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Assessing exposure of pygmy blue whales to existing threats to inform offshore wind farm development

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Executive summary

The offshore renewable energy (ORE) sector is rapidly developing in Australian waters to meet the country's carbon emission targets. However, new developments in the marine environment may pose added risk to threatened species. The ORE industry and State and Commonwealth agencies responsible for licensing and regulation of this new industry urgently require evidence-based data and information to support decision-making and to drive efficient regulatory processes in relation to threatened species.

The Eastern Indian Ocean pygmy blue whale (*Balaenoptera musculus brevicauda)* was identified as a priority species by industry and Government for understanding potential impacts in relation to ORE developments. The Eastern Indian Ocean stock of this subspecies ranges from the Subtropical Convergence (~40 – 45°S) to Southeast Asia (~2°N) with most of its documented distribution within the Australia Exclusive Economic Zone. The pygmy blue whale distribution overlaps with various anthropogenic activities across their range, with some level of exposure to pressure and threats already existing. The pygmy blue whale distribution range in Australia delineated by the Australian Government also overlaps four of the six declared areas for ORE development. As the ORE industry is still in the early development stages, spatial information on the activities and threats to pygmy blue whales from this industry are unavailable. However, spatial data on other industry threats is available. The aim of this study was to assess exposure of pygmy blue whales to existing threats to inform offshore wind farm development.

To achieve this aim, all available spatial data were compiled to quantify the relative distribution of pygmy blue whales (full range and foraging) and threats (vessel strike, underwater noise, pollution, entanglement, displacement and climate change). Then, the overlap and exposure to individual threats and cumulative threats were quantified across these distributions and within areas declared for ORE development. Threat exposure analysis included expert elicitation to gather unavailable data on the probability of exposure to a threat occurring from the spatial overlap between the pygmy blue whale distribution and anthropogenic pressures.

High overlap occurred between the pygmy blue whale distribution, and two of the six ORE declared areas; the Indian Ocean and Southern Ocean Declared Areas (73 to 100%), as well as with the most important distribution areas (areas of highest use by pygmy blue whales). At least four of the six threats considered occurred within the declared areas, with the Gippsland Declared Area overlapping with all six threats and displaying the highest values of cumulative threat intensity (maximum of 0.67 and mean of 0.28 ± 0.09). However, overlap between threats and species distributions does not necessarily indicate impact. Our assessment of exposure to these threats (and therefore potential impact), informed by a robust expert elicitation process, indicated a relatively low level of exposure of pygmy blue whales to existing threats within Australian waters, particularly those that occur within declared ORE areas.

The project delivered four complimentary components (spatial data and maps) that can be directly incorporated by industry, managers and regulators as spatial layers into impact assessment, EPBC referrals, feasibility license assessments and mitigation: 1) Compiled spatial data and quantified the full and foraging relative distributions of pygmy blue whales in

Australia, 2) Quantified the distribution and intensity of existing threats and spatial overlap with the relative distributions of pygmy blue whales, 3) Used expert elicitation to assess the probability that the spatial overlap between whales and pressures would result in exposure to a threat and 4) Integrated components 1, 2 and 3 to quantify and map the cumulative threat exposure of pygmy blue whales to existing threats across their distribution and in relation to ORE declared areas.

The spatial data produced here on the distribution of pygmy blue whales, important areas, and the threat distribution and cumulative exposure has been made freely available through Seamap (https://seamapaustralia.org/) and the pygmy blue whale distribution (full and foraging), as well as all relative distributions quantified in this study have been provided to DCCEEW to inform the blue whale Biologically Important Area (BIA) review. To ensure the sustainable development of the ORE industry in Australia in relation to this sub-species, we also suggest further data collection/liberation of existing data for data analysis to fill data gaps.

Our study identified several gaps in data and knowledge, which need to be considered in the interpretation of our results. These were: 1) the need for spatial data during the southern migration of pygmy blue whales (vast majority of existing data is from the northern migration), 2) only limited spatial data exists in some areas within their distribution (e.g., southwestern Western Australia, the Great Australian Bight, Bass Strait and the Subtropical Convergence), 3) the need for continued spatial data collection to improve sample size/representativeness, 4) compilation and analysis of existing passive acoustic monitoring data to determine temporal and spatial patterns among the different blue whale sub-species in the southeast, and 5) the absence of empirical data on impacts to threats for pygmy blue whale.

1. Introduction

Australia is one of many of the world’s nations to have committed to reducing carbon emissions to halt the effects of climate change (Paris Agreement 2015). Development and use of renewable energy is crucial to achieving this commitment, and offshore renewable energy (ORE) systems and offshore wind farms (OWF) in particular, have been identified as key solutions (Abaei et al. 2024). However, there are potential risks to threatened species that must be considered as construction and operation of marine infrastructure can expose them to a range of pressures and threats. For example, strikes and anthropogenic noise production from vessel activities (and other sources, e.g. pile driving and seismic testing) are considered major threats for many marine megafauna species including marine mammals, fishes, invertebrates, marine birds, and reptiles and may result in lethal and sub-lethal effects (McCauley et al. 2003, Calambokidis et al. 2019, Duarte et al. 2021, Womersley et al. 2022, Ferreira et al. 2023).

Six areas in Australia have been declared for development of ORE; off Bunbury in southwest Western Australia, the Southern Ocean, Bass Strait, Otway and Gippsland regions in Victoria, and the Hunter and Illawarra regions in New South Wales. As such, Commonwealth (and State) agencies responsible for licensing and regulation under environmental legislation (e.g., *Environment Protection and Biodiversity Conservation Act 1999 – EPBC* Act) urgently require scientific, evidence-based data and information to support decision-making, and to drive efficient regulatory processes for this new industry. The Commonwealth Department of Climate Change, Energy, the Environment and Water (DCCEEW) published a guidance document for proponents outlining the key environmental factors for developing OWF projects under the EPBC Act. In this document, they identify the need for consideration of potential cumulative impacts to the marine ecosystem and fauna from development projects, and to assess overlap with biologically important areas for listed threatened and migratory species (DCCEEW 2023a). Additionally, the regulator of offshore industries; the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) in their Research Strategy 2023-2025 states the need for improved understanding on species, processes and industry activities to support impact and risk assessment as a primary goal for the agency (NOPSEMA 2023).

Several *EPBC* Act-listed fauna species were prioritised by DCCEEW and NOPSEMA to support ORE developments including two *EPBC* Act-listed Endangered baleen whales; the blue whale (*Balaenoptera musculus*) and southern right whale (*Eubalaena australis*). Understanding potential impacts of ORE on these species, and specifically, the need for data on their distribution and foraging areas in relation to ORE developments were considered key data gaps (DCCEEW 2023, NOPSEMA 2023). This project is focussed on that need for pygmy blue whales and, specifically, the Eastern Indian Ocean pygmy blue whale (*Balaenoptera musculus brevicauda*), which is one of three recognised blue whale subspecies in the Southern Hemisphere. Pygmy blue whales migrate between Australia and Southeast Asia (Double et al. 2014, Möller et al. 2020, Thums et al. 2022) with inter-annual foraging sites within Australian waters of the Great Southern Australian Coastal Upwelling System (GSACUS) and Perth Canyon (Gill 2002, Double et al. 2014, Möller et al. 2020, Thums et al. 2022), although opportunistic foraging may occur throughout their migration (Thums et al. 2025).

The areas pygmy blue whales use overlaps with at least four declared ORE development regions (all except those in NSW) (Commonwealth of Australia 2015) potentially exposing the species to threats from this industry. Pygmy blue whales may already be experiencing some level of threat exposure to potential impacts from other offshore activities such as oil and gas (O&G) exploration and production, fishing and shipping activity (Ferreira et al. 2023), (although noting that some mitigation is in place for O&G activities). Exposure to vessel strike and underwater noise from these offshore activities, among other stressors can elicit physiological and behavioural responses, such as deterrence from feeding, with potential consequences to fitness and health of individuals and populations (Nowacek et al. 2007, Weilgart 2007, Avila et al. 2018). The development of OWF exposes pygmy blue whales to similar threats and potentially of increasing magnitude if these anthropogenic threats co-occur. These may result in displacement from important areas (e.g. foraging areas) via habitat modification and underwater noise from increased vessel movement and pile driving for wind turbine foundations, as well as increased strike risk (Edrén et al. 2010, DCCEEW 2023a, Farmer et al. 2023). This is concerning to the recovery of pygmy blue whales, given this species has low population size (McCauley et al. 2018) and low fecundity (Lockyer 1984, Branch 2008).

Under the EPBC Act, the instrument that addresses pygmy blue whale recovery is the Conservation Management Plan for the Blue Whale (CMP). The objective of the CMP is to minimise anthropogenic threats to allow for their recovery with listed threats including whaling, climate change, noise interference and vessel disturbance (Commonwealth of Australia 2015). The CMP outlines the distribution of pygmy blue whales in Australia as well as spatial areas of importance to them, so called Biologically Important Areas (BIAs) for foraging and migration. The CMP further details that “anthropogenic noise in biologically important areas will be managed such that any blue whale continues to utilise the area without injury and is not displaced from a foraging area”. Biologically Important Areas have been delineated in the CMP, but in early 2023, DCCEEW commenced consultation with stakeholders to update the blue whale biologically important areas. At the time of undertaking this research (and at publishing this report), the update to the blue whale BIA was not finalised.

The previous pygmy blue whale distribution and BIAs are a decade old (Commonwealth of Australia 2015) and there have been several published papers in the intervening years (Garcia-Rojas et al. 2018, McCauley et al. 2018, Möller et al. 2020, Davenport et al. 2022, Sahri et al. 2022, Thums et al. 2022, Ferreira et al. 2024, Mustika et al. 2024, Thums et al. 2025). Given this we sought to compile all the available data and quantify the pygmy blue whale distribution and foraging and migration areas as well as the most important areas (areas of highest use) as a first step needed to assess the exposure of pygmy blue whales to potential threats from OWF.

DCCEEW designates BIAs using a protocol which involves data elicitation, expert panels and establishing thresholds to identify regions where protected species aggregate for critical life stages including Reproduction, Foraging, Migration and Resting (DCCEEW 2023b). The process uses the spatial data (points usually) to create polygons and adds a spatial buffer to form a closed boundary. For wide ranging species like pygmy blue whales, these polygons are extremely large (thousands to hundreds of thousands of square kilometres). To focus management and mitigation efforts within such a broad area, it is useful to define the relative importance of all areas across the distribution/BIA. This quantity is not available in the BIA polygon approach, rather it encapsulates all areas that meet the thresholds equally. Quantifying areas of higher relative importance in the range of areas used by wide ranging animals is a common approach to identify priority areas for conservation (Lascelles et al. 2012, Ferreira et al. 2021, Fossette et al. 2021, Peel et al. 2024) and such approaches are used to identify important areas for biodiversity, for example, Marine Important Bird and Biodiversity Areas (mIBAs) for seabirds (Lascelles et al. 2012, Cleasby et al. 2020). Such quantification of relative use by a species is also a key first step to quantifying exposure to threats (single threats and cumulative) (Halpern and Fujita 2013, Maxwell et al. 2013, Ferreira et al. 2023)

As the ORE industry is still in the early development stages, the spatial distribution of ORE threats is unavailable. However, spatial data on other industry threats is available (Ostwald et al. 2021, Ferreira et al. 2023, McLean et al. 2024). Undertaking an assessment of the exposure of this priority species to existing threats in areas designated for development of ORE, will assist in the management and decision-making in relation to this developing industry as proponents and regulators can take into account the potential impacts of other projects (cumulative impacts) within each declared area (DCCEEW 2023a), as well as ensuring projects are spatially separate from species important areas (DCCEEW 2023a). However, simply mapping overlap between species and threat distributions does not constitute impact, only exposure to threats. Understanding whether impact may occur requires empirical data on the effect, impact and consequence of the exposure to anthropogenic pressures and threats (Table A 1). Although some data is available for some threats, i.e. noise (McCauley et al. 2000b, Croll et al. 2001, Hückstädt et al. 2020), this information is generally not broadly spatially available. Therefore, we sought to use expert elicitation (Fisher et al. 2012) to better inform our measure of exposure to threats using expert knowledge.

The aims and objectives of this study are therefore to assess exposure of pygmy blue whales to existing threats to inform OWF development. Four components were involved to address this objective: 1) compilation of data from multiple sources (telemetry, surveys, etc) to update the distribution of pygmy blue whales in Australian waters, including their foraging distribution, and to identify areas of higher relative importance (areas of higher use), 2) compilation of spatial data on existing threats that may potentially impact pygmy blue whales (vessel strike, underwater noise, pollution, entanglement, displacement and climate change), 3) calculate the spatial overlap between pygmy blue whales and existing threats using a cumulative exposure analysis, informed by the probability of exposure to threats occurring from this spatial overlap using an expert elicitation process (Fisher et al. 2012) and 4) map the cumulative threat exposure of pygmy blue whales across their distribution and assess the overlap with ORE declared areas.

The outputs of this research (this report, maps and spatial products) are designed to advance our understanding of the current level of exposure of pygmy blue whales to existing pressures that exist within areas declared for ORE. This will ultimately assist Government with *EPBC* Act triggers, proponents with site selection (avoiding areas with existing threats and areas of higher use by pygmy blue whales) and in designing impact avoidance and mitigation strategies, and regulators in assessing risk assessment by proponents. In turn, we hope that this will support better protection of pygmy blue whales and more informed/efficient approval decisions.

2. Methods

2.3 Pygmy blue whale distribution

To calculate cumulative threat exposure for Eastern Indian Ocean pygmy blue whales, we first developed an up-to-date relative distribution map by compiling all the spatial data available for this sub-species in Australian waters. This included author collected datasets and other available datasets uncovered from author knowledge, and through searches of public data repositories and published and grey literature. Data sharing agreements were setup as required. The data types included satellite telemetry, sightings data, and model outputs of pygmy blue whale habitat suitability models using telemetry and passive acoustic monitoring data (Table 1). Only spatially explicit datasets were able to be used in developing the relative distribution map, i.e. where GPS coordinates were available for each whale detection/observation. A relative distribution map, using a 10 km × 10 km grid across the Australian Exclusive Economic Zone (EEZ), was made from each data type. Separate maps were needed as the analysis of different types of data can be complex with each data type having specific statistical distributions, assumptions and biases (Miller et al. 2019). Where behaviour data were available, we developed a foraging distribution in addition to an overall distribution for pygmy blue whales.

2.3.1 Satellite telemetry

The compiled satellite telemetry dataset included a sample size of 60 whales. Telemetry data from individual whales was only considered where the tracking duration was longer than one week and with sufficient location data transmitted. This compiled dataset (Table 1) included tracks from whales tagged in the GSACUS off the Bonney Coast in South Australia (n=12; Möller et al. 2020), Portland in Victoria (n=4; Garcia-Rojas et al. 2018, and unpublished data provided by Blue Whale Study); Perth Canyon (n=28; McCauley et al. 2004, Double et al. 2014, Owen et al. 2016, Davenport et al. 2022, Thums et al. 2022), Geographe Bay (n=1; McCauley et al. 2004), Ningaloo in Western Australia (n=13; Thums et al. 2022, Thums et al. 2025); and in the Savu Sea Marine Protected Area, Indonesia (n=2; Mustika et al. 2024). Most whales were tagged during the summer foraging season or at the onset of, or during, their northbound migration (n=58), except for the two whales tagged in Indonesia during their southbound migration. The tracking dataset provided whale location estimates obtained via geolocation, ARGOS and Fastloc GPS. Geolocations were estimated using the Wildlife Computers geolocation processing software, GPE3, from observations of twilight and temperature collected by the tag and reference data for sea surface temperature and bathymetry. ARGOS locations are calculated by CLS Argos using the Doppler shift of the satellite signal and the known location of the satellite and provided to the user. The LocSolve algorithm from Wildlife Computers was used to calculate GPS positions using the raw data collected by the tag (satellite ID and range data) and transmitted to the Wildlife Computers Data Portal, combined with precise satellite ephemeris data to refine the location estimates. The dataset spanned over 22 years with a range of tag models and attachment methods used. Please see the cited references above for specific tag device details and deployment methods.

A state-space model (SMM) (Jonsen et al. 2003, Jonsen et al. 2005) was applied to the raw pygmy blue whale tracking data (ARGOS and GPS only) using the R package *aniMotum*

(Jonsen et al. 2023). The SSM accounts for error associated with location estimates, autocorrelation between successive locations, and their turning angle and speed. We followed established procedures previously applied to part of this dataset (Ferreira et al. 2024) to ensure model convergence and to apply a move persistence model to obtain an objective classification of the underlying behaviour along the track of a whale. In summary, the move persistence model (Jonsen et al. 2019, Jonsen et al. 2023) provides a move persistence index related to the speed and directionality of each movement step in a continuum between 0, representative of slow movement with high turning rate during ‘area restricted search’ (foraging) behaviour, and 1, representing fast directional movement indicative of migration or transit behaviour.

