National Environmental Science Programme

Characterising anthropogenic underwater noise to improve understanding and management of acoustic impacts to marine wildlife

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Important Disclaimer

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EXECUTIVE SUMMARY

In modern times there has been significant global increases in anthropogenic underwater noise from a range of sources, such as commercial shipping, oil and gas exploration, recreational and military sound sources. There has been growing concern regarding the impact of anthropogenic noise on the marine environment and vulnerable marine species.

This project examines the noise contribution of vessel traffic to the main Australian Exclusive Economic Zone (EEZ).

The main deliverables arising from the project are:

- Typical noise map of the main Australian EEZ for larger or commercial vessels (April – September) available online[1]. Map also provided to NESP Marine Biodiversity Hub project SS2 – *'Interpreting pressure profiles'*
- A finer scale noise study of the Southern Great Barrier Reef Marine Park[1]
- A study of vessel noise in high conservation areas
- The initial development of a shipping noise signature database
- Acoustic Zoning of Australia to aid in future Australian acoustic modelling[1]
- A wind noise map for the main Australian EEZ[1]
- Small vessel studies to help quantify small vessel noise
- 3 published papers, 4 in review/prep and 1 technical report
- A virtual stakeholder workshop held October 2020
- Special topic e-book Research Topic 'Impacts of shipping on marine fauna' for the journal Frontiers in Marine Science, Marine Conservation and Sustainability

Two examples of the use of noise mapping for management are given:

- Quantification of ship noise exposure on Matters of National Environmental Significance (MNES) with a case study of East Australian humpback whales in the Great Barrier Reef
- Ship noise in high conservation areas, with Beagle Marine Park as an example.

Overall, our main findings were:

- It is feasible to use the quantitative approach to derive a large-scale noise map that allows shipping noise, as a pressure, to be better integrated into marine spatial management. (For example, Beagle Marine Park).

[1] Data available online. See Appendix C

- When relying on opportunistic recordings of ships for the purpose of building a database of ship sound signatures, conforming to the ISO standard will be very difficult within Australian waters due to the sparsity of isolated vessels at the required water depths. To comply with ISO, vessels would have to deliberately detour into deeper water and move past hydrophones at a predetermined distance.
- It is possible to derive acoustic zones for the Australian EEZ that allow for the efficient computation over large spatial scales making the sound propagation computation feasible.
- That wind is a significant contributor of noise to background noise levels in the Australian EEZ. However, there are still areas of Australian EEZ where cumulative vessel noise is greater than the cumulative wind noise, including the North-West of Western Australia, the eastern seaboard of Victoria and New South Wales and the waters of the Great Barrier Reef off Queensland and Coral Sea.
- The case study of East Australian humpback whales in the Great Barrier Reef demonstrated the usefulness of the noise models to investigate noise exposure levels on a particular species of interest. Fine-scale noise modelling enabled significantly better assessment of noise impacts to species of interest by avoiding the averaging over larger grid cells and accompanying uncertainty in received levels at specific animal locations.
- For small vessels (e.g. non-AIS equipped recreational vessels), vessels within a given size class and design type were found to display significant differences in estimated source levels. Indeed, the same vessel recorded travelling at the same speed can display significant variability, depending on the operating conditions. Estimated source levels displayed positive, non-linear relationships with speed that differed among the tested vessels. This relationship is therefore potentially vessel-specific and to quantify it requires that measures be taken at a wide range of speeds.
- Under specific conditions (e.g., spatially restricted areas such as channels, speed restrictions), Passive Acoustic Monitoring can provide useful estimates of small-vessel numbers in shallow water and assist in validating modelled exposure levels experienced by marine fauna. However, confidence in these estimates is limited when multiple boats are present at the same time or where vessel behaviours vary significantly (e.g., changes in speed or direction).
- To integrate additional anthropogenic noise sources into a cumulative framework we recommend first incorporating comparable sound sources (e.g. the chronic noise sources together and similar pulsed sources together) and then considering the main different noise types separately in a more general risk assessment framework (e.g. NESP Marine Biodiversity Hub project SS2).

1. INTRODUCTION

There have been significant global increases in anthropogenic underwater noise over the past century from a range of sources, such as commercial shipping, oil and gas exploration, recreational and military sound sources. An increasing body of research over the past few decades has demonstrated anthropogenic noise can impact marine animals (Popper & Hawkins 2016). Many marine animals, and especially marine mammals, rely on sound for short and long-range communication (e.g., to coordinate group behaviour or in support of mating behaviour), foraging (i.e., by listening to the sounds of prey or using biosonar to find prey), and navigation (i.e., passive listening to the environment or biosonar) (Erbe et al. 2016, Hawkins & Popper 2016, Rako-Gospić & Picciulin 2019, Richardson et al. 1995). Sound exposure may affect an animal's ability to detect biologically meaningful sounds or it may impair hearing mechanisms temporarily or permanently. Impacts can range in response from no adverse impacts, to temporary behavioural responses and stress, to significant, longer term habitat avoidance, hearing loss and, in extreme cases, physical injury and mortality (Finneran 2015, Popper & Hawkins 2016). Consequently, anthropogenic noise is recognised as a marine pollutant (UN Commission for the Law of the Sea (UNCLOS)) and acknowledged as a global issue that the international community needs to address.

There is increasing concern that commercial shipping contributes to a significant portion of the underwater noise generated by human activity, which has been driven by globalisation and marine transport network expansion, urbanization, and greater demand for natural resources (Southall et al. 2017). In 2014, the International Maritime Organisation (IMO) adopted guidelines (MEPC.1/Circ.833) to reduce underwater noise from commercial ships, which recognised that underwater radiated noise from shipping can have short-term and long-term impacts on marine life. Given the increases in man-made underwater noise and the observed effects on marine life around the world (e.g., right whales in the USA (Rolland et al. 2012)), there is an urgent need for a greater understanding of the impacts of noise within Australian waters and for guidance on measures to avoid or mitigate these impacts on marine animals. While there is a national policy addressing the acoustic impacts of seismic surveys on whales, little is known regarding the effects of noise pollution for most marine species in Australia and no specific legislation governs it.

The noise arising from Australia's large fleet of recreational vessels are also of concern, particularly in shallow reef habitats such as the Great Barrier Reef World Heritage Area (GBRWHA) where predictions are that by 2040 up to 500,000 recreational boats will be registered in Queensland and potentially traversing reef waters. Although small, these vessels travel in very close proximity to the reef and even within the reef matrix of individual reefs, so that the impacts of noise occur within the reef community. Recent research has shown sound from outboard motors has negative impacts on predator-prey relationships, physiology and the behaviour of reef fishes, the reproduction and parental behaviour of adult reef fish and the survivorship of their young (Jain-Schlaepfer et al. 2018, McCormick et al. 2018). Together, this growing body of research shows that small vessels are an important source of pollution, especially in places like coral reef and seagrass areas where ecosystem processes occur.

This report provides an overview of the project's work, with more detail given in the referenced papers and technical reports (see Appendix D). A glossary of common terms used throughout this document is given in Appendix A.

Details of the data/maps produced by this project are given in Appendix C.

1.1 Objective and aims

This project provides characterisation and quantification of shipping noise within the Australian Exclusive Economic Zone (EEZ) and noise maps to inform management agencies of the spatial and temporal extent of shipping noise. Acoustic models are informed by targeted input data to reliably estimate cumulative noise (from ships) over the entire EEZ. The contribution of shipping noise to the marine soundscape is quantified, and sound exposure levels on Matters of National Environmental Significance (MNES) estimated to evaluate the potential impact of underwater ship noise. With projected increases in shipping within Australia, the outputs from the project allow initial estimates of shipping noise and an assessment of the effects of predicted increases in shipping and how this relates to changes in noise levels. These are initial steps toward informing on the development of underwater noise guidelines.

The specific aims of the project are:

1. Quantify ship noise source spectra measurements for the predominant large commercial vessel types from both IMOS data and newly deployed hydrophone arrays (Section 2.1);
2. Develop shipping noise maps for Australia (Section 0);
3. Quantify the contribution of shipping noise to the natural soundscape in comparison to wind-driven noise (Section 3);
4. Quantify ship noise exposure on MNES within a World Heritage place (Section 4);
5. Characterise noise from prominent noise sources within high value conservation areas (Section 5);
6. Investigate quantifying small boat noise (Section 0) and;
7. Investigate the feasibility of adding other anthropogenic noise sources to these maps (Section 7).

1.2 Prior NESP ship noise research in Australia

During the late stages of the NESP Marine Biodiversity Hub Project C5 '*Quantification of risk from shipping to large marine fauna across Australia*', key partners and research-users were engaged to inform the development of this project. A key step was convening a multi-stakeholder workshop to discuss progress with Project C5, and opportunities and stakeholder needs for an underwater shipping noise project. A workshop was subsequently convened in Canberra at the offices of Geoscience Australia in November 2017. The workshop was attended by representatives of relevant stakeholder organisations including Australian Antarctic Division, Australian Maritime Safety Authority, CSIRO, Defence Science and Technology Group, Department of the Environment and Energy, Geoscience Australia, IMOS, Maritime Safety Queensland, National Environmental Science Program and Parks Australia.

The specific aims of the workshop were to:

- Provide a brief overview of noise mapping projects overseas and the underlying management imperatives
- Present preliminary findings of shipping noise maps from NESP Marine Biodiversity Hub project C5
- Identify management priorities related to underwater noise by relevant stakeholders
- Provide an overview of the future proposed NESP shipping noise project
- Discuss future direction and development of noise maps for Australia

Details of the workshop are outlined in Peel et al. (2017) and can be found at the following link on the NESP Marine Biodiversity hub website.

1.3 Covid19 Impacts on Project

Due to covid19 state border restrictions, researchers were not able to travel from Western Australia to Queensland to conduct the planned fieldwork in the Great Barrier Reef in 2020. The fieldwork focussed on humpback whales that occur in the GBR during their breeding season and could not be re-scheduled due to the timing of the humpback whale migration and was consequently cancelled. This fieldwork was to inform the fine-scale study in the GBR (Section 4) and provide in-situ noise recordings for model validation of the coarser 5 km x 5 km ship noise model undertaken at the scale of the EEZ. The lack of this project component also resulted in a missed opportunity to collect impact study data on how the whales are responding in the presence of vessels in, and close to, the shipping lane. An acoustic tracking study of the whales could enable an understanding of how males are spatially responding to vessel noise as well as any acoustic impacts on their song production (their acoustic mating display).

Similarly, the small vessel fieldwork planned was also impacted by the WA travel restrictions, although with the project extension this work was managed to be completed.

2. ACOUSTIC MODELLING OF CUMULATIVE SHIP NOISE

Erbe, C., Peel, D., Smith, J.N., Duncan, A, and Schoeman, R.P.

Anthropogenic ocean noise is increasingly considered a chronic, habitat-level stressor requiring area-based management tools (Ellison et al. 2012). The EU and U.S. currently have regulations focussed on the environmental status and acoustic integrity of habitat in terms of the noise within the marine soundscape. For more continuous and pervasive sound sources like shipping noise, which occurs over large geographic scales and long durations, it is necessary to match the modelling scale with the scale of the noise source.

Modelling of cumulative sound exposure levels (C-SEL) of shipping traffic in Australian waters was undertaken for a typical 'winter' (1 April – 30 September) within the Australian EEZ. C-SEL is representative of the total sound of shipping traffic at any location in space integrated over a specified time period, which in this case is 6 months. Cumulative ship noise maps were developed using:

1. Ship source spectra and levels for different categories (Table 1) of vessel size (see Section 2.1),
2. Automatic Identification System (AIS) data on distribution (and density) of vessels (see Section 2.2),
3. Hydro- and geoacoustic parameters of the ocean that were clustered yielding 28 marine acoustic zones, in each of which sound propagates in similar ways, and
4. Sound propagation models run for each zone, producing ship noise maps from the ship density maps over the 6-month period.

This resulted in:

5. Cumulative ship noise maps at a 5 km x 5 km spatial resolution within the Australian EEZ. A summary of the whole process is given in Figure 1 and more detail is given in Erbe et al. (2021b).

Table 1 Summary vessel classes considered

Size Class	Details
1	<25 m length
2	25-50 m length
3	50-100 m length
4	100-200 m length
5	≥200 m length

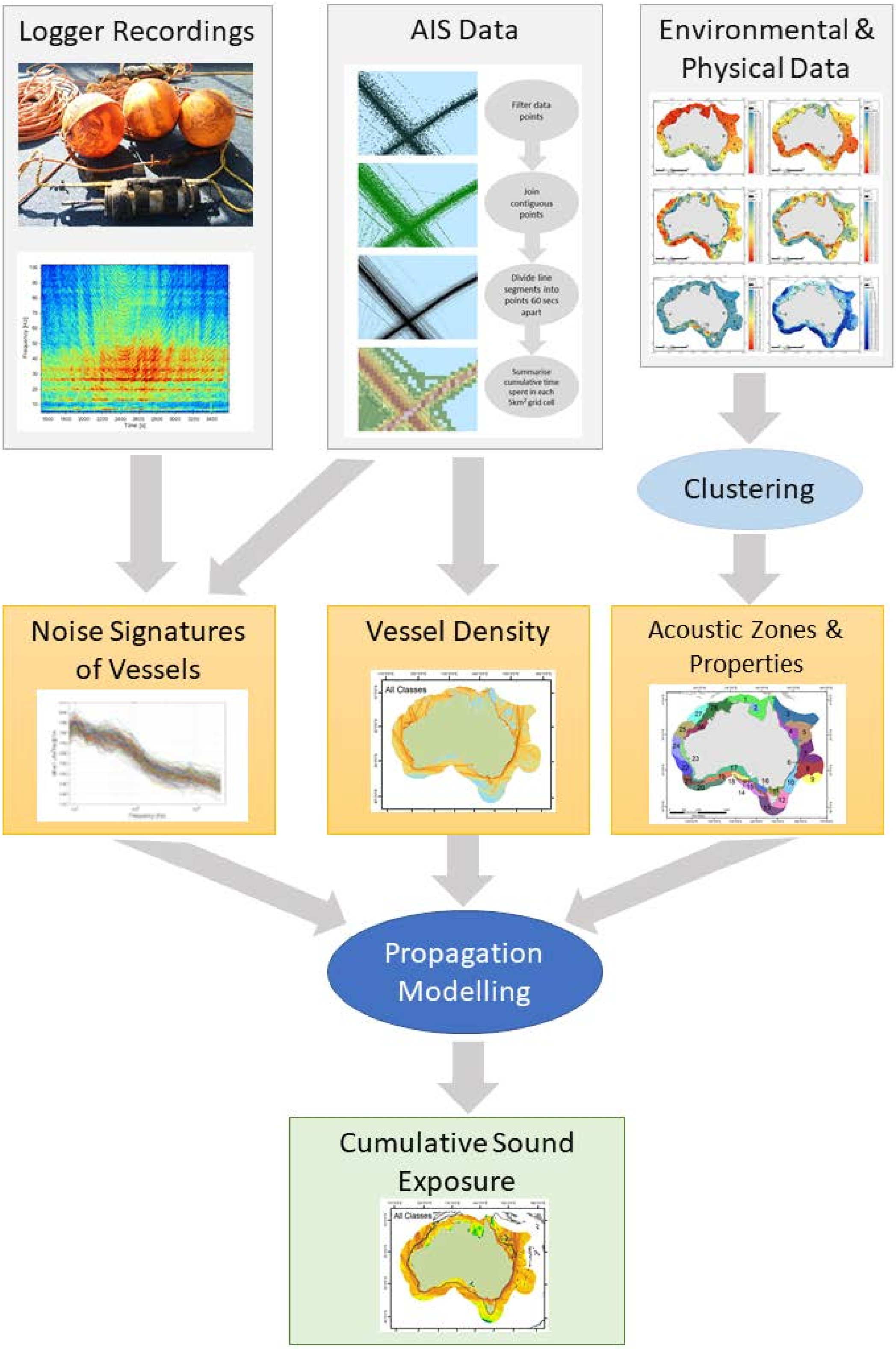

Figure 1 Flowchart of planned overall process for noise modelling

2.1 Underwater noise signatures of ships in Australian waters

A detailed report was produced of the work (Erbe et al. 2020) relating to quantifying ship noise source spectra measurements for large commercial vessel types from both IMOS data and newly deployed hydrophone arrays, and can be found at the following link on the NESP Marine Biodiversity Hub website. The following provides an overview of the work.

To build the noise map we need to understand the sound ships make. That is ship source spectra and levels for different categories of vessel size.

The project plan was to record ship noise using a moored logger.

2.1.1 Data from 3D array

The International Standardisation Organisation (ISO) has developed an international standard for recording and measuring ship noise (International Organization for Standardization, 2016, 2019). Ship noise is recorded with a vertical array of three hydrophones (Figure 1).

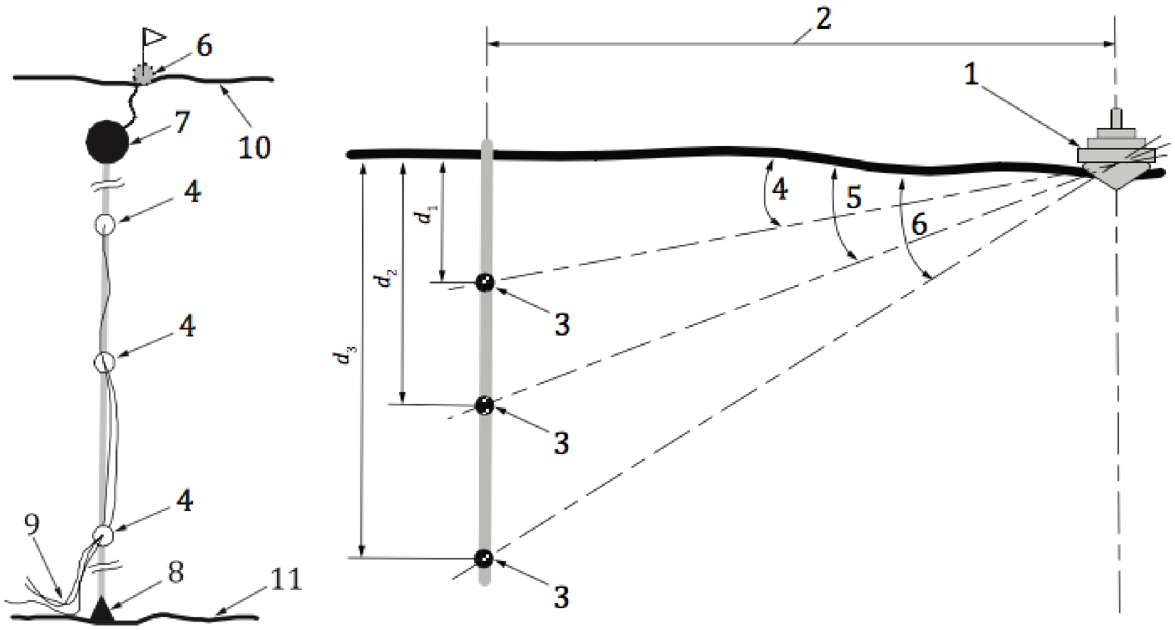

Figure 2 Left: Sketch of a vertical array for ship noise measurements
It consists of the hydrophones (4), an optional surface buoy (6), a subsurface float (7), an anchor (8), signal lines to shore (9) unless autonomous recorders are used at the locations 4, sea surface (10) and seafloor (11). Right: Sketch of a ship (1) passing at distance (2) from the hydrophone array (3), whereby the hydrophones are at slant

angles 15°(4), 30°(5), and 45°(6) from the ship (International Organization for Standardization, 2016).

We looked for potential sites where the ISO requirements of water depth and range from the ship could be met using common shipping routes (based on AIS data), for example off Fremantle WA, see Figure 3. The vertical array was deployed 37 nm offshore of Fremantle, WA (31°39'15.8" S, 115°10' 30.5" E) on the 14/06/2019 in approximately 120 m water depth (Figure 3). Deployment of the acoustic vertical array was undertaken using the Inception II 16.76 m charter vessel from Andro Maritime Services Australia. The duration of the deployment was a total of 56 days, with retrieval on 09/08/2019.

From this data, only 2 vessels were found to make passes that met the ISO requirements. It was apparent that due to the depth requirement and then position of shipping lanes in Australian waters, building a noise signature library opportunistically (i.e., without control of each vessel's movement past the hydrophones) of sufficient size using the ISO standard would be impossible. It was decided to relax the requirements and examine instead archival IMOS logger data to mine for isolated vessel passes (see Section 2.1.2).

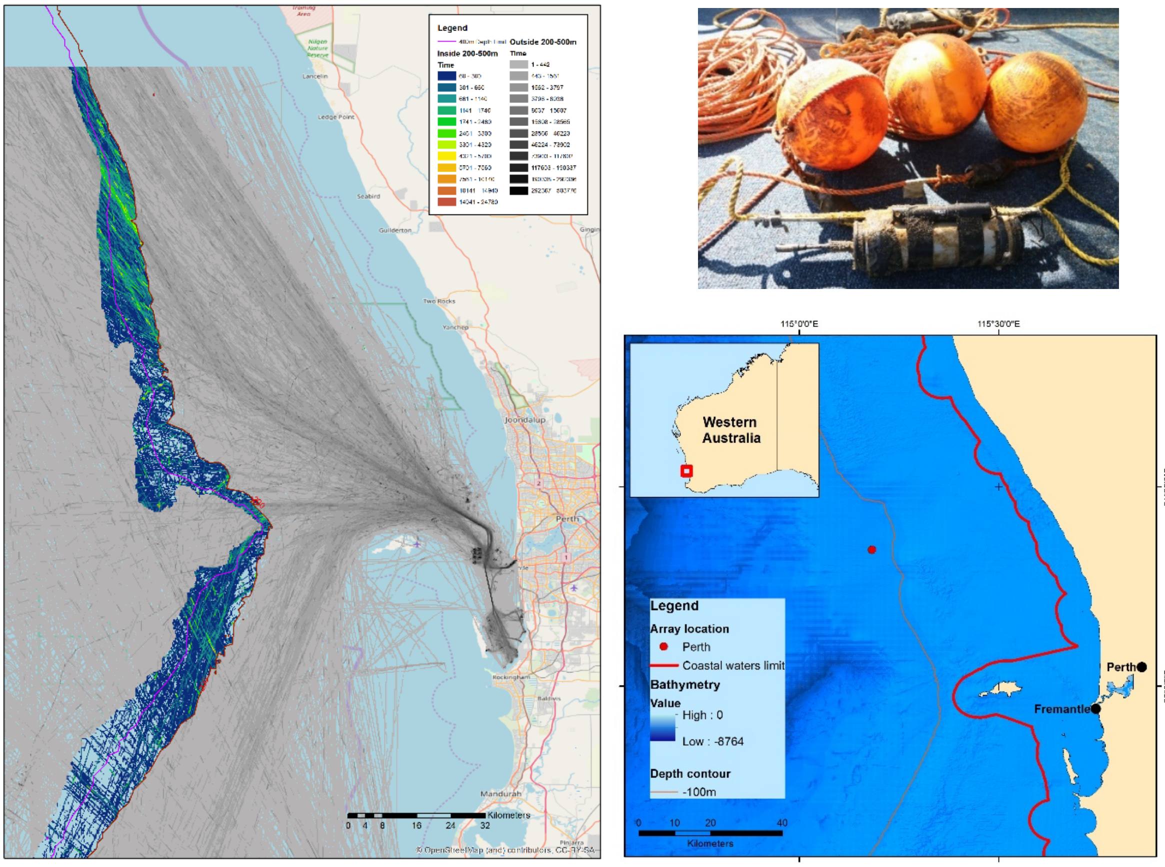

Figure 3 Mapping of AIS-equipped vessel traffic for determination of suitable logger deployment sites (left), 3D array (top right) and location of logger (bottom right)

2.1.2 Archival IMOS Data

Estimates of the noise source spectra of ships were obtained using geo-referenced AIS data (see Appendix A) and acoustic data from the Integrated Marine Observing System (IMOS). The results of applying the software to recordings from an initial set of five IMOS deployments from two locations (Perth Canyon W.A. and Portland S.A.) and spanning a total of 1463 days, are presented in Erbe et al. (2020).

