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Article title: Acoustic masking of blue whale calls by ship noise in Northern Chilean Patagonia

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Abstract:

Anthropogenic underwater noise is a threat to baleen whales because it reduces communication space through acoustic masking. Northern Chilean Patagonia is a critical feeding ground for the Endangered Southeast Pacific blue whale (*Balaenoptera musculus*), with substantial levels of overlapping ship traffic. We quantified the effects of ship noise on blue whale communication space with an acoustic masking modelling framework coupled with real satellite-tagged whale tracks and Automatic Identification System (AIS) vessel data. Communication space was estimated for the two blue whale call types (song calls and D-calls) under natural wind-noise conditions, current ship traffic, and simulated 10-knot and 8-knot vessel speed-limit scenarios. Across four tagged whales, current ship traffic noise reduced communication space by an average of 25% for song calls and 47% for D-calls, with maximum masking reaching 68% and 97%, respectively. Masking varied over time according to whale location, bathymetry, wind conditions, and vessel traffic. Vessels >100 m generated the highest median masking, 29% for song calls and 50% for D-calls. Considering all vessel types together, an 8-knot speed limit reduced median masking to 5–9% for song calls and 22–32% for D-calls, depending on the tracked whale. This study is the first to estimate communication masking using real blue whale movement tracks, providing a realistic assessment of the temporal and spatial variability in loss of communication space. Our results demonstrate that vessel speed reduction can simultaneously reduce communication masking and ship-strike risk in the most important known feeding ground for Southeast Pacific blue whales.

Introduction:

Noise pollution is a major threat to wildlife conservation with known effects from the molecular and physiological level up to the scale of community ecology (Barber et al., 2010; Kight and Swaddle, 2011; Shannon et al., 2016). It has been linked to increased stress levels (Blickley et al., 2012), habitat degradation (Ware et al., 2015), reduced antipredator and/or foraging effectiveness (Luo et al., 2015), change in community structure (Bunkley et al., 2017), and communication disturbance (Naguib, 2013), among others. In the case of cetaceans, which are highly dependent on sound as their main sense, noise is known to mask communication (Clark et al. 2009), increase stress levels (Rolland et al. 2012, Williams et al. 2022), modify habitat use patterns (Kavanagh et al. 2019) and trigger abrupt behavioral responses related to mortality by gas and fat emboli (Bernaldo de Quirós et al 2019).

Northern Chilean Patagonia (NCP) is known as a critical feeding ground for Endangered Southeast Pacific blue whales (*Balaenoptera musculus*), where they prey mainly on subantarctic krill (*Euphausia vallentini*) (e.g., Bedriñana-Romano et al., 2018, 2021; Buchan

& Quiñones, 2016; Galletti Vernazzani et al., 2017; Huckle-Gaete et al., 2004). Blue whales produce loud song and non-song calls throughout their migratory range (e.g., Buchan et al., 2014; Romagosa et al., 2020; Stafford et al., 1999, 2009). Southeast Pacific (SEP) or Chilean blue whales present in NCP produce a highly stereotyped regional song dialect, known as “Southeast Pacific 2” or “SEP2” (Buchan et al., 2014, 2015, 2021, 2022). In addition to regional song calls, blue whales also produce non-regionally distinct, highly variable downswept calls or “D-calls” (Thompson et al., 1996), which are also produced by SEP blue whales (Buchan et al., 2021, 2022; Saddler et al., 2017). The long-range song calls are presumed to be produced by males (Oleson et al., 2007) and are thought to serve reproductive function, while D-calls are thought to be short-range social calls produced by both males and females when animals are in close proximity (Lewis et al., 2018) and have been reported during a range of behaviours including feeding (Lewis et al., 2018; Oleson et al., 2007) and possible reproductive behaviours (Schall et al., 2019).