Time weighting was applied to the state-space modelled pygmy blue whale tracks (n=58) and geolocation (n=2) following the method described by Ferreira et al. (2021). Satellite tags are likely to transmit more locations soon after tagging and reduce with time due to premature detachment of tags, biofouling of the tag or tag failure (Block et al. 2011). This means that the number of tagged individuals will also reduce as time goes by and with distance from the tagging site, resulting in a spatial and temporal bias of the data towards the tagging location. Time weighting accounts for the decrease in the number of locations and individuals tracked as animals move away from the tagging site. In summary, the time difference between successive locations of an individual’s track is weighted by the number of tagged individuals that also transmitted locations on the same relative day (e.g., Day 1 being tagging day and n days after that) (Block et al. 2011, Ferreira et al. 2021). Because these locations are separated by hundreds of kilometres we perform time weight by grouping individuals that were tagged at the same location (e.g., Ningaloo, Southwest Western Australia, Southeast Australia, and Indonesia)

The complete satellite tracking dataset was analysed to calculate the entire distribution of pygmy blue whales. We also calculated foraging distribution using location estimates where foraging movement behaviour was detected by the move persistence model. To do this, we used the global median value of move persistence for the complete tracking dataset (median move persistence = 0.8) as a threshold to assign a category of “foraging” to locations with move persistence values below the threshold (move persistence ≤ 0.8, Thums et al. 2022). Although other behaviours such as resting and reproduction may also result in similar values of move persistence, we are not able to separate these potential behaviours without actual behaviour data (i.e., depth/activity data to identify lunge feeding) and such information was only available for a small proportion of the dataset (Thums et al. 2025). However, these methods are commonly used to infer foraging (Jonsen et al. 2005, Hays et al. 2006, Breed et al. 2012, Bestley et al. 2013, Arnould et al. 2015, Bestley et al. 2015, Thums et al. 2017, Ferreira et al. 2018, Hindell et al. 2020, Möller et al. 2020, Peel et al. 2024) and a recent validation shows that move persistence data aggregated across numerous individuals can define broad foraging areas (Thums et al. 2025).

We followed the methods described by Ferreira et al. (2021), Thums et al. (2022), Ferreira et al. (2023) to calculate relative distribution of pygmy blue whales using the satellite tracking dataset. We overlaid all satellite tracking data, counted the number of satellite tracked pygmy blue whales in each 10 km × 10 km grid cell and then divided it by the total number of satellite tracked whales so that 1 was the cell with most whales and 0 represented a cell with no whales. We also calculated the normalised proportion of whales in each grid cell per month. If gaps in time (> 5 days) and space (locations in areas >50 km apart) occurred in a track, we split the track during the analysis to avoid over-interpolation between used areas, but considered all sections of the track as one unique individual when calculating distribution.

For the foraging relative distribution, we did a similar analysis but used time spent instead of number of whales, as when foraging, animals spend more time in an area (Ferreira et al. 2021). We calculated the time spent within grid cells for each whale's satellite track but only using locations where the movement behaviour was indicative of foraging as defined by the move persistence index ≤ 0.8. We overlaid all individuals and summed all time spent values within a grid cell and then normalised the sum between 0 (no use) and 1 (maximum use) to provide a normalised measure of relative distribution (Ferreira et al. 2021).

Table 1. Datasets included in the analysis indicating collection method, type of data, location and number of datasets, and source.

Data collection method	**Location**	**Data type**	**Year**	**Number of individuals sampled**	**Reference/source**
Satellite telemetry	Perth Canyon	Tracking locations (GPS, Argos)	2003,2007-2009,2011-2012, 2021-2022	26	McCauley et al. 2004, Double et al. 2014, Thums et al. 20224 Australian Antarctic Division (unpublished)
Satellite telemetry	Geographe Bay	Tracking locations (Argos)	2002, 2014	1	McCauley et al. 2004
Satellite telemetry	Perth Canyon	Tracking locations (Geolocation)	2021	2	Thums et al. 2025
Satellite telemetry	Ningaloo	Tracking locations (GPS, Argos)	2019-2020,2024	13	Thums et al. 2022, Thums et al. 2025, Australian Institute of Marine Science (unpublished)
Satellite telemetry	Portland, VIC	Tracking locations (Argos)	2005	4	Blue Whale Study and Garcia-Rojas et al. 2018
Satellite telemetry	GSACUS/Bonney Coast, SA	Tracking locations (Argos)	2015	12	Möller et al. 2020
Satellite telemetry	Indonesia	Tracking locations (Argos)	2022	2	Mustika et al. 2024
Vessel survey	Australia EEZ	Sightings	2002-2019		Marine mammal observer data, AAD 2023
Vessel survey	Southeast Australia	Sightings			Marine mammal observer data from Offshore resource industry – Beach Energy, Conoco Phillips, Esso
Aerial survey	Southeast Australia	Sightings	2002-2007		Gill 2002, Offshore resource industry – Beach Energy
Opportunistic (may also be structured) sightings	Australia EEZ	Sightings	Downloaded Nov 2023		https://www.ala.org.au/ https://seamapaustralia.org https://happywhale.com/ https://www.environment.vic.gov.au/biodiversity/victorian-biodiversity-atlas https://www.gbif.org https://www.naturalvaluesatlas.tas.gov.au/
Catch records	Australia EEZ	Sightings	1800s-1900s		International Whaling Commission
Habitat suitability model output (telemetry)	Australia EEZ	Model prediction	2024		Ferreira et al. 2024
Habitat suitability model output (PAM)	Northwest WA	Model prediction	2022		Thums et al. 2022

2.3.2 Sighting data

Sightings of pygmy blue whales were compiled from public data repositories including Atlas of Living Australia (https://www.ala.org.au/), OBIS-SEAMAP (https://seamap.env.duke.edu/), the Victorian Biodiversity Atlas (https://www.environment.vic.gov.au/biodiversity/victorian-biodiversity-atlas/about-the-vba), Happy Whale (https://happywhale.com/home), GBIF (https://www.gbif.org/) and the Tasmanian Natural Values Atlas (https://www.naturalvaluesatlas.tas.gov.au/). Presence data were collated from aerial surveys in southern Australia (Gill 2002), and the Bass Strait region (as part of offshore resource industry monitoring surveys), and from vessel surveys led by the offshore resource industry and the marine mammal observer (MMO) dataset hosted by the Australian Antarctic Division (AAD 2023). For the sightings from MMO and the public repositories, whales were not always identified to the subspecies and were often noted as “unidentified blue whale”. Of the sighting data, 39% were recorded as pygmy blue whales and 61% as unidentified blue whales. All datasets were plotted together and compared to remove duplicate observations reported in more than one repository.

Historical pygmy blue whale catch records were obtained from the International Whaling Commission (IWC; https://portal.iwc.int/) to fill in data gaps within their likely distribution (Branch et al. 2007). The dataset included historical (1800s-1900s) whale catch positions to the nearest latitude and longitude degree, to the nearest minute or only approximately to the nearest 5 or 10 degree square. The dataset does not identify the subspecies, and it is likely that records identified as ‘blue whale’ included both pygmy blue whale and the Antarctic blue whale (*Balaenoptera musculus intermedia*). We used the method developed by Branch et al. (2025) to classified catch records as pygmy blue whales *vs* Antarctic blue whales based on their measured length and the region where they were caught. Information and spatial layers for effort (survey lines) were not available for any of the sighting datasets, thus, all the sighting data were combined and analysed together as presence only data. The relative distribution for the sighting dataset was obtained by counting the number of observations per grid cell and then normalising the values between 0 (no whales) and 1 (max number of observations) to allow for combining with other relative distribution maps.

2.3.3 Habitat suitability model predictions

Predictions of suitable habitat from existing habitat suitability models developed using part of the tracking dataset included here (Ferreira et al. 2024), and from a model using acoustic data (prediction of number of singers) in northwest Australia (Thums et al. 2022) were also used in the analysis. Spatial predictions for the habitat suitability model were validated using spatially varying estimates of accuracy and normalised between 0 and 1 (Ferreira et al. 2024). Habitat suitability modelling using satellite telemetry data was done for migratory (move persistence index > 0.8) and foraging (move persistence index ≤ 0.8) movement behaviour separately (Ferreira et al. 2024).

2.3.4 Pygmy blue whale relative distribution and foraging distribution

We calculated a combined relative distribution and a combined foraging relative distribution for pygmy blue whales in Australia to be used in the cumulative assessment (see section 3.5). Calculating the combined relative distribution was achieved by summing the relative entire distribution calculated from the satellite tracking data (normalised proportion of whales in a grid cell), the sightings data, and each of the habitat suitability model predictions (built with tracking data for migration behaviour or PAM data). Both model predictions were down-weighted to 25% to avoid overestimation of areas where only model predictions were available. We considered the overall distribution is also representative of their migration distribution as pygmy blue whales will display temporary high use (and foraging) during their migration (Thums et al. 2025). The combined foraging distribution included the foraging relative distribution calculated from satellite tracking data (normalised time spent in a grid cell) and the habitat suitability model predictions for foraging (also down weighed to 25%) from Ferreira et al. (2024). The combined distributions were again normalised between 0 (no whales) and 1 (maximum whales). The term ‘relative distribution’ was used here because the minimum and maximum values are relative to the range within a distribution, e.g. we cannot directly compare different metrics such as time spent vs number of whales. Hence, by normalising the values of each relative distribution between 0 and 1, we ensured that the different metrics used (time spent, proportion of whales, habitat suitability, number of singers) were within the same scale allowing us to combine them and map spatial patterns of high and low used within the combined distributions.

We then calculated the mean value for the distribution and the foraging distribution within the ORE declared areas. Spatial data representing the zones established under legislation that have been declared for ORE by the Australian Government were obtained from Geoscience Australia (https://amsis-geoscience-au.hub.arcgis.com/datasets/geoscience-au::offshore-renewable-energy-infrastructure-regions/about).

We also determined the most important foraging and distribution/migration areas for pygmy blue whales using the foraging and entire distributions, respectively. The most important foraging areas were defined as the top 50% of the cumulative frequency (akin to a 50% kernel density) distribution of the combined, normalised foraging distribution (Soanes et al. 2013, Ferreira et al. 2021). The most important areas for the distribution/migration were calculated as the top 75% of the cumulative frequency distribution based on the combined, normalised entire distribution (Soanes et al. 2013, Ferreira et al. 2021).

2.4 Threats

The existing threats to pygmy blue whales in Australia have been identified as vessel strike, underwater noise, pollution, entanglement, displacement and climate change (Commonwealth of Australia 2015, Ferreira et al. 2023, McLean et al. 2024 and with input from regulatory agencies) (see Table A 1 for terminology). Each threat was associated with one or more pressures linked to human activities in the marine ecosystem (Table 2). Spatial data for each of the pressures were obtained from open free sources (Table A 2) and we were restricted to pressures that matched pygmy blue whale distributions within Australian waters in space and time (as current as possible) to understand current cumulative exposure to existing threats.

2.4.1 Pressures

Commercial shipping

We used the dataset from the Australian Maritime Safety Authority that encompasses vessel locations from automatic identification system (AIS) fitted aboard all Australian vessels of 300 gross tonnage and greater to represent commercial shipping (Table A 2). The AIS data is provided as monthly point locations for each vessel track. We compiled the most recent data available at the start of the analysis (January to December 2023) to map shipping intensity. Vessel tracks for all months combined were overlaid with the spatial grid for the study area (10 km × 10 km) and the number of tracks in each grid cell was counted. The number of tracks in each grid cell was subsequently normalised between 0 (no shipping) and 1 (maximum shipping intensity) as a measure of commercial shipping intensity that was associated with the threats of ship strike and pollution (vessel discharges) (Table 2). We also used an existing spatial layer representing the cumulative noise from shipping vessels from acoustic models (Erbe et al. 2021) to represent the threat of underwater noise associated with commercial shipping (Table A 2).

Fishing

We obtained information for fishing effort within the Australian EEZ as fishing hours per grid degree cell from the Global Fishing Watch dataset (https://globalfishingwatch.org/) for the entire year of 2020 (latest data freely available). The dataset included fishing hours for a range of gear types including purse seiners, drifting and set longlines, set gillnet and fixed gear, trawlers and pots and traps. We extracted the fishing effort data to the 10 km × 10 km grid and normalised grid cell values (fishing hours) to be between 1 (maximum fishing intensity) and 0 (no fishing). Fishing intensity was associated with the threats of ship strike and pollution (Table 2). Additionally, as all fisheries and gear types included in this dataset have the potential to lead to megafauna entanglement (loglines, nets and pots), this spatial layer was used to calculate the threat of entanglement (Table 2, Table A2).

Offshore oil and gas exploration and operations

Spatial layers for offshore oil and gas (O&G) exploration and operations included location data for active wells (in exploration phase), offshore platforms, pipelines, seismic surveys and infrastructure in decommissioning phase or near future decommissioning (i.e., proposed activity with approved environmental plans by NOPSEMA). Spatial layers were obtained from the National Offshore Petroleum Information Management System (NOPIMS; https://www.ga.gov.au/nopims). These spatial layers represent multiple pressures that are linked to different threats, and they were processed differently depending on the pressure/threat (Table 2, Table A 2).

Based on published literature and environmental plans for approved O&G development projects and ecological impact assessments available in the regulator website (https://info.nopsema.gov.au/), a buffer of 2 km radius classified as intensity 1 was constructed around offshore platforms to represent the distance where underwater noise from normal operation and support vessels are heard (McCauley et al. 1998). A second buffer extending to 5 km from platforms was created and assigned an intensity of 0.5, as this is considered the average distance underwater noise from vessels associated with platform operations are still heard (McCauley et al. 1998). As there was a large overlap among buffers, we overlaid all 2 km and 5 km noise buffers, summed the intensity in each grid cell and normalised between 1 and 0 to represent chronic underwater noise from O&G exploration and operation. We also used the 2 km buffer to represent platform footprints as potential barriers to whale movement and to characterise the footprint of potential pollution plume associated with discharge waters during their regular operation (Table 2).

Oil spills

During environmental planning of drilling and exploration activities, companies need to model the dispersal of potential unplanned spills, indicating the areas potentially affected, risks, management, mitigation and treatment plans for such events (NOPSEMA 2019). We reviewed oil spill modelling from multiple approved environmental plans across Australia (https://info.nopsema.gov.au/) to estimate the area around sources (platforms, wells and pipelines) that could be potentially affected by oil spills from these sources. Although local and regional environmental settings, as well as discharge amount, will influence the dispersal process, taking all this into consideration was beyond the scope of this project. Here, we assigned buffers around platforms and pipelines that represented the average distances defined in approved environmental plans. A buffer of 20 km was constructed around each platform and pipeline and assigned as intensity 1. This buffer represented the area where the oil slick could be expected to be visible on the water surface with concentrations ($\geq 10 g/m^3$) that are considered to be harmful to marine mammals and require cleanup (Bonn Agreement Oil Appearance Code 2016, NOPSEMA 2019). Another buffer extending to 500 km was created around the location of these structures to indicate areas affected by dissolved entrained oil with concentration of ≥ 50ppb and/or entailed oil of ≥ 100ppb that are considered to exert sublethal toxic effects to sensitive species (NOPSEMA 2019). This buffer received a score of 0.5. We overlaid all buffers over the study area grid, summed the intensity in each grid cell and normalised between 1 and 0.

Seismic activity

Spatial layers related to offshore seismic exploration activity included 2D seismic survey lines and boundaries of 3D seismic surveys areas. We overlaid the layers with the 10 km ×10 km grid, and then counted and summed the number of 2D survey lines and 3D survey areas in each grid cell and normalised between 0 (no surveys) and 1 (maximum number of surveys) to create a distribution of seismic surveys associated with the threat of underwater noise (Table 2).

Decommissioning

Two buffers (2 km with intensity of 1 and 5 km with intensity of 0.5) were also created around offshore wells and pipelines currently in decommissioning phase to account for the added underwater noise associated with decommissioning activities. These were identified using environmental risk assessments from industry for decommissioning activities involving removal and noise producing activities approved by NOPSEMA in Commonwealth waters (https://www.nopsema.gov.au/).

Climate change

Remote sensed sea surface temperature was obtained from National Oceanic and Atmospheric Administration Goddard Institute for Space Studies (NOAA GISS)- Surface Temperature Analysis version 4 (GISTEMP v4). This layer represented the averaged (2014-2024) global temperature anomaly against a historical baseline (1951-1980) and was used as a proxy of the threat of climate change (Table 2 and A 2). We also obtained a spatial layer from the Copernicus Marine Ocean Monitoring Indicator (OMI) representing the global trend of surface ocean pH since 1985 to represent ocean acidification associated that can lead to changes in prey availability associated with the threat of climate change (Table A 2).

Table 2. List of threats and pressures considered in the analysis. Details of spatial layers used are included in Table A 2.

Threat	Pressure	Details
Ship strike	Commercial ships	Ships (> 300 gross tonnage) with draft of > ~5m and speed of 11 to 20 knots
	Fishing vessels	Australian fishing vessels (15-20m), draught of 1-2m, and speed of 5-10 knots
Underwater noise	Chronic underwater noise	Noise from regular (over weeks, months years) and current marine activities such as shipping, normal operation of O&G platforms, decommissioning
	Acute underwater noise	High intensity noise with large footprint associated with a seismic survey
Pollution	Chronic pollution	Dissolved pollutants, minor oil slick from shipping, normal operation of O&G platforms (e.g., discharge waters)
	Oil spill	Dissolved, entrained and floating oil from unplanned spills from O&G platforms, wells and pipelines
Entanglement	Fishing gear	Nets, lines, pots
Displacement	Infrastructure at sea	Offshore oil and gas infrastructure
Climate change	Habitat change	Changes in ocean temperature from optimal environmental conditions
	Prey availability	Changes in ocean temperature and pH leading to changes in prey availability and distribution

2.4.2 Threat distributions

We combined all pressures associated with each threat to create their distribution (Table 2 and Table A 2). This was done by overlapping all spatial layers for pressures associated with each threat and summing their intensity in each 10 × 10 km cell. We then normalised the summed values between 1 (maximum intensity) and 0 (no threat present) as a measure of threat intensity that allowed us to compare the distributions among threats.