This ship source level data is essential in the cumulative noise modelling process given it provides the source levels of the different types/class sizes of ships being modelled. This data contributes to the start of an Australian database of ship noise data, although it had a limited range of vessel types (mainly all cargo vessels and some tankers) and future acoustic logger deployments will need to strategically identify areas that maximises this, if this is an aim. Given the limited types of vessel classes obtained from the IMOS data within a period with which there is good, reliable AIS data (> 2012), this data has been directly used to validate source spectra from the existing literature of ship source levels (Section 2.1.1).

2.1.1 Existing Vessel Spectra

Ship source spectra were taken from the Research Ambient Noise Directionality (RANDI) model (Breeding et al. 1994; also see Erbe et al. 2012) and integrated into full-octave bands: ≥10 - <20 Hz, ≥20 - <40 Hz, ≥40 - <80 Hz, ≥80 - <160 Hz, ≥160 - <320 Hz, ≥320 - <640 Hz, ≥640 - <1280 Hz, and ≥1280 - <2560 Hz (Figure 4). The broadband source levels were: 148, 160, 172, 187, and 193 dB re 1 µPa m, for the five classes, respectively. Recent literature shows that the RANDI source level of the small vessel class is on the lower edge of *in-situ* measurements, in particular for powerful small vessels such as whale-watching vessels (e.g., Erbe et al. 2016).

The IMOS ship noise source spectra data provided a good sample size for cargo ships ≥ 200 m in length (N = 150), which was used to compare to existing models (RANDI) that were used in the cumulative ship noise modelling. The validation process demonstrated that the broadband RANDI source level prediction was within the range of the IMOS data for the tested size class (even though the RANDI spectra had a slightly different shape), and, in lieu of substantive validated source spectra data to verify the model for other size classes, the RANDI model was applied in the ship noise modelling.

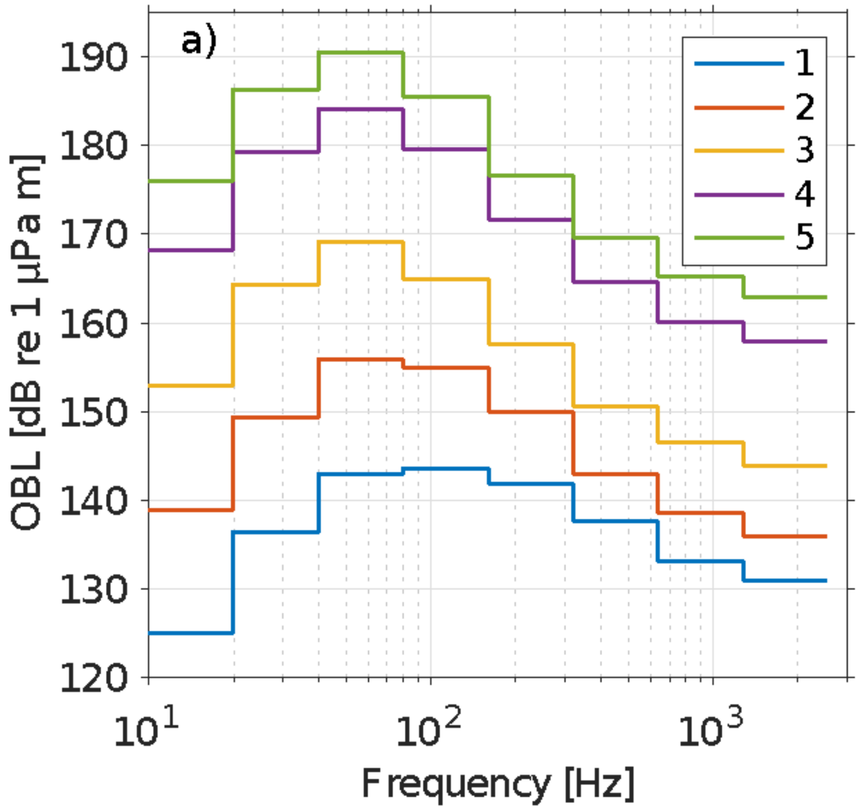

Figure 4 Ship source levels as full-octave band levels (OBL) for ships of lengths <25 m (Class 1), ≥25 - <50 m (Class 2), ≥50 - <100 m (Class 3), ≥ 100 - <200 m (Class 4), and ≥200 m (Class 5)

Conclusion A : Noise Signatures

- Conforming to the ISO standard, it will be very difficult to build a large database of signatures within Australian waters if we have to rely entirely on opportunistic recordings (i.e., without control over vessel course past hydrophones in deeper water).
- Instead, sophisticated sound propagation models need to be used to compute ship source spectra from opportunistic passes in environments where the ISO conditions cannot be met. The advantage of the method is that resulting source spectra are independent of the environment in which the ships were recorded and the correspond to a monopole sound source, which can be directly imported into sound propagation models for noise mapping in similar or different environments.

2.2 Vessel Distribution

To build a noise map we require the vessel density, which was estimated from Automatic Information System (AIS) data, as detailed in Appendix A. The data was filtered (see Appendix A), processed and a vessel density calculated (see

Figure 5) for a 5 km x 5 km UTM projected grid for the main Australian Economic Zone.

The ocean noise model requires time spent in a grid cell, since polling rates can be irregular, some processing and/or interpolation was required (see Appendix A for conditions).

For the mapping in this project, a combination of 2015 and 2016 'winter' months (April-September) were used. Although newer AIS data was available, the table of vessel information we have built was most accurate for <2016. Densities for six size classes (as per Table 1) were calculated (Figure 6). The distribution of speed within each class is given in Figure 7.

Conclusion B : Vessel Distributions

- Previous NESP project C5 and this project have developed an efficient system/ framework to process AIS vessel data at the national scale.
- This can provide fine-scale vessel density. However, it should be noted, this is for AIS equipped vessels only. Large commercial vessels are well represented but small recreational vessels are only a sample of vessels that choose to equip themselves with AIS.
- The AIS processing rules (Appendix Table 1) to decide when not to interpolate the AIS were optimised for coastal regions where it is not known where vessels travel between large polling gaps. However, for the noise mapping in areas far-offshore where vessels are travelling in very predictable straight-line paths, a larger tolerance could be used. This can be seen by small gaps in final noise maps in offshore areas of low vessel density.

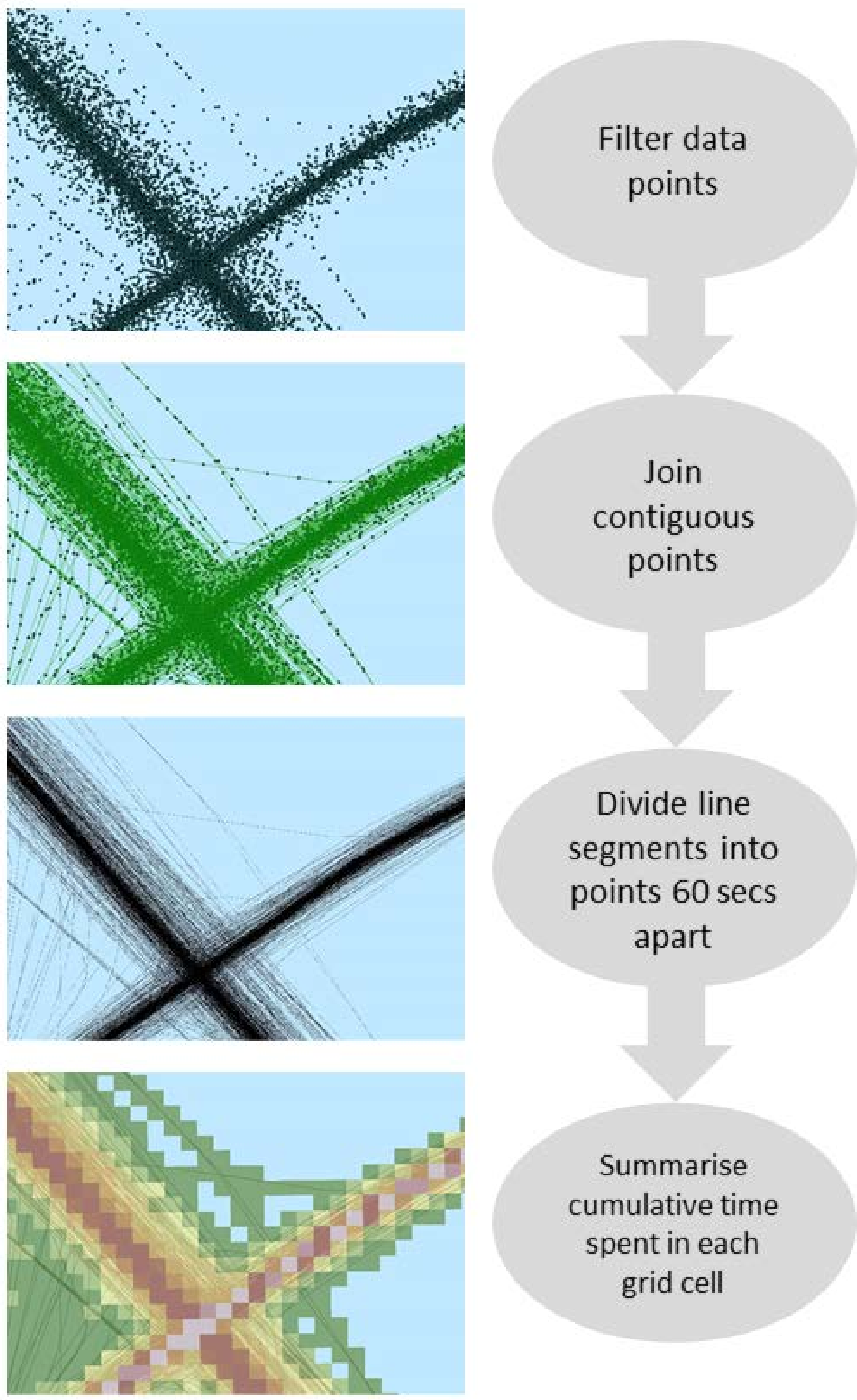

Figure 5 Example of the AIS data processing

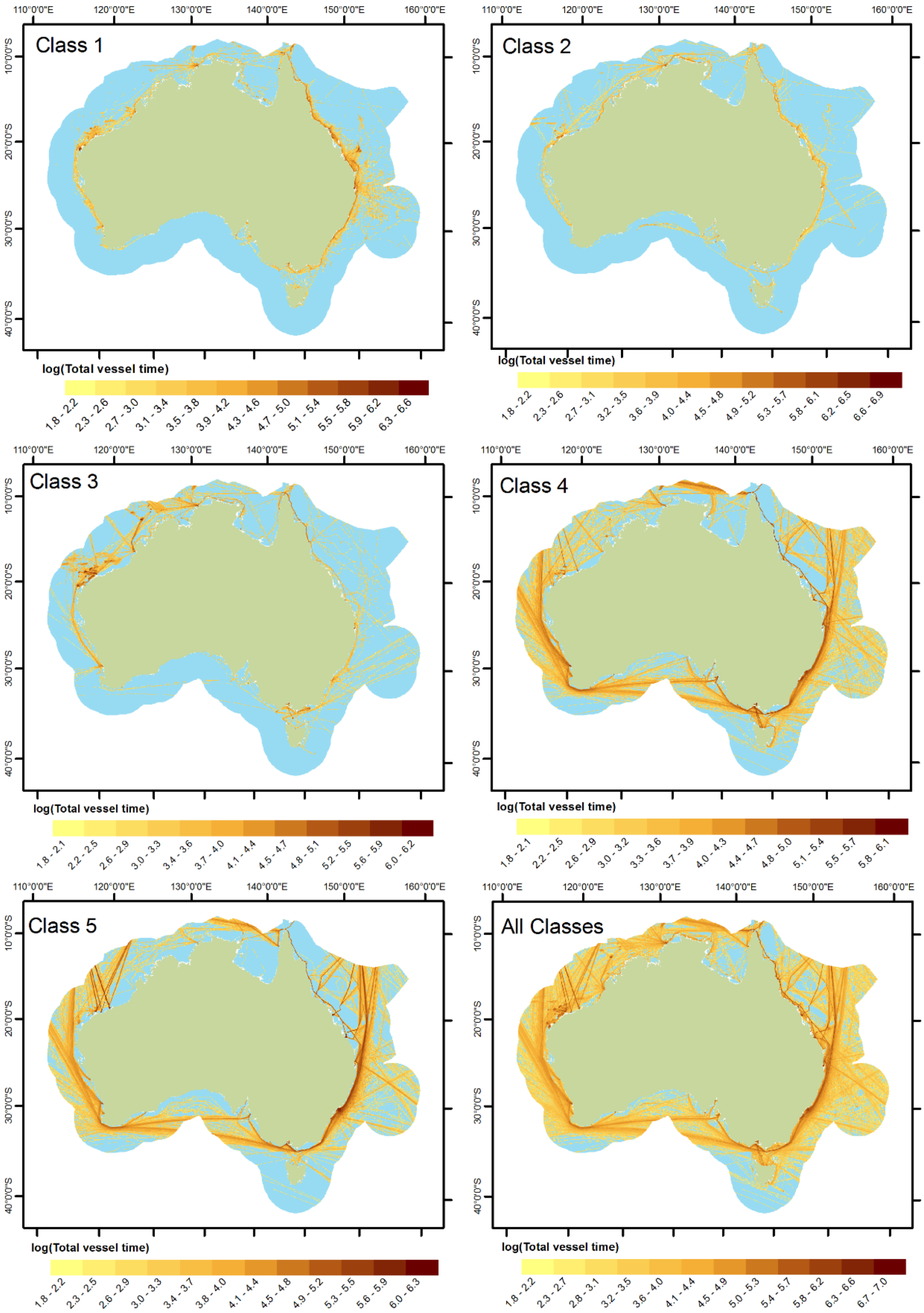

Figure 6 Typical vessel density winter (April-September) by vessel length

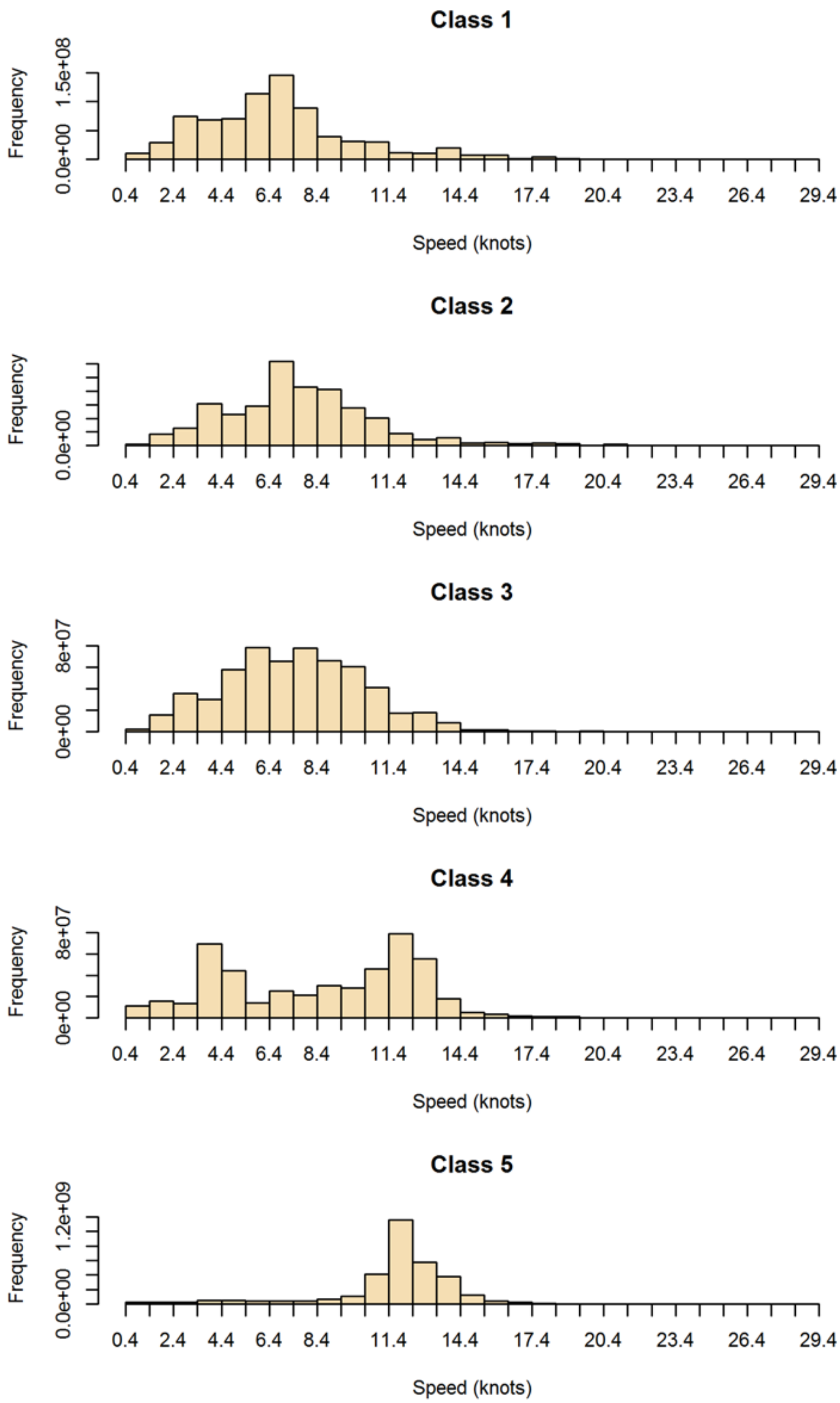

Figure 7 Distribution of vessel speed within each length class (Table 1) over the 6-month period (April-September)

2.3 Geo-acoustic parameters and marine acoustic zones

A paper was produced detailing this work (Erbe et al. 2021a) and can be found at the following link. The following provides an overview of the work.

As the area to be modelled increases, so does the computational effort. The effort is more easily handled if broken down into smaller regions that could be modelled separately, and their results merged. The goal of our study was to split the Australian maritime Exclusive Economic Zone (EEZ) into a set of smaller acoustic zones, whereby each zone is characterised by a set of environmental parameters that vary more across than within zones. The environmental parameters chosen reflect the hydroacoustic (e.g., water column sound speed profile), geoacoustic (e.g., sound speeds and absorption coefficients for compressional and shear waves), and bathymetric (i.e., seafloor depth and slope) parameters that directly affect the way in which sound propagates (see Figure 8).

The acoustic zones are based on the clustering of hydroacoustic, geoacoustic, and bathymetric variables. These three types of variables have different drivers and their spatial patterns are quite different. So, the clustering process is a compromise, which results in different variables dominating the separation of different acoustic zones.

The water column parameters, on which the zones are based, vary with season (i.e., sea surface temperature, sea surface salinity, and sound speed). While we used parameters from the austral winter, the clusters might be different in the austral summer, which would need to be modelled separately.

The clustering process used a finite mixture model resulting in 20 acoustic zones (Figure 10), although eight zones were represented twice in geographically separated locations within the EEZ yielding 28 geographically distinct zones (Figure 11). Zones that were not connected were relabelled and given different zone labels. This resulted in 28 acoustic zones (see Figure 10) and a description of each zone is given in Table 2. Full details are given in Erbe et al. (2021).

Having these zones, a sound propagation model can be set up for each zone separately and sound sources can be modelled within each zone. Noise maps can then be merged into an EEZ-wide map. At the zone boundaries, the sound from sources within one zone needs to be modelled into the neighbouring zones, adding to the sound map of each of the neighbouring zones.

Conclusion C : Acoustic Zones

- A total of 28 acoustic zones were produced for the Australian EEZ for atypical winter season
- Having these zones, a sound propagation model can be set up for each zone separately and sound sources can be modelled within each zone.

Table 2 Interpretation of zones given by the clustering.

Zone	Name	Description
1	Northern Tropical Shelf	Hot northern zone, shallow water with low salinity. Borders appear to align with salinity change.
2	Muddy Tropical Shallow	Two areas of northern Australia, one offshore in the West and one in shallow water in the Gulf of Carpentaria. Their predominant features are a muddy sea bed, hot temperature, and low salinity.
3	Eastern Tropical 1	Excludes coastal waters but spans a range of depths. Separate from neighbouring Zone 5 to the South by water column sound speed profile. Zones 1- 3 and 20 have the steepest downward refracting gradients. An abrupt change in salinity defines the border with Zone 1.
4	Tropical Shelf	Exists on both coasts. Mostly shallow, sandy, coastal water. Hot temperature, medium salinity.
5	Eastern Tropical 2	Geoacoustic parameters drive the border with Zone 4, hydroacoustic parameters (i.e., sound speed profiles) drive the borders with Zones 3 and 7.
6	Sub-Tropical to Temperate Shelf	Exists on both coasts. Warm, shallow, sandy.
7	Eastern Sub-Tropical Deep	Inner bound at continental shelf. Hydroacoustic parameters drive the separation from Zone 8.
8	Eastern Temperate Deep 1	Inner bound at continental shelf. High sea surface salinity. Less downward refracting than Zone 7.
9	Eastern Temperate Deep 2	Inner bound at continental shelf. High salinity. Less downward refracting than Zone 8.
10	Southern Temperate Shelf	Shallow water bounded by the continental slope. High salinity. Sandy seafloor.
11	Southern Cold	Covers shallow coastal Tasmania but also extends to deep water South-East of Tasmania. Cold water with a strong surface duct in July.
12	Southern Cold Deep	Most southerly zone. Cold. Less saline surface water than Zone 11. The least sound-focusing sound speed profiles.
13	Great Australian Bight Temperate Deep 1	Southern, cold, deep. Inner bound at continental shelf. Shallower yet thicker sediment than Zone 14.
14	Great Australian Bight Temperate Deep 2	Southern, cold, deep.
15	Southern Thick Sediment	An area (2 locations) between Zones 10 and 13 with very high sediment thickness.
16	Western Temperate Deep 1	Offshore with a sandy, shallower band resulting in different seabed acoustic properties from neighbouring Zones 14 and 17. Sound speed gradients at 40-1000m different from neighbouring zones. Inner bound at continental shelf.
17	Western Temperate Deep 2	Inner bound at continental shelf. Cooler and more saline than Zone 18 to the North.
18	Western Sub-Tropical Deep	Offshore, warm. Inner bound at continental shelf.
19	Western Tropical Offshore	Warm-hot. Downward refracting July profile. Inner bound at continental shelf. Shallower than Zone 2 to the North and Zone 18 to the South.
20	Western Tropical Shelf	Shallow water. Wide, sandy continental shelf. Hot sea surface; strongly downward refracting.