A recent study by Bedriñana-Romano et al. (2021) shows a concerning overlap between marine traffic and blue whale habitat in NCP. This overlap is of concern due to the increased risk of ship strikes (Nisi et al., 2024; Toro et al., 2025; Winkler et al., 2020) and the known masking of whale vocalisations by ship noise (Clark et al., 2009). Communication masking is caused by collective ambient noise (in this case, vessel noise), reducing the ability of a sender and a receiver in two-way communication to effectively perceive, recognize, and decode each other's sounds (Clark et al., 2009). This is inherently difficult to determine experimentally and, therefore, modelling approaches have been used to quantify the effects of masking by estimating the loss of communication space of a vocalising individual (i.e. sender communication space) under natural ambient vs. vessel noise scenarios (Clark et al., 2009; Hatch et al., 2008; Hatch et al., 2012; Pine et al., 2018). For example, Hatch et al. (2012) found that North Atlantic Right Whales (*Eubalaena glacialis*) have lost 63–67% of their communication space due to the addition of vessel noise compared to historical low-noise conditions.

It is important to remember that sender communication space (sensu Clark et al 2009), or sensory volume (sensu Burnham, and Duffus 2023) are theoretical model-derived simplifications and are not the same as the actual communication space (sensu Clark et al 2009) or active space (sensu Burnham, and Duffus 2023). Actual communication space should be derived empirically and is a smaller area where information is successfully transferred between sender and receiver and cannot be known given limitations in our knowledge of audition, cognition, behaviour, motivation and other factors.

Reductions in ship noise levels will reduce the masking, and this could be achieved for individual vessels through 1) ship, propeller, and engine design modifications (Mckenna et al. 2013), and 2) operational speed reductions (Leaper et al., 2014; Pine et al., 2018). Leaper et al. (2014) hypothesize that speed reductions could reduce the overall broadband acoustic

footprint of shipping by approximately 50%-65%. In NCP, a 2023 initiative proposed a 10 kt speed limit to reduce the risk of fatal ship strikes to large whales, which has yet to be implemented, based on recommendations from previous studies (Redfern et al., 2024; Vanderlaan & Taggart, 2007). Also, 8 kt speed limits have been recommended to reduce noise (McKenna et al., 2013). If adhered to, speed reductions could reduce masking risk of vessel noise.

Despite numerous studies of SEP blue whale acoustics in NCP (Buchan et al., 2014, 2015, 2021, 2022) and the high levels of marine traffic described in this area (Bedriñana-Romano et al., 2021), no studies have examined the impacts of vessel noise on blue whale communication space. The goal of this study was to examine the masking effect of vessel noise on SEP blue whale communication space in the NCP feeding ground and the potential effects of masking reduction of potential 8 kt and 10 kt vessel speed limits. For this, instead of simulating animal movements (e.g., Hatch et al 2012), we will use real animal tracks from satellite-tagged blues whales (Bedriñana-Romano et al 2021) and model masking as they move through the study area and encounter real vessel traffic.

Methods:

Modelling approach for communication masking

Our modelling approach was based on Clark et al. (2009) to estimate masking of sender communication space, where sender communication space is defined as the maximum area surrounding a sound-producing blue whale within which acoustic communication with potential listening conspecifics could occur, and where masking is the relative amount of change in sender communication space under varying ambient noise conditions. This was modelled for four satellite-tagged blue whales, on an individual basis, without examining multiple sender communication spaces. For each tagged whale, we calculated the single sender communication space under changing noise conditions, i.e., a) wind noise, b) wind + vessel noise, c) wind + vessel noise with an 8 kt or 10 kt speed limit, along the animal's movement track over a grid of possible receiving animals distributed throughout the NCP study area. This allowed us to examine changes in communications space caused by natural variations in sound propagation (i.e., due to changing bathymetry), natural variations in ambient noise levels (i.e., changes in wind patterns), and increased anthropogenic noise due to encounters with ships (using vessel traffic data) at real speeds and modelling speed limits.

Blue whale telemetry data

A blue whale satellite tag dataset, initially used to study blue whale movement patterns and environmental drivers (Bedriñana-Romano et al., 2021), was used in this study. From this dataset, data from four tagged blue whales (B12, B13, B14, and B15) were selected, as they spatiotemporally matched available vessel traffic data for the study area. The study period ranged from the 4th of February to the 16th of June 2019. The methods used for tagging and analysing telemetry data have been described in detail elsewhere (Hucke-Gaete et al., 2018; Bedriñana-Romano et al., 2021). Briefly, fully-integrated, consolidated satellite tags (Zerbini et al., 2005) were deployed using a custom-modified air-compressed line-thrower in February of 2019.