2.5 Expert elicitation

We adapted the method and protocol developed by Fisher et al. (2012) for expert elicitation to assess the probability of threat exposure occurring as a result of the overlap between pygmy blue whales and each pressure. In summary, this method allowed us to fit a statistical distribution to the information provided by an expert on the probability values (range, mean and median), ensuring that the expert input has a measure of uncertainty and credible bounds around estimates (Fisher et al. 2012).

We identified blue whale experts as researchers publishing on blue whales nationally and internationally (including in the field of ecology, movement, acoustics and physiology), and those working in conservation management of Australian marine mammals. Experts were identified through a review of the published literature (peer reviewed and grey) and also informed by existing working groups within Australia (e.g. expert panel for the pygmy blue whale Biologically Important Areas update) and globally (IUCN expert panel). Twenty-five experts were identified and invited to contribute to this process.

A series of questions were developed (Table A3) based on each of the threats associated with each pressure for which spatial data was available (Table A2). Those experts who accepted the invitation had a one-on-one online or in-person meeting (~1h duration) with the lead author (L Ferreira) where they were asked each question (Table A 3) one by one and asked to give their opinion on the probability (from 0 to 1) of pygmy blue whales being exposed to each pressure/threat given overlap occurring between blue whales and each pressure/threat (Table A 3). Experts were reminded to answer based on their own expertise and knowledge of pygmy blue whale ecology and behavior, and their knowledge of the actual pressure. In providing their opinion on the probability of exposure to each pressure, they were instructed to first provide an estimate of the absolute maximum and minimum values for the probability of exposure to each pressure, and once this was established they were further asked to provide their best guess of the most accurate value of the probability within that range. Using a custom code in the software R (RStudio 2012), feedback was provided in real time by plotting the distribution of the expert's answers and explaining the influences of their input on the distribution that was calculated. If this did not align with the expert's knowledge for each question, values of range and best guess were adjusted by the expert iteratively to ensure good alignment between expert knowledge and the probability distribution produced with their input. Finally, experts were asked how confident (sureness) they were in the values they provided. If experts reported a confidence (sureness) of less than 50% out of 100% (indicating low expertise), their input was not included in the subsequent threat exposure analysis (See below).

The protocol we followed was specifically designed to reduce common biases associated with expert elicitation, including: use of most recent experiences (an expert's tendency to recall recent or important events) by incorporating initial preparation reminding the expert of their relevant experience; anchoring (where the expert adjusts all of their values according to their best guess) by eliciting the most extreme values first (Low Choy et al. 2010); and under/overconfidence by eliciting the level of sureness (Kynn 2008). A detailed description on the elicitation process is described in Fisher et al. (2012).

We used a Beta distribution for plotting the shape of the distribution of the expert's answers for best guess, minimum and maximum bounds and sureness. Beta distribution was used as it is a flexible statistical distribution suitable for modelling uncertainty. This approach allowed us to create a distribution of potential values (probability of threat exposure from 0 to 1, centred around the median) associated with each pressure for each expert (Low Choy et al. 2010). These statistical distributions (for each question and for each expert) further allowed us to visually represent expert input, assess expert confidence (through the shape of the distribution curve) and knowledge (how distributions differed among experts) and account for the uncertainty around values provided (distribution tail around the median). We then selected random samples from each expert distribution for each question ($x= 1000/N$; with x being the number of samples taken from each expert distribution to sum to 1000 values for each question, N as the number of experts that provided input for each question). We did this to account for the level of sureness and bounds around the expert input, e.g. values closer to the median would be more likely to be randomly selected as they are more common within the distribution, although values associated with the tail of the distribution would also be selected to account for uncertainty and credible bounds. We used the expert-defined probability of exposure to each pressure ($P_{i,j}$) in equation 6.A.1 to calculated cumulative threat exposure (See below).

2.6 Cumulative threat exposure

We calculated cumulative threat exposure as the spatial overlap between the entire and foraging distributions of pygmy blue whales and the cumulative distribution of pressures considered in our study using a method adapted from the cumulative impact score developed by Halpern et al. (2008) and Maxwell et al. (2013) (see Figure A 1 for the method workflow). The intensity of each pressure in each grid cell was weighted by incorporating the probability of it leading to exposure using the expert-defined probability of exposure for each pressure. The cumulative exposure of pygmy blue whales to existing threats was calculated for each 10 km × 10 km grid cell as:

$$CE = D_{b,i} \times \sum_{i=1}^{n} med\left(T_i \times P_{i,j}\right) \qquad (6.A.1)$$

Where D is the normalised pygmy blue whale relative distribution (*b;* e.g., foraging or entire distribution) for a given grid cell *i*, T is the normalised intensity of each pressure at grid cell *i* (number of cells in the gridded study area from 1 to n) and $P_{i,j}$ is the sample (1000 randomly selected values) of the distribution obtained from the expert elicitation for each pressure *j* in grid cell *i*. We multiplied the intensity of each pressure *j* in each grid cell *i* by the 1000 samples from expert distributions (probability of exposure) and subsequently calculated the median value of the weighted pressure intensity for each grid cell for each pressure.

The cumulative threat exposure (*CE*) was calculated by multiplying the relative distribution of pygmy blue whales with the sum of the median values of all pressures in each grid cell and then normalising the values to between 0 (no exposure) and 1(maximum treat exposure within pygmy blue whale distribution). We then mapped cumulative threat exposure in space for the foraging distribution and for the entire distribution separately and identified areas where pygmy blue whales have greater exposure to existing threats. We also assessed the *CE* distribution and mean *CE* within each declared ORE area that overlapped with pygmy blue whale distribution. We also calculated and mapped exposure to each threat separately by considering only the pressures associated with each threat (Table 2) in the equation above.

3. Results

3.1 Pygmy blue whale distribution

We determined the relative distribution of pygmy blue whales using the different data types and sources listed in Table 1 (Figure 1). The satellite tracking datasets allowed us to create a relative distribution using all the satellite tracking data and a foraging relative distribution by using the satellite location estimates where movement behaviour was indicative of foraging (move persistence values < 0.8) (Figure 1a,b). The relative distribution (entire distribution) highlighted the areas used by most individuals (Figure 1a) that matched high use areas within the foraging distribution off the Bonney Coast within the GSACUS, off Perth (within Perth Canyon) up to offshore of the Abrolhos Islands and offshore of Ningaloo up to offshore of around 19°S latitude (Figure 1b). The distribution also represented areas used as migratory pathways, particularly along Western Australia and offshore northwest Australia (Figure 1a), where most of the tracking data available is concentrated (see Table 1).

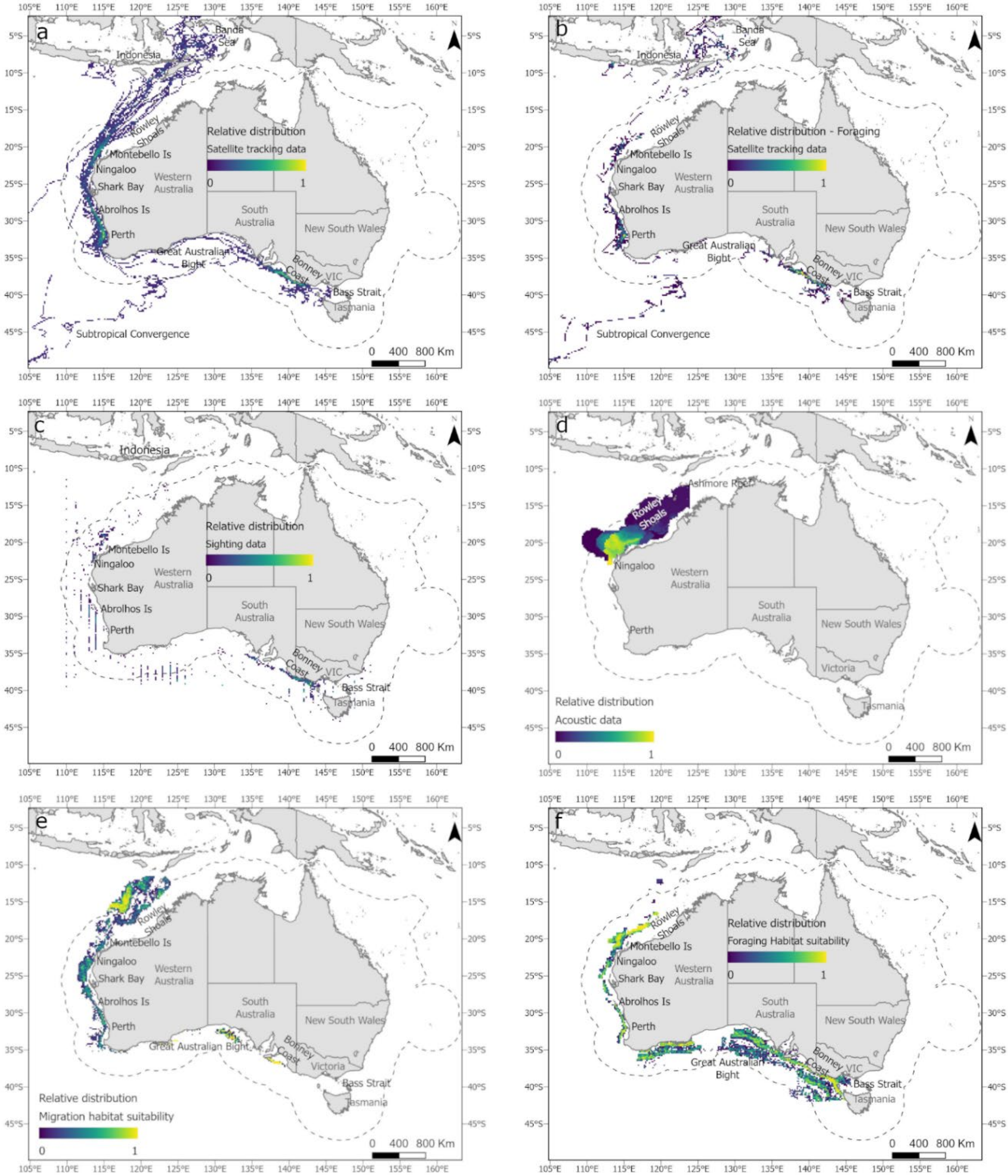

Figure 1 Normalised relative distribution of pygmy blue whales based on data type. a) Entire relative distribution (satellite tracking data), b) Foraging relative distribution (satellite tracking data), c) Sighting data, d) Habitat suitability modelled using acoustic data (number of singers) from the north-west (Thums et al. 2022), e) Migration habitat suitability modelled using migration satellite telemetry points (Ferreira et al. 2024), f) Foraging habitat suitability modelled using foraging satellite telemetry points (Ferreira et al. 2024). Dashed contour indicates the Australian Exclusive Economic Zone.

The monthly relative distribution of pygmy blue whales using the entire satellite tracking dataset showed a clear seasonal pattern in their use of Australian and Southeast Asian waters (Figure 2). The distribution was limited to the GSACUS and Subtropical Convergence in January and February (Figure 2a-b) and expanded west in March and April (Figure 2c-d) when whales started the northern migration. High use of known foraging grounds off Perth Canyon (off Perth, Western Australia) and off the Bonney Coast within the GSACUS (Victoria) was persistent until May (Figure 2a-e). In June, satellite tracked pygmy blue whales were detected off Ningaloo and the northwest of Australia, with some whales already reaching Indonesia and the Banda Sea at that time (Figure 2f). However, the relative distribution also included areas off the Bonney Coast and Great Australian Bight during June and July as one of the whales tagged off the Bonney Coast remained in southern Australia and did not move north as expected (Figure 2f-g). Pygmy blue whales remained in the Banda Sea and Indonesia regions between July and September/October when they started the southern migration (Figure 2g-j), noting that the satellite telemetry dataset only contains four whales (two whales tagged during the southern migration and two whales tagged in the northern migration but tags stayed long enough to track their southbound movements) that had tracks long enough to provide data on the southern migration. During November and December, the distribution represented the southern migration towards southern Australia and the Subtropical Convergence (Figure 2k-l). Similar to the relative distribution, the foraging distribution also followed seasonal patterns with forging concentration in southern Australia between November and February, extending to Western Australia in March and July and to Banda Sea between August and October (potentially also linked to other behaviours such as reproduction and/or resting).

The relative distribution of pygmy blue whales using the sightings data indicated similar high use areas as the satellite tracking data off the Bonney Coast and offshore of northwest Australia, mostly driven by survey and MMO datasets (Figure 1c, Table 1). Historical whaling data expanded the sightings distribution to areas where satellite tracking data was limited such as in offshore areas of southwestern and western Australia (Figure 1c). However, the data were spatially and temporally patchy resulting in a sparse, non-continuous distribution. The distribution created from the habitat suitability model prediction using acoustic data (number of singers) for northwest Australia (Thums et al. 2022) indicated higher use of the area between Ningaloo and Rowley Shoals, with lower values for the northern areas in that region (Figure 1d).

Finally, the distribution based on the habitat suitability model predictions (for foraging and migration) using the satellite tracking data (Ferreira et al. 2024) indicated a semi-continuous distribution for Western Australia for both migration and foraging behaviours (Figure 1e,f). The distribution created using the habitat suitability model predictions for foraging included a large area on the shelf off the Bonney Coast and in offshore waters in southern Australia (Figure 1e) but the migration distribution showed some patchiness due to model predictions not being validated (likely as result of limited data in that region) (Figure 1f). Additionally, all relative distributions for each data type did not extend to the eastern side of Bass Strait nor to eastern Australia (Figure 1), with only a few exceptions for the satellite tracking and sightings datasets (Figure 1a-c).

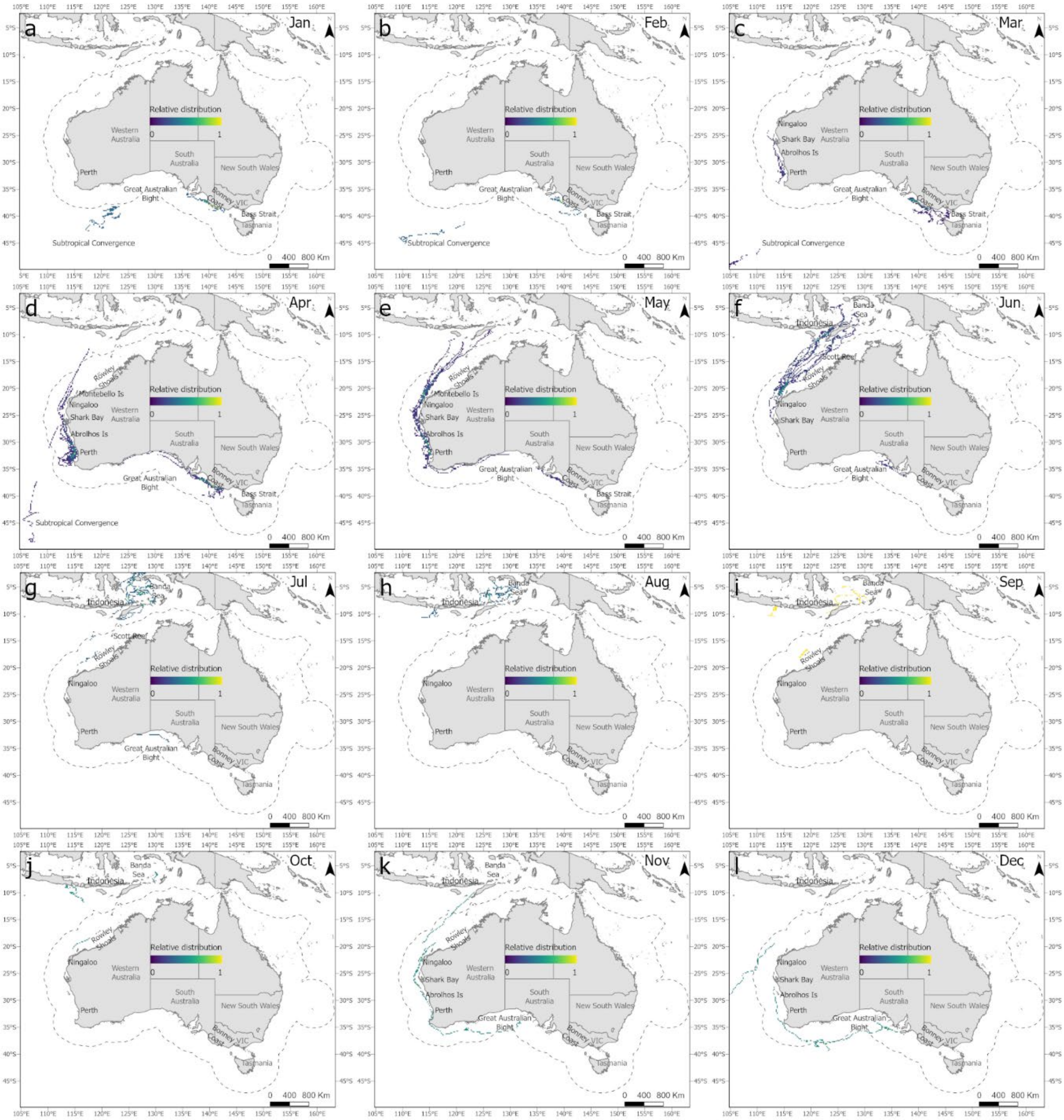

Figure 2 Relative distribution of pygmy blue whales using satellite tracking data based on all pygmy blue whale satellite telemetry data for January (a), February (b), March (c), April (d), May (e), June (f), July (g), August (h), September (i), October (j), November (k) and December (l).