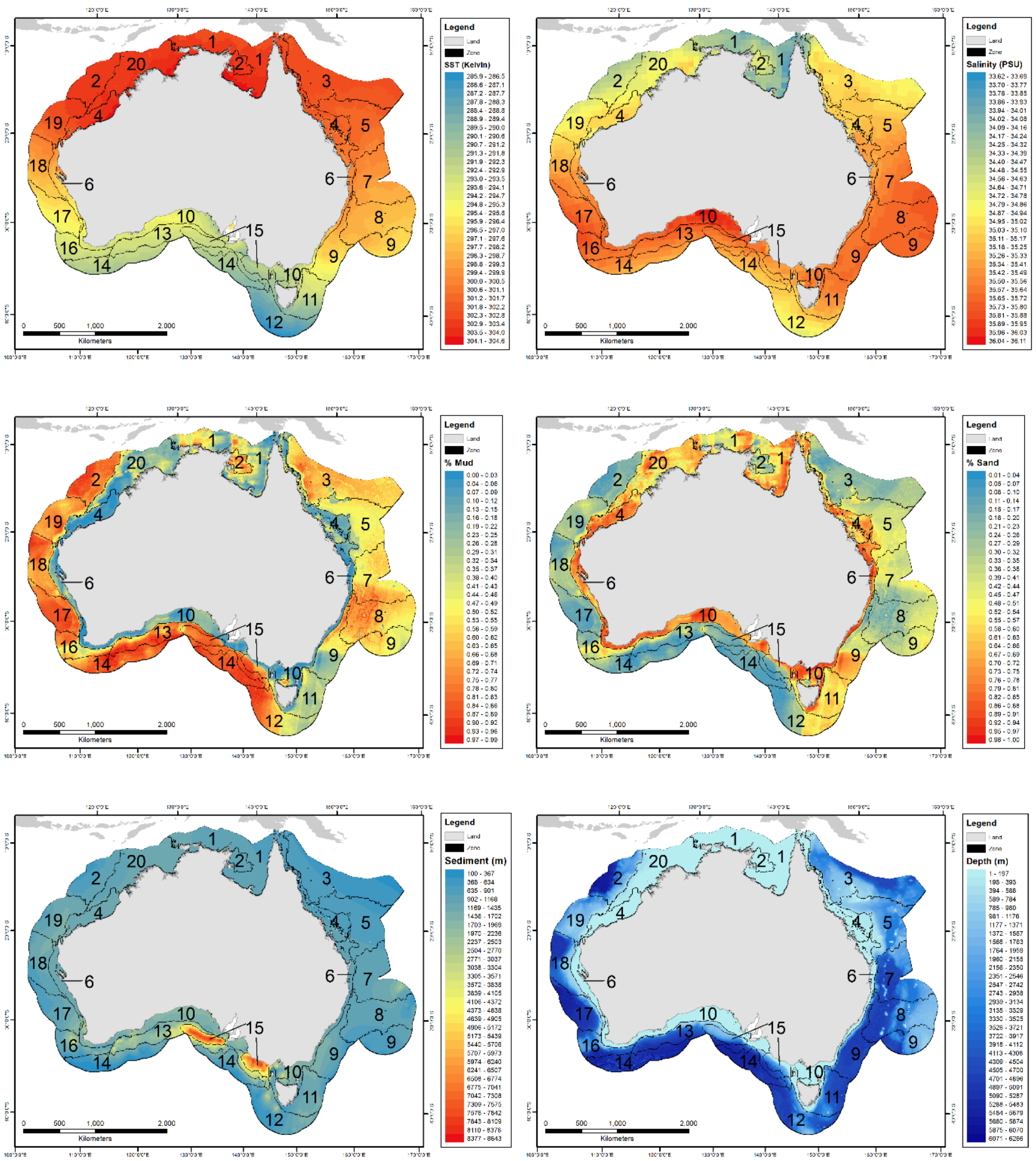

Figure 8 Maps of selected physical variables with acoustic zones overlaid: Sea surface temperature (SST), sea surface salinity, seafloor %mud, seafloor %sand, sediment thickness, and water depth.

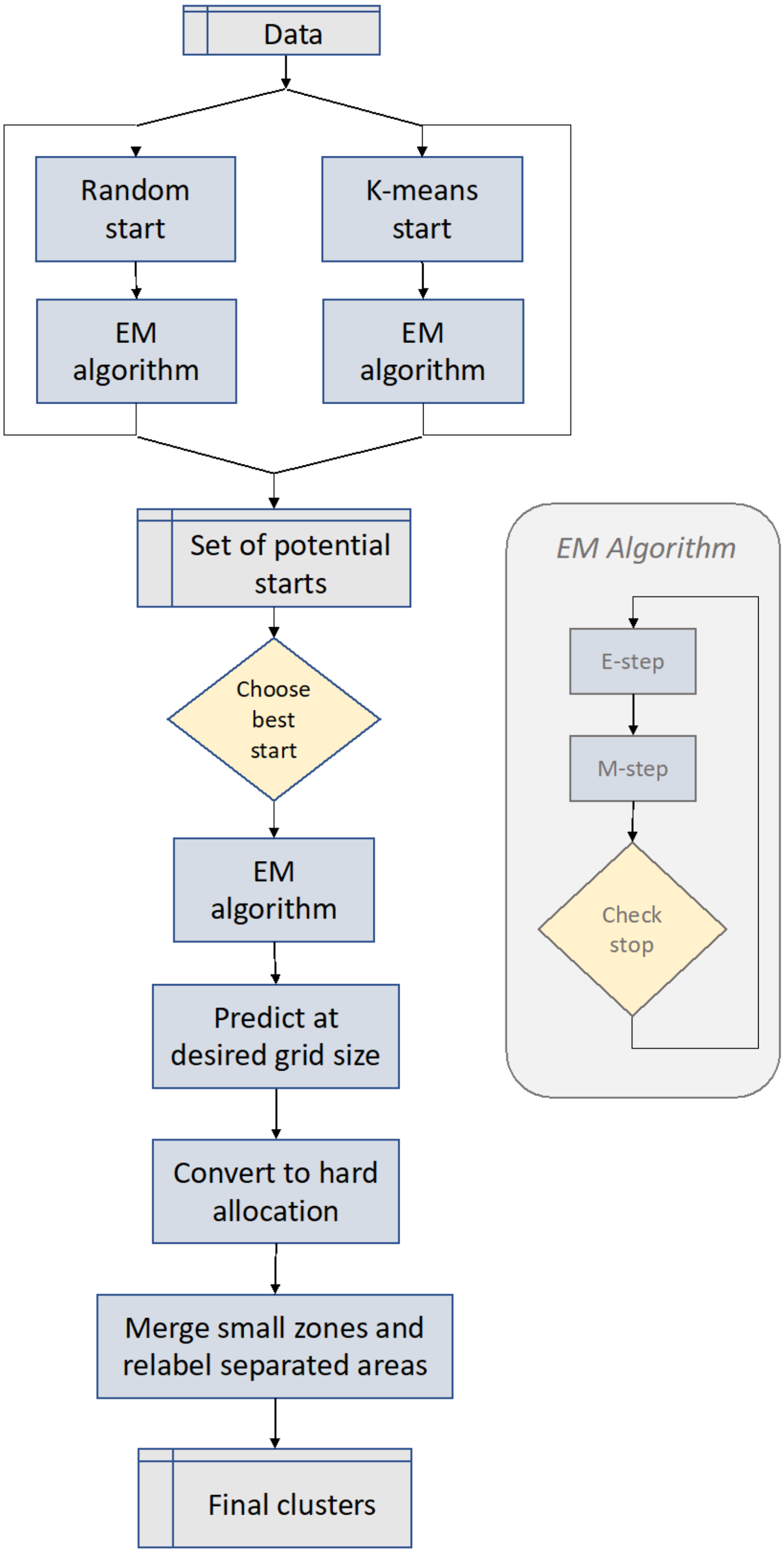

Figure 9 Flow chart of the clustering process to determine acoustic zones.

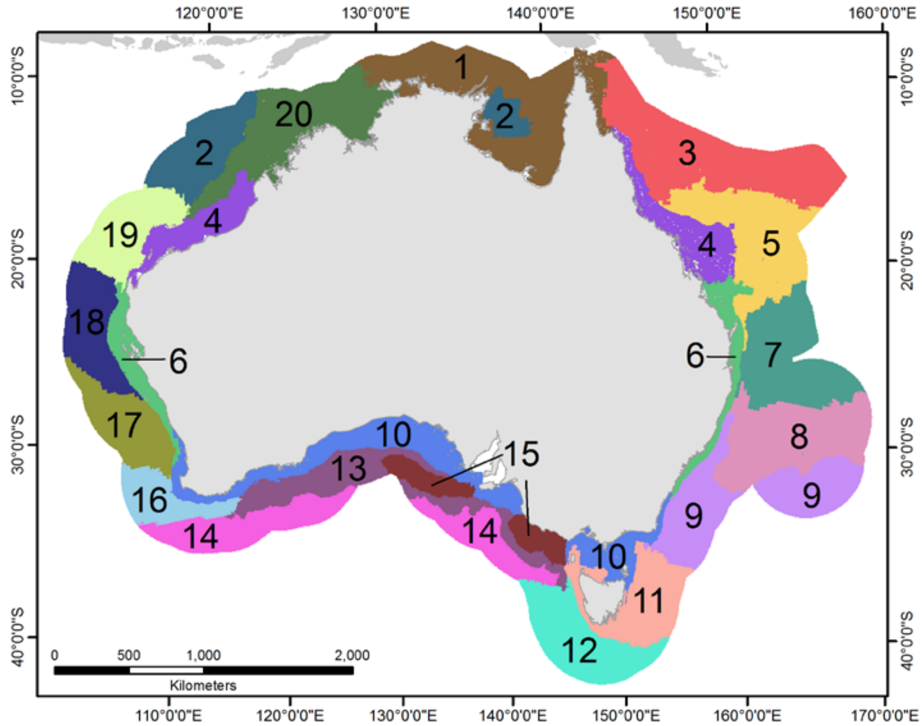

Figure 10 Map of the 20 acoustic zones, including eight zones represented twice in geographically separated locations within the Australian EEZ for austral winter.

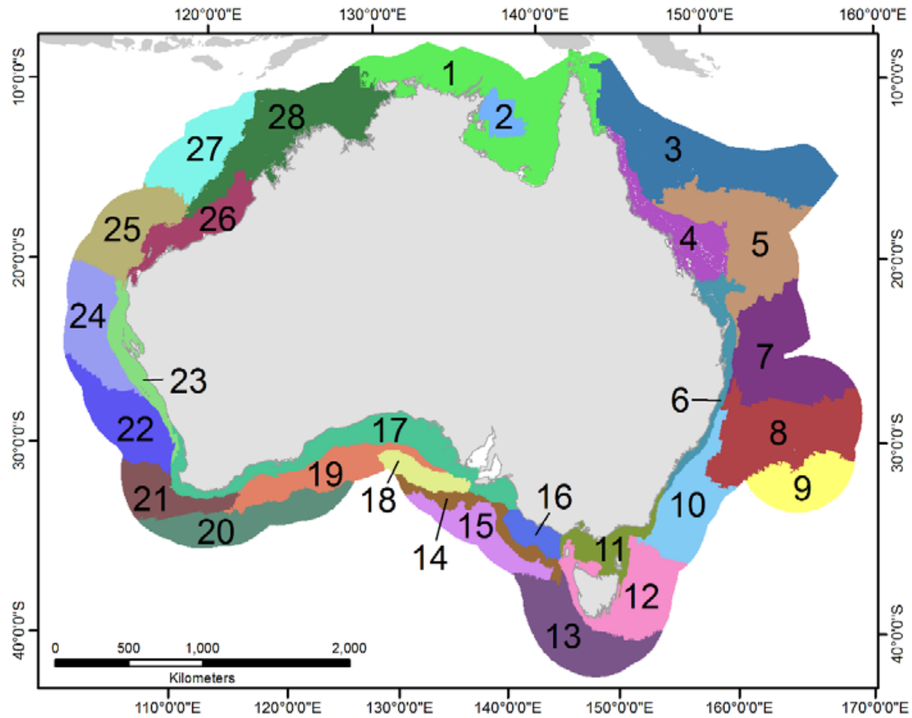

Figure 11 Map of the 28 acoustic zones, after assigning geographically separated zones with individual zone numbers, within the Australian EEZ for austral winter.

2.4 Sound Propagation Modelling

In the previous section (Section 2.3), the Australian EEZ was broken up into 28 acoustic zones (Figure 11), whereby each zone was characterised by a unique set of hydroacoustic, geoacoustic and bathymetric parameters of the seafloor. The idea was to set up one sound propagation environment for each zone and then model all of the ships in that zone. From the perspective of sound propagation modelling, the fewer zones there are, the simpler the modelling exercise.

2.4.1 Source-receiver transects within acoustic zones

Sound propagation models were run for each of the 28 marine acoustic zones. To do this, all of the grid cells with ships in them (irrespective of vessel class size) were identified and 36 radial lines (source-receiver transects) were run from each cell at 10-degree intervals to a distance of 100 km (i.e., 36, 100-km source-receiver transects), along which bathymetry was extracted every 5 km and land was masked.

Bathymetries over all 36 transects and around all cells with ships were passed through an unsupervised Kohonen neural network (i.e., self-organising map) with 900 neurons based on bathymetric shape (Vesanto et al. 2000), which were then clustered using K-means clustering into 64 clusters (Vesanto and Alhoniemi 2000).

2.4.2 Sound propagation models

Sound propagation over each centroid bathymetry was modelled with the software RAMGeo in AcTUP V2.8 (software link; Duncan & Maggi, 2006) based on zone-specific acoustic environments consisting of three layers: the water column, an unconsolidated surface sediment layer, and a consolidated calcarenite sediment layer as a half-space. Water column parameters included the zone's mean sound speed profile (Erbe et al. 2021) and water density profile. Water densities were calculated based on the UNESCO formula for sea water density (UNESCO, 1981), using representative temperature and salinity data extracted from the World Ocean Atlas. Unconsolidated surface sediment layers throughout the EEZ comprised predominantly fine material (silt-sand) and was modelled as a fluid. Surface sediment layer thickness was estimated at 0.5 m within the sediment-poor carbonate platform and 2 m for the remaining section of the coast. When modelling underwater sound propagation, the most common source of uncertainty is data relating to the seafloor composition. It was assumed that the Australian continental shelf consists, of a calcarenite seabed. Generalisation of unconsolidated and consolidated sediments simplifies the modelling process but results in both over- and underprediction of cumulative sound levels. For example, modelling with a thick unconsolidated sediment layer and/or a soft seabed structure will underestimate received levels in areas that are, in fact, characterised by a thin unconsolidated layer and/or a hard seabed structure. More fine-scale details on the seafloor composition could be added to improve model accuracy.

RAMGeo modelled sound transmission loss for the centre frequencies of eight full-octave bands (i.e., centre frequencies 16-2000 Hz) over a range of 100 km and up to 7100 m depth (max depth of EEZ = 6388 m). The source depth for all ships was chosen as 5 m below the sea surface. An example *RAMGeo* output at 640 Hz for the 64 centroid bathymetries of Zone 15 is shown in Figure 12. Transmission loss results were reduced to depths 10 - 200 m at 10 m resolution and ranges of 2.6 km, 5 km, 10 km, to 100 km. Frequency-dependent absorption was applied following Fisher and Simmons (1977) to obtain the final depth and range dependent propagation loss results.

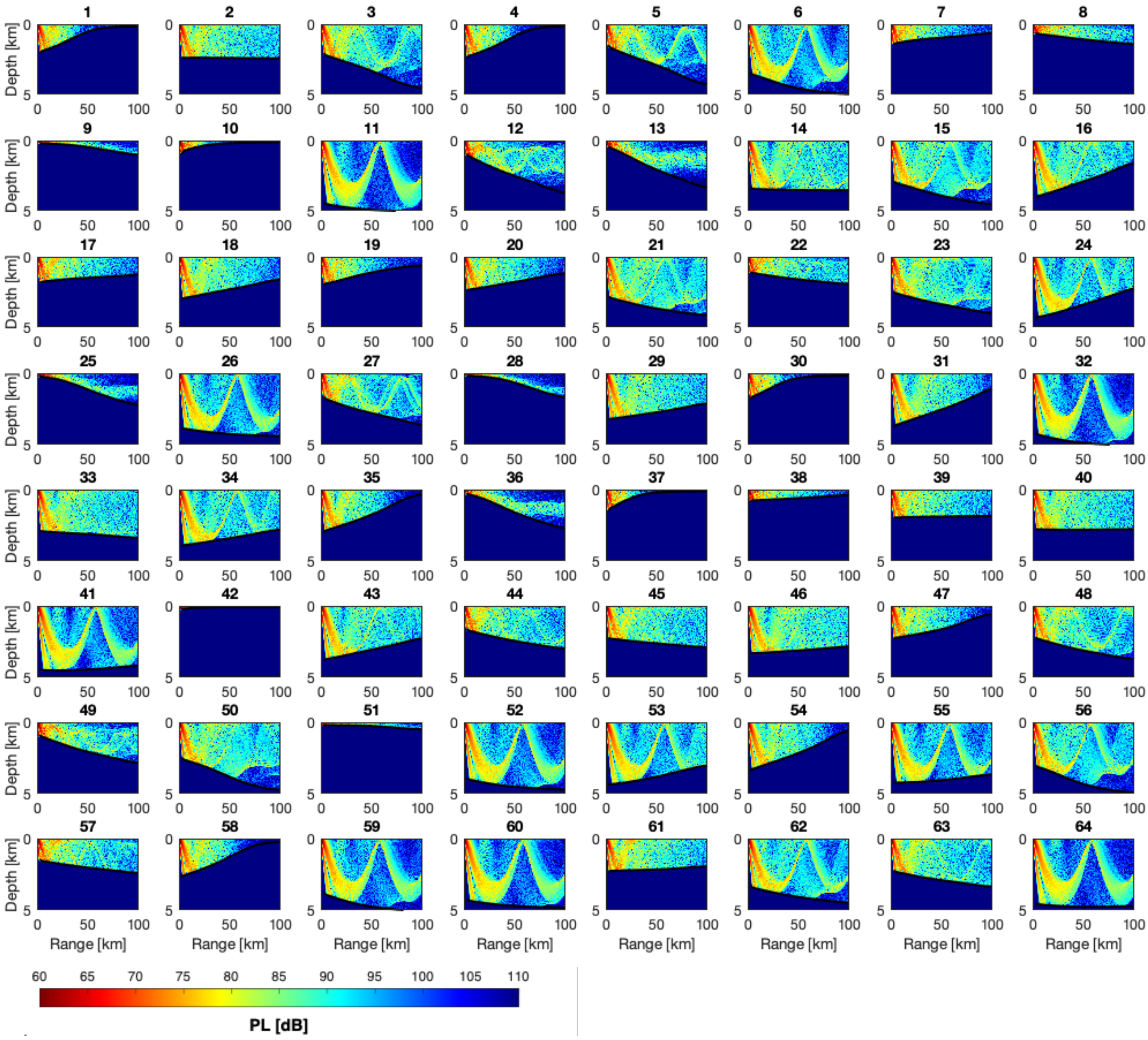

Figure 12 Plots of propagation loss (PL) in dB as a function of range and depth along the 64 centroid bathymetries from Zone 15, for a frequency of 640 Hz. The darkest red corresponds to 60 dB and the darkest blue to 110 dB. X-axes are range [km] and Y-axes are depth below the sea surface [km], scaled linearly.

Cumulative received levels and ship noise maps

Australia-wide maps of cumulative ship noise (by class) for a typical 'winter' (1 April – 30 September) based on 2015/16 data are shown in Figure 13. These are available here and a summary visualisation is here.

To calculate cumulative ship noise, we first calculated the received levels for the different ship classes. This followed a similar approach as was undertaken for the propagation loss models. Within each acoustic zone, one ship class was processed at a time. The source cells corresponding to one ship class were found and 36 100-km radials were cast at 10-degree intervals around each source cell, and bathymetry was extracted along each radial and sampled in 5 km steps. Then, stepping through the source cells for this ship class in this zone, for each of the 36 radial transects, the best matching centroid bathymetry was found using the SOM already developed during the propagation loss modelling. For each frequency modelled, propagation loss (PL) along this centroid was recovered and subtracted from the corresponding octave band source level (SL) plus the cumulative time (T, in dB) of this ship class in this source cell, yielding received levels (RL):

$RL = SL + 10 \log_{10}(T) – PL$

In this equation, SL is a number, the octave band source level expressed as a mean-square pressure level [dB re 1 μPa^2] at the modelled frequency. The duration term is also a number [dB re 1 s]. PL [dB], however, is a matrix with values in depth and range. Therefore, RL is a matrix of depth versus range. It measures the received sound exposure level [dB re 1 $\mu Pa^2 s$].

At each depth, RL was interpolated to the 5-km grid of the EEZ. This yielded a 4-dimensional matrix of longitude, latitude, depth, and frequency, covering the entire EEZ. The matrix was populated cumulatively by summing sound exposure (i.e., in linear, not logarithmic terms) over all 36 transects about each source cell, before taking $10\log_{10}$ again to yield sound exposure level.