A continuous-time correlated-random-walk model which accommodates observational error and movement parameters variation in relation to oceanographic variables was implemented for processing raw telemetry data. The tagging methods employed in this study were approved by the Institutional Animal Care and Use Committee of the National Marine Mammal Laboratory of the Alaska Fisheries Science Center, National Marine Fisheries Service, U.S. National Oceanic and Atmospheric Administration. All methods employed in this study were carried out in accordance with the guidelines of the Subsecretaría de Pesca y Acuicultura (SUBPESCA) of Chile, which provided full authorization to conduct this research to RH-G through resolution #221 of the Chilean Ministry of Economy and Tourism.

Study area and receiver grid

The NCP study area included the Corcovado Gulf, Moraleda Channel and adjacent open ocean area, and was centred on the tracks of the four tagged blue whales during the study period (Fig. 1A). To determine communication range for all tracks over the study period, a receiver grid was generated to cover the study area (latitude -70 to -20 degrees and longitude -100 to -72 degrees). A 2 km² receiver grid was created out to 50 km from each whale track; 4 km² from 50 to 250 km, and 8 km² out to 250 km to 2,000 km. This was to optimise resolution near the calling whale (sender) whilst covering the required area and keeping the computational cost manageable. The maximum range (2,000 km) was set so that the SNR would be -6 dB at this range for a Source Level (SL) of 174 dB re: 1 µPa at 1 m (based on Indian Ocean pygmy blue whale SL from Samaran et al. 2010), and a Transmission Loss (TL) rate of $17 \cdot \log_{10}(r)$, with a Noise Level (NL) of ~66 dB (from wind noise model, see below).

Masking calculation

Our masking calculation was based on the calculations in Clark et al. (2009). We have used as many of the same abbreviations as possible, but in some cases, we have modified them for simplicity. At each receiver point in the grid, the SEP blue whale song and D-call receive levels (RL dB) were estimated using a simple, practical spreading-loss model to estimate sound propagation. The propagation model used was intermediate between spherical and

cylindrical spreading, and was obtained for the same latitudinal and longitudinal ranges of the study area from the GEBCO Compilation Group (2023) at 1-arc-minute resolution.

Signal excess (SE) for each point was calculated using RL and the parameters in Table 1: A frequency band of 20-25 Hz was taken for song calls and 38-88 Hz for D-calls (Buchan et al., 2015, 2021). Source levels for song calls were assumed at 174 dB re: 1μPa at 1 m (Indian Ocean; Samaran et al., 2010) and at 166 dB re: 1μPa at 1 m for D-calls, based on measurements in the Atlantic by Berchok et al. (2006). A detection threshold (DT) of 10 dB, a directivity index (DI) of 0 dB, and a signal gain (SG) of 16 dB were assumed, as per Clark et al. (2009). Source-receiver depths (SRD), i.e., the depths of calling and listening whales, were assumed to be 20 m (as per Clark et al., 2009).

Table 1. Blue whale call-specific sound parameters were used in calculations of communication space. Band (Hz) is the low-high frequency range of the ⅓ octave bands used for calculating Rls. SL: Source Level of whale call from the literature; DT: detection threshold; DI: directivity index; SG: signal gain; SRD: source receiver depth.

Call Type	Band (Hz)	SL (dB)	DT (dB)	DI (dB)	SG (dB)	SRD (m)
Song	20-25	174	10	0	16	20
D-Call	38-88	166	10	0	16	20

Signal excess

was calculated by:

$$SE = RL - DT + DI + SG - NL \text{ (eq. 1)}$$

where DT is the detection threshold assumed at 10 dB, DI is the directivity index assumed at 0 dB, and SG is the signal gain assumed at 16 dB (as per Clark et al. 2009). Noise level (NL) was estimated under a) wind noise, b) wind + vessel noise conditions, and c) wind + vessel noise conditions with an 8 kt or 10 kt speed limit (see section below), providing SE values for the entire grid under natural noise conditions (a), vessel noise conditions (b) and an 8 kt or 10 kt vessel speed limit (c).