When all relative distributions were combined, the distribution for pygmy blue whales included a large continuous area along the shelf break in Western Australia but also in areas off the shelf north of Ningaloo, and a semi-continuous area on the shelf in southern Australia (Figure 3). High use within the whole distribution included areas off the Bonney Coast, areas between Perth and the Abrolhos Islands and between Ningaloo and just north of the area offshore of the Montebello Islands (Figure 3a). The combined foraging distribution was represented by semi-continuous areas with high use reflecting known foraging areas off

Perth and the Bonney Coast (Figure 3b). Reflecting the relative distribution using each data type (Figure 1), the combined distribution did not extend to the eastern side of Bass Strait and the eastern coast of Australia (Figure 3).

The most important distribution/migration (75% of combined distribution) areas extended as semi-continuous areas on the continental shelf from off the Bonney Coast within the GSACUS to the Great Australia Bight in southern Australia, and in southern Western Australia around Esperance (Figure 4a). In Western Australia, important distribution/migration areas extended from the southwest to Indonesia and Timor-Leste as a continuous area, covering most of the Australian EEZ both at and beyond the continental shelf break (Figure 4a). The important foraging areas (top 50% of grid cells of the combined foraging distribution) included a large proportion of southern Australian waters, both on and off the continental shelf from just east of Tasmania to west of Esperance, and the shelf break from Cape Naturaliste to Abrolhos Is, Shark Bay and Ningaloo and areas off the shelf between Ningaloo and Rowley Shoals (Figure 4b).

The combined distribution and foraging distribution and most important distribution/migration and foraging areas also overlapped with multiple Australian Marine Parks (Figure A 2). Marine parks off Rowley Shoals, Montebello Is and those in coastal areas in Western Australia (Ningaloo to Perth, and off Esperance) had almost complete overlap with the whole distribution and migration important areas (Figure A 2a,c). The foraging distribution and important foraging areas overlapped with a similar number of parks as the whole distribution and migration areas, but the overlap occurred in areas closer to shore in Western Australian and further offshore in southern Australia (Figure A 2b,d).

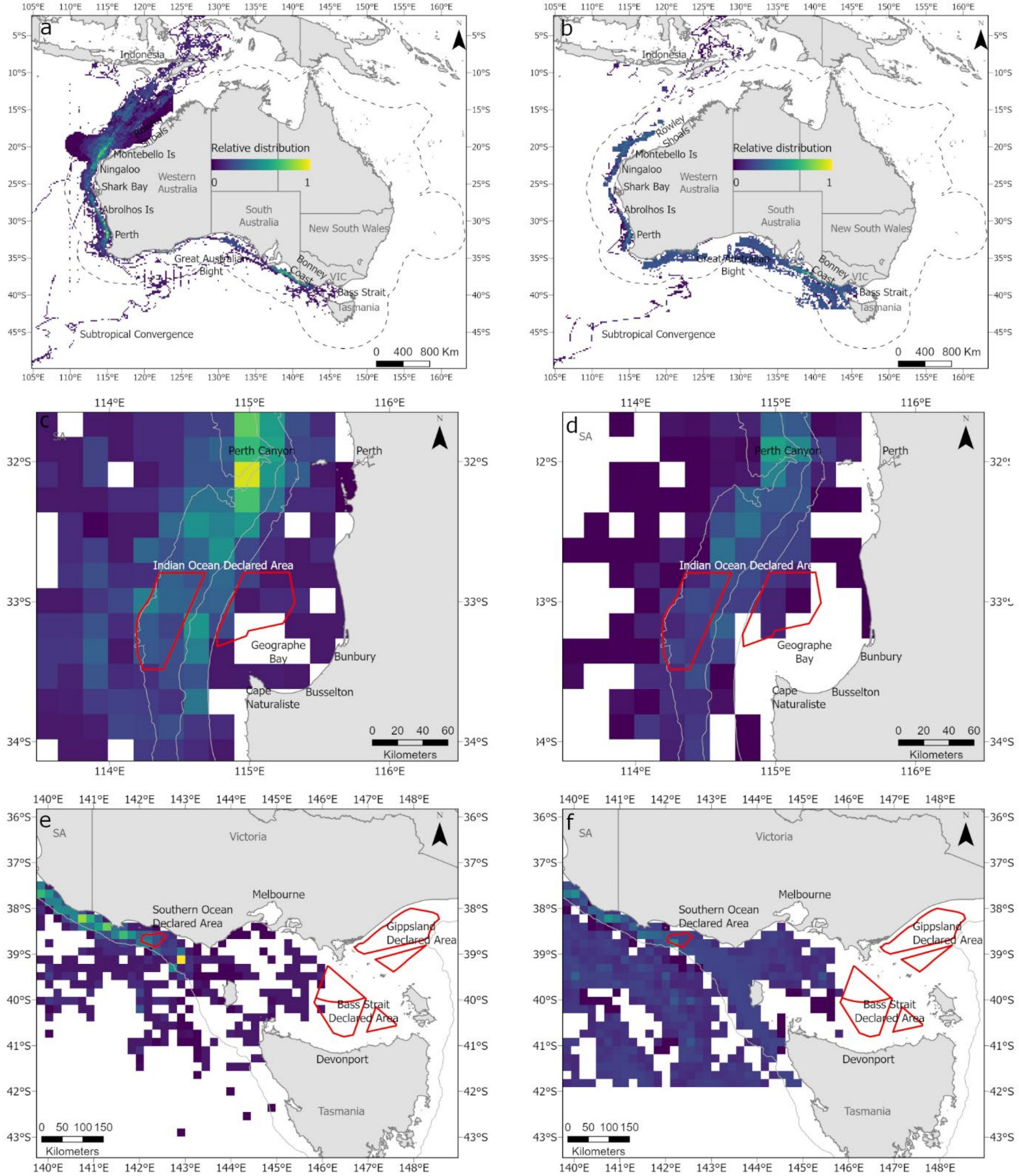

Figure 3 Relative pygmy blue whale combined distribution (a,c,e) and combined foraging distribution (b,d,f), showing the full extent of each distribution (a,b), and also zoomed to ORE Declared Areas in Western Australia (c,d) Victoria (Bonney Coast) and Bass Strait (e,f). Solid grey lines in b-f indicate the 100 m, 200 m and 1000 m bathymetric contours and dotted back lines in panels a and b indicate the Australian EEZ. Colour scale for relative distribution represents areas of higher (yellow), medium (green) and lower use (blue) within each the distribution.

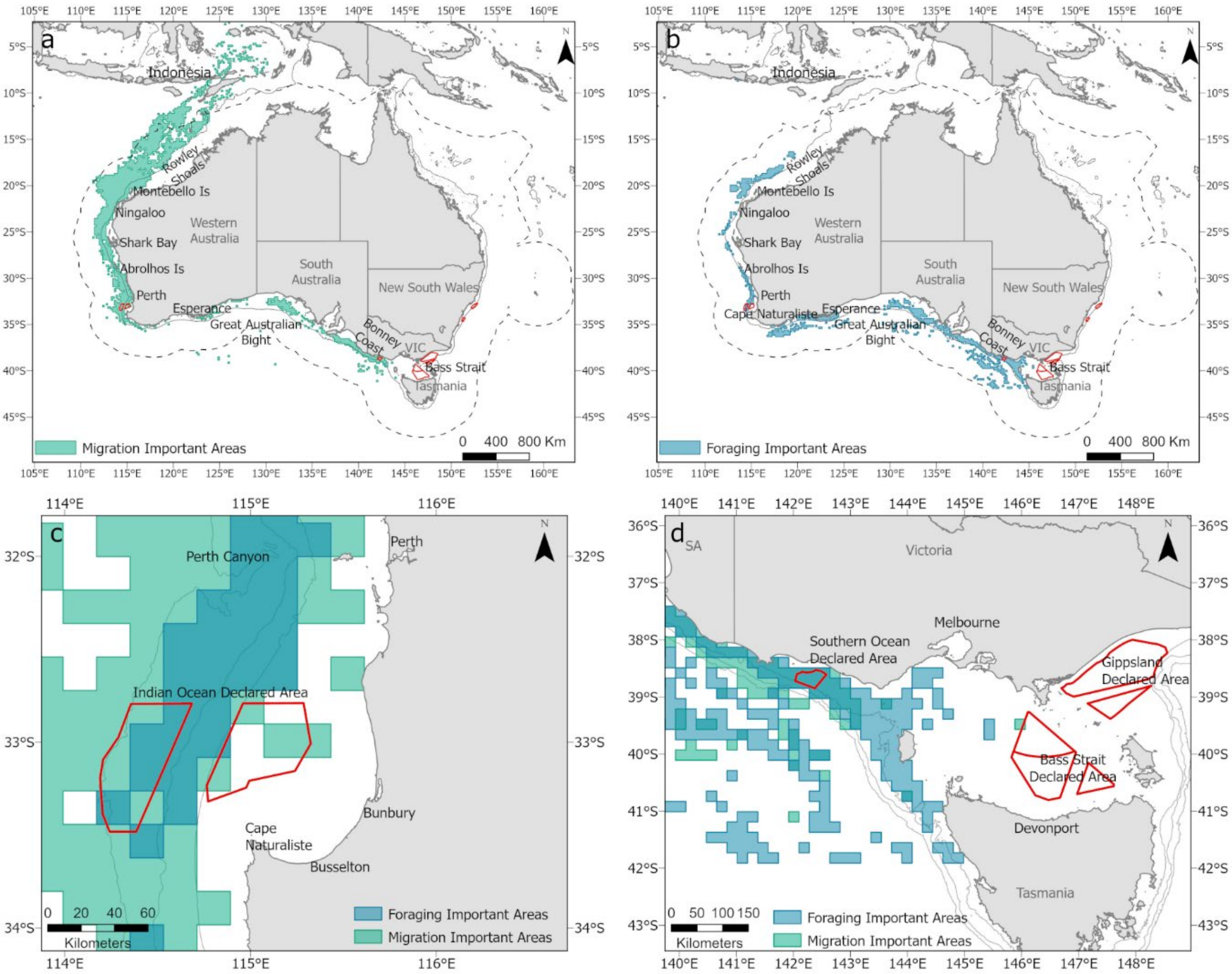

Figure 4 Important distribution/migration (a) and foraging (b) areas overlaid with ORE declared areas (red polygons), and most important areas zoomed to ORE declared areas in Western Australia (c), Victoria and Bass Strait (d). Dashed contour in a-b indicate the Australian EEZ. The light grey contours in panels a and b indicate the continental shelf extent and the grey contours in c and d represent the 100 m, 200 m and 1000 m bathymetric contours.

Although the Indian Ocean ORE Declared Area off Bunbury, WA overlapped with the combined pygmy blue whale distribution, the mean distribution value within that declared area was only 0.19 ± 0.11 (range of 0.06 – 0.4;Figure 3, Figure 5, Table A 4). In comparison, high use areas associated with Perth Canyon ~60 km to the north of the declared area showed values greater than 0.6 (Figure 3c-d). The pygmy blue whale foraging distribution within the Indian Ocean Declared Area had a mean value of 0.11 ± 0.08 (range of 0 – 0.2) (Figure 3, Figure 5, Table A 4). The pygmy blue whale distribution also overlapped with the Southern Ocean ORE Declared Area in Victoria with mean value of 0.26 ± 0.09 (range 0.2 – 0.4), and 0.24 ± 0.08 (0.2 – 0.5) for the foraging distribution (Figure 3, Figure 5, Table A 4). There was no overlap between the combined pygmy blue distribution and the Gippsland ORE Declared Area and those on the east coast of Australia (Figure 3e,f), and a minor overlap occurred between the full distribution (no overlap for foraging distribution) and the Bass Strait ORE Declared Area with mean value of 0.07 ± 0.04 (range 0 – 0.08) within this declared area (Figure 3, Figure 5, Table A 4).

Declared ORE areas showed some overlap with the most important distribution/migration and foraging areas (Figure 4, Table A 4). The Indian Ocean Declared Area had an overlap of 89% with the pygmy blue whale distribution, 86% with the foraging distribution, and 72.8% and 31% with important distribution/migration and foraging areas, respectively (Figure 3, Figure 4, Table A 4). The Southern Ocean Declared Area had 100% overlap with the pygmy blue whale combined distribution and foraging distribution and important areas (Figure 3, Figure 4, Table A 4), i.e. the entire declared area was encompassed within distributions. A minor overlap also occurred between the Bass Strait Declared area and the pygmy blue whale distribution and the important distribution/migration area (2.5% and 0.3%, respectively) (Figure 3, Figure 4, Table A 4).

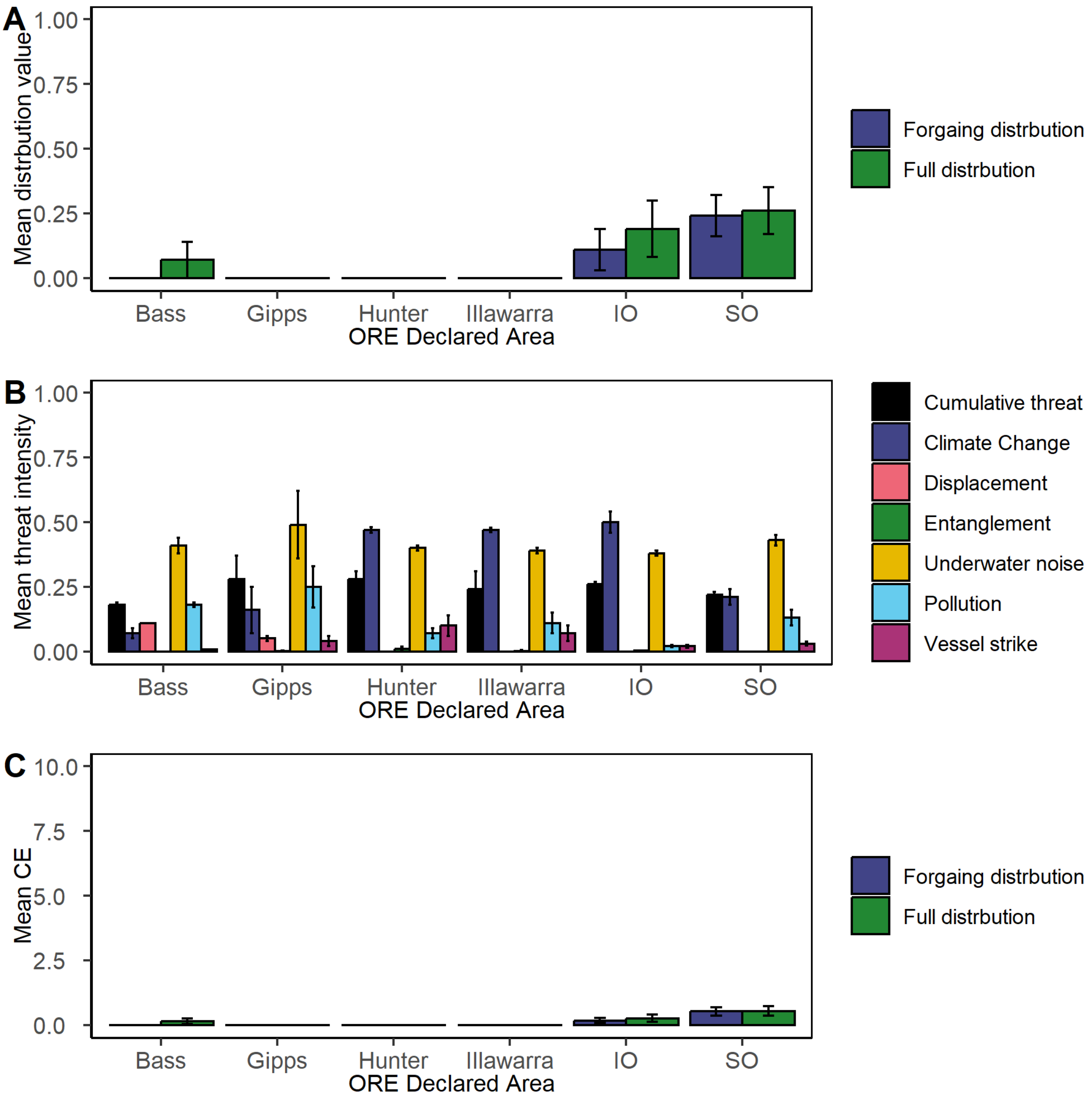

Figure 5. Mean values (±SD) of pygmy blue whale relative distribution (a), threat intensity (b) and cumulative threat exposure (CE) (c) within each ORE Declared Area. O = Indian Ocean, SO = Southern Ocean, Bass = Bass Strait, Gipps = Gippsland. Note that mean distribution value (a) and mean threat intensity (b) ranges from 0 to 1, whereas mean CE ranges from 0 to 10 (c).