Broadband sound exposure levels were computed by summing sound exposure over frequency, thereby reducing the matrix to three dimensions, then converting to dB. Finding the maximum sound exposure level over the top 200 m further reduced it to 2 dimensions, representing the 'worst case' of exposure for animals that dive over this depth. One such map is presented for each ship class, as well as cumulatively over all five classes. These maps of cumulative sound exposure level (C-SEL) were accumulated over six months encompassing the austral winter. They can be read as average mean-square sound pressure level maps by subtracting the 6-month duration in dB re 1 s:

$SPL = C\text{-}SEL – 10\log_{10}(182\ d * 24\ h/d * 60\ min/h * 60\ s/min\ /s) = C\text{-}SEL – 72$ dB re 1 s

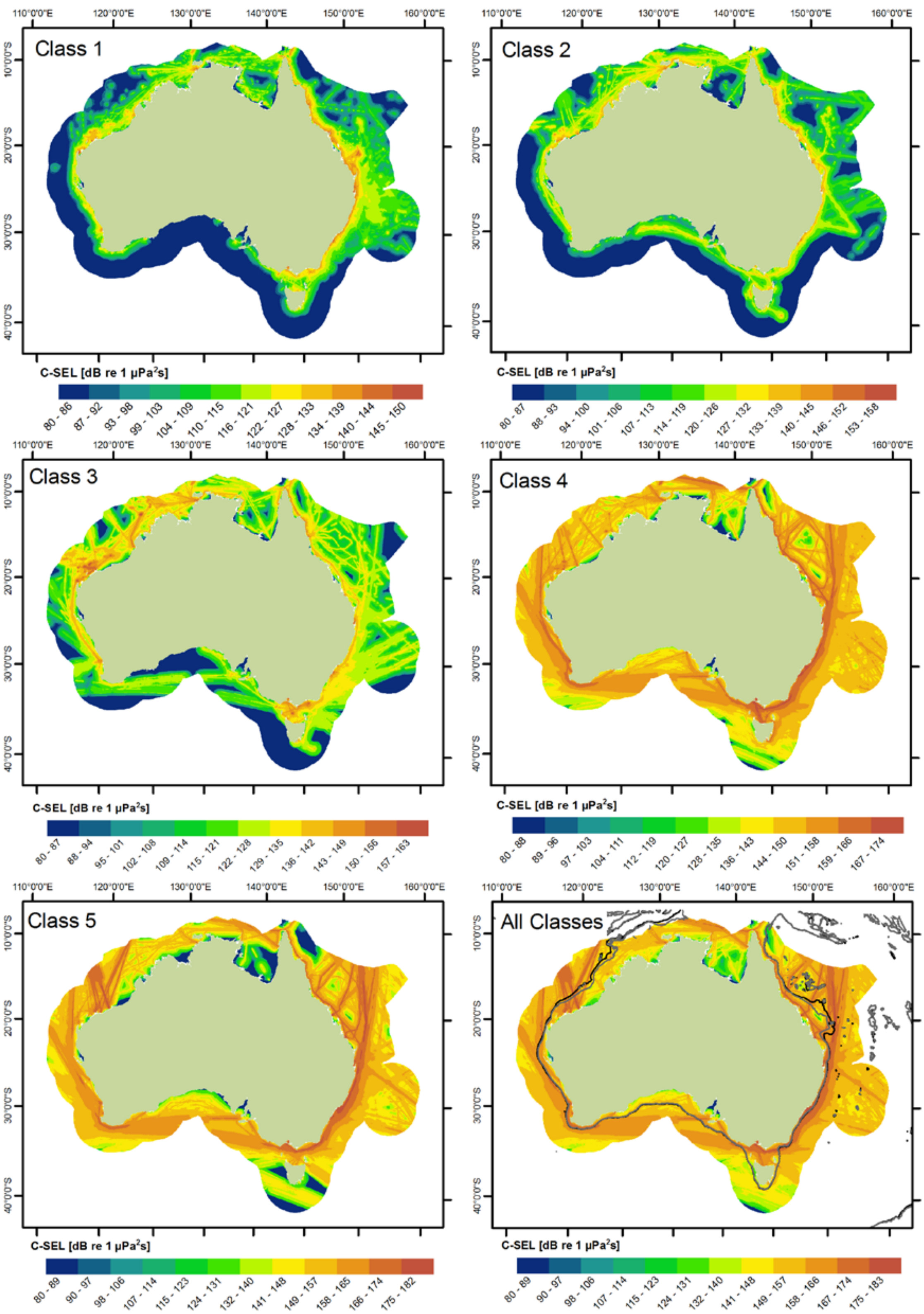

Figure 13 Maps of cumulative sound exposure levels (C-SEL) from shipping in the Australian EEZ, by ship class, and cumulatively over all classes (Table 1).

Conclusion D : Summary for cumulative noise modelling

- We developed and applied a quantitative approach to derive a large-scale noise map so that shipping noise, as a pressure, can be better integrated into marine spatial management.

- The models provide a quantitative framework that could be used for simulating the acoustic consequences of proposed industrial developments in Australia, such as expansion of shipping ports and associated traffic around ports related to natural resource exports e.g. Queensland and NW Australia.

- The models allow quantitative forecasting and hindcasting to assess how trends in shipping may translate to trends in noise levels.

- Overlaying the noise maps with marine animal distribution maps will indicate areas of risk (i.e., high noise and high animal density) and areas of opportunity (i.e., low noise and high animal density) for marine spatial management.

- Furthermore, predictions can be overlaid on marine wildlife distribution maps to evaluate impacts of anthropogenic noise in the critical habitats of vulnerable species, such as how it relates to a species hearing sensitivity. This will lead to better integration of anthropogenic ship noise into marine spatial management, and ultimately towards a cumulative framework for quantifying underwater noise.

3. MODELLING WIND NOISE

Erbe, C., Schoeman, R.P., Peel, D. and Smith, J.N.

The marine soundscape consists of natural physical sounds (e.g., generated by rain, wind, waves, subsea seismic activity, and ice breakup and ridging), biological sounds (e.g., from cetaceans, fish, and crustaceans), and anthropogenic sounds (e.g., from vessels, sonars, offshore exploration, and construction). “Ambient noise” usually refers to the background level in a soundscape and can include physical, biological, and anthropogenic sources (Erbe et al. 2016). Wind-driven noise is an example of a pervasive, physical, ambient noise. A paper will be produced of the work (Erbe et al. 2021) relating to quantifying wind noise in Australia. The map data can be found here (link), an interactive visualisation here on Seamap (link) and the following provides an overview of the work.

The aim is to quantify wind noise, a natural contribution of noise, to the marine soundscape, and compare to shipping noise to enable a better understanding of where shipping noise is likely to be a significant contributor to the soundscape.

Hourly data on surface wind speed (10 m altitude) were obtained from the Australian Bureau of Meteorology (Durrant et al. 2013) based on the NOAA NCEP Climate Forecast System version 2 (Saha et al. 2014). The data varies in spatial and temporal resolution (4, 10, 24 arcminute grids), which we projected and re-sampled to a 5 km x 5 km UTM grid. Over all grid cells, wind speed ranged between 0.5 and 30 m/s (i.e., 1 to 58 knots).

Wind speeds were binned to match the sea states represented in the ‘Wenz curves’ and noise spectra were assigned to each wind speed bin (Wenz 1962; Figure 14b). The ‘Wenz curves’ were converted to linear power spectral density, then integrated over frequency, before applying $10\log_{10}$ to yield broadband mean-square sound pressure levels. Expressed as root-mean-square sound pressure levels, the associations became:

- 79 dB re 1 μPa for ≥ 1 - < 3 knots
- 87 dB re 1 μPa for ≥ 3 - < 7 knots
- 92 dB re 1 μPa for ≥ 7 - < 11 knots
- 99 dB re 1 μPa for ≥ 11 - < 21 knots
- 105 dB re 1 μPa for ≥ 21 - < 48 knots
- 113 dB re 1 μPa for ≥ 48 knots

The wind map was produced by converting these hourly root-mean square sound pressure levels to linear mean-square sound pressures ($10^{(windDB/10)}$) and integrating over time. Taking $10\log_{10}$ of this total yielded cumulative sound exposure levels over the two 6-month periods (April-September and October-March) in each grid cell (see Figure 15 and Figure 16), which was comparable to the cumulative sound exposure levels of shipping noise. For each cell, we then subtracted shipping noise (which was modelled for April to September) from the corresponding winter wind noise to get the difference between the two (Figure 17).

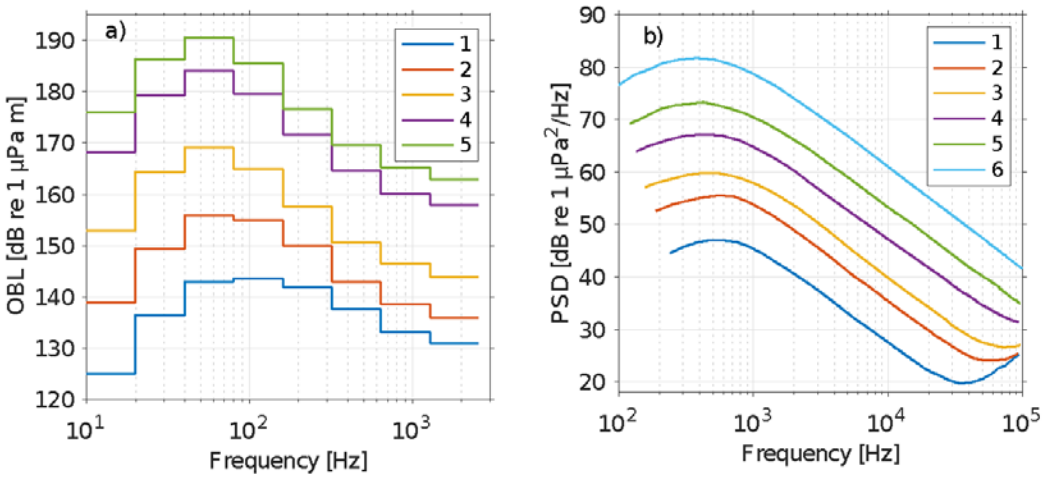

Figure 14 a) Ship source levels as full-octave band levels (OBL) for ships of length classes <25 m (Class 1), ≥25 - <50 m (Class 2), ≥50 - <100 m (Class 3), ≥ 100 - <200 m (Class 4), and ≥200 m (Class 5). b) Power spectral density levels (PSD) of wind noise at wind speeds ≥1 - <3 kn (Curve 1), ≥3 - <7 kn (Curve 2), ≥7 - <11 kn (Curve 3), ≥11 - <21 kn (Curve 4), ≥21 - <48 kn (Curve 5), and ≥48 kn (Curve 6).

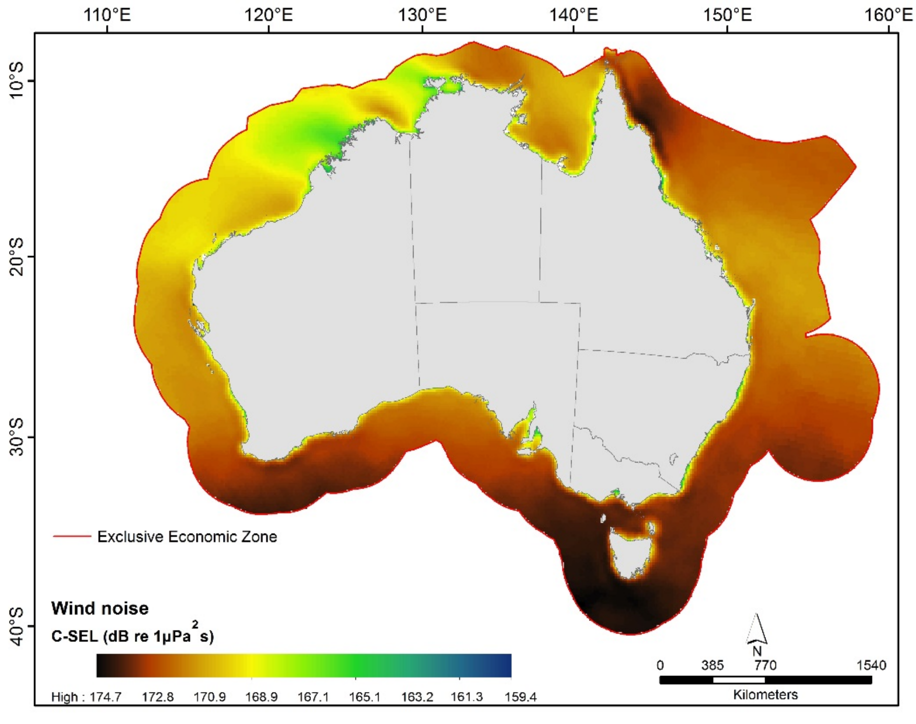

Figure 15. Map of modelled wind noise within Australia's Exclusive Economic Zone for April-September.

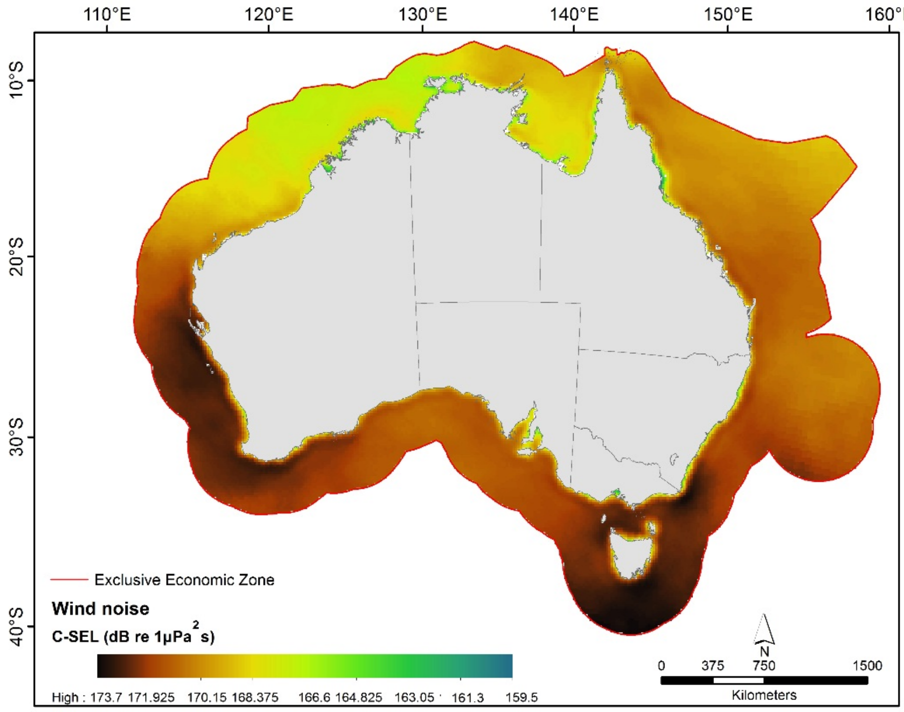

Figure 16. Map of modelled wind noise within Australia's Exclusive Economic Zone for October-March.

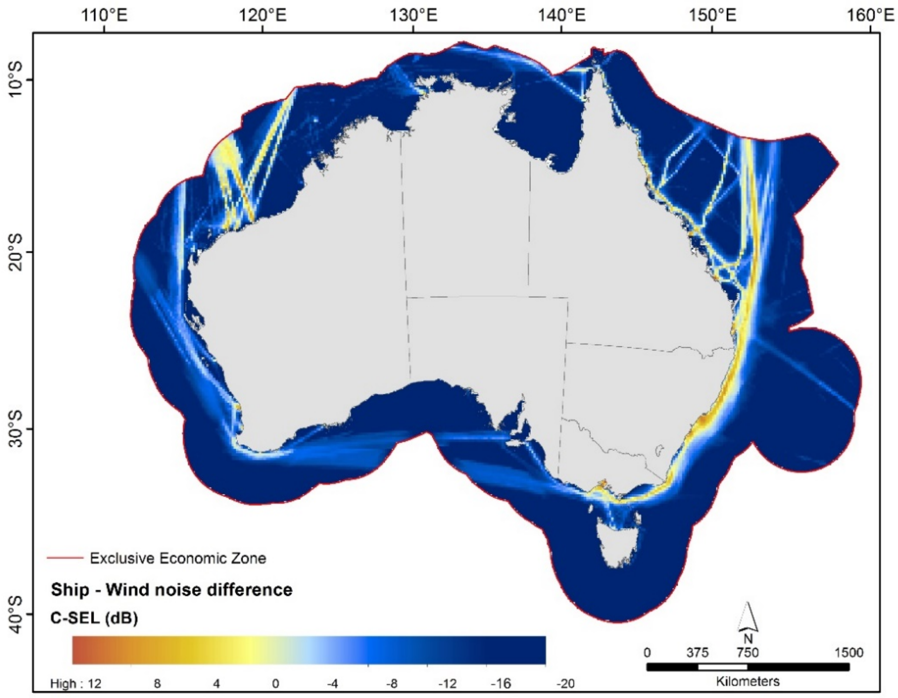

Figure 17 Map of modelled noise difference between ship and wind noise within Australia's Exclusive Economic Zone.

From the difference in shipping noise and wind noise (Figure 17), we can identify areas where shipping noise is a greater contributor of noise into the soundscape compared to natural wind-driven noise. Figure 17 shows that wind is a significant contributor of noise to background noise levels, although in areas where there are higher levels of shipping (Figure 6) and hence higher levels of shipping noise, shipping noise can be detected above natural noise levels. Specifically, this is the case in the North West of Western Australia, the eastern seaboard of Victoria and New South Wales and the waters of the Great Barrier Reef. The map of Summer wind (Figure 15) versus winter wind (Figure 16) demonstrates the spatial and temporal variability of natural noise contributions that need to be considered when undertaking noise modelling. As a further comparison we can look at the modelled wind noise worldwide (Figure 18).

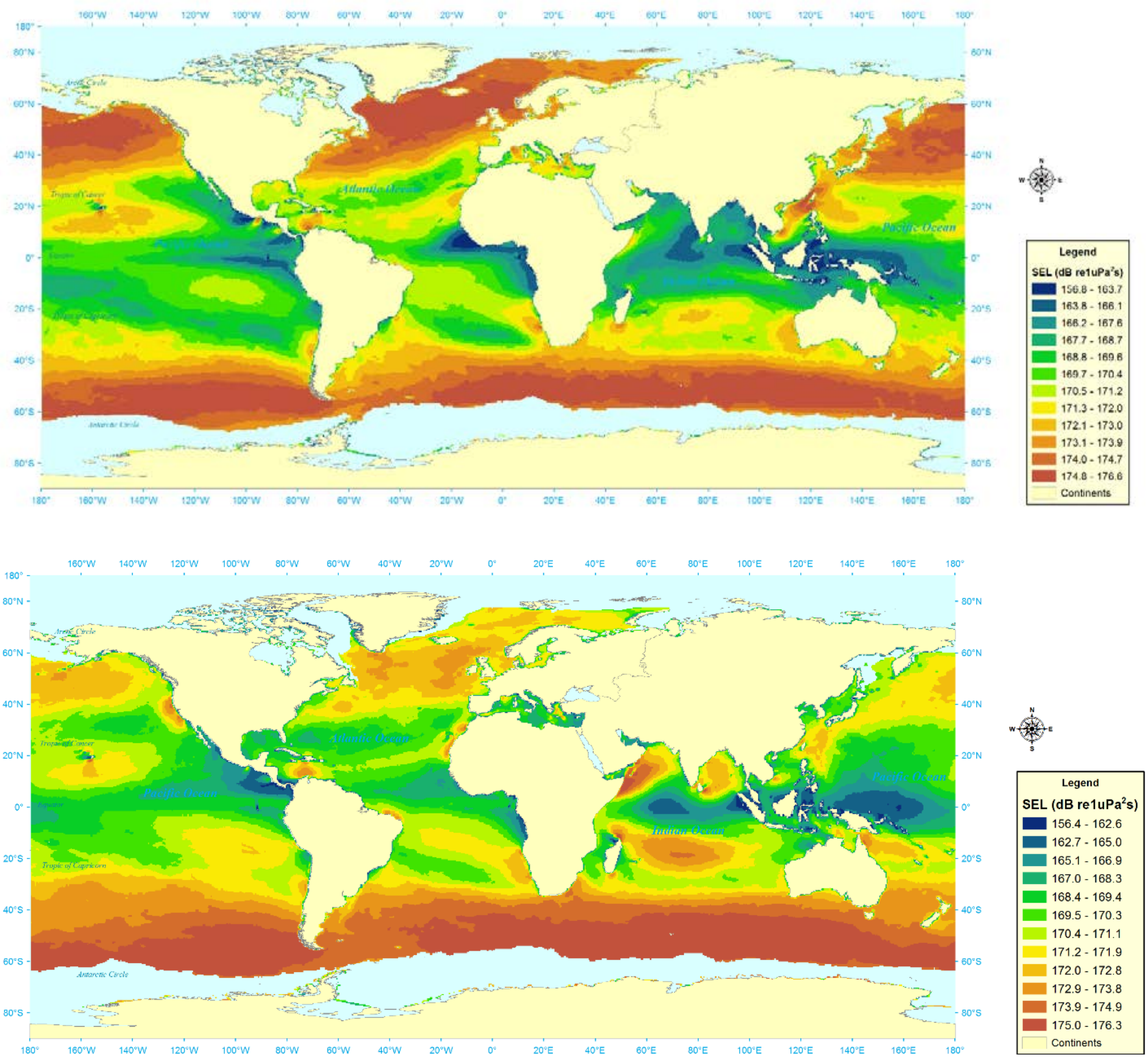

Figure 18 Map of modelled wind noise worldwide for April-September(top) and October-March (bottom)

Conclusion E : Wind noise modelling

- Wind is a significant contributor of noise to background noise levels
- Modelling wind noise allows a comparison of cumulative sound exposure levels between wind and shipping noise. This enables areas to be identified that might have a greater contribution of shipping noise above natural, wind-driven noise. These areas include the North-West of Western Australia, the eastern seaboard of Victoria and New South Wales and the waters of the Great Barrier Reef off Queensland.

4. QUANTIFICATION OF SHIP NOISE EXPOSURE ON MNES – CASE STUDY

Smith, J.N., Erbe, C., Peel, D. & Schoeman, R.P.

The following is a case study that focuses on fine-scale noise modelling applied to humpback whales in the GBR to demonstrate the potential uses of noise maps. This approach demonstrates the usefulness of the noise models to investigate noise exposure levels on particular species of interest, which could include endangered species or common species in highly noisy environments. The main motivation was to demonstrate the application of noise maps to a species with good data/knowledge available regarding distribution/abundance and highlight potential noise impacts. This does not specifically relate noise level maps to actual impacts, which is an important next step. For management purposes, it is often important to model ship noise at a finer resolution to better account for changes in sound propagation conditions, not only for the geoacoustic environment but also to better capture differences between vessel classes.

4.1 Great Barrier Reef and East Australian humpback whale breeding population

The Australian east coast population (breeding stock E1) of humpback whales migrate to the tropical waters of the Great Barrier Reef (GBR) for mating and calving (Simmons and Marsh 1986, Chaloupka and Osmond 1999, Smith et al. 2012, Smith et al. 2020b), within the Great Barrier Reef World Heritage Area (GBRWHA) and Marine Park (GBRMP). The whale population is currently undergoing a rapid, exponential rate of increase (~11% per annum) following near extinction from commercial whaling (Bejder et al. 2016, Noad et al. 2019). The high rate of population increase ultimately increases interactions with multiple human activities and the potential for anthropogenic impacts (e.g. vessel strike and ship noise exposure; Peel et al. 2018) during their migration along the Australian coastline and on their breeding ground. The potential impacts to the whales on their breeding ground from vessels include both vessel strike and noise exposure. Humpback whales are well known for their use of song as an acoustic breeding display with a recent study suggesting ships may affect the song behaviour of whales, with whales stopping singing when ships are close (Tsujii et al. 2018).

