the migrating population. This may not be correct if in some years whales are migrating at differing distances from the coast. It is also known that this dataset contains counts only for two months of the migration season, is not calibrated for double counts and may have bias from varying numbers of observers and spotting ability. Regardless, a brief investigation of the Cape Solander data (digitized from Pirotta et al., 2020) showed that the 4 years where whales were observed in lower numbers than predicted by the fitted population growth model aligned with three negative mean SOI values from the previous year (2003: −6.15, 2012: 13.30, 2015: −3.03; 2016: −11.23). This suggests our hypothesis that the SOI influencing migration numbers is plausible and warrants further investigation regarding possible mechanisms.

Going forward, it would be ideal to develop a series of possible management responses which could be used to minimize occurrences of whale interactions with fisheries. Such management responses may include spatial or temporal fishing restrictions (if fine-scale whale migrations were better understood) or alterations to fishing methods. These management responses could be evaluated by simulation under a variety of scenarios in terms of minimizing risk of entanglements and potential economic impact on fisheries. Such simulations have recently been completed for the US swordfish fisheries as part of management responses to loggerhead turtle (*Dermochelys coriacea*) interactions (Smith et al., 2021).

5 | CONCLUSIONS

This paper demonstrates that oceanographic and climatic conditions in eastern Australia influence the likelihood of humpback whales becoming entangled in demersal fish traps and sets the scene for further research into fine-scale movements of humpback whales in coastal areas. By better understanding the use of coastal environments by humpback whales it may be possible to implement management strategies including dynamic ocean management to minimize the occurrence of negative human-whale interactions such as entanglements in fishing gear.

AUTHOR CONTRIBUTIONS

Project Conception: Daniel D. Johnson, Susan Crocetti, Andrew Marshall; Data Collection and Curation: Andrew Marshall, Daniel D. Johnson, Formal Analysis: Hayden T. Schilling; Writing – Original Draft: Hayden T. Schilling; Writing – Review & Editing: Adelaide V. Dedden, Susan Crocetti, Geoff Liggins, Shona Lorigan, Andrew Marshall, Tracey L. Rogers, Amandine Schaeffer, Iain M. Suthers, Daniel D. Johnson; Funding: Daniel D. Johnson; Supervision: Iain M. Suthers, Daniel D. Johnson, Amandine Schaeffer.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Entanglement data is property of NSW Department of Planning and Environment and can be accessed via a data sharing agreement with the department. DFT data is property of NSW Department of Primary Industries Fisheries and can be accessed via a data sharing agreement with the department. SOI data is freely available at http://www.bom.gov.au/climate/enso/soi/. The BRAN2020 is available from the CSIRO https://doi.org/10.25914/6009627c7af03. The IMOS oceanographic data (current speed, etc.) are available from https://portal.aodn.org.au/. Code used in this analysis is available from: https://github.com/HaydenSchilling/Whale-Entanglements.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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