3.2 Threats

The relative distribution of each threat considered in our analysis indicated clear regional patterns with defined areas of high intensity for most threats. The threat of shipping strike indicated clearly defined shipping corridors of highest intensity (> 0.5) along the coastline of Queensland, New South Wales, Victoria and Western Australia, and crossing offshore areas of the Great Australia Bight and northwestern and northern Australia (Figure 6a). The threat of ship strike overlapped with all declared ORE areas, encompassing 100% of each of these areas within the threat distribution (Figure 5, Figure 6, Table A 4). However, the average intensity of the threat of shipping strike was relatively low (≤ 0.1;Figure 5, Table A 4) within declared areas. The threat of underwater noise had moderate intensity (~0.3) across Australian waters, with highest intensity (> 0.7) in offshore areas off northwestern Western Australia and in the Bass Strait (Figure 5, Figure 6b, Table A 4). This threat also encompassed 100% of all declared ORE areas displaying the highest mean intensity values of all threats within declared areas (mean intensity ranged from 0.38 within Indian Ocean Declared Area to 0.49 in the Gippsland Declared Area; Figure 5, Table A 4).

The threat of pollution also showed clearly defined areas of highest intensity that were associated with regions known for exploration of offshore O&G in northwestern Western Australia and southeast Victoria and New South Wales (Figure 6c). Similarly, the threat of climate change was highest in these areas, but also in the Coral Sea off Queensland (Figure 6d). Both the pollution and climate change threats also encompassed 100% of all declared areas (Figure 5, Figure 6, Table A 4). Mean intensity within each declared area for pollution ranged from 0.02 (Indian Ocean Declared Area) to 0.25 (Gippsland Declared Area), and for climate change from 0.07 (Bass Strait Declared Area) to 0.5 (Indian Ocean Declared Area) (Figure 5, Table A 4).

The threats of displacement and entanglement had smaller spatial footprint than the other threats, with displacement being restricted to the northwest of Western Australia and Bass Strait (Figure 6e) and entanglement distributed as narrow clusters within the shelf and shelf edge with relatively low intensity (< 0.3; Figure 6f). The distribution of displacement did not overlap with the Indian Ocean, Southern Ocean, Illawarra and Hunter declared areas and had a small overlap of low intensity with the Bass Strait Declared Area (only one grid cell representing 0.5% of the area and with intensity of 0.11) (Figure 5, Figure 6e, Table A 4). This threat had moderate overlap with the Gippsland Declared Area (40.6%), although with low mean intensity (0.05 ± 0.11) (Figure 5, Figure 6e, Table A 4).

The distribution of the threat entanglement did not overlap with the Southern Ocean and Bass Declared areas with minimal overlap with the Indian Ocean Declared Area (1.6%, representing only one grid cell) and small overlap with the Gippsland Declared Area (13.1%) (Figure 5, Figure 6f, Table A 4). However, this threat had 100% overlap with teg Illawarra and Hunter declared areas. Mean intensity within each declared area was very low (≤ 0.01;Figure 5, Table A 4).

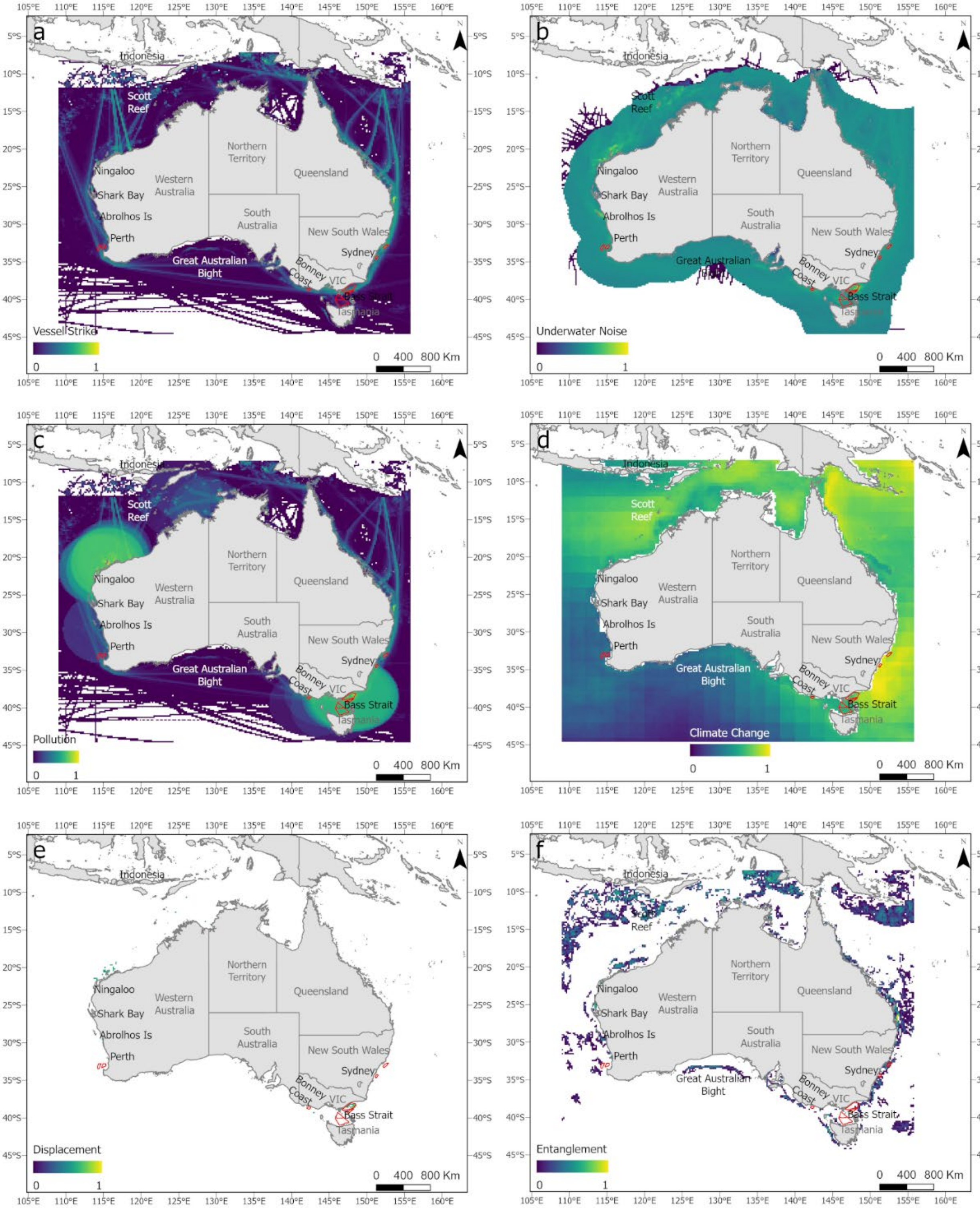

Figure 6 Relative distribution of anthropogenic threats including ship strike (a), underwater noise (b), pollution (c), entanglement (d), displacement (e) and climate change (f). Details of spatial layers and pressure associated with each threat are in Table 2.

The cumulative threat distribution encompassed the whole Australian EEZ with the highest intensity of cumulative threat occurring off northwest Australia (0.94), Brisbane/Queensland (1) and Gippsland/Bass Strait (0.67) (Figure 7a). All six threats overlapped in areas of high threat intensity off northern Western Australia and Gippsland/Bass Strait (Figure 7b). Overall, the Australian EEZ was characterized by low cumulative threat intensity (0.23 ± 0.07), though on average 4 ± 1 threats co-occurred within a grid cell. The cumulative threat distribution also encompassed 100% of each of the ORE declared areas (Table A 4, Figure 5, Figure 7). Four threats (pollution, underwater noise, climate change and vessel strike) occurred within the Indian Ocean Declared Area with a mean cumulative threat intensity of 0.26 ± 0.01 (range 0.23 – 0.28) (Figure 5, Figure 7c-d, Table A 4). Four threats (pollution, underwater noise, climate change and vessel strike) also co-occurred within the Southern Ocean and Bass Strait declared Areas (Figure 7e-f), with mean cumulative threat intensity of 0.22 ± 0.01 (range 0.21 – 0.24) and 0.18 ± 0.01 (range 0.16 – 0.24), respectively (Table A4). All threats (6) co-occurred within the Gippsland Declared Area with a mean cumulative threat intensity of 0.28 ± 0.09 (range 0.08 – 0.67) (Figure 5, Figure 7e-f, Table A4).

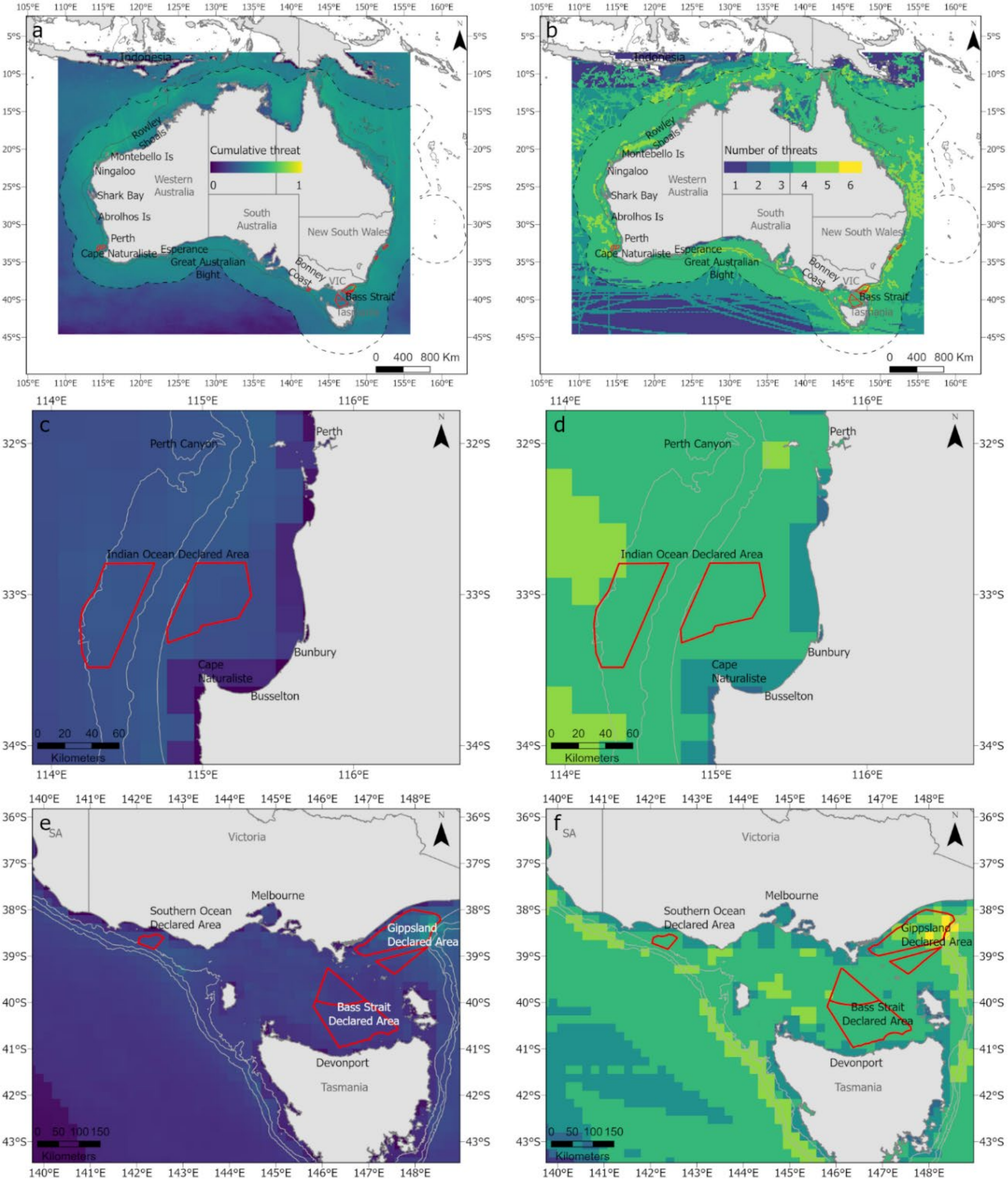

Figure 7 Relative distribution of cumulative threat intensity (a,c,e) and number of co-occurring threats within a grid cell (b,d,f), also zoomed to ORE Declared Areas in Western Australia (c-d) and in Victoria and Bass Strait (e-f). Dashed contour in a-b indicate the Australian EEZ. The light grey contours in panels a and b indicate the continental shelf extent and the grey contours in c and d represent the 100 m, 200 m and 1000 m bathymetric contours.

3.3 Expert elicitation

We received input from 12 experts (April to August 2025) (Table 3) out of the 25 that were invited (several experts expressed interest but couldn't meet before the report was finalised). For each question (Table A 3), we only considered the statistical distribution (to be included in the calculation of exposure) of experts that indicated sureness >50% regarding their input. Hence, the number of expert distributions for each pressure ranged between three for shipping and eight for underwater noise (see panels in Figure 8). The probability distributions from experts indicated high agreement, expert knowledge and confidence in expert input, however these varied among pressures (Figure 8). For example, experts had good agreement on the relatively low probability of vessel strike from fishing vessels (Figure 8b) and entanglement in fishing gear (Figure 8g), however only a small number of experts (N=3-4 experts) indicated high confidence in providing input for these pressures. Most experts agreed that chronic and acute underwater noise (N=8 experts for each) and prey availability (N=7 experts) have high probability of exposure (Figure 8e,f,j). For other pressures there was some overlap among experts with a small number of experts providing contrasting inputs. During the feedback sessions, most experts emphasised the low scores of confidence (< 50%) was a result of lack of empirical data on the actual interactions between pygmy blue whales and some of threats being considered with only anecdotal evidence informing their input their assessment. Thus, indicating low exert knowledge on the subject/question.

Table 3 Summary of area of profession, country and area of expertise for the twelve experts that participated in the elicitation process

	N experts
Profession	
Academic	8
Management	1
Consultancy/NGO	3
Country	
Australia	7
Indonesia	1
USA	3
Europe	1
Expertise	
Acoustics	2
Cetacean Ecology	6
Cetacean physiology	1
Animal tracking	2
Management	1

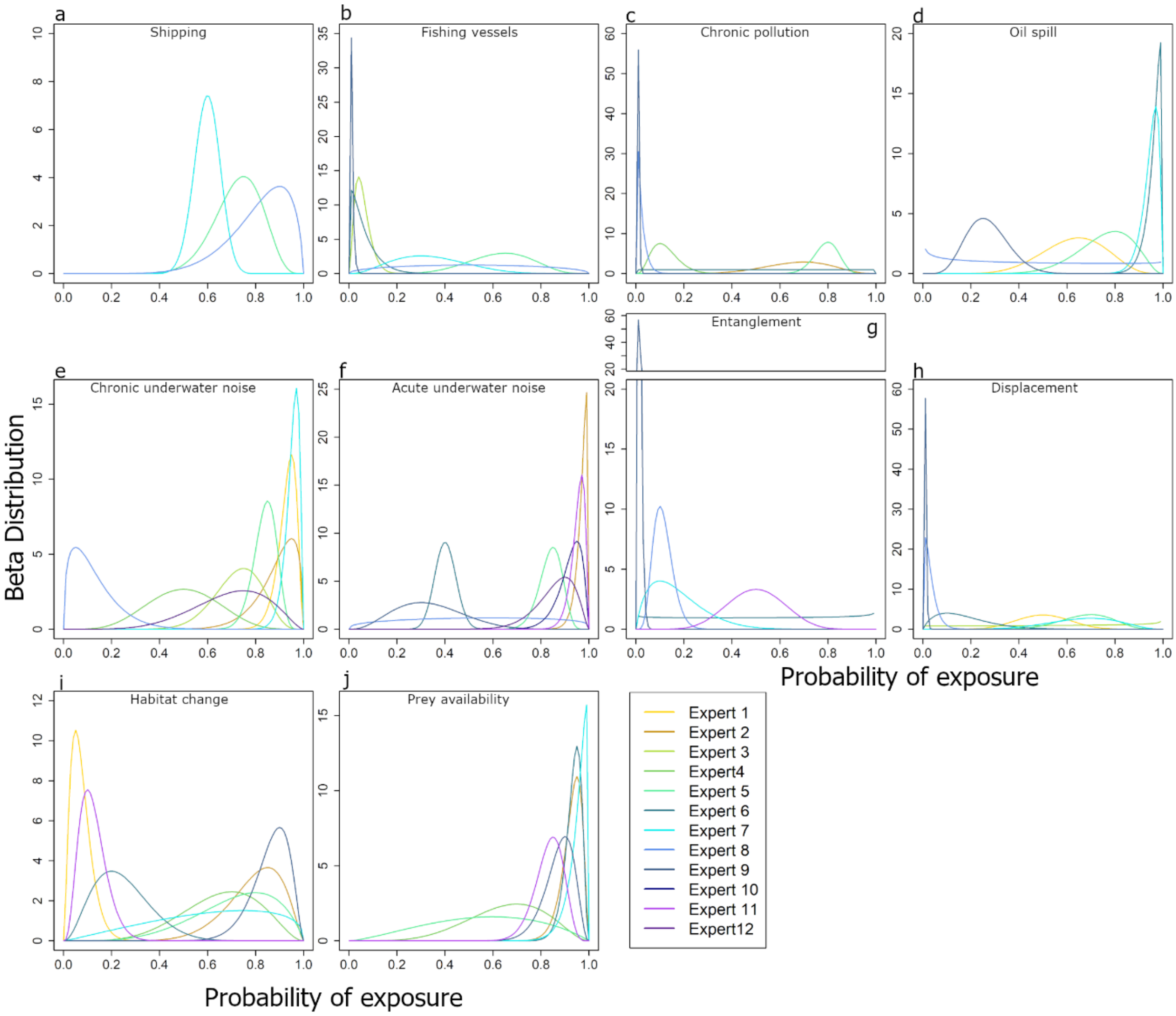

Figure 8 Beta distributions (based on the answers from each expert) of the probability of the exposure of pygmy blue whales to existing pressures overlapping with their distribution listed in Table 2: commercial shipping (a), fishing vessels (b), chronic pollution (c), oil spill (d), chronic underwater noise (e), seismic (f), entanglement in fishing gear (g), displacement (h), habitat change (i) and prey availability (j).