For each receiver point area (km²), the SE was weighted by a probability of recognition (PR) term, and the sum of all the receiver point areas, weighted by the recognition function, was the sender communication space (CSs) as per equation 2 below (based on equation 12 in Clark et al. 2009).

$$CSs = \sum_{i=1}^R f(SE)_i \cdot PR(SE)_i \text{ (eq. 2)}$$

Where i is the number of receivers,

$f(SE)_i = 0$ for $SE < 0$ dB, $f(SE)_i = 1$ for $SE \geq 0$ dB,

$PR(SE)_i = 0.5 + \frac{(1-0.5)}{18} \cdot (SE)_i$ for $0 \text{ dB} \leq SE \leq 18 \text{ dB}$,

$PR(SE)_i = 1$ for $SE \geq 18 \text{ dB}$.

CSs were then estimated for the entire grid under a) wind noise conditions (CSwind), b) wind + vessel noise conditions (CSvessel), and c) wind + vessel noise with a 10 kt speed limit, and d) wind + vessel noise with an 8 kt speed limit. Communication space loss (CSloss) was calculated as CSwind+vessel (with and without as a percentage of CSwind, i.e., CSs under vessel noise conditions as a percentage of CSs under natural noise conditions (eq. 3) (based on equation 13 from Clark et al. 2009); the inverse of this is the percentage of CSs masking (Ms) under vessel noise conditions (eq. 4) (based on equation 16 from Clark et al. 2009). CSloss and Ms were examined for vessel-noise conditions with and without the 10-kt speed limit.

$$CS_{loss} = \frac{(CS_{wind+vessel})}{(CS_{wind})} \times 100 \text{ (eq. 3)}$$

$$M_s = 1 - CS_{loss} \text{ (eq. 4)}$$

Vessel and wind noise modelling
Vessel automatic identification system (AIS) data were purchased from www.marinetraffic.com. All ships are required to have an AIS if they have a gross tonnage of 300 t or more, or a length overall of 20 m, or carry more than 12 passengers. Small vessels that do not meet the above requirements, which in Chile include most of the artisanal fishing fleet, are not required to carry an AIS and are therefore not included in this database. The tracks for each vessel were then decimated to 10-minute-resolution waypoints. Vessel noise was modelled using vessel metadata derived from AIS data, including latitude and longitude coordinates, vessel class, length, and speed. The SL for each vessel for each 10-minute waypoint was calculated using the model defined in Macgillivray & de Jong (2021). To examine the occurrence of different vessel speeds, we mapped vessel tracks per speed class (< 10 kts, >= 10 kts, >= 15 kts, >= 20 kts, >= 25 kts). To examine the impact of a possible 8 kt or 10 kt speed limit on CSloss and Ms, vessel speeds were capped at these limits, and vessel noise was modelled. We also examined the effect of this speed limit on masking for three vessel class sizes (0-50m, 50-100m, >100m). Supplementary Material Figure 1 shows an example of the method used to cap vessel speed and determine waypoint time changes (from AIS data).

Wind speed data were obtained for latitude -70 to -20 degrees and longitude -100 to -72 degrees from the National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce (NCEP 2015). The NCEP operational Global Forecast System analysis and forecast grids are on a 0.25 by 0.25 global latitude longitude grid. Grids include analysis and forecast time steps at 3-hourly intervals from 0 to 240 and at 12-hourly intervals from 240 to 384. Model forecast runs occur at 00, 06, 12, and 18 UTC daily. Wind noise was modelled using NCEP gridded wind speed data, decimated to 10-minute resolution, and the NL for the grid was calculated using the model defined by Hildebrand et al. (2021). Other sound sources were not taken into account in this analysis, for example, other biological sounds (e.g., other whale species), earthquake and seismic noise, or noise from small vessels not included in the AIS database.

Results:

All four blue whales were tagged within the Moraleda Channel area south of the Corcovado Gulf (Fig. 1). Animals B12 and B14 largely used the open gulf area, with B12 moving into the Pacific in the middle of the deployment. Animals B13 and B15 remained within the channels of the inner sea. This allowed us to examine masking in different contexts, i.e. more or less geographically confined.

Vessel traffic strongly overlapped with the areas where the four tagged animals moved (Fig. 2). Highest vessel densities occurred within the inner sea (Fig. 2). For all vessel speeds, 50th percentile was 8.1 kts, and the 75th percentile was 10 kts and maximum recorded speed was 30.1 kts (Fig. 3). Vessels <50 m and between 50 and 100 m had similar 50th (6.7-6.8 kts) and 75th (approximately 9 kts) percentiles, however very large vessels (> 101m) had a 50th percentile at 11.5 kts and a 75th percentile at 12.8 kts (Fig. 3).