Spatial habitat modelling of humpback whales in the GBR demonstrates the highest densities of whales in the southern GBR lagoonal region within the GBRMP. Two main areas of higher whale density during peak whale abundance in winter (July – September) are located near the Whitsundays and offshore of Mackay (Figure 19). There does not appear to be any distinct separation of calving versus mating areas, given groups with calves are sighted among groups without calves in both inshore and offshore areas. Although, calving areas (based on groups with calves) generally occur throughout the GBRMP, whereas mating groups are predominantly restricted to the southern GBR. The predicted distribution suggests an inshore coastal distributional movement of groups with calves as the breeding season progresses from July to September (Smith et al. 2012, Smith et al. 2020a, Smith et al. 2020b). The high density area of humpback whales in the southern GBR lagoon is an important wintering area that the whales use for calving and mating during the breeding season and significantly overlaps with the GBR inner shipping route (Figure 19).

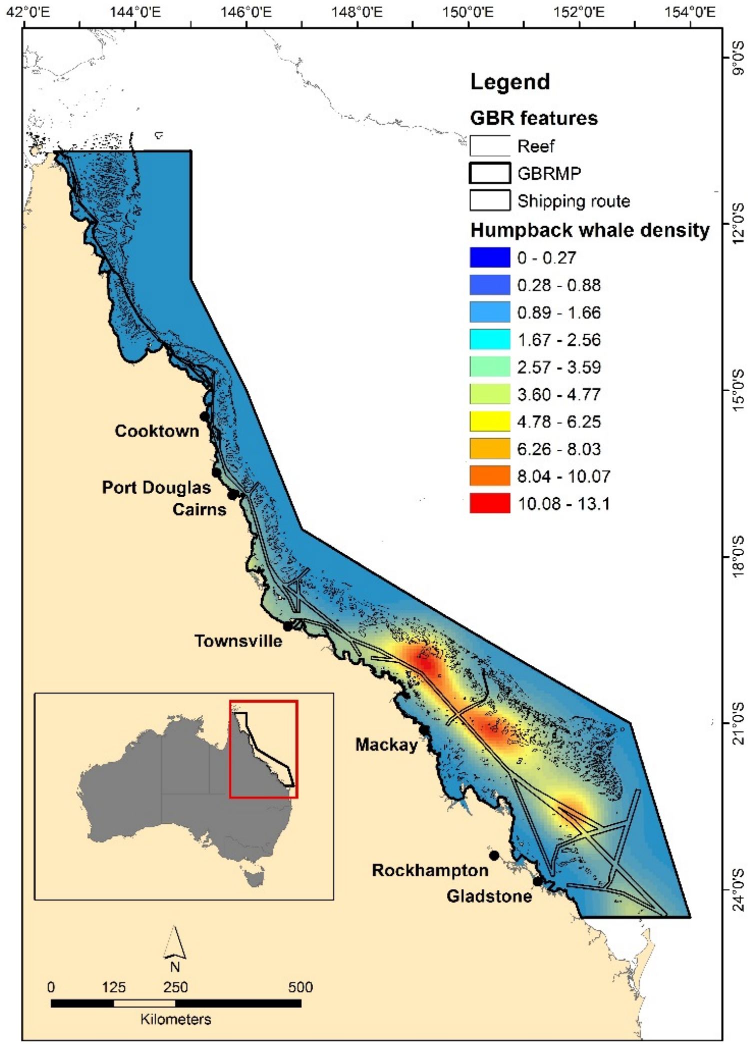

Figure 19 Map of the modelled distribution of humpback whales in the Great Barrier Reef for all animals, including adult and calf groups.

4.2 Species vocalisation and hearing range

To understand the potential impacts of noise on a species of concern, it is important to get an understanding of their hearing sensitivity to know whether the noise can be perceived and whether certain frequency ranges may have a potentially higher impact based on hearing sensitivity.

Humpback whale song and social sound vocalisations range in frequencies from approximately 100 Hz to 4 kHz (Tyack and Clark 2000), with harmonics ranging to at least 24 kHz (Au et al. 2006). The frequency range within which the whales vocalise can provide insight into the hearing range of humpback whales.

Currently, there are no direct measures of hearing for any baleen whale because the animals are too large to conduct the necessary audiogram tests with. The most viable alternative is to simulate the audiogram through modelling the ear functions based on the anatomy (Tubelli et al. 2018). Recent studies based on experimental approaches using the middle ear anatomy suggest the best hearing range of the humpback whale is between approximately 15 Hz and 3 kHz, and potentially up to 9 kHz (Tubelli et al. 2018). Consequently, we see good congruence between their vocalisation range and anatomical hearing tests which suggests humpback whales have very good low frequency hearing, likely between 15 Hz and 4 kHz and an upper cut-off frequency up to 9 kHz.

The median sound pressure levels of the five size class of ships and modelled auditory threshold of humpback whales are shown in Figure 15, and only energy above the audiogram is assumed audible. Animals with better hearing sensitivity at low-to-mid frequencies (50–500 Hz) experience the most ship noise (e.g. baleen whales). The peak of the ships' modelled sound energy is at around 50-60 Hz, resulting in this low frequency noise at higher sound levels remaining audible over the longest ranges, and occurs within the humpback whale best hearing range.

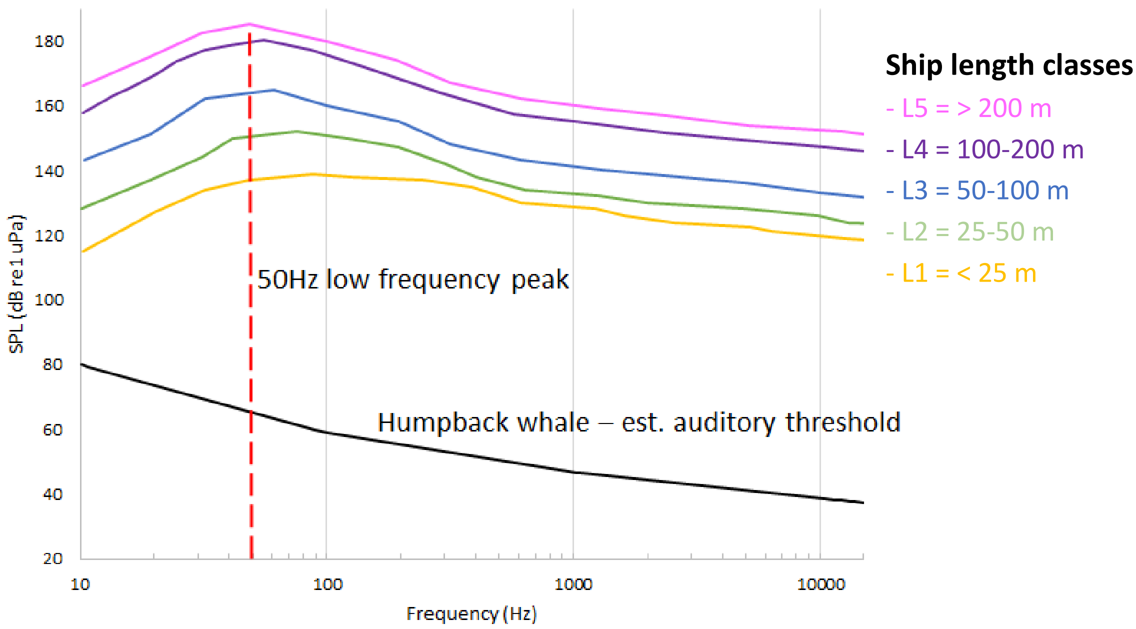

Figure 20. Graph of the median sound pressure levels of five different vessel size classes in dB re 1 Pa@1 m and the peak SPL at 50-60 Hz frequency in relation to the estimated humpback whale auditory threshold. Audiogram data adapted from Erbe et al. 2014.

4.3 Acoustic modelling of the GBR

A small section of the Great Barrier Reef Marine Park was selected to perform a more detailed model. This corresponded to the main area of high humpback whale density within the Marine Park and equated to approximately an 800 x 800 km area (Figure 21). Model results include noise from vessels inside the selected subset of the Marine Park and within a 100 km buffer from the subset. The GBR occupies approximately ~270,000 km^2 of the continental shelf on the northeast margin of Australia (Mathews et al. 2007).

The propagation of sound in the ocean is affected by the hydroacoustic parameters of the water, the geoacoustic parameters of the seafloor, and the bathymetry (Jensen et al. 2011). The bathymetry of this area in the GBR can be broadly divided into the two main areas of continental shelf and slope, with the continental shelf being relatively shallow water depth (0 – 90 m) and the deeper, steep, continental slope (90 - > 4000 m) (Figure 22). Subdivision of the shelf can be partitioned based on shelf-parallel sediment distribution patterns and water depth into an inner shelf (0-20 m water depth), middle shelf (20 – 40 m) and outer shelf (40 – 90 m). The seafloor grain size of surface sediments varies across the Marine Park region, with changes observed between the continental shelf and the continental slope. Generally, sediments on the shelf comprise relatively low amounts of gravel and mud, and high amounts of sand. This differs from the continental slope, which contains less gravel and sand than the shelf and higher mud concentrations (Mathews et al. 2007).

For acoustic modelling of the GBR area of interest, the Geoscience Australia 2009 bathymetry grid (250 m) and temperature and salinity (average of Jun. – Sept.; whale breeding season) from the AIMS eReefs platform (https://ereefs.aims.gov.au/ereefs-aims) at a resolution of 2.5 x 2.5 km were used. Source-receiver transects were extracted in 2.5-km steps out to a maximum range of 100 km for each ship class separately, and clustered into 64 groups for each ship class. Sound propagation over each bathymetry centroid was modelled based on one acoustic environment consisting of a 1 m unconsolidated sediment layer, and a consolidated calcarenite layer as a half space (Table 3) and a mean GBR sound speed profile (Figure 23). RAMGeo modelled sound transmission loss for the centre frequencies of eight full-octave bands (i.e., centre frequencies 16-2000 Hz) over the full range of 100 km and up to 4900 m depth. The source depth was set to 1.5 m for ships < 25 m, 3 m for ships 25 - 50 m, 6 m for ships 50 - 200 m, and 7 m for ships > 200 m (Erbe et al., 2012). Source cells were assigned a received level at 888 m.

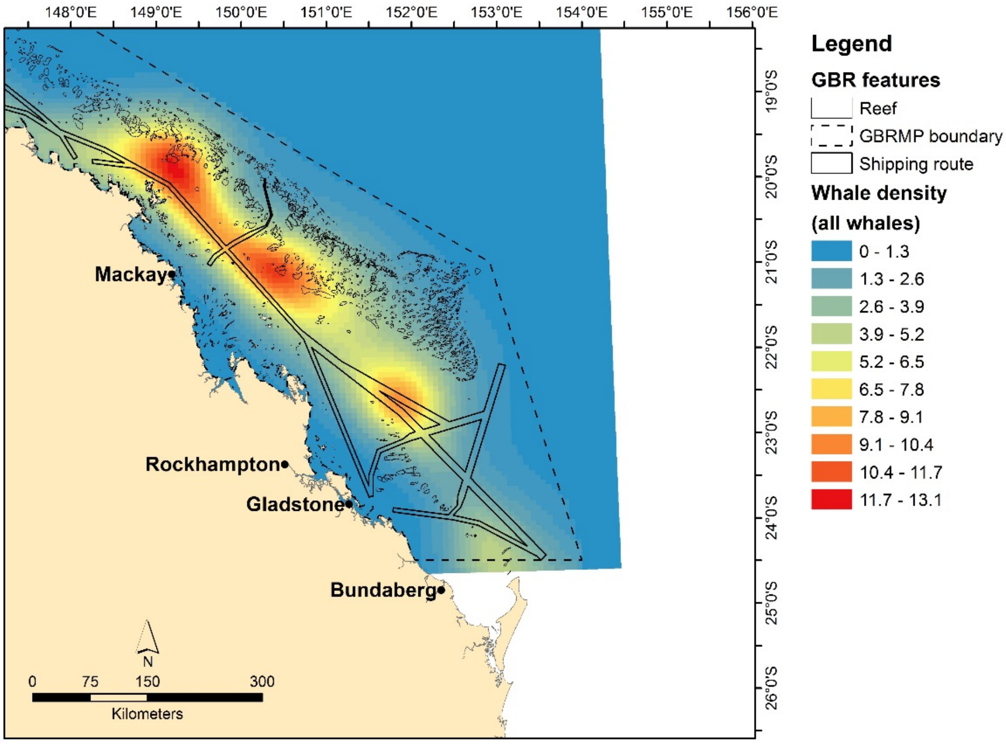

Figure 21. Model of the relative density of humpback whales in the GBR.

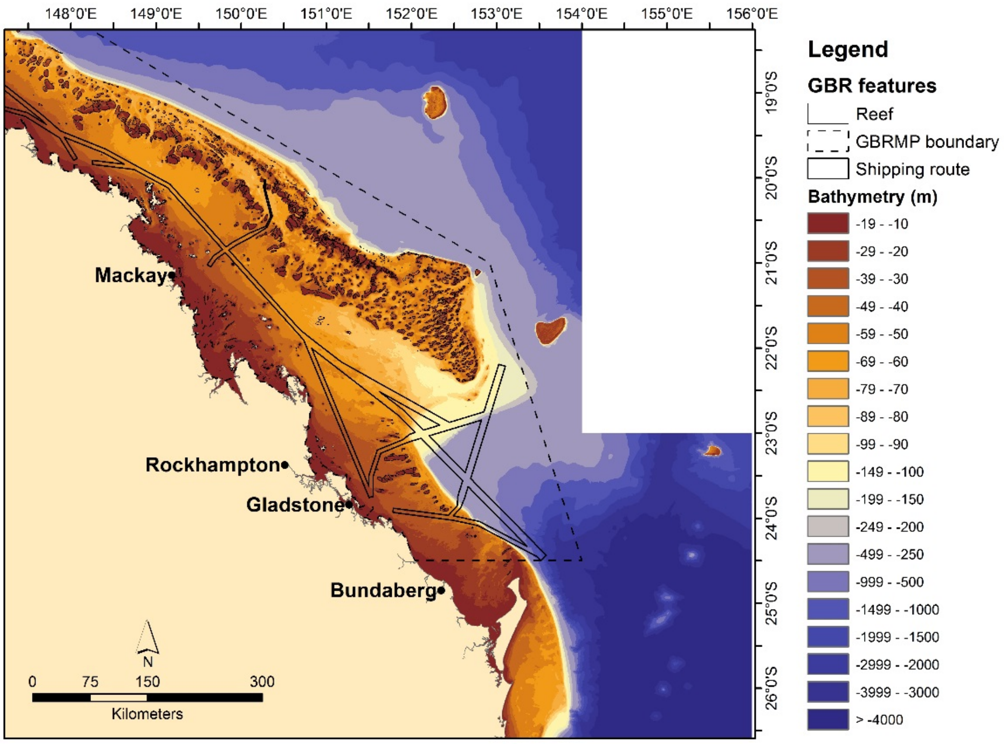

Figure 22. Bathymetry of the Great Barrier Reef and Coral Sea in the area that noise modelling was conducted. Source: Beaman R.J. (2017).

Table 3 Geoacoustic properties for the Great Barrier Reef Marine Park. Unconsolidated properties are from Jensen et al. (2011) and consolidated properties are from Duncan et al. (2009).

Layer	Unconsolidated	Consolidated
Thickness (m)	1	∞
Density (kg/m^{-3})	1873	2400
Compressional wave speed (m/s)	1640	2800
Compressional wave attenuation (dB/λ)	0.83	0.1
Shear wave speed (m/s)	0	1400
Shear wave attenuation (dB/λ)	0	0.2

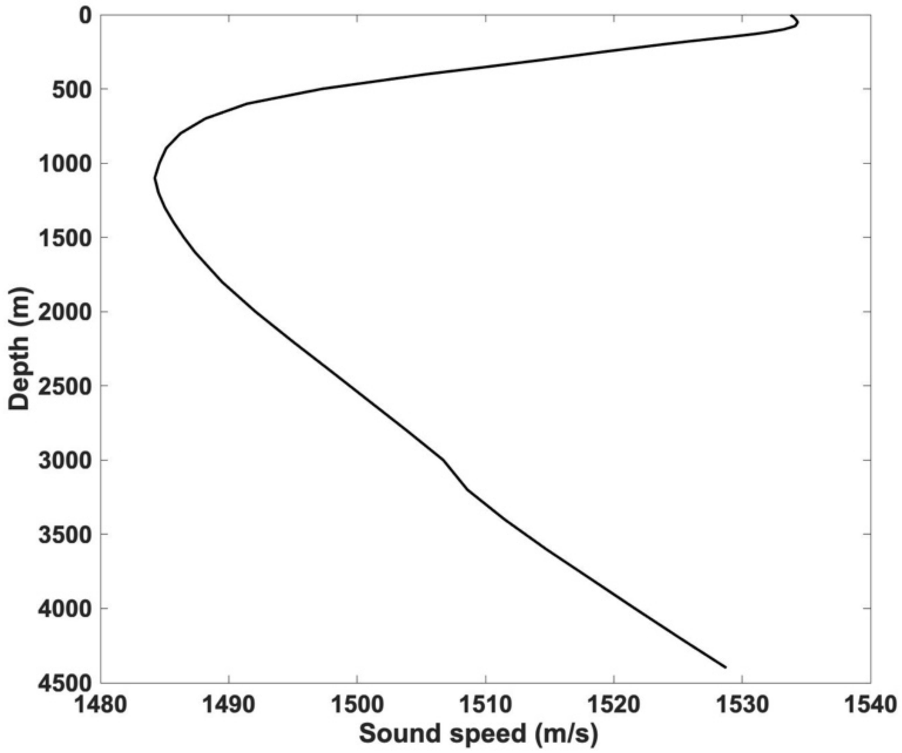

Figure 23. Sound speed profile for the Great Barrier Reef ship noise propagation model

4.3.1 Ship noise and species density models

The following ship noise models for each of the five different size class of ships (Figure 24-Figure 29) show the propagated ship noise levels within the area of highest whale density in the GBR (Figure 21). It should be noted that the scales for ship noise are different for the five different classes, and that noise levels increased as the size of the ship increased (Figure 20). The noise models demonstrate the spatial difference between the different size classes of vessel and different noise footprints.

Ship noise-whale density hotspots

The amount of any species' habitat or Biologically Important Area (e.g. used for foraging or mating) that is affected by noise can be identified by comparing the modelled noise maps and whale density models. This enables us to see areas where noise is high and animal density is high to develop risk maps, indicating where marine spatial planning efforts have the most impact. We can then look at identifying noise hotspots with species of interest or species of conservation concern.

Aside from an overlay of noise models with spatial models, a quantitative approach can also be undertaken to identify noise hotspots for marine species. First, noise maps were normalised and scaled to range from 0 to 1 by subtracting the minimum received energy over all cells from the entire map and then dividing each cell by the maximum received energy. The whale density model was also normalised to 0 to 1 in the same way. The normalised noise model and whale density model were then multiplied to identify noise hotspots for humpback whales. In areas where the ship noise was high (i.e. close to 1) and where animal density was high (i.e. close to 1) the product was high, indicating a ''hotspot''. In areas where either the noise energy or the animal density was high and the other one was low, the product was low (i.e. close to zero) indicating a region of little concern.

Given vessels of all size classes are likely to use the Great Barrier Reef, it is logical to use the cumulative ship noise model of all vessel classes combined to investigate the level of ship noise exposure to humpback whales (Figure 24). However, it is possible to look at certain vessel size classes as well (Figure 25 - Figure 29), which shows us the different areas that vessels are operating. As expected, larger vessels (> 100 m) are using the defined shipping lanes, which is where the ship noise will predominantly be centred, and larger vessels also emit higher noise levels. The relative risk noise hotspot map (Figure 30) shows the largest risk of ship noise exposure to humpback whales is centred in, and around, the inner shipping lane. This is because of the high co-occurrence between whales and ships in these areas (Figure 21 and Figure 24).

Future work

The relative risk noise hotspot maps are capable of identifying areas of high density of whales and high levels of ship noise, although impact studies are required to understand exactly how the whales are responding in the presence of vessels in the shipping lane. An acoustic tracking study of the whales could enable an understanding of how males are spatially responding to vessel noise as well as any acoustic impacts on their song production (their acoustic mating display). This was planned in 2020, although was not able to be undertaken due to COVID-19 restrictions on travel.

We could further refine the model for species other than baleen whales by using audiogram-filtering when developing the noise models. This essentially models the ship noise by filtering it by the animal's audiogram and the frequencies that it is likely to perceive. The audible energy in each receiver cell is then integrated over all ship positions in the same way it has been described in Section 2 of this report. The result is a map representing audible acoustic energy from shipping acoustic energy that may be perceived by the auditory system of the various marine mammals.

Additional efforts are needed to validate these predictions with empirical data and localised in-situ sound recordings. Acoustic measurements collected at ranges greater than the sampled grid size to the main shipping routes are needed to ground truth the model. This will provide an estimate of error to the ship noise models and will enable the ability to correct the fine-scale models of ship noise. It will also provide new ship noise signature data that will inform the ship noise signature estimates of the different vessel size classes that are inputs into the noise models.

Finally, the approach we have undertaken has focussed on larger vessel ship noise, although another important source is likely to be noise from small boat traffic, given many small boats do not log AIS positions and can exist in large numbers in certain areas for recreational fishing, boating or whale-watching. Repeated disturbance from small boats can alter the behaviour of humpback whales. We have accounted for some small vessel traffic which was within the AIS data (Figure 25), although this should be considered an under representation of small vessel traffic noise. However, in the case of humpback whales in the GBR, it is also likely that large vessels might have the greater noise impact because the shipping lane is closest to the high whale density area. Small vessel noise could be important for other marine species of interest.