3.4 Cumulative threat exposure

The maximum cumulative threat exposure (*CE)* value within the full distribution of pygmy blue whales in Australia was 2.2 and the maximum value for the foraging distribution was 1.9 out of a potential maximum value of 10 (Figure 9). Maximum *CE* for the full distribution occurred in Victoria with *CE* of 0.8-2.2 occurring in the shelf waters off the Bonney Coast within the GSACUS and offshore waters off northwestern Western Australia (between Ningaloo and Montebello Islands) (Figure 9a). For the pygmy blue whale high use foraging areas off the Bonney Coast, Perth Canyon and northwest Western Australia, medium relative values (0.7-1.9) occurred (Figure 9b). The areas identified with higher relative *CE* also showed higher exposure to each individual threat (Figure A 3 and Figure A 4). Areas of the

Bonney Coast and Victoria had highest exposure in relation to underwater noise (Figure A 3a-b), vessel strike (Figure A 3e-f), and climate change (Figure A 4a-b). Perth Canyon had highest exposure to underwater noise (Figure A3a-b). The northwest of Western Australia had highest exposure to underwater noise and pollution (Figure A 3a-d) and displacement (Figure A 4e-f). Western Australia also had the highest exposure to entanglement near the Abrolhos Islands (Figure A 4c-d).

Cumulative threat exposure for the pygmy blue whale distribution overlapped with three out of the six ORE Declared Areas when considering the full distribution and with only two Declared Araes for the foraging distribution (Figure 9, Table A 4). Cumulative threat exposure within the Indian Ocean Declared Area ORE declared area was relatively low with a mean value of 0.26 ± 0.14 (out of a maximum of 10) and was moderate (0.54 ± 0.19 out of a maximum of 10) for the Southern Ocean Declared Area (Figure 5, Figure 9, Table A 4). The full pygmy blue whale distribution had minimal overlap with the Bass Strait ORE Declared Area with mean *CE* of 0.15 ± 0.11 (out of a maximum of 10; Figure 5, Figure 9, Table A 4). Similar to the full pygmy blue whale distribution, cumulative threat exposure to threats for the pygmy blue whale foraging distribution within ORE declared areas were low for the Indian Ocean Declared Area (mean *CE* of 0.17 ± 0.1 out of a maximum of 10) and moderate for the Southern Ocean Declared Area (0.52 ± 0.16 out of a maximum of 10) (Figure 5, Figure 9, Table A 4). No overlap occurred between the cumulative threat exposure for the foraging distribution of pygmy blue whale and the Bass Strait and Gippsland declared areas as the distribution did not extent to those areas (Figure 5, Figure 9b,d,f, Table A 4).

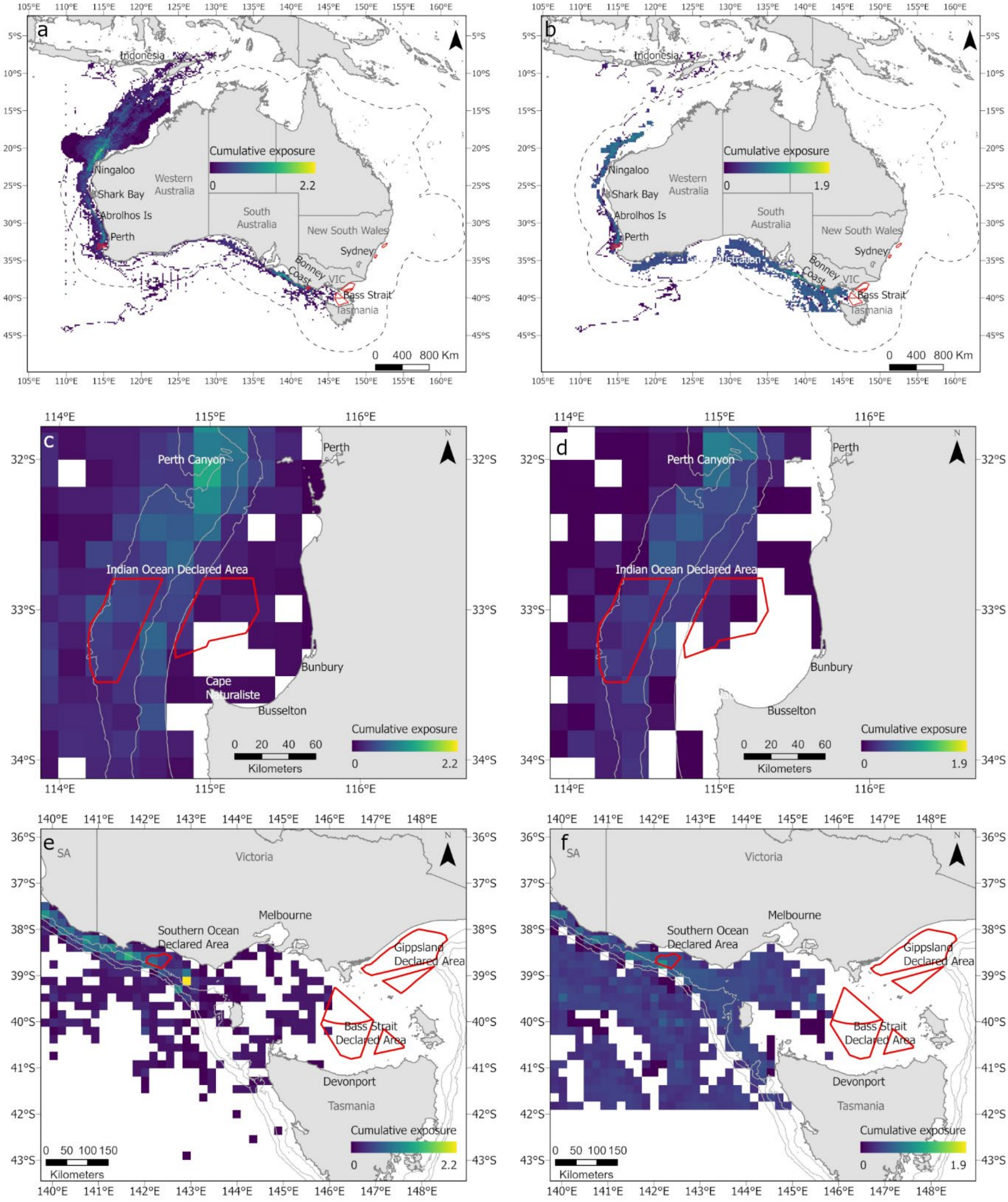

Figure 9 Cumulative threat exposure to pygmy blue whales for the full distribution (a,c,e) and foraging distribution (b,d,f) of pygmy blue whales, also zoomed to ORE Declared Areas in Western Australia (c-d) and in Victoria and Bass Strait (e-f). Dashed contour in a-b indicates the Australian EEZ. The light grey contours in panels a and b indicate the continental shelf extent and the grey contours in c-f represent the 100 m, 200 m and 1000 m bathymetric contours.

4. Discussion

In this study we assessed the exposure of pygmy blue whales to existing threats to inform offshore wind farm development. The results showed that the current level of exposure of pygmy blue whales to existing threats addressed here is relatively low (≤ 2 out of 10) within their distribution and lower within ORE declared areas (<0.5 out of 10) based on the available data. However, the Indian Ocean and Southern Ocean ORE areas overlapped with the important distribution/migration and important foraging areas and the overlap was as high as 100% for the Southern Ocean declared area and 72.8% and 31% for the Indian Ocean Declared Area for the most important distribution/migration and foraging areas respectively.

At least four of the six threats considered occurred within the declared areas, with the Gippsland Declared Area overlapping with all six threats and displaying the highest values of cumulative threat intensity (maximum of 0.67 and mean of 0.28 ± 0.09). However, the Gippsland Declared Area had no overlap with the Eastern Indian Ocean pygmy blue whale distribution and this was similar for the Bass Strait Declared Area (negligible overlap). Whether this is a result of data gaps or that this and other blue whale sub-species do not occur there is unclear.

Further data collection or analysis of existing datasets (that are not publicly available and therefore not included here) is required to determine their occurrence and use of these areas. This is important to understand as the Gippsland and Bass Strait regions could potentially experience an increase in the intensity and number of threats in the near future (2-10 years) due to the large number of decommissioning proposals planned for the region (https://www.nopsema.gov.au/offshore-industry/decommissioning) in addition to the development of ORE. Gaps in the pygmy blue whale spatial data may have also impacted our ability to adequately assess exposure of pygmy blue whales to existing threats in the Indian Ocean declared area. Below we discuss each of the components of the research in more detail.

4.1 Pygmy blue whale distribution

Satellite tracking data was used as the main source of information to define the full distribution and foraging distribution for pygmy blue whales in the eastern Indian Ocean. These updated distributions build on information published previously (Double et al. 2014, Möller et al. 2020, Thums et al. 2022) and highlighted areas of known high use in the GSACUS, southwest and northwest Western Australia. However, the number of tagged whales included in the analysis is still unlikely to be representative of the Eastern Indian Ocean population (Branch et al. 2007, McCauley et al. 2018), with inter-individual variability on routes, seasonality and foraging areas of preference being apparent in the data.

In an attempt to alleviate this problem, the spatial information available for pygmy blue whale distribution from satellite tracking was complemented by other sources of data including sightings (structured surveys, opportunistic sighting records, industry marine mammal observer data, historical whaling) and spatial predictions from species distribution models. However, most of the structured survey data was concentrated in southeast Australia where long-term aerial surveys have been carried out in relation to the foraging aggregation within the GSACUS (Gill 2002, Gill et al. 2011), with limited survey data for other regions. Hence, the low values within the sighting data distribution for the Perth Canyon is not representative of the importance of the area for pygmy blue whales (see McCauley et al. 2004, Rennie et al. 2009, Double et al. 2014, Garcia-Rojas et al. 2018, Jolliffe et al. 2019, Thums et al. 2022). Similarly, the only spatially explicit PAM data available was for the northwest of Western Australia (Thums et al. 2022).

Although PAM is a method used over larger areas, it's spatial data predominantly consists of point sources of noise loggers listening over variable ranges (dependent on numerous factors) (McCauley et al. 2000a, Gavrilov et al. 2018, Jolliffe et al. 2019, Jolliffe et al. 2021), and is largely not available in a format conducive to spatial analysis (i.e., a location with latitude and longitude associated with number of whales detected). Despite some biases in the spatial coverage and resolution of some of the complementary datasets, combining multiple sources and types of data allowed the expansion of the pygmy blue whale distribution (and foraging distribution) to areas beyond the Australian EEZ in the southwest and western regions of Australia. It also allowed the inclusion of very small areas in New South Wales, Bass Strait and Tasmania (small number of observations from freely available datasets), which are currently not covered by the satellite tracking dataset. However, caution must be taken as the few records that exist for pygmy blue whales in eastern Australia may represent a separate pygmy blue whale population (Southwest Pacific) (Barlow et al. 2018, Attard et al. 2024).

In contrast to some previous studies, we did not assign migration behaviour based on fast and directed movement and then develop the migration distribution from there (Moller et al. 2015, Thums et al. 2022, Ferreira et al. 2024). Instead, the full distribution was used as it is likely to provide a better representation of their migratory routes (and it ensured a larger dataset). This is because pygmy blue whales have been shown to feed during their migration and the classification of migratory *vs* foraging behaviour can be difficult for such short-term foraging (Thums et al. 2025). Hence, using full movement paths to define both their full distribution and migration distribution likely overcomes some of these issues. In addition, full distributions are presented for each month of the year to account for the temporal variations throughout their range.

The monthly distributions indicated a clear pattern within their distribution between feeding areas in temperate latitudes to tropical waters, as previously described (Double et al. 2014, Möller et al. 2020, Sahri et al. 2022, Thums et al. 2022, Ferreira et al. 2024). However, the temporal representation of the distribution showed here also highlighted the negligible tracking data available for pygmy blue whales during their southern migration (September to November) and showed that not all whales followed the expected seasonal movements for the species (e.g., one whale was present in the GSACUS in June/July when whales are expected to be off northwest Western Australia on their northern migration to the tropics).

The estimated foraging distribution provided support for the importance of known foraging grounds in Perth Canyon and GSACUS as shown by the multiple streams of data used, including satellite tracking (Double et al. 2014, Möller et al. 2020, Thums et al. 2022, Thums et al. 2025), aerial and boat surveys (Gill 2002, Rennie et al. 2009, Gill et al. 2011), passive acoustic (McCauley et al. 2000a, McCauley et al. 2004) and species distribution models (Thums et al. 2022, Ferreira et al. 2024). However, despite some whales moving towards the Subtropical Convergence Zone, there is a lack of information on their movement and distribution in that region, which has been shown to be a foraging aggregation area based on acoustic detections, boat surveys and limited satellite telemetry (tracks included in this study)

(Double et al. 2014, Garcia-Rojas et al. 2018), as well as from historical catches (Branch et al. 2007). Although this area is outside the Australia EEZ, its management and conservation has significant consequence for the Eastern Indian Ocean stock of pygmy blue whales that is listed under the EPBC Act and thus managed by the Commonwealth through a recovery plan (Commonwealth of Australia 2015).

We calculated a relative distribution of pygmy blue whales and used it to delineate the most important (based on use) area for foraging and the entire distribution/migration. We did the latter step to attempt to assist DCCEEW with the BIA process and to provide a similar output (polygon) to be used (by proponents, regulators, etc) while the pygmy blue whale BIA was under review. However, the relative distribution is far more useful than the simple polygon of important areas as it provides values of importance (low to high time spent or number of whales) across the species distribution. Using the Southern Ocean Declared area as an example, the overlap of this declared area with the most important foraging area was 100% (Figure 4d), which may be alarming, whereas when looking at the values of relative distribution of pygmy blue whales within the area of overlap (Figure 3b and f), it ranged from 0.2 – 0.5; i.e. low to moderate time spent by pygmy blue whales. This information tempers initial alarm as it shows that the Southern Ocean Declared Area does not overlap with the highest area of use (values of 0.6 – 1.0) by pygmy blue whales within the GSACUS, which is further to the northwest off the Bonney Coast (Figure 3b). Of course, for a Threatened species, this level of use by pygmy blue whales may still be concerning, but it highlights how more information can be extracted from a relative distribution over a simple polygon to assist proponents with siting their infrastructure to avoid impact to threatened species.

4.2 Threats

Most of the threats considered in the study were distributed throughout Australian waters (particularly underwater sound, pollution, vessel strike and climate change), with no area free from the presence of cumulative threats as seen in previous studies (Ferreira et al. 2023). Underwater noise and climate change were the most pervasive threat out of those considered here, with maximum mean intensity 0.49 to 0.50 (ranges from 0 (low) -1 (high)), respectively, within ORE declared areas (Table A 4). The Gippsland Declared Area had the highest intensity value for the threats of underwater noise and pollution (0.25) and cumulative threats (0.28, as did the Hunter Declared Area). Climate change threat was highest for the Indian Ocean Declared Area (0.5, Table A 4), and this was one of the two ORE Declared Areas that had high overlap with the pygmy blue whale distribution.

The Southern Ocean Declared Area was the other ORE Declared Area with high overlap with the pygmy blue whale distribution, which had low to moderate intensity values for three (out of six) threats; pollution (0.13), underwater noise (0.43), climate change (0.21). The mean cumulative threat intensity values for these two declared areas were 0.26 and 0.22 for the Indian Ocean and Southern Ocean Declared Areas respectively. It is important to note that there are likely other threats to pygmy blue whales that we were not able to include here because no spatial data exists for it at the scale of the pygmy blue whale's range (e.g. plastic pollution).