Taking the example of blue whale B12 at time 00:28, Figure 4 illustrates the difference in communication space of each call type under wind-only conditions, highlighting the long-range nature of song calls compared to D-calls. Under wind+vessel conditions, we see a significant reduction of communication space, resulting in 89% masking for D-calls and 38% for song calls at this time. This reduction occurs over open water, where sound propagation, regardless of its source, is unhindered by landmasses.

Masking reached a maximum of 97.3% for D-calls and 68.4% for song calls during the study period. It was on average around $47\% \pm 23\%$ for D-calls and $25\% \pm 20\%$ for song calls, and varied greatly throughout the study period for all four whales and both call types (Figs. 5 and 6). Under all speed scenarios, masking was greater for D-calls vs. song calls. For both call types, masking was reduced by the 10 kt speed limit, and even more so by the 8 kt limit (Figures 5 and 6): Under no speed limit conditions, median masking was 54% (D-calls) and

27% (song calls) for animal B12; 38% (D-calls) and 17% (song calls) for animal B13; 53% (D-calls) and 21% (song calls) for animal B14; and 38% (D-calls) and 13% (song calls) for animal B15 (Fig. 6). Under a 10 kt speed limit condition, median masking was 43% (D-calls) and 16% (song calls) for animal B12; 34% (D-calls) and 14% (song calls) for animal B13; 47% (D-calls) and 15% (song calls) for animal B14; and 33% (D-calls) and 10% (song calls) for animal B15 (Fig. 6); and under an 8 kt speed limit, median masking was 28% (D-calls) and 8% (song calls) for animal B12; 25% (D-calls) and 9% (song calls) for animal B13; 32% (D-calls) and 9% (song calls) for animal B15; and 22% (D-calls) and 5% (song calls) for animal B15 (Fig. 6).

Among all size classes, the ≥ 101 m vessels were responsible for the highest maximum values of masking for both D-calls and song calls. Under no speed limit, median levels (29%) for song calls masking was over four times higher than the other two size classes (7 % for the 51-100 m class; and 3% for the <50 m class) (Fig. 7). For D-calls, median levels (50% masking) for the ≥ 101 m vessels were over twice as high as for the two other size classes (31% for the 51-100 m class; and 16% for the <50m class) (Fig. 7). The 8 kt and 10 kt speed limits had significant impacts on masking, the lower the speed limit the lower the masking. Greatest impacts were seen in the 51-100 m class, and even more so in the ≥ 101 m, and 0% masking was even achieved for song calls with an 8 kt speed limit for the <50m and 51-100m vessel classes.

Discussion:

Animal communication space is inherently variable in marine habitats due to environmental conditions that influence sound propagation, including temperature, salinity, bathymetry, and coastline configuration. Previous work has shown that the detection ranges of blue whale vocalizations can vary substantially under different oceanographic conditions, particularly with varying bathymetry (e.g. Gutierrez et al., 2025). In addition to these spatial factors, temporal variability in ambient noise, particularly driven by wind (e.g., Hildebrand et al. 2021), further contributes to fluctuations in communication space, as illustrated by Figures 4 and 5. Other natural noise sources, such as seismic activity (e.g., Hildebrand et al. 2009), are likely to contribute to this variability as well.

In addition to natural variability, vessel noise is known to be a major driver of communication masking as we show in this study, and found in many other studies e.g., Clark et al., (2009); Hatch et al., (2008); Hatch et al., (2012); Pine et al., (2018). Average masking of 47% for D-calls and 25% for song calls over the study periods and across all animals, indicates that this stressor should be considered as part of the conservation of the Chilean blue whale population. Masking was higher for D-calls compared to song calls because they have smaller propagation ranges (due to lower source levels and higher frequencies) and given that these call types have different functions, the impact of masking may affect behaviour and biological processes differently. Song calls are thought to serve

as a long-range reproductive display by males only (Oleson et al., 2007), whereas D-calls have been reported in social, foraging (Oleson et al., 2007), and possible reproductive scenarios (Schall et al., 2019) where individuals are in close contact. Our results show that ship noise disproportionately impacts close range social communication.