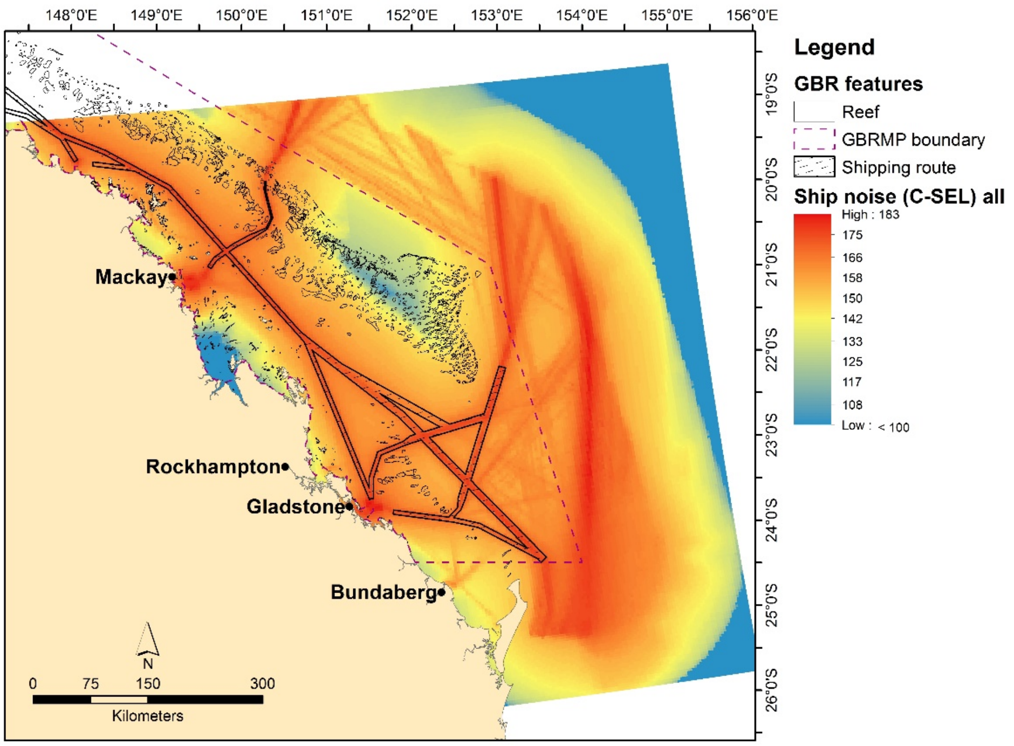

Figure 24 Map of the modelled cumulative ship noise for all vessel types in the Great Barrier Reef and Coral Sea.

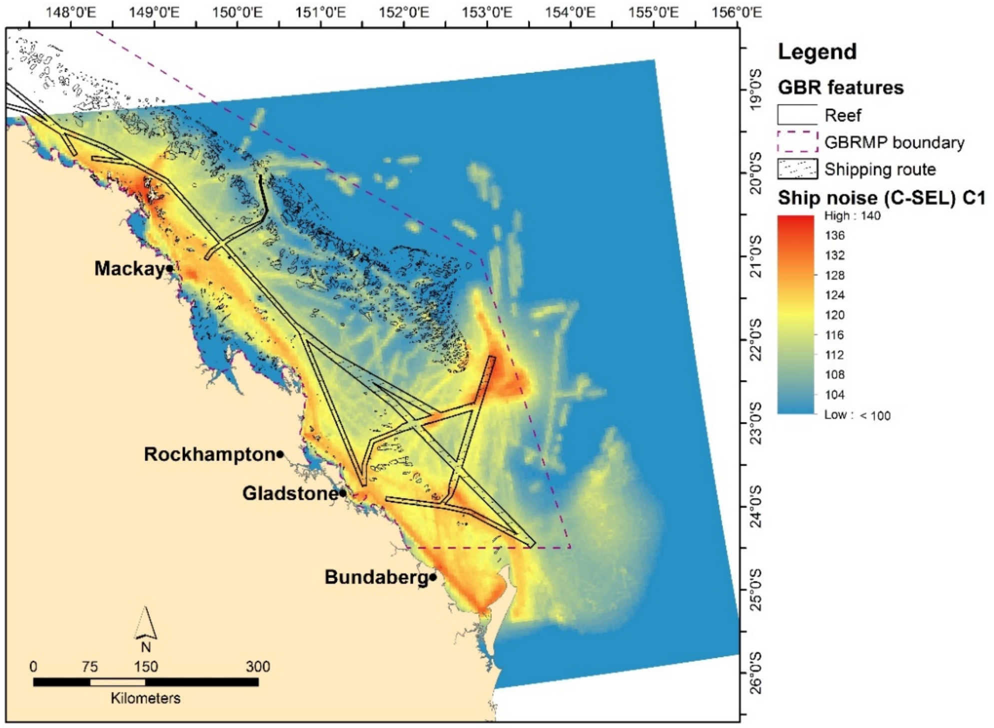

Figure 25 Map of the modelled cumulative ship noise for Class 1 (< 25m) vessel types in the Great Barrier Reef and Coral Sea.

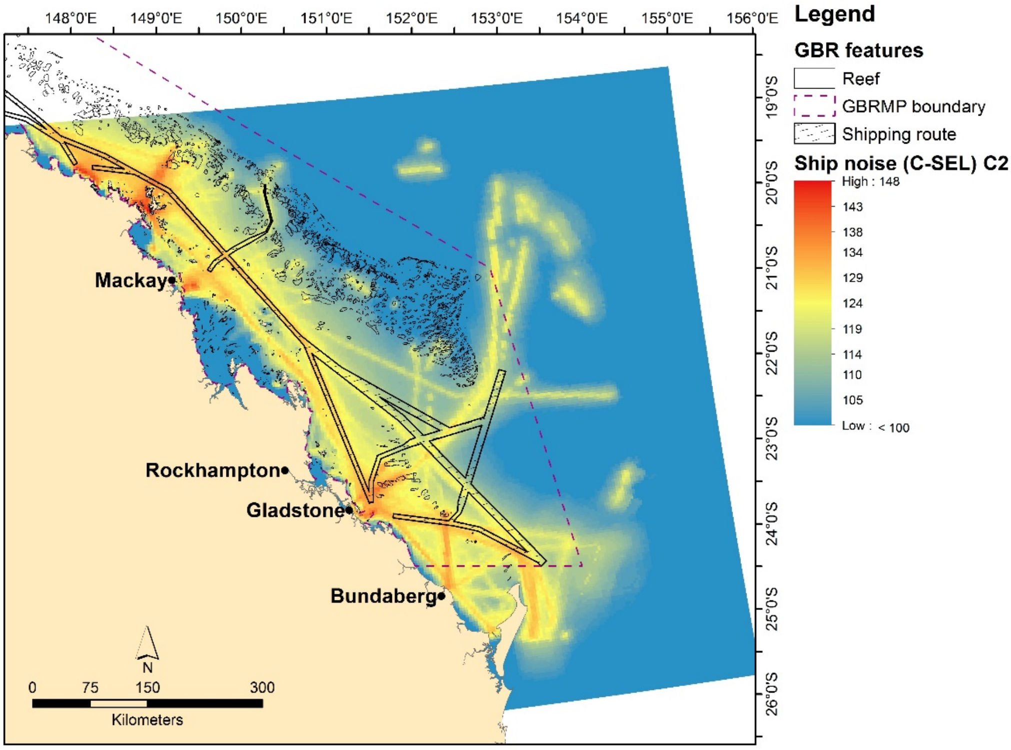

Figure 26 Map of the modelled cumulative ship noise for Class 2 (25-50m) vessel types in the Great Barrier Reef and Coral Sea.

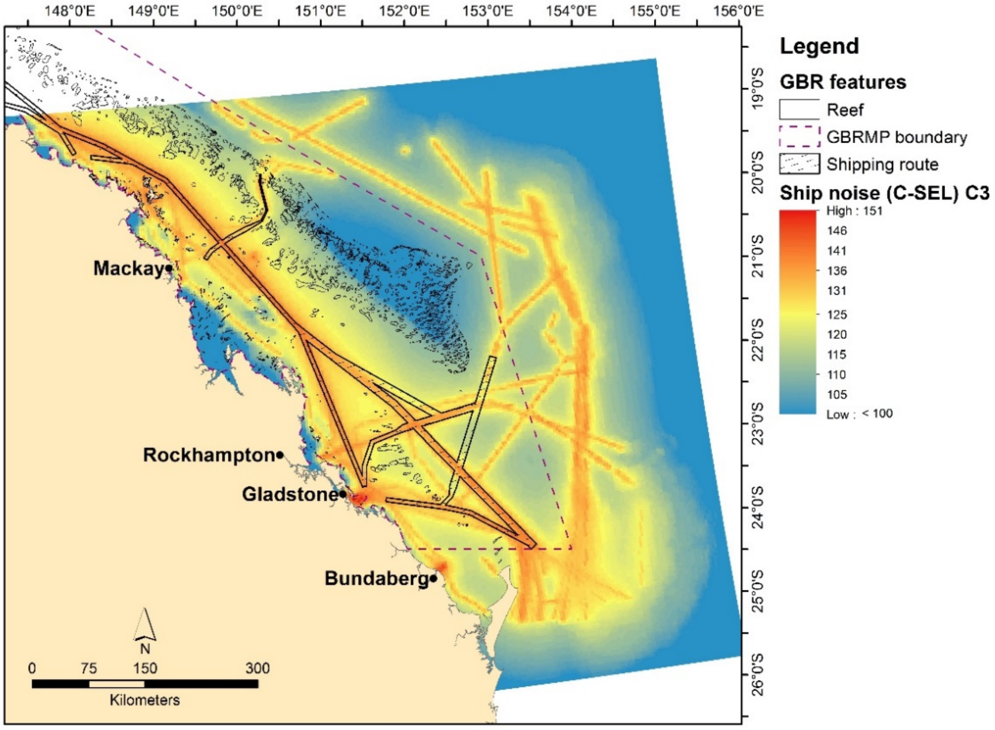

Figure 27 Map of the modelled cumulative ship noise for Class 3 (50-100m) vessel types in the Great Barrier Reef and Coral Sea.

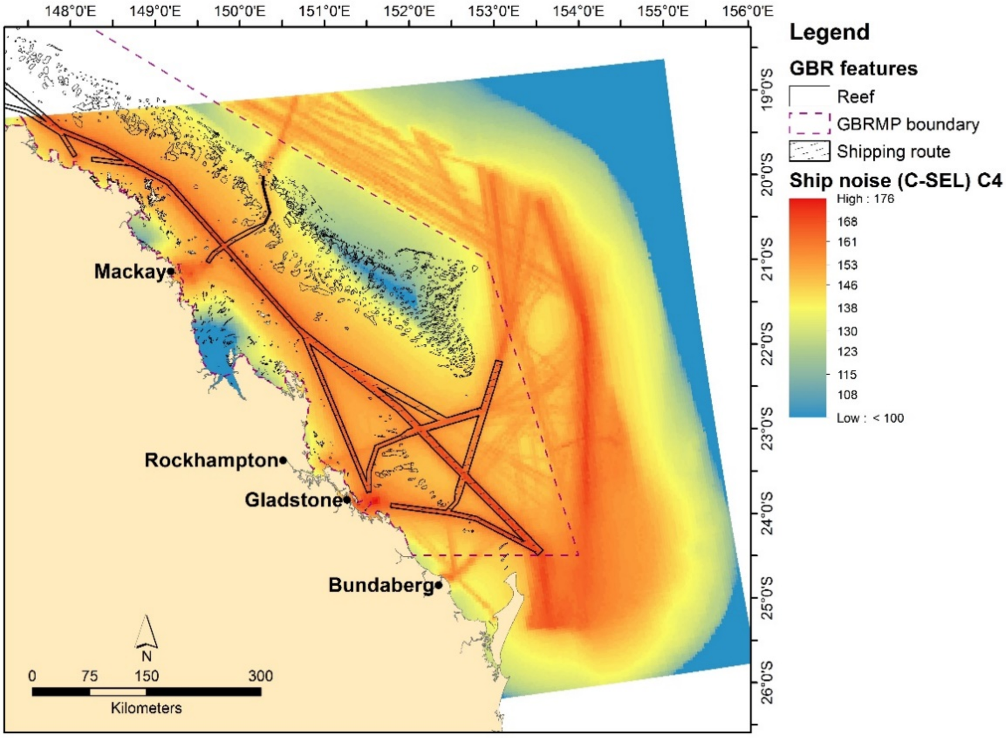

Figure 28 Map of the modelled cumulative ship noise for Class 4 (100-200m) vessel types in the Great Barrier Reef and Coral Sea.

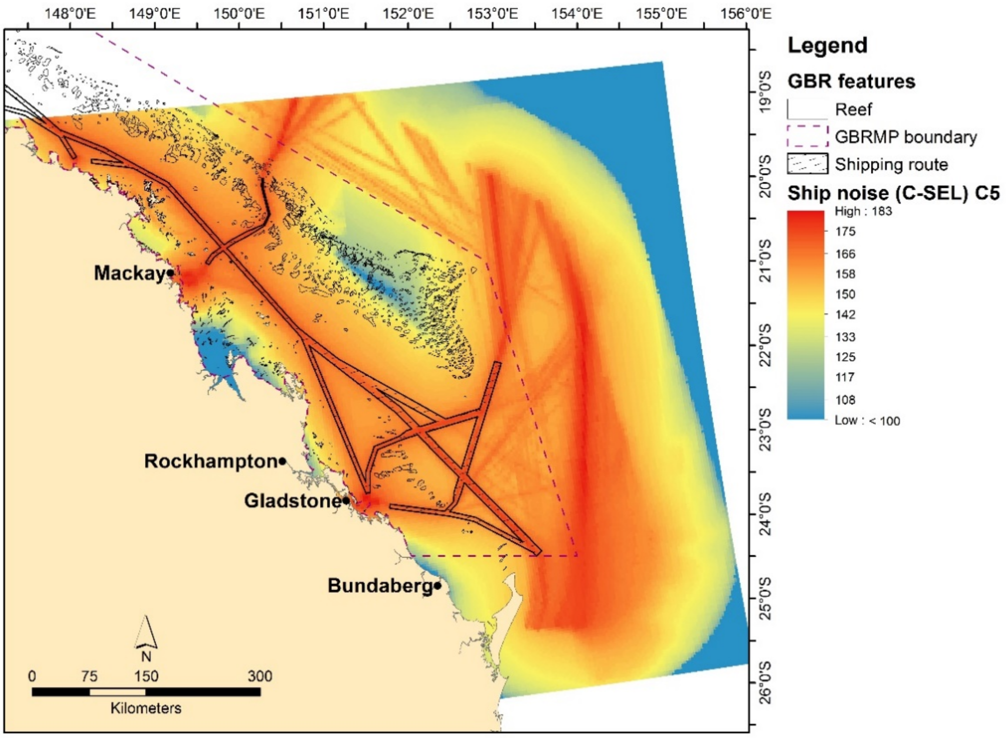

Figure 29 Map of the modelled cumulative ship noise for Class 5 (≥ 200m) vessel types in the Great Barrier Reef and Coral Sea.

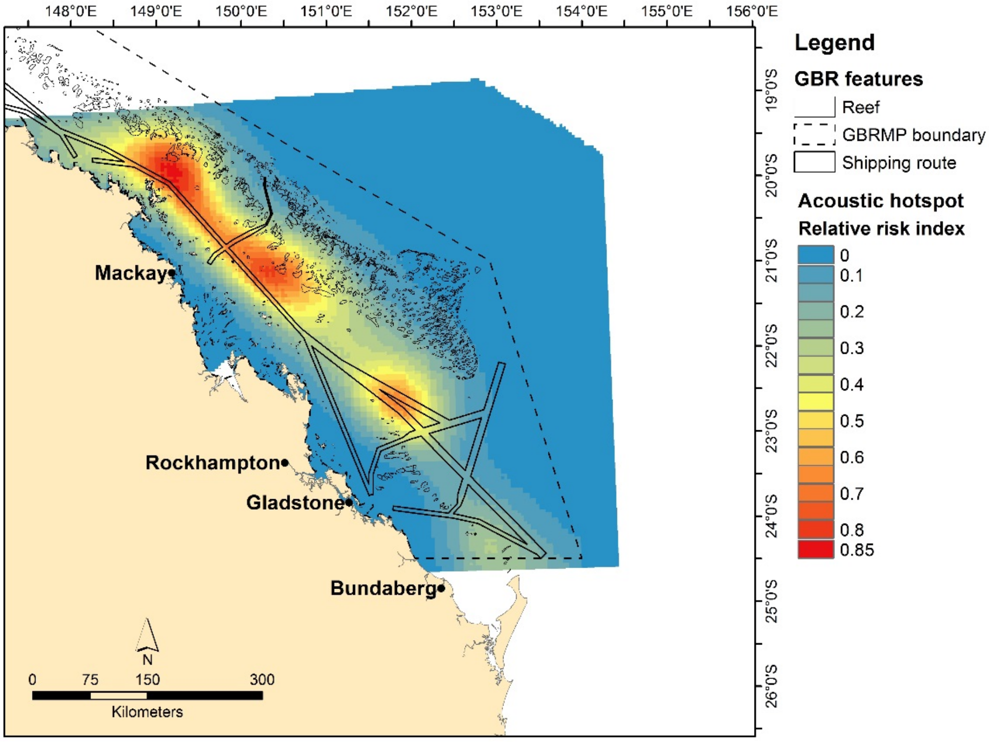

Figure 30 Map of the modelled relative risk of noise exposure for humpback whales in the Great Barrier Reef and Coral Sea.

Conclusion F : MNES Case Study

- Areas of interest, such as the Great Barrier Reef, can be divided up into smaller acoustic zones to enable fine scale noise modelling to more accurately reflect differences in geoacoustic properties, bathymetry features and dynamic oceanographic variables that might change seasonally or monthly e.g. SST, salinity.
- This approach demonstrates the usefulness of the noise models to investigate noise exposure levels on a particular species of interest, which could include endangered species or common species in highly noisy environments.
- Fine-scale noise modelling enables significantly better assessment of noise impacts to species of interest by avoiding the averaging over larger grid cells and accompanying uncertainty in received levels at specific animal locations.

5. SHIP NOISE IN HIGH VALUE CONSERVATION AREAS

Smith, J.N., Erbe, C., Peel, D. and Schoeman, R.P.

The Australian Commonwealth government manages 60 marine parks, 58 of which are managed by Parks Australia, covering approximately 3.3 million square kilometres (or almost 40% of Australia's Exclusive Economic Zone). For the remaining two marine parks, the Great Barrier Reef Marine Park Authority manage the GBRMP and the Australian Antarctic Division manage the Heard Island Marine Reserve. Australian Marine Parks and the GBRMPA are established based on consideration of values, which include natural, cultural, heritage and socio-economic values. The natural values of AMPs include the available habitat, the species and communities that exist within marine parks and the processes that support their connectivity, productivity and function. Typically, AMPs are managed based on a balance of all of these values, to enable their use while managing the pressures placed on them.

Many of Australia's commercial shipping lanes pass through, or near to, Australian Marine Parks. This is particularly evident in Australia's Coral Sea and North-West marine regions (Figure 31), which show high sound levels of shipping noise. Here, we provide a quantitative, evidence-based assessment of the shipping noise as a pressure on AMP values. This research on underwater noise allows us to explore the idea of the acoustic integrity of an area, which can be inter-related to some of the natural values of marine parks. Passive Acoustic Monitoring (PAM) is the approach taken to get a quantification of shipping noise within this study, although this is just one type of noise within the marine environment. PAM has the ability to characterise and quantify many different noise types and their contribution to the marine soundscape of the marine parks and other high conservation value areas.

Focussing on shipping noise as one particular noise source, we are able to quantify and spatially map the extent of this pressure as it relates to AMPs. This is a necessary step for any further investigation of potential impacts to marine fauna from anthropogenic underwater noise. By quantifying ship noise, we have the ability to identify areas within Marine Park Networks that are quieter versus noisier areas, in terms of areas experiencing more or less exposure to shipping noise. This can be assessed in terms of the contribution of shipping noise to the marine soundscape, with quieter areas subject to less exposure to shipping noise (e.g., Gulf of Carpentaria, Great Australian Bight and Tasman Fracture Marine Parks) versus areas routinely exposed to higher levels of shipping noise (e.g., Great Barrier Reef, Coral Sea and Argo-Rowley Terrace Marine Parks). This provides a national perspective that could be used to allocate effort, or identify areas of priority, if the aim is to manage underwater noise and develop guidelines in marine protected areas. These maps could be used for either established Marine Park areas, or for areas under consideration for protection.

Given the marine soundscape consists of various sound sources, including natural physical sounds (e.g., generated by rain, wind, waves, subsea seismic activity, and ice breakup and ridging), biological sounds (e.g., from cetaceans, fish, and crustaceans), and anthropogenic sounds (e.g., from vessels, sonars, offshore exploration, and construction), it is desirable to understand the contribution of particular anthropogenic sounds like ship noise with respect to

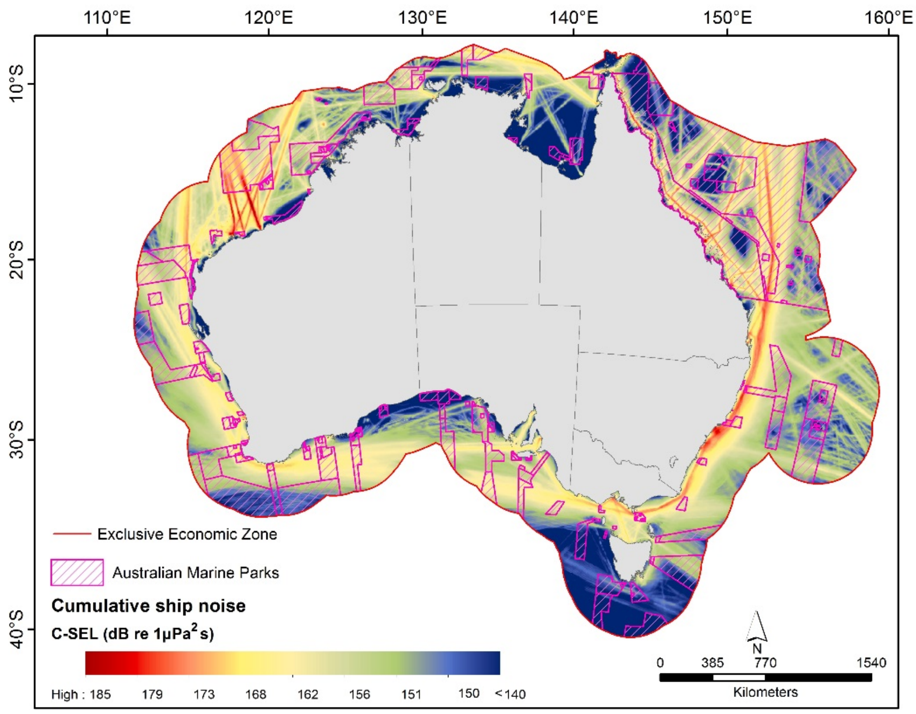

Figure 31. Map of modelled ship noise and overlay of Australia's Marine Parks and GBRMP.