4.3 Expert Elicitation

The spatial overlap between species distributions and threats cannot be used to infer an actual interaction and/or effect (and vice-versa) from the overlap alone. Here, we overcame this by using an expert elicitation protocol to infer the probability of exposure given the overlap between pygmy blue whale distribution and each pressure. The expert elicitation approach was based on a method developed to facilitate a robust and repeatable process to obtain expert knowledge where empirical data is unavailable (Fisher et al. 2012). Although expert knowledge is now commonly used for conservation science, it is often criticised for its subjectivity and lack of measures of accuracy (Cooke 1991, Seoane et al. 2005, McBride et al. 2012). The approach used here highlighted the lack of expert knowledge (which is related to the measure of uncertainly and low confidence in the input from experts) on the potential probability of interactions when pygmy blue whales overlap with some of the pressures assessed as part of the study. The lack of empirical data was also indicated by the fact that some experts gave opposite inputs for some of the pressures, as their input relied on anecdotal information which may vary among expert's experience and study region (Table 4).

This issue was addressed by taking random samples within each of the expert distributions (that provided a sureness score >50%) and using 1000 samples from the combined distributions for each pressure in the calculation of exposure, allowing us to account for the variability in expert knowledge instead of simply using the expert's best guess. However, it is possible that the values of cumulative threat exposure presented here would significantly change, and potentially increase, if data (and therefore knowledge) on the actual impact and consequence of interactions between whales and human activities became available.

4.4 Cumulative threat exposure

The results based on our analysis of the available datasets suggest a relatively low overall cumulative threat exposure to existing threats for the full and foraging distributions of pygmy blue whales (2.2 from a potential maximum of 10). Within the ORE declared areas, this was even lower; 0.15 to 0.54 out of potential maximum of 10). This is somewhat encouraging in the context of the development of a major new offshore industry. The cumulative threat exposure reported here are the mean values calculated across each grid cell in the declared area. Ideally, proponents would choose to site their infrastructure in grid cells with the lowest cumulative threat exposure to pygmy blue whales to reduce impact to this threatened sub-species from the additional threats that their activities may contribute.

However, there are some biases in the spatial and temporal extents and resolution of the datasets collated in the study that warrant some caution in the interpretation of the cumulative threat exposure analysis. For example, acoustic and anecdotal data (not available for this study) indicate potential use by pygmy blue whales off the southwest Western Australia region (near the Indian Ocean declared Area) during their southern migration (see Recalde-Salas et al. 2014) and for Bass Strait, where very few sighting records (P. Gill, Pers. comm.) and some acoustic data (McCauley et al. 2018) exist. The existing tracking data, however, did not show use of Bass Strait (with the exception of one whale on the western side of Bass Strait). Additionally, there is still limited data available for the southern migration (n=4 pygmy blue whales satellite tracks; Möller et al. 2020, Thums et al. 2022, Ferreira et al. 2024, Mustika et al. 2024) and for areas between southern Australia and southern Western Australia, with most of the recent tag deployments focusing on the Perth Canyon and northwest Western Australia (Thums et al. 2022, Thums et al. 2025). In addition, although ORE declared areas in Bass Strait and Gippsland had minimal or no overlap with the pygmy blue whale distributions we calculated, they may occur in the region. And other pygmy blue whale populations (e.g., Southwest Pacific that is hypothesised to migrate between New Zealand and Australia) and the Antarctic blue whale (McCauley et al. 2018) may also co-occur in those areas. However, little data on their movement and space use is available for all the subspecies in the region. Our calculation of the relative distribution of pygmy blue whales in the ORE declared areas and in southeast Australia in general is based on the available data. If more data from these areas became available or was collected that showed pygmy blue whale use of these areas, then the cumulative threat exposure would change.

Here, cumulative threat exposure accounted for the spatial overlap between pygmy blue whales and threats, but not the temporal overlap between species and human activities. This is because there is still limited data available to map and predict the distribution of pygmy blue whales at monthly temporal scales (Ferreira et al. 2024). Hence, the results of the analysis presented should not be considered as final or static, as they are likely to change with time and across space and when additional spatial data on pygmy blue whales is available.

4.5 Management implications

The spatial data produced here on the distribution of pygmy blue whales, important areas, and the threat distribution and cumulative threat exposure is freely available through Seamap (https://seamapaustralia.org/). Government and proponents can use the spatial outputs to assist decision making regarding the development of the ORE industry. Specifically, the pygmy blue whale distribution maps and spatial data (Figure 3) we provide here have already been provided to the Threatened and Migratory species section of DCCEEW to inform the review of the Biologically Important Areas (BIAs). These data can also assist in informing DCCEEW (Migratory Species and Renewables Regulatory Practice) on their assessment of the potential risks of ORE projects to the recovery of the pygmy blue whale population by allowing them to assess the presence (and intensity of use) of pygmy blue whales in ORE declared areas. In addition, our outputs are provided at the range of the pygmy blue whale, allowing for the consideration of our assessment of existing threats in ORE declared areas alongside the regional context of the species distribution (i.e., proximity to high use areas). Similarly, maps of existing threats (Figure 6 and 7) and cumulative threat exposure (Figure 9) can inform industry and regulators (NOPSEMA) during ecological risk assessment of proposed ORE activities and trigger potential management and mitigation for any added pressure and threat to the species from proposed activities.

Although the ORE industry is not expected to mitigate existing threats from other marine industries and activities, it is important that the baseline level of threats within those areas (Table A 4) is considered by the proponent when planning their feasibility license and ecological risk assessment, and by regulators (NOPSEMA) when assessing proposals. Considering that the ORE industry will likely add to the existing threats assessed and mapped here, we recommend that ORE projects consider avoiding areas with high intensity of existing threats and especially areas of higher relative use by pygmy blue whales. Further, they should use our outputs (e.g. pygmy blue whale temporal distribution; Figure 2) to restrict threatening activities to times of the year when pygmy blue whales are not present.

Our analysis also allowed us to identify key data gaps for pygmy blue whales in Australia:

1. The near lack of spatial data during the southern migration (n=4 satellite tracks available for this study), impacting component 1.
2. Regional spatial data gaps on pygmy blue whale occurrence and use (including southwestern Western Australia, the Great Australian Bight, Bass Strait and the Subtropical Convergence), impacting components 1 and 4.
3. Limited data to determine robust temporal patterns within the species range, impacting component 1
4. The lack of empirical data at the spatial scale of use of pygmy blue whales to inform the effect, impact and consequence of the exposure to anthropogenic pressures and threats, impacting components 3 and 4.

The limitations and data/knowledge gaps we have outlined support the need for continued collection of spatial data on pygmy blue whales to ensure the sustainable development of the offshore renewable industry in Australia in relation to this (and other) blue whale sub-species. The main research needs for pygmy blue whales in Australia are outlined below.

1. Continued and increased collection and sharing of spatial data (satellite telemetry and/or structured surveys) at local (within ORE Declared Areas) and regional spatial, and temporal scales (southern migration), including other populations and subspecies.
2. Increase in behavioural and ecological studies of the subspecies to inform risk assessment in relation to potential effects of exposure to threats.
3. Incorporation of existing PAM data into spatial datasets to assist filling data gaps. This would involve additional analysis of PAM data not often available or conducted and require collaboration between PAM experts and spatial ecologists.
4. Collection of pygmy blue whale movement data on the southern migration by deploying telemetry devices in Indonesia or Timor Leste in October/November. Note that such deployments will only last a few months at most, so this would only likely fill data gaps in Western Australia, but there are few sites to access the whales on their southern migration.

5. Conclusion

Our objective to assess the exposure of pygmy blue whales to existing threats to inform offshore wind farm development was satisfied through delivery of four complimentary components:1) Compile spatial data to quantify the full and foraging relative distributions of pygmy blue whales in Australia, 2) Quantify the distribution and intensity of existing threats and spatial overlap with the relative distributions of pygmy blue whales, 3) Use expert elicitation to assess the probability that the spatial overlap between whales and pressures would result in exposure to a threat and 4) Integrating components 1, 2 and 3 to quantify and map the cumulative threat exposure of pygmy blue whales to existing threats across their distribution and in relation to ORE declared areas.

For component 1, we show that three out of the six declared ORE areas overlap the pygmy blue whale distribution; Indian Ocean, Southern Ocean and Bass Strait Declared areas, however, there was only negligible overlap for the latter declared area. It is unclear whether the negligible overlap with the Bass Strait declared area is due to data paucity or lack of occurrence in this area. While high overlap occurred with the most important areas (similar to BIAs) we delineated for Indian and Southern Ocean ORE Declared areas, the relative use by pygmy blue whales across these declared areas was low to moderate. This low to moderate use for the Indian Ocean ORE area may have also been impacted by data paucity in this area.

For component 2, we show that for the two ORE Declared Areas that had high overlap with the pygmy blue whale distribution; Indian and Southern Ocean Declared Areas, four (out of six) threats co-occurred (pollution, underwater noise, climate change and vessel strike) but there was only low mean cumulative threat intensity of 0.26 and 0.22 respectively (out of a maximum possible score of 1). The Gippsland Declared Area encompassed areas of highest cumulative threat intensity (maximum of 0.67, although mean value was 0.28) and although our analysis suggests the Eastern Indian Ocean pygmy blue whale does not occur here, other pygmy blue whale populations and/or blue whale sub species may. Despite the apparent low intensity of existing threats within declared areas, it is worth noting that we have only been able to map threats for which spatial layers exist.

For component 3, the experts largely considered that pygmy blue whales had high probability of being exposed to chronic and acute underwater noise and reduced foraging success across their range due to climate change. Although there was large variation in the individual expert opinion for some pressures, our protocol of creating a probability distribution for each expert and pressure, and sampling those to inform the calculation of cumulative threat exposure, accounted for this variation and our approach also explicitly accounted for expert knowledge and confidence.

For component 4 we show that the cumulative threat exposure of pygmy blue whales to existing threats across their range (*CE* score of ~2 out of a maximum value of 10) and in ORE Declared Areas that overlap the pygmy blue whale distribution (*CE* <1 out of 10) is low. The limitations noted at the other points are also relevant here along with others outlined in the discussion.

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Appendix A

1. Supplementary Tables

Table A 1. Definition of terminology

Terminology	Definition
Pressure	Spatial layer related to an activity or infrastructure that is associated with one or multiple threats (for example: shipping)
Threat	Threat is a stressor, action or event that causes harmful effects that may impact the environment and species (strike, underwater noise, chemical pollution). A pressure may be associated with multiple threats (for example: shipping is associated with strike, underwater noise and pollution)
Effects	The degree to which a species is susceptible to harm from exposure to a pressure or threat.
Normalised distribution	Transforming the raw values of the distribution intensity to between 0 (minimal values) and 1 (maximum values) for comparison among different metrics and to allow for different distributions to be combined.
Cumulative threat	Account for the cumulative effect of multiple threats co-occurring in space and time
Cumulative impact	The effects of a threat to an individual, taxa and/or population (strike = injury, death; noise: behavioural changes; chemical pollution= health condition), accounting for the cumulative effect of multiple threats co-occurring in space and time
Risk	Risks are the likelihood × the consequence of the impact but taking mitigation into consideration. As proponents for ORE development have yet to do their impact assessment process to provide information on mitigations, we cannot include risk in this analysis, but it could be added in a later stage.
Important areas	Area within distribution with highest values encompassing the top 50% (foraging) and 75% (overall distribution) of the cumulative frequency distribution. Akin to the 50% and 75% utilisation distribution (UD) as the minimum area in which the animal has 50%, or 75%, probability of being found.
Habitat suitability	Predicted suitable habitat derived from modelling the relationship between environmental data and whale presence (probability of occurrence).

Table A 2 List of spatial layers used to map pressures including type of data, metric used in the mapping, threats and pressures associated with each spatial layer and source of data.

Spatial layers	Type of data	Metric	Pressure	Threats	Source
Commercial shipping	AIS ship data for 2023	Number of ship locations in a grid cell	• Commercial ships • Chronic pollution	• Ship strike • Pollution	Australian Maritime Safety Authority (AMSA)
Fisheries	Gridded fishing hours	Total fishing hours in grid cell	• Fishing vessels • Chronic underwater noise • Fishing gear	• Ship strike • Pollution • Entanglement	Global Fishing Watch
O&G platforms	Point location	2 km and 5 km buffers	• Chronic underwater noise • Chronic pollution	• Underwater noise • Pollution	National Offshore Petroleum Information Management System (NOPIMS) NOPSIMS
		20 km and 500 km buffers	• Oil spill	• Pollution	
		2 km and 5 km buffers (Decommissioning)	• Chronic underwater noise	• Underwater Noise	
		2 km buffer	• Infrastructure at sea	• Displacement	
O&G wells	Point location	20 km and 500 km buffers	• Oil spill	• Pollution	

Spatial layers	Type of data	Metric	Pressure	Threats	Source
		2 km and 5 km buffers (Decommissioning)	• Chronic underwater noise	• Underwater Noise	
O&G pipelines	Line location	20 km and 500 km buffers	• Oil spill	• Pollution	
		2 km and 5 km buffers (Decommissioning)	• Chronic underwater noise	• Underwater noise	
Seismic	2D survey lines and 3D survey extent polygons	Number of surveys in a grid cell	• Seismic	• Underwater noise	
Shipping noise model	Model prediction	Cumulative noise from shipping vessels	• Chronic underwater noise	• Underwater noise	Erbe et al. 2021
Sea surface temperature	10-y average SST variation against baseline	SST anomaly	• Habitat change • Prey availability	• Climate change	NOAA GISS Surface Temperature Analysis
Ocean PH	Global trend of surface ocean PH	PH trend	• Prey availability	• Climate change	Copernicus Marine Ocean Monitoring Indicator (OMI)

Table A 3 List of questions asked to each expert during elicitation process following protocol developed by Fisher et al. 2012

Probability of occurring interaction
1. Given that areas that pygmy blue whales use overlap with cargo ships, what is the probability of a ship strike occurring?
2. Given that areas that pygmy blue whales use overlap with fishing vessels, what is the probability of a vessel strike occurring?
3. Given that areas that pygmy blue whales use overlap with O&G exploration, production and shipping activity, what is the probability of whales being exposed to chronic pollution (low concentration)?
4. Given that areas that pygmy blue whales use overlap with O&G exploration and production, what is the probability of whales being exposed to an oil spill?
5. Given that areas that pygmy blue whales use overlap with O&G exploration and production and shipping, what is the probability of whales being exposed to chronic underwater noise pollution (lower/medium levels)?
6. Given that areas that pygmy blue whales use overlap with O&G exploration and production, what is the probability of whales being exposed to acute underwater noise pollution (e.g. high underwater noise levels)?
7. Given that areas that pygmy blue whales use overlap with fishing activity, what is the probability that entanglement with fishing gear will occur
8. Given that areas that pygmy blue whales use overlap with areas with O&G exploration and aquaculture where infrastructure can act as a barrier to their movement and habitat use, what is the probability of these to displace whales from their 'normal' activity?
9. Given that areas that pygmy blue whale whales use overlap with areas where ocean PH and temperature are changing, and that these are associated with physiological niche, what is the probability of change in their distribution?
10. Given that areas that pygmy blue whales use overlap with areas where ocean PH and temperature are changing, and that these are associated in prey (plankton) availability, what is the probability of reduced foraging success?

Table A 4 Overlap (%) between each ORE declared area and the distribution of pygmy blue whales (full and foraging and most important areas; Figure 3 and 4), threats (Figure 5 and 6) and cumulative exposure (Figure 8), and mean (± standard deviation) intensity/use value of each distribution (species distribution = use, individual threats and cumulative threats = intensity) within each declared area. Overlap is given as a percentage of the total area of the declared area encompassed within each distribution. Pygmy blue whale distribution and threat distribution values range between 0 and 1, whereas cumulative threat exposure ranges between 0 and 10. Mean intensity (threats)/use (species distribution) is calculated across all cell values of each normalised distribution (values range between 0 and 1) within each ORE declared area.