Masking was overall higher for animals B12 and B14 compared to B13 and B15, which can be explained by use of different parts of the study area due the combined action of two possible effects: a) Differences in overall communication spaces between different parts of the study area, where overall space is lesser for B13 and B15 compared to B12 and B14 due to more geographically constrained contexts (shallower water column and confined bodies of water) so masking has little effect on an already limited communication space. b) Differences in vessel types between different parts of the study area, where larger, louder vessels are more likely to use open gulf areas, leaving smaller quieter vessels using the confined channels.

The implementation of vessel speed restrictions demonstrated a clear reduction in masking. Across all individuals and call types, both 10 kt and 8 kt speed limits reduced median masking levels, with greater reductions observed at lower speeds. This pattern is consistent with previous studies showing that reductions in vessel speed can significantly reduce acoustic impacts. For example, Pine et al. (2018) reported reductions in communication masking ranging from 25–43% in belugas, 15–27% in bowheads, 16–33% in bearded seals, 24–33% in ringed seals, and 2–8% in cod under a 10-knot speed limit, depending on vessel type. Vessel size also played a key role in determining masking levels. The largest vessels (≥ 101 m) contributed disproportionately to masking, with median levels for song calls over four times higher than smaller vessel classes, and more than double for D-calls. Speed limits (10 kt and 8 kt) had the greatest impact on masking for these larger vessels, indicating that management measures targeting this class could yield substantial masking reduction benefits.

From a management perspective, reducing vessel speeds to 10 kt provides measurable improvements in communication space, while an 8 kt limit yields even greater reductions in masking. Marine traffic mitigation strategies must also consider ship strike risk, given evidence of particularly high ship strike rates in Chilean waters (e.g., Bedriñana et al. 2018, Toro et al. 2025). The largest vessels, responsible for the highest masking, account for the majority of fatal ship strikes, and the probability of lethality exceeds 0.80 at speeds above 5 knots (Garrison et al., 2025). Vessel speed reductions have been shown to reduce strike risk, with compliance rates of up to 95% associated with estimated reductions in modelled mortality of 21–29% (Rockwood et al., 2021).

Vessel speed limit decisions must also consider the costs and benefits to the shipping industry and broader societal impacts. As outlined by Wolfe and Mathis (2023), costs to vessel operators that may increase under speed reduction measures include vessel capital

costs, administrative and overhead costs, inventory carrying costs, container capital costs, and auxiliary fuel costs associated with longer transit times. In contrast, reduced vessel speeds can decrease main propulsion fuel consumption and the associated fuel expenditures. The authors further show that speed reductions generate societal benefits through lower emissions of greenhouse gases and air pollutants, resulting in reduced societal costs associated with climate change and impacts on human health. Lastly, for all vessel speed reduction measures, it is important to consider a safety deviation provision, which can allow mariners an exemption from speed limits under any conditions that restrict vessel maneuverability and prevent safe navigation at low speeds. Beyond speed limits, alternative means of reducing underwater radiated ship noise should also be considered, particularly vessel and propeller design (McKenna et al., 2013). In recent years, the shipping industry has made significant efforts to reduce noise (Spence, 2025).

This is the first study to use real tagged blue whale tracks, rather than animats, to model blue whale communication space and masking. These results highlight the susceptibility of low-frequency baleen whale communication to impacts from anthropogenic noise, particularly in areas of high vessel density, as shown in previous studies in other parts of the world (Clark et al., 2009; Hatch et al., 2008; Hatch et al., 2012; Pine et al., 2018). These results demonstrate that vessel speed reduction is an effective mitigation measure for reducing both acoustic masking and collision risk. The strongest benefits for noise reduction are achieved at lower speeds (8 kts) and for larger vessels (≥ 101 m), which are the primary contributors to both noise and ship strike mortality (Garrison et al., 2025). Integrating speed management into conservation strategies in seasonal high-use whale habitats, such as the inner sea and adjacent oceanic areas of NCP, could therefore provide substantial conservation and ecological benefits.