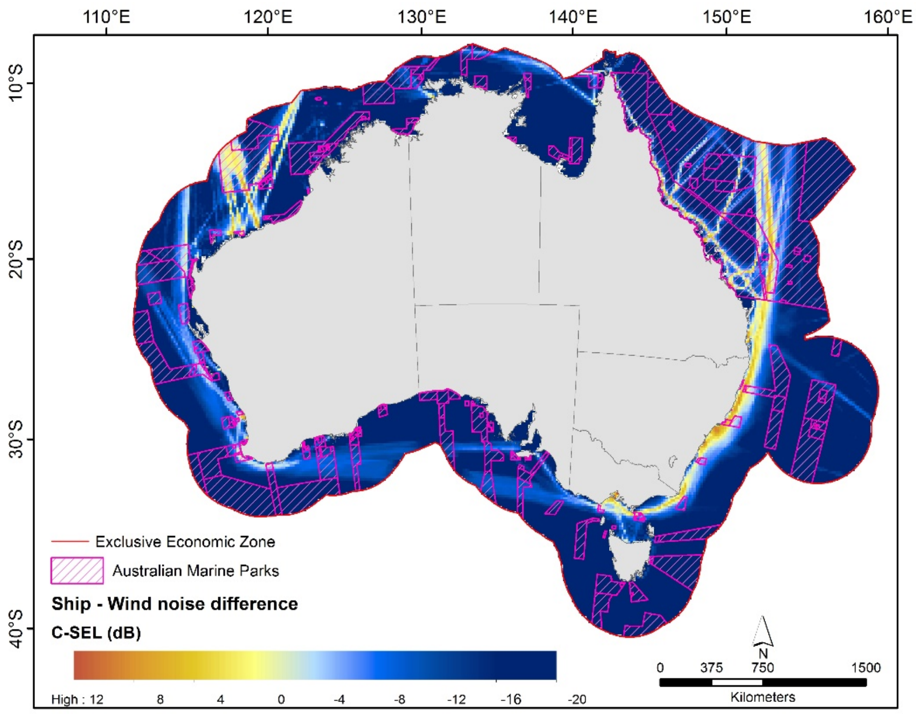

Figure 32. Map of the modelled noise difference between ship and wind noise, overlayed on Australia's Marine Parks and GBRMP.

these other sound inputs. Using the difference between wind and ship noise models, we can identify areas within marine protected areas that have higher contributions of sound levels from ship noise relative to noise from natural processes, such as wind (Figure 32). From a marine spatial planning perspective and managing multiple uses of a Marine Park, this is important information when considering cumulative pressures and other proposed human activities that might add noise to the marine soundscape.

In this section, we have quantified and mapped the cumulative noise levels of ships that have AIS systems. Fundamentally, the noise from ships has been estimated through the use of underwater noise recorders (i.e. hydrophones) using passive acoustic monitoring. Shipping noise is just one particular type of noise input into the marine soundscape and aside from measuring ship noise, PAM can also be used to characterise the marine soundscape and measure natural (e.g. wind), biological (e.g. fish, dolphins, whales) and other anthropogenic (e.g. small boats) noise within marine protected areas. PAM is a viable monitoring approach although realistic expectations need to be set at the outset of the development of any acoustic monitoring program (Mooney et al. 2020).

Given PAM is capable of characterising different noise sources in the marine soundscape, it is also possible to use for monitoring compliance in relation to human presence in no–take areas, such as the occurrence of recreational vessel traffic (e.g. recreational fishers) in sanctuary zones. More work is being done on the acoustic signatures of small vessels, as highlighted in Section 6, which will enhance our characterisation of small vessels in passive acoustic data. Nevertheless, at the very least it has the ability to detect the occurrence of vessels in areas, or at times, that vessels are prohibited, which may inform surveillance monitoring programs.

5.1 Australian Marine Parks and noise: Beagle Marine Park case study

The maps in Figure 31 and Figure 32 demonstrate two ways in which cumulative ship noise models can be used to assess the pressure of shipping within AMP’s. We can spatially quantify the presence and levels of ship noise within a marine park to obtain an understanding of the extent of ship noise as a pressure (Fig. 31), which is a necessary step for any assessment of potential impacts to marine fauna from anthropogenic underwater noise. Using the difference between wind and ship noise models, we can also spatially identify which marine protected areas have contributions of ship noise higher than background (e.g. wind) levels (Figure 32). This is important information from a marine spatial planning perspective when considering cumulative pressures and other proposed human activities that might add noise to the marine soundscape. Table 4 identifies the AMP’s in which ship noise is evident above ambient wind noise levels, reflective of areas of higher industrial activity and/or on major shipping routes. In addition to those listed in Table 4, the Great Barrier Reef Marine Park is also identified as having higher ship noise levels above background wind levels.

Table 4. Australian Marine Parks that demonstrate higher levels of sound in the marine soundscape from ship noise compared to wind-driven noise.

Australian Marine Park Network	Australian Marine Park
Coral Sea	Coral Sea
Temperate East	Central Eastern, Solitary Islands, Hunter
South-East	Beagle, East Gippsland, Apollo
South-West	South-West Corner, Two Rocks
North-West	Argo-Rowley Terrace, Dampier

5.1.1 Beagle Marine Park

We have selected Beagle Marine Park as a case study due to it being identified as one of several Marine Park's that exhibit ship noise levels greater than ambient wind noise, it is a small, high-use commercial/recreational area MP and there is a current and ongoing focus into the immediate future to map the natural values of the MP. This is just one of the MP's that exhibit noticeable levels of ship noise above ambient wind noise (Table 4), and it was not possible to explore all of these MP's. The main motivation was to demonstrate the application of the ship noise maps to a MP of commercial/recreational use that experiences high levels of transiting vessel traffic on a finer scale. Beagle Marine Park lies in the Bass Strait between Victoria's Wilsons Promontory and Tasmania's Flinders Island (Figure 33). There are a number of important natural values that have breeding, nursery, or feeding areas in the vicinity of Wilsons Prom (seabirds, pinnipeds and great white sharks), but an understanding of the implications of this and the use of the Beagle MP by these natural values is limited. This Marine Park provides important foraging grounds for pygmy blue whales and nearby breeding colonies of seabirds. The rich marine life it contains also attracts top predators, such as the great white shark and orcas, although it is possible this is limited to seasonal interactions.

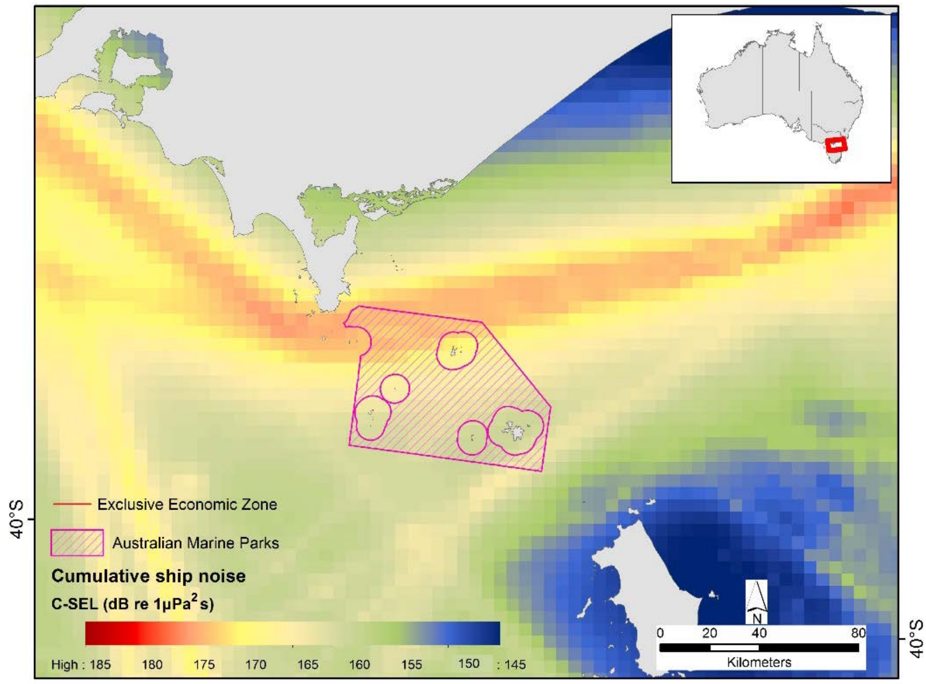

Figure 33. Map of the Beagle Marine Park in Australia's South-East Marine Park Network, with an overlay of cumulative ship noise.

The Beagle Marine Park occurs close to busy shipping lanes of vessels transiting along the Australian eastern seaboard to Melbourne, predominantly in the northern extent of the MP. These northern parts of the Beagle MP exhibit the higher levels within the range of shipping noise similar to other high ship noise areas in Australia, for example in the Coral Sea and North-west Marine Park Network (Figure 33, Table 4). The greater effort of mapping the natural values within the Marine Park will be essential for identifying potential noise impacts on key natural values and enable future spatial risk assessments that could investigate noise exposure. A viable approach for monitoring the occurrence of natural values within the Marine Park, as well as characterising the anthropogenic (e.g. ship noise) sources of noise, could be achieved by establishing a passive acoustic monitoring (PAM) program. A PAM program could effectively monitor identified natural values such as whales, dolphins and fish, whereas acoustic listening stations as part of the IMOS could be used to monitor tagged sharks and fish. The main point to note, is that this type of eco-acoustic monitoring of biodiversity and marine soundscape mapping does not need to be done in isolation. Instead, value to acoustic monitoring is often gained through incorporation of other complementary monitoring methods (e.g. visual surveys). PAM does however, have the advantage of longer-term, autonomous collection of data that can occur 24 hours, 7 days a week.

Conclusion G : High Value Conservation Area

– Passive acoustic monitoring can be a valuable and viable monitoring approach to obtain quantifiable metrics associated with biological occurrence of species and inform on natural values of marine protected areas.

6. QUANTIFYING NOISE FROM SMALL[2] VESSELS IN AUSTRALIA'S COASTAL WATERS

Parsons, M.J.G., Erbe, C., Meekan, M.G., and Parsons, S.K.

6.1 Background

Management of vessel noise initially requires knowledge of vessel numbers, movement, and quantified acoustic signals to model the levels of exposure that individuals may experience over a given spatio-temporal range. This has been realised for large (>25 m) ships through a recent review and meta-analysis on the drivers of radiated noise from these vessels (Chion et al. 2019), and by tracking commercial ships using the global automated identification system (AIS). However, coastal waters and inland waterways are predominantly used by 'small' (<25 m) vessels, for which there is a paucity of data on their acoustic signatures and the drivers of their spectra and broadband source levels. Additionally, many of these vessels do not have to register for AIS and, as most are owned or chartered by the general public, they are predominantly used for recreational purposes. For these reasons, predicting numbers, speeds, directions, time-on-water and idling time etc. of small vessels is a non-trivial task, and one that is ultimately a more complex undertaking than for large ships.

To assist in quantifying the contributions of small vessels to local soundscapes and better understand how different numbers of vessels affect the exposure levels experienced in a given area, this component of Project E2 set the following objectives:

1) Characterise the acoustic output of representative small vessels
2) Review the available literature on acoustic signatures of small vessels and conduct a meta-analysis to characterise the drivers of their estimated source levels
3) Relate sound pressure levels at a given location to the number of passing vessels

[2] <25 m in length

6.2 Characterise the acoustic output of example small vessels

A paper was published detailing this work (Parsons et al. 2020). The following provides an overview of the work.

6.2.1 Methods and Results

This study estimated the radiated noise levels (RNLs) and environment-affected source levels (ASLs) (collectively termed as 'source levels') of three vessels of varying engine power (30, 90 and 180 hp), but similar lengths (each ≈6 m in length) at Lizard Island, Great Barrier Reef, Australia. For each vessel, the closest point of approach (CPA) was recorded at various ranges between 10 and 100 m by ten OceanInstruments ST300 SoundTraps, across a flat, 10 m deep sandy lagoon, for multiple passes at multiple speeds (5, 10, 20, 30 km h^{-1}). Broadband (80-20,000 Hz) and one-third octave propagation losses were determined using linear-regression of the received levels taken at multiple ranges (50-80 measures for each vessel and speed scenario). Backpropagating the received level from each recording using the determined losses produced a total of ≈330 RNLs and ASLs for each vessel. From the slowest to fastest speeds, median RNLs ranged between 153.4 and 166.1 dB re 1 µPa m, whereas estimated ASLs ranged from 146.7 to 160.0 dB re 1 µPa m. The source levels generally increased with speed and power, though the relationship between speed and source level appeared non-linear in the $\log_{10}$-domain and measuring a greater range of speeds would be required to determine the exact relationship. At the slower speeds tested at Lizard Island, almost all energy in all three vessels occurred below 200 Hz and increased up to 10 kHz at the faster speeds, i.e. within the hearing sensitivity range of most fishes and invertebrates, and overlapping with that of many marine mammals. One-third octave band-level RNLs were determined for each vessel-speed scenario, together with their interpolated received levels with range. This provided estimates of the frequency-dependent sound pressure levels received on the seafloor with range from the vessel that could be match to the hearing sensitivity of species of interest.

Conclusion H : Characterise the acoustic output of example small vessels

- Estimated source levels of the three vessels studied at Lizard Island were greater than those for the same size class estimated by the RANDI model.
- Vessels within a given size class and design type can display significant differences in estimated source levels. Indeed, the same vessel recorded travelling at the same speed can display significant variability, depending on the operating conditions.
- Estimated source levels displayed positive, non-linear relationships with speed that differed among the tested vessels. This relationship is therefore potentially vessel-specific and to quantify it requires that measures be taken at a wide range of speeds.
- A meta-analysis of all reported data is suggested to ensure source levels used in propagation models are reflective of those generated by specific vessel types and behaviour at the site of interest.

6.3 Review the available literature on acoustic signatures of small vessels and conduct a meta-analysis to characterise what drives vessel source levels of this size class in Australia's coastal waters

A paper was produced detailing this work (Parsons et al. 2021a). The following provides an overview of the work.

Findings from Objective 1 illustrated that there is significant variability in the source levels of small vessels and that some drivers of small vessel noise may be vessel-, operation- and condition-specific, similar to the findings for large vessels (e.g., Chion et al. 2019). To reliably estimate the source level of any individual small vessel requires the collation and meta-analysis of multiple previous studies, similar to that completed for large vessels. We reviewed the available literature on such vessels and conduct statistical analysis on the drivers of variance in the estimated source levels.

6.3.1 Methods and Results

We assessed available literature and retrieved additional data associated with studies conducted by the authors to construct a dataset of source levels (radiated noise levels, monopole source levels and environment-affected source levels) and associated variables that may contribute to broadband level estimates of small vessels. A total of 17 studies met initial criteria for inclusion in our meta-analysis, that provided data on 11 different vessel types (electric, skiff, monohulls, rigid hull inflatable boat {RHIB}, catamaran, sailing boat, fishing, tug, military, landing craft and cargo). Seven of these studies included information to be used in statistical modelling. We applied a Generalized Additive Mixed Model (GAMM) to the final dataset, which included 1315 datapoints, from 49 vessels, within the four vessel types for which we had sufficient data to generate a reliable model (skiffs, monohulls, RHIBs, and catamarans). Further detail can be found in Parsons et al. (in prep).

Conclusion I : Review the available literature on acoustic signatures of small vessels and conduct a meta-analysis to characterise what drives vessel source levels of this size class in Australia's coastal waters

- There have been relatively few published reports on the source levels of small vessels and only seven since 2000 that provide information on the associated vessel specifications, operations, environmental conditions and analysis techniques to allow statistical modelling of the potential drivers of acoustic output.

- All modelled vessel types displayed a positive relationship between source level and speed, agreeing with the consensus that regulating speed can mitigate instantaneous impacts of vessel noise on marine fauna.

- Data acquisition and modelling methods also affect source level estimates. In particular, low-frequency (<100 Hz) energy can be underestimated if the methods of accounting for propagation losses are inaccurate, or are omitted if the reported bandwidth does not include energy at those frequencies.

- ISO criteria for reporting RNLs cannot easily be met in the coastal waters where small vessels are normally found, and even reports following those standards likely underestimate low-frequency noise. Thus, the development of appropriate shallow-water criteria is recommended for the provision of monopole source levels or environment-affected source levels and a comprehensive study in deep- and shallow-water environments to compare subsequent estimates.

- Reporting broadband level estimates alone is insufficient information to support management decisions. To allow sound levels to be related the frequency-specific hearing sensitivity of marine fauna and facilitate future comparisons of vessel noise studies, octave or one-third octave band levels of every vessel pass should be reported, as a minimum.

6.4 Relate sound pressure levels to the number of passing vessels in an area

A paper was produced detailing this work (Parsons et al. 2021b). The following provides an overview of the work.

The variation in small vessel source levels observed in the Objective 2 literature review and meta-analysis highlighted that the relationship between the number of small vessels and sound pressure levels within an area can be complex. It is not simply a case of identifying the number of vessels, as their physical characteristics and behaviour play an important role in emitted noise levels. This study conducted simultaneous acoustic and visual recordings of vessels passing through shallow water habitats and took the experience gained through that process to provide insights into the information other data sources can provide on vessel usage (e.g. remote aerial imagery, boat ramp surveys, axel counters, supplying handheld GPS units to vessels to understand behaviour).

6.4.1 Methods and results:

We deployed four OceanInstruments ST300 Soundtrap acoustic pressure sensors roughly 1 km from the Coral Bay boat ramp, at multiple ranges (25, 50, 100, 200 m) from a vessel channel leading away from the boat ramp and mooring area. These sensors recorded the sounds of passing vessels and resulting sound pressure levels in the ≈2 m deep waters, for a two-week period in November 2020. On selected days, visual observations were conducted from the boat ramp to assess vessel numbers leaving and arriving at the ramp, passing through the vessel channel, or traversing the waters without using the prescribed channel.

The acoustic and visual data were then compared to investigate relationships between confirmed vessel usage and on-going sound pressure levels. These data were also compared to similar recordings and visual observations taken in the Swan River in November 2016. Further details are given in Parsons et al. (in prep).

Observations made during this study, combined with experience from the previous similar studies contributed to the following qualitative assessment of potential methods to estimate vessel numbers in an area:

- Remote sensing techniques, such as satellite imagery can offer an estimate of vessel numbers and locations, at a particular time of day, but this is only snapshot in time. This information is limited to vessel numbers and a coarse estimate of vessel size only. Given the broad range of potential source levels estimates that would apply to this data, remote sensing alone is likely insufficient data for modelling exposure levels.
- Recreational boating activities are determined by the weather, tide, public holidays, and social events (e.g., Melbourne Cup, AFL grand final). Therefore, predicting the most appropriate sampling time during the day is a non-trivial task.
- Providing GPS units to recreational and charter vessels may provide the exact tracks for a handful of vessels, but this is only a small proportion of the total number using areas where recreational activities, such as fishing or scuba diving are prevalent.
- In some areas, volunteer sea rescue groups will monitor vessels logging on and off, as they depart and return each trip, providing information on usage of some boat ramps. However, many recreational fishers depart early, shortly after sunrise, before the volunteer service commences and, anecdotally (author. pers. obs.), a high proportion of vessels do not log on or off to sea rescue services.
- Axel sensors located at the head of a boat ramp can detect the number of trailer-carrying vehicles entering and departing. However, they do not always count the number of vessels on the water.
- Direct manual or video surveys can provide exact numbers of vessels entering and departing a boat ramp. However, the shallow draft of small vessels means they can depart in any direction, thus boat ramp surveys do not necessarily provide information on the direction vessels take.
- Acoustic recordings can detect passing vessels at significant ranges (>200 m in 2 m of water, over a thick layer of coarse sand and limestone seabed), however, visual observations are required to confirm the range and often whether a single or multiple vessels are present.
- Where vessels exhibit 'milling' behaviour or significantly vary speed, sound pressure levels can exhibit large variations and struggle to confirm whether noise originates from one or more vessels or identify when one vessel arrives and another departs an area.
- The variability in source level and behaviour of small vessels means that, even in speed and space restricted areas, there is significant overlap in received sound pressure levels over a given period.

Conclusion J : Relate sound pressure levels to the number of passing vessels in an area

- Under specific conditions (e.g., spatially restricted areas such as channels, speed restrictions), PAM can provide useful estimates of small vessel numbers in shallow water and assist in validating modelled exposure levels experienced by marine fauna. However, confidence in these estimates is limited when multiple boats are present at the same time or where vessel behaviours vary significantly (e.g., changes in speed or direction).
- The most accurate way to estimate how vessel numbers and behaviours relate to exposure levels in a given area is to combine multiple data sources (acoustic, visual, remote imaging) in a targeted study that includes sampling multiple vessel access points.

7. FEASIBILITY OF ADDING OTHER ANTHROPOGENIC NOISE SOURCES

Erbe, C., Peel, D., and Smith, J.N.

So far, we have presented maps of cumulative sound energy inserted into the ocean by ships and wind. There are a number of other anthropogenic noise sources (see Table 5). Theoretically, any of these other sound sources can be added to the map and their energy input can be compared to those of ships and wind. The question is what type of map is useful to management.

Seismic airgun surveys, for example, are a very different sound source. Compared to ships, which emit sound continuously, seismic airgun arrays produce very brief and broadband pulses in succession. The effects on animals from such pulsed sound are different to the effects from continuous sound. Hence, it might not make sense, from a management perspective, to map cumulative sound energy for seismic airguns. Dredging and mining activities are more comparable to ships in terms of sound emission and so are more readily mapped in terms of cumulative energy. Pile driving for offshore windfarm construction or port development is another pulsed sound, as are military sonars.

In essence, all of these sources can be mapped. There are source levels and spectra in the literature from example recordings of all of these sources. Their sound propagation can be modelled the same as we modelled ship noise propagation. Some of the other sources are highly directional (e.g., seismic airguns) and this directionality can be accounted for in modelling. Received levels can be mapped and accumulated. But what quantity is ultimately useful for the management of noise impacts from this diversity of sound sources is still unclear is some cases.

One developing area of research is to assess pressures (including noise) in a more general risk assessment framework (e.g. NESP Marine Biodiversity Hub project SS2, see Hayes et al. 2021). So, one avenue to deal with the disparate range of sound sources is to treat them as separate pressures within the cumulative risk analysis. It may make sense to first combine comparable sound sources that can be integrated e.g. the chronic noise sources together and similar pulsed sources together.

Table 5 Summary of anthropogenic noise sources

Source	Type	Comment
Commercial Shipping	Chronic	Developed in this project. High resolution positional data available in AIS. Sound source signatures can be collected with acoustic loggers as per this project
Small Vessels	Chronic	See Section 0
Anchored Vessels	Chronic	See Section 7.1
Seismic Exploration	Pulsed	CSIRO data -2010 (See Figure 35) Newer data available here: weblink
Wind Farms	Pulsed (During construction) and chronic (Operation)	Regarding future developments During construction and operation
Port development/ Pile Driving	Pulsed	Coastal and port development projects and associated noise impacts assessed under the Environmental Impact Assessment process
Dredging	Chronic	
Trawling/Fishing	Chronic	VMS and AIS data provide positional data. Fishermen logbook or Statistical models (e.g. Peel and Good 2011) can be used to identify activity and location
Military Operations	Pulsed	Data generally not available

7.1 Stationary Vessels

The noise analysis in this project is for moving vessels (based on a speed cut-off of 0.4 knots to allow for drifting and GPS error). However, with engines running stationary vessels will also contribute ocean noise. We can use the AIS data to establish stationary vessels[3].