	Overlap (%)						Mean intensity (threats)/use (whales)					
	Indian Ocean	Southern Ocean	Bass Strait	Gippsland	Illawarra	Hunter	Indian Ocean	Southern Ocean	Bass Strait	Gippsland	Illawarra	Hunter
Pygmy blue whale												
Full relative distribution	89.0	100	2.5	0	0	0	0.19 ±0.11	0.26 ±0.09	0.07 ±0.04	-	-	-
Foraging relative distribution	86.0	100	0	0	0	0	0.11 ±0.08	0.24 ±0.08	-	-	-	-
Most important distribution/ migration area	72.8	100	0.3	0	0	0	-	-	-	-	-	-
Most important foraging area	31	100	0	0	0	0	-	-	-	-	-	-
Threats												
Vessel strike	100	100	100	100	100	100	0.02 ±0.006	0.03 ±0.007	0.007 ±0.01	0.04 ±0.02	0.07 ±0.03	0.10 ±0.04
Underwater noise	100	100	100	100	100	100	0.38 ±0.01	0.43 ±0.02	0.41 ±0.03	0.49 ±0.13	0.39 ±0.01	0.40 ±0.01
Pollution	100	100	100	100	100	100	0.02 ±0.004	0.13 ±0.03	0.18 ±0.008	0.25 ±0.08	0.11 ±0.04	0.07 ±0.02
Climate change	100	100	100	100	100	100	0.50 ±0.04	0.21 ±0.03	0.07 ±0.02	0.16 ±0.09	0.47 ±0.008	0.47 ±0.01
Displacement	0	0	0.5	40.6	0	0	0	0	0.11*	0.05 ±0.01	-	-

	Overlap (%)						Mean intensity (threats)/use (whales)					
	Indian Ocean	Southern Ocean	Bass Strait	Gippsland	Illawarra	Hunter	Indian Ocean	Southern Ocean	Bass Strait	Gippsland	Illawarra	Hunter
Entanglement	1.6	0	0	13.1	100	100	0.003*	0	0	0.0008 ±0.003	0.002 ±0.003	0.01 ±0.009
Cumulative threats	100	100	100	100	100	100	0.26 ±0.01	0.22 ±0.01	0.18 ±0.01	0.28 ±0.09	0.24 ±0.07	0.28 ±0.03
Cumulative threat exposure												
Full relative distribution	89.0	100	2.5	0	0	0	0.26 ±0.14	0.54 ±0.19	0.15 ±0.11	-	-	-
Foraging relative distribution	86.0	100	0	0	0	0	0.17 ±0.1	0.52 ±0.16	-	-	-	-

* *Only one grid cell of overlap thus mean was not calculated.*

2. Supplementary Figures

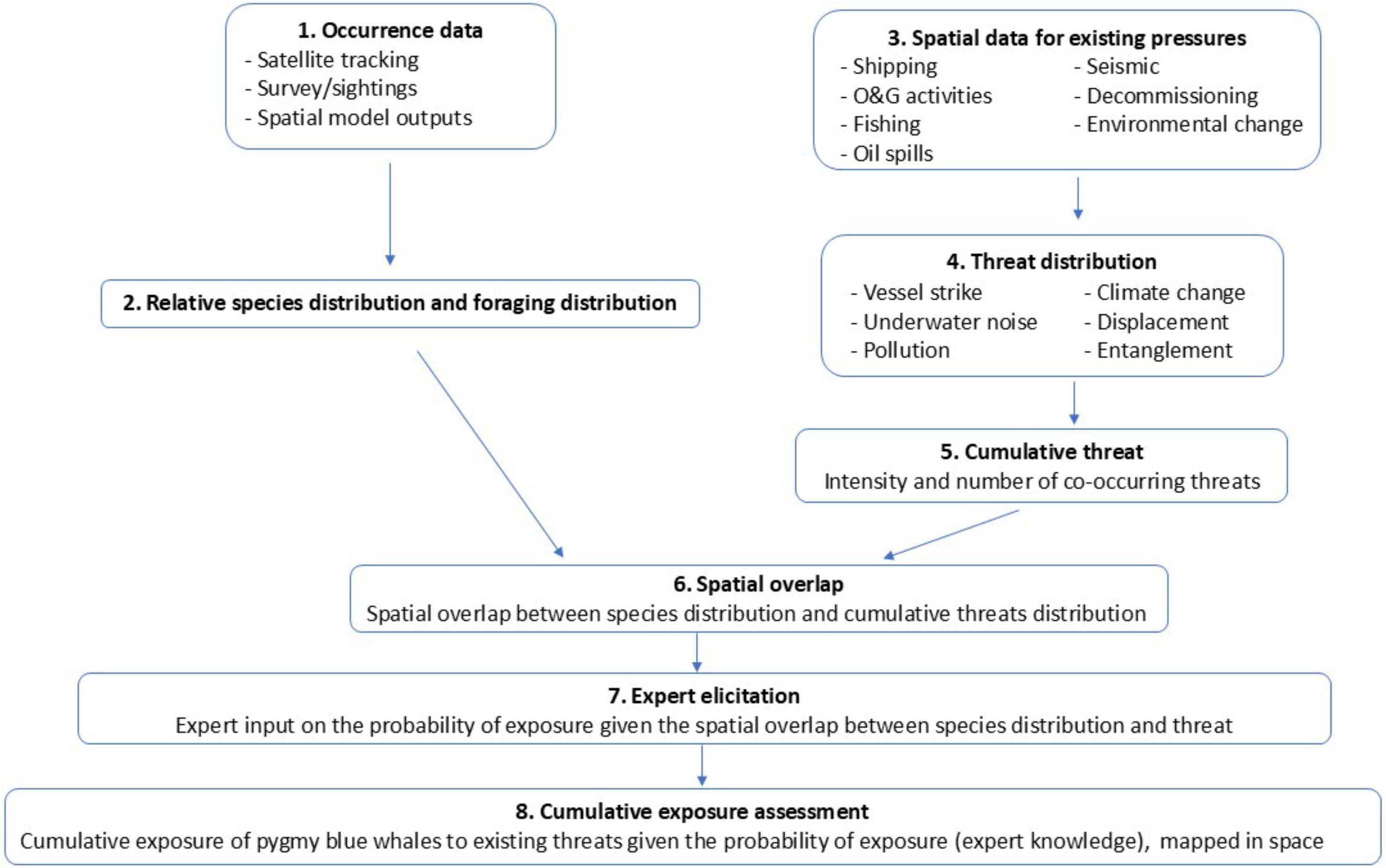

Figure A 1 Workflow for the cumulative threat exposure assessment framework used in the study

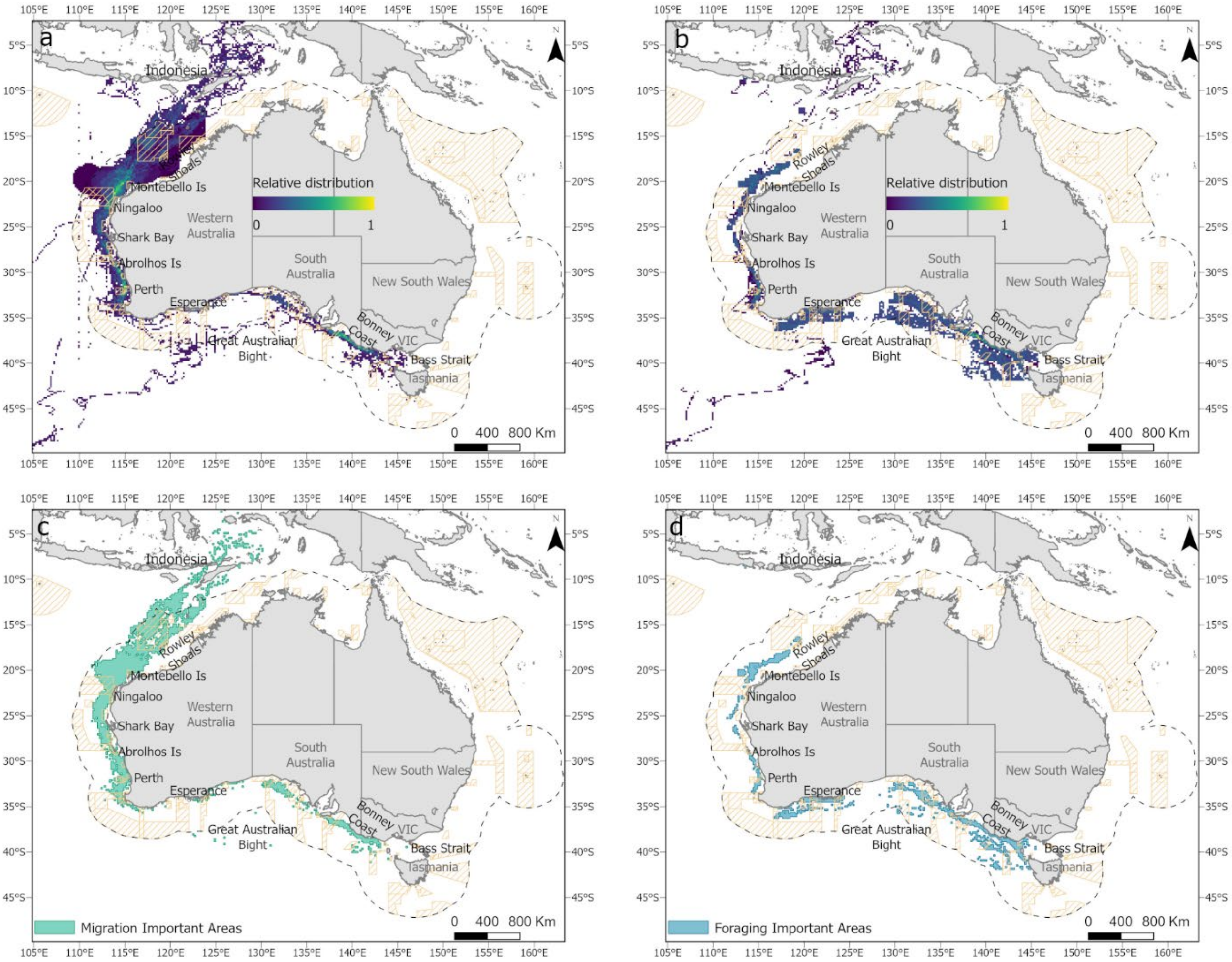

Figure A 2 Combined full relative distribution (a), combined foraging relative distribution (b), distribution/migration most important areas (c) and foraging most important areas (d) of pygmy blue whales overlaid with Australian Marine Parks (hatched orange polygons) within the Australian EEZ (dashed line).

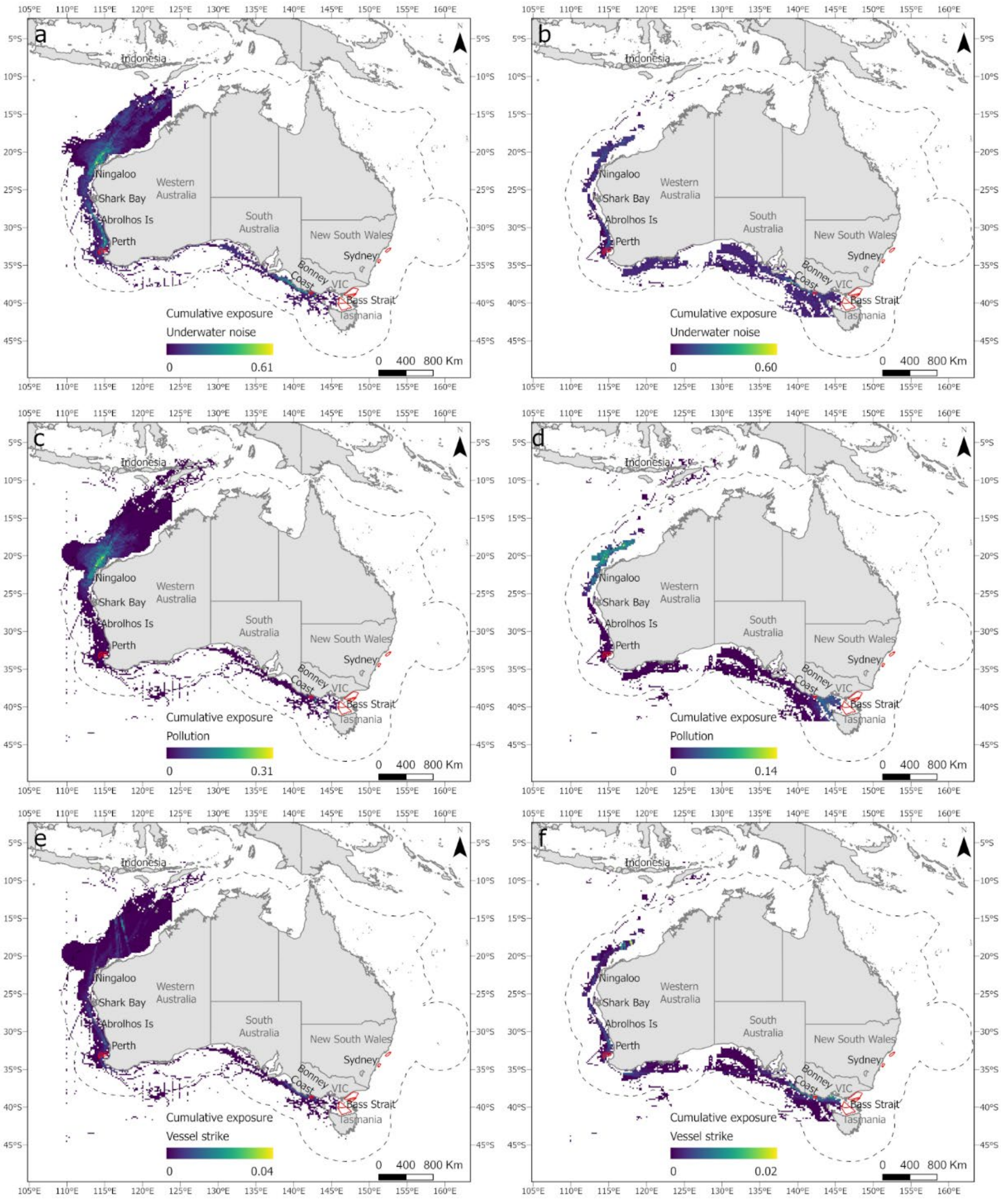

Figure A 3 Threat exposure for the full (a,c,e) and foraging (b,d,f) distribution of pygmy blue whales in relation to individual threats: underwater noise (a-b), pollution (c-d), ship strike (e-f). Dashed line indicates Australia EEZ, light grey contour indicates continental shelf, and red polygons are Declared Areas for ORE. Details of spatial layers and pressures associated with each threat are in Table 2.

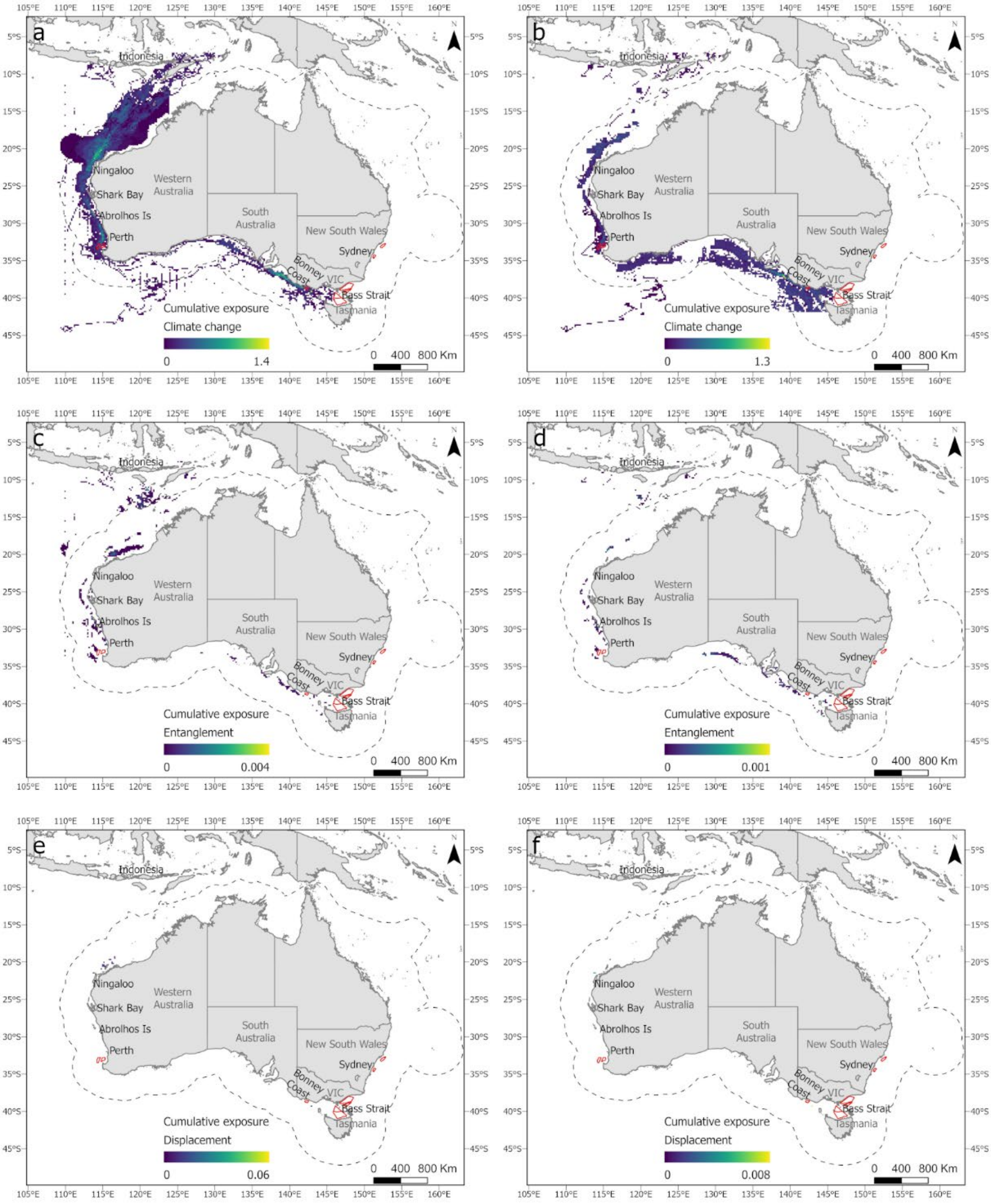

Figure A 4 Threat exposure for the full (a,c,e) and foraging (b,d,f) distribution of pygmy blue whales in relation to individual threats: climate change (a-b), entanglement (c-d), displacement (e-f). Dashed line indicates Australia EEZ, light grey contour indicates continental shelf, and red polygons are Declared Areas for ORE. Details of spatial layers and pressures associated with each threat are in Table 2.

CONTACT

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