Figures:

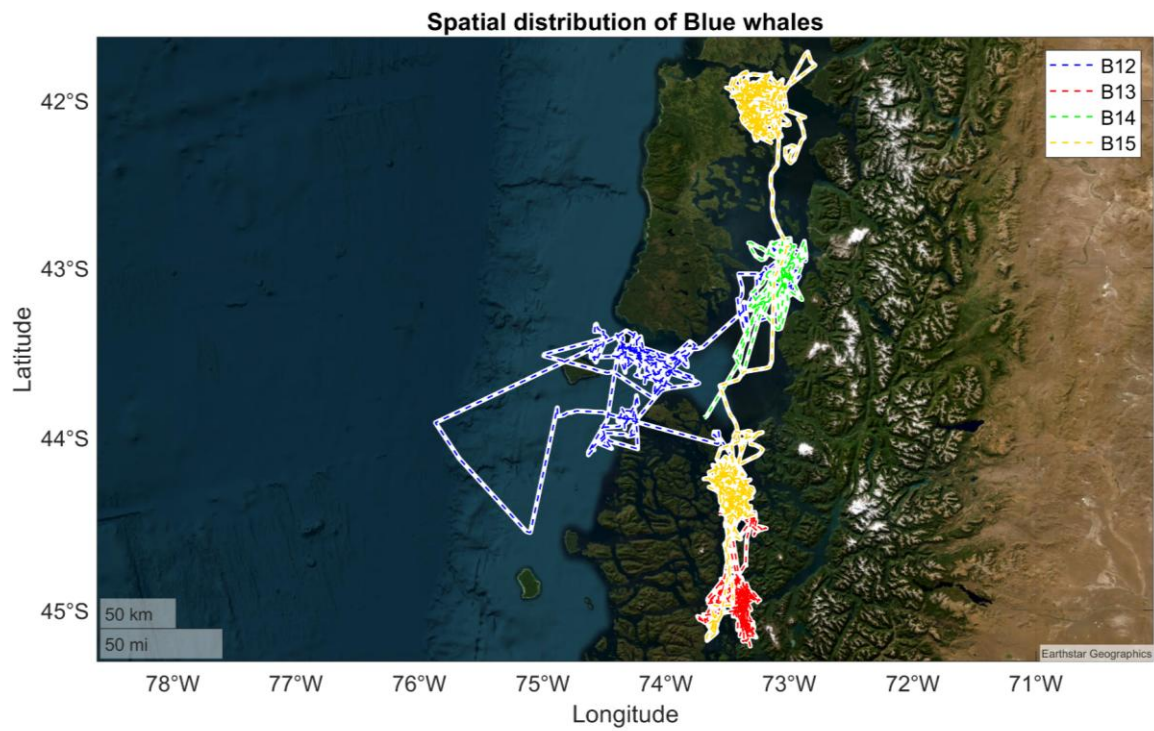


Figure 1. Movement tracks of the four tagged blue whales included in this study, B12 (blue), B13 (red), B14 (green), B15 (yellow), from Bedriñana-Romano et al. (2021).