So looking at all vessels <0.4 knots we had an issue where AIS coverage was low there were long gaps between polls which gave an indicated low speed but the distance travelled was quite large. So we also used a few extra criteria, such as vessels are not allowed to drift more than 100 m. To remove vessels that were navigating rivers/reefs or turning, we then identified vessels that had spent >4 hours continuously at a location 'stopped'. This gives basically a set of each 'anchorage' event of every AIS equipped vessel in the Australian EZ over a specific calendar year. Each event in the data has a location, length of stay, and size of the vessel (length in m), see Figure 34.

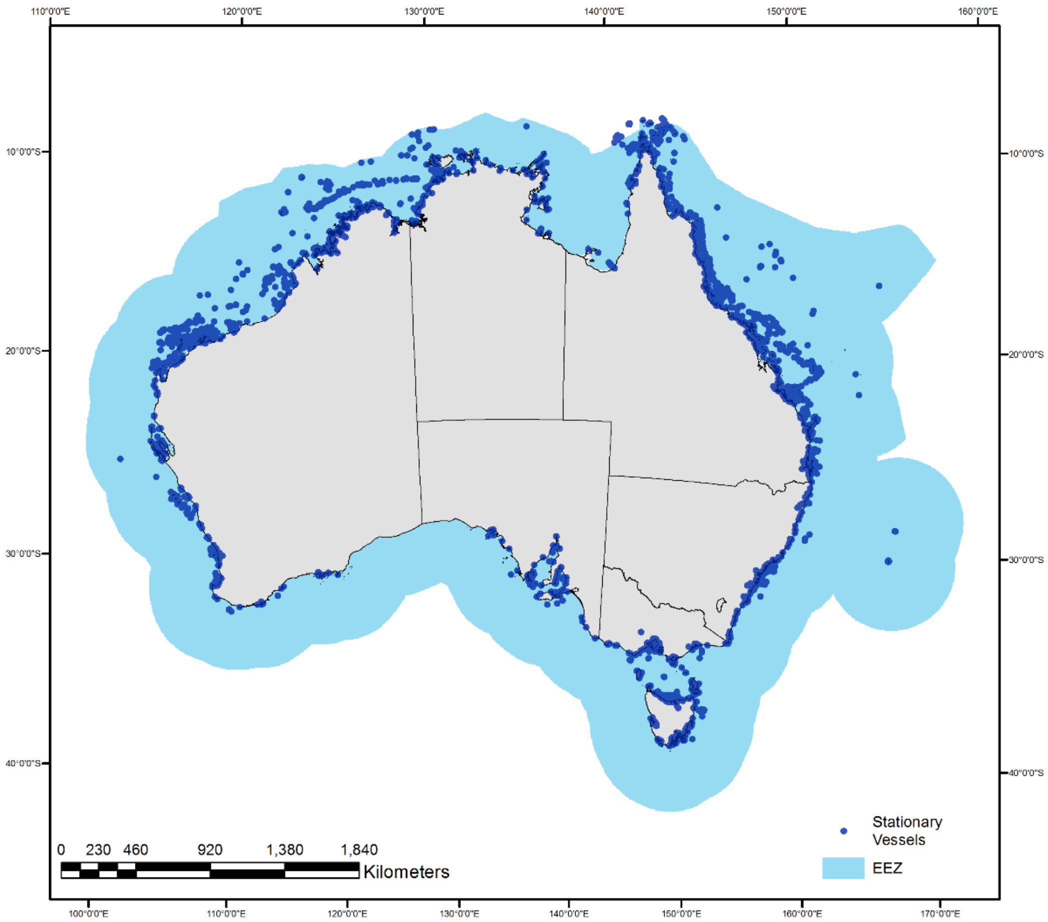

Figure 34 Map of 'Anchorage' events based on movement in AIS data for 2015.

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[3] Due to AIS coverage this will mainly cover larger commercial vessels with smaller recreational vessels will not really be covered well.

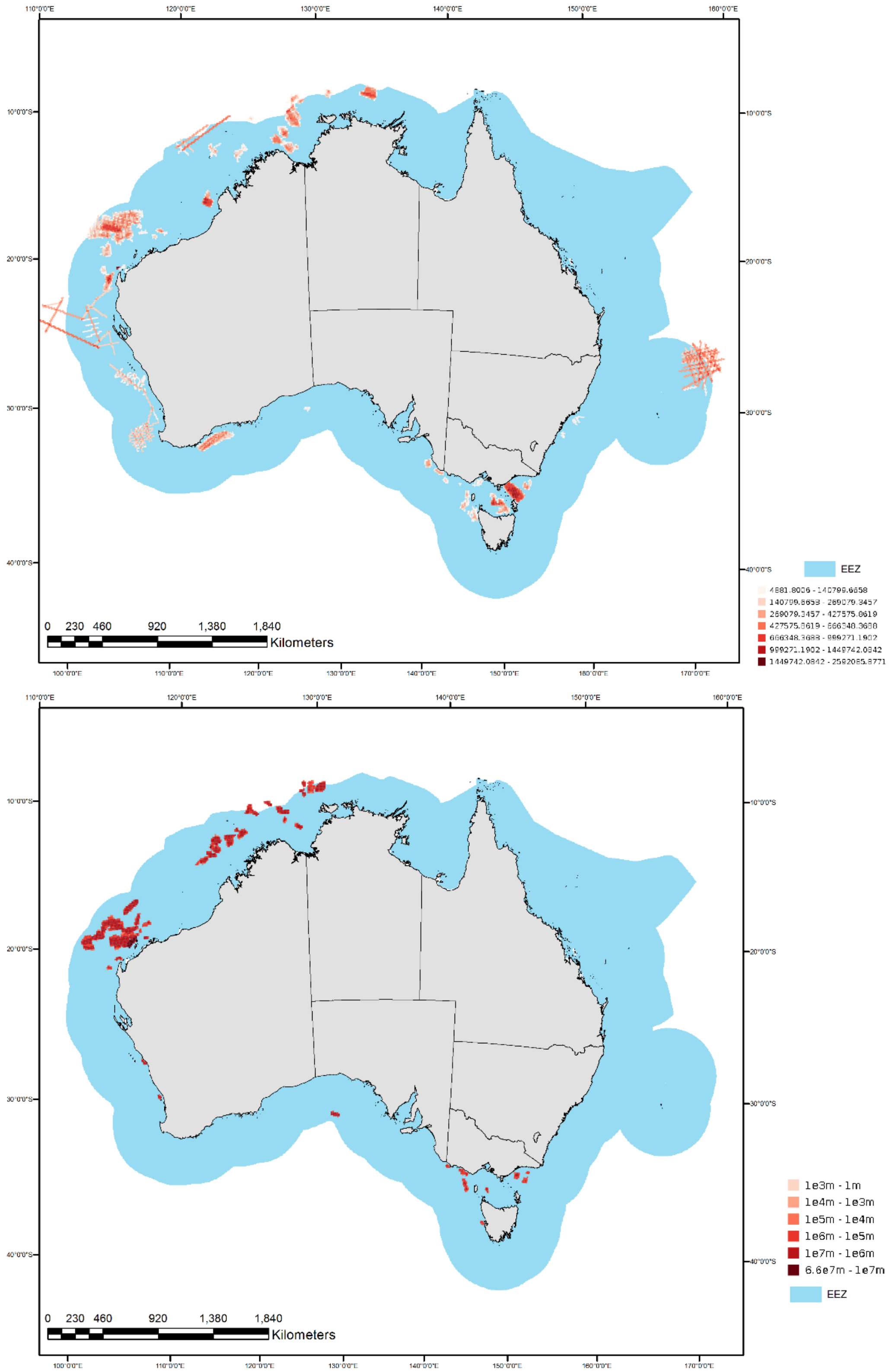
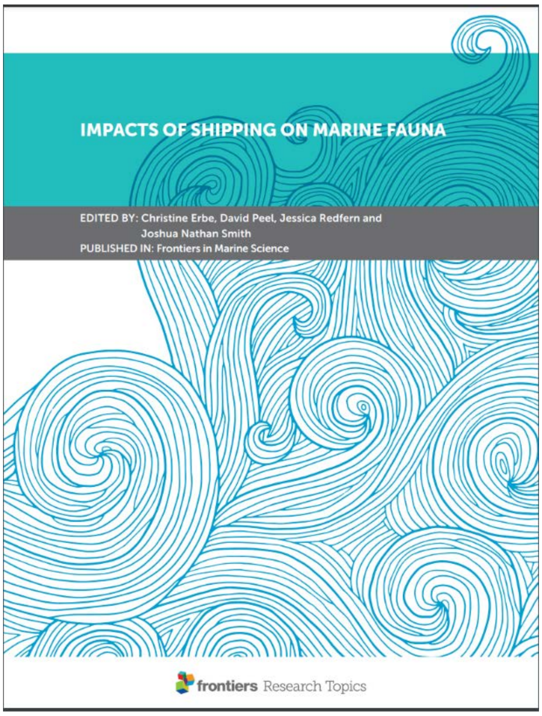


Figure 35 Map of mining seismic activity 2006-2010, 2D surveys (top) and 3D surveys (bottom).See data link

8. MISCELLANEOUS OUTPUTS

8.1 Special Issue publication on the 'Impacts of shipping on marine fauna'

Three of the researchers on this Project E2 on ship noise (Erbe, Peel and Smith) and Jessica Redfern (New England Aquarium), were guest editors on the Research Topic 'Impacts of shipping on marine fauna' for the journal *Frontiers in Marine Science, Marine Conservation and Sustainability* during 2018-19.



The Research Topic consolidates the research on the diverse impacts of shipping, on a variety of marine fauna, with examples from the equatorial regions to both north and south poles. It provides a summary of the current understanding of shipping impacts on marine fauna and the best methodologies for studying these impacts. This culminated in the publication of 23 research articles within the Research Topic covering a range of areas. As editors, an editorial for the Research Topic was also published (Erbe, C., J. N. Smith, J. V. Redfern and D. Peel (2020). "Editorial: Impacts of Shipping on Marine Fauna." Frontiers in Marine Science 7: 637. doi: https://doi.org/10.3389/fmars.2020.00637).

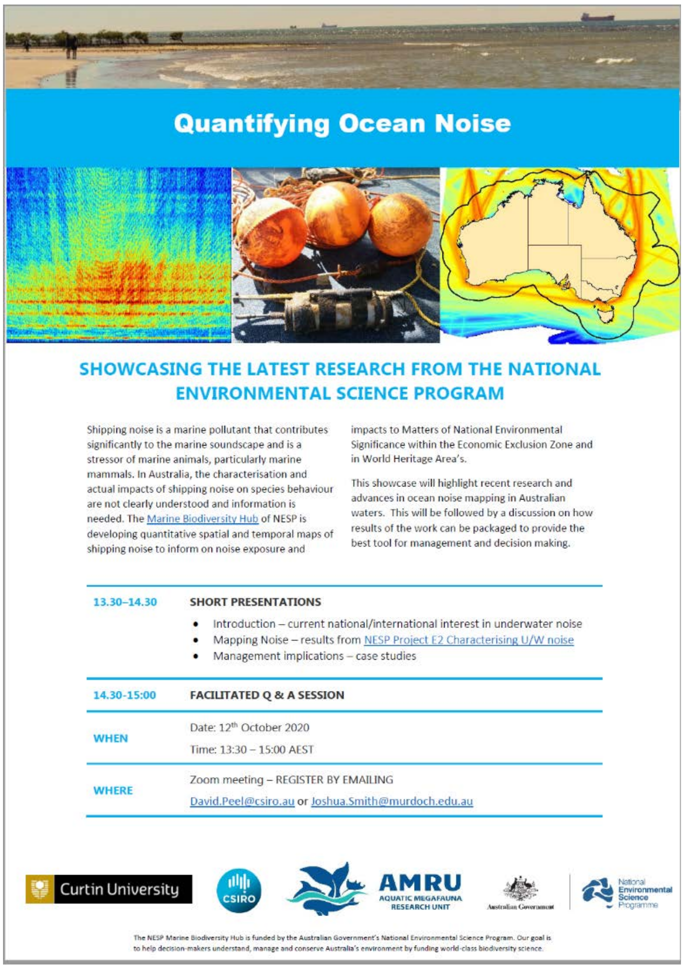
A link to the Special Issue on the journals website can be found here, which also contains downloads for the E-book pdf and E-book EPUB.

8.2 Virtual shipping noise showcase of project outputs

On the 12th October 2020 a virtual workshop was held with stakeholders to highlight recent research and advances in ocean noise mapping in Australian waters. The workshop invited attendees included 35 people from 7 stakeholder organisations: AMSA, CSIRO, Department of Agriculture, Water and the Environment, GBRMPA, Geoscience Australia, Parks Australia, WA Department of Biodiversity, Conservation and Attractions and Maritime Safety Queensland.

The showcase involved a presentation of approach and 3 examples of applications:

1) Putting ship noise into context: Comparison to natural wind-driven noise
2) Species conservation - Quantifying noise exposure on marine wildlife- GBRWHA
3) Identifying quiet areas and human activities in marine parks



9. FUTURE CONSIDERATIONS

- **Need to continuously grow database of ship noise signatures**
  The assessment and quantification of cumulative sound exposure levels of ships is only as good as the input of data into the models. Often inputs of ship noise source levels (i.e. source spectra) into sound propagation models are obtained from more general computer models (e.g. Research Ambient Noise Directionality model) that are not specific to the locale of interest. Consequently, the more comprehensive the dataset of ship noise signatures from different classes of vessels, the more accurate and specific to Australia the cumulative ship noise models will be. We recommend the establishment of a databank of Australian ship source spectra as started by the work from this NESP Marine Biodiversity Hub E2 project (Erbe et al. 2020a), which will allow replacing the RANDI model, with monopole source spectra from actual measurements. More specific data around the different factors that affect noise signatures of ships (e.g. loaded versus unloaded while underway) which can affect the output of the ship's sound levels should also be obtained. This requires a coordinated passive acoustic monitoring program of long-term, moored passive acoustic recorders to obtain the data.

- **Other noise sources in a cumulative framework?**
  We have presented maps of cumulative sound energy for both ships and wind evident in the marine soundscape. An understanding of the ambient (background) noise levels is important to put anthropogenic noise into context. There are many types of anthropogenic noise sources that human activities input into the marine soundscape. Many of these types of noise sources are different types of sound. Seismic airgun noise are very short, broadband, pulsed sounds whereas ship noise is more continuous and pervasive. Ultimately, it will be necessary to investigate the cumulative noise impact from multiple noise sources, although what quantity is useful for management is unclear and requires further exploration

- **Better handling of temporal variation**
  The current noise map is static. However, the ocean and the marine fauna potentially impacted by noise are dynamic spatially and temporally. Temporal noise maps could be produced but to get animal exposure we would also need a better understanding of marine fauna movement rather than static species distribution.

- **Derive meaningful management criteria**
  There is an increasing awareness of the potential cumulative impact from various anthropogenic noise sources on marine ecosystems, which creates the need to develop appropriate measures of impact to alleviate pressure from multiple stressors. There are many approaches that can be taken such as applying noise exposure criteria to determine 'effect zones' which can quantify the percentage of time exceeding a certain threshold. Further work needs to be done to derive meaningful noise criteria to assess impacts of underwater noise on marine fauna.

- **Animal perception**
  Studies that investigate the impact of noise on species of interest could further refine cumulative noise models by developing noise models that are audiogram-weighted to the species of interest. This essentially models the ship noise by filtering it by the animal's audiogram and the frequencies the species are likely to perceive within their better hearing sensitivity.

- **Develop a passive acoustic monitoring program**
  The only way to monitor and quantify underwater noise in a meaningful way that provides consistently collected and analysed data, is to develop a coordinated passive acoustic program. A passive acoustic program could be modelled on the previous IMOS Acoustic Observatories program, which ceased in 2017.

- **Ongoing ambient noise / soundscape monitoring to identify trends.**
  In many parts of the world (e.g. European Union and United States of America) it is part of regulations and law to monitor the input of noise by human activities into the marine soundscape. A co-ordinated program will help to develop long term goals that over several decades can address trends in underwater noise levels. It is difficult to develop hind-cast models to estimate previous levels of underwater noise.

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APPENDIX A – GLOSSARY OF TERMS

AIS

Automatic identification system. Provides a database of vessel positions. See Link.

Clustering

A method to divide data into groups that are similar

Cumulative Sound Exposure Level (C-SEL)

C-SEL is the total sound energy of shipping traffic at any location in space integrated over a specified time period

Frequency

The number of pressure waves that pass by a reference point per unit of time, measured in Hertz (Hz) or cycles per second. Symbol: f. 1 Hz is equal to 1 cycle per second.

Geoacoustic

Relating to the acoustic properties of the seabed.

Hydrophone

An underwater microphone (or transducer) that measures sound pressure, for recording or listening to underwater sound.

Octave

The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

1/3 Octave Band

The energy of sound split into a series of adjacent frequency bands, each being 1/3 of an octave wide.

Received Level (RL)

The sound level measured (or that would be measured) at a defined location, often in the far-field.

Sound Exposure Level (SEL)

Measure of the total energy of a signal over the duration.

Sound Pressure Level (SPL)

The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004).

Sound Speed Profile

The speed of sound in the water column as a function of depth below the water surface.

Source Level (SL)

The sound level measured in the far-field and that is scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. The SL is expressed in terms of pressure (dB re 1 μPa at 1m or sound exposure (dB re 1 μPa2·s at 1 m).

Spectrogram

A visual representation of acoustic amplitude as a function of frequency and time.

Transmission Loss (TL)

The decrease in acoustic intensity, or sound level, between two stated points resulting from an underwater sound wave spreading (propagating or attenuating) away from an acoustic source. Also referred to as propagation loss.

APPENDIX B – AIS DATA PROCESSING

This section contains information on the vessels and Automatic Identification System (AIS) data used in the project.

The Automatic Identification System (AIS) regularly records equipped vessels' locations and other information. There are two types of AIS, Class A and Class B:

Class A – Vessels covered by the International Convention for the Safety of Life at Sea (SOLAS)

- Vessels ≥ 300 gross tonnage engaged on international voyages
- Vessels ≥ 500 gross tonnage engaged on domestic voyages
- All commercial passenger vessels of any size

Class B – Non SOLAS vessels

- For example, domestic commercial vessels and pleasure craft

For more detail see

www.amsa.gov.au/safety-navigation/navigation-systems/about-automatic-identification-system

All the analysis described in the main report used both types. The large Class A vessel coverage is comprehensive whereas for the smaller non-SOLAS craft of Class B coverage is not complete since installing AIS is voluntary.

For this project, raw AIS data was obtained from AMSA for 2013-2020 and processed by CSIRO (e.g. In the raw data, the AIS system can produce multiple entries for a single location from various satellites etc. and hence needs to be cleaned). Furthermore, polling rates can vary considerably depending on location, equipment and vessel density. Therefore, the data was sampled to a minimum 5-minute polling frequency. This sample rate represents a good compromise between data set size and spatial uncertainty due to unknown path/locations between polling (given a typical average/mean vessel speed of ~12 knots, the distance traversed in 5 mins would equate to ~1.852 km).

Summary tables were compiled listing each unique vessel (based on MMSI) and summarising the values in the available data for various information (e.g., length, beam, draught, type, class, name, IMO, etc.). By doing this, we could easily discern vessels with missing or multiple values

This processed data was then filtered and further processed as per rules in the following tables.

Appendix Table 1: AIS line creation validity criteria

FILTERING	CRITERIA	COMMENT
Max polling interval time (Δt)	If $\Delta t \leq 30$ mins then keep	Although the data is sampled at a poll every 5 mins, due to technical issues on some occasions polling is less frequent. We added this limit as beyond that the path/track of the vessel between the poll locations is highly uncertain
Longer polling time (Δt) but straight travel Δcog	If 30 mins $\leq \Delta t \leq$ 60 mins And $\Delta cog \leq 5°$ Then keep	If the polling interval Δt is longer but the vessel seems to be travelling reasonably straight (based on the change in course over ground Δcog), we are still reasonably confident we can interpolate where the vessel was between polls
Longer polling time (Δt) but <u>not</u> straight travel Δcog	If 30 mins $\leq \Delta t \leq$ 60 mins And $\Delta cog > 5°$ Then remove	
Long polling time	If $\Delta t > 60$ remove	If the polling interval Δt is too great, we cannot be certain the path the vessel took and so we delete the transect (the code has the option to leave the start and end points, in the data as they are certain locations, we did not use this option for our analysis)
Ship tracks with apparent positional errors	Distance traversed equates to travel that equates to ≥ 60 knots	Occasionally due to corrupt data, bad gps fix, or a mix up in reported mmsi from another vessel, vessels can jump at impossible speeds. These are removed.
Land	Leave in the data	Due to gps errors or corrupt data, a very small number of locations correspond to land. Any obvious land points will be filtered out automatically at the grid stage.
Valid mmsi only	201,000,000 ≤ mmsi ≤ 775,999,999	Mmsi outside this range are invalid and produced by corrupt data.

APPENDIX C – PROJECT DATA AVAILABILITY

The following data produced by this project is available:

Acoustic Zones of Australia

https://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=0c1bb667-29b2-4848-ade7-a98417121a66

Vessel Noise Map for Australian EEZ

Visualisation Link

https://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=480847b4-b692-4112-89ff-0dcef75e3b84

Ocean Wind Noise for Australian Waters

Visualisation Link

https://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=0d3c7edc-463a-4fa0-8039-4d5a779035c3

Great Barrier Reef fine scale noise

https://metadata.imas.utas.edu.au/geonetwork/srv/eng/metadata.show?uuid=9e27e495-5bd3-4e9c-a956-b387cbefdd4a

Underwater Noise Signature of Ships in Australian Waters

https://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=fa4f8288-5dbf-450a-bfa1-6a83764a94ad

APPENDIX D – LIST OF SUPPLEMENTARY PROJECT PAPERS/REPORTS

The following papers/technical reports were produced in the project and provide detail on much of the methodology detailed in this report:

Erbe, C., Peel, D., Smith, J.N. and Schoeman, R.P. (2021). Marine Acoustic Zones of Australia. *J. Mar. Sci. Eng. 9*, 340. doi: https://doi.org/10.3390/jmse9030340

Erbe, C., Schoeman, R.P., Peel, D., and Smith, J.N. (2021). It often howls more than it chugs: Wind versus ship noise under water in Australia's maritime regions. Journal of Marine Science and Engineering, 9(5), 472. https://www.mdpi.com/2077-1312/9/5/472

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Smith, J.N., Schoeman, R.P., Peel, D., and Erbe, C. (2021) Impacts of shipping on humpback whales in the Great Barrier Reef, in prep.

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