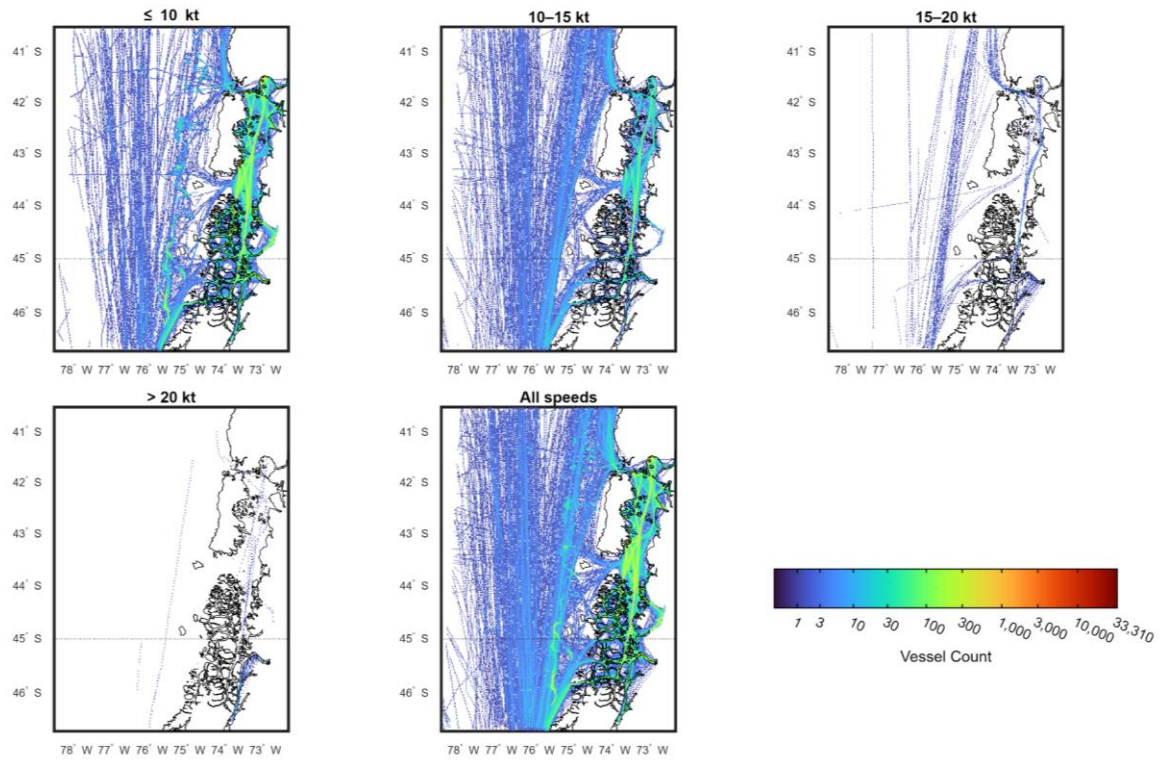


Figure 2: Spatial distribution of vessel speeds (≤ 10 kt, 10-15 kt, 15-20 kt, >20 kt) in the study area.

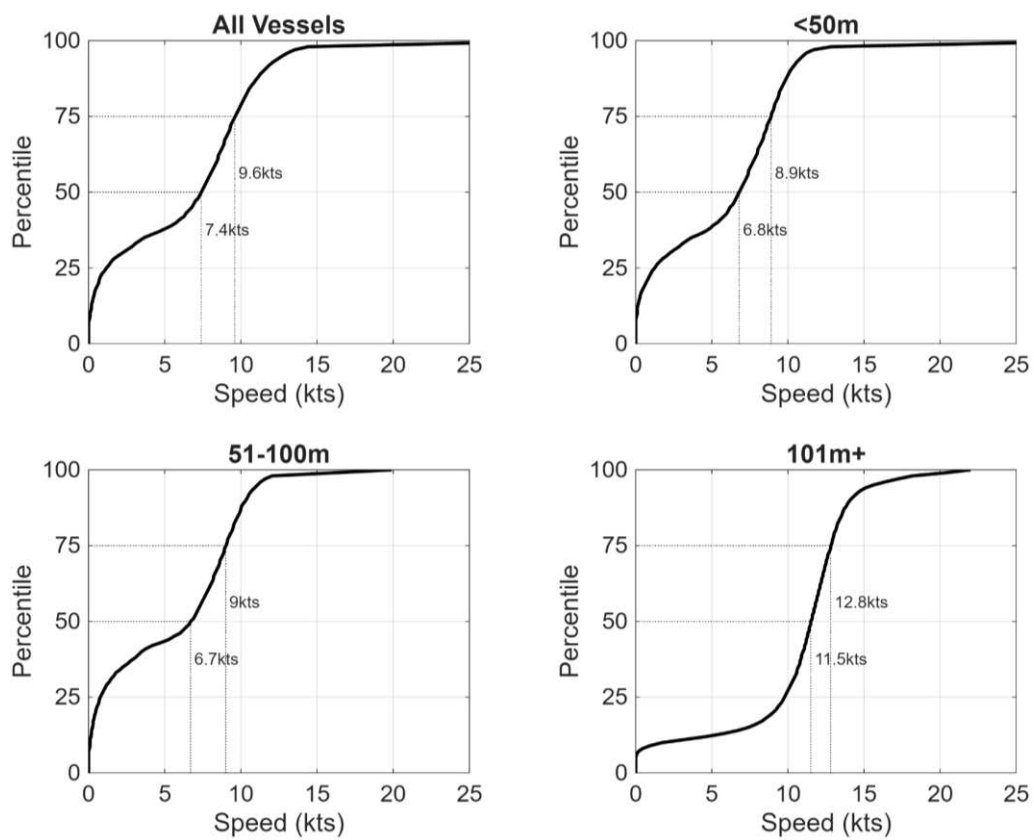


Figure 3. Distribution of vessel speeds (kts) in the study area per vessel size, showing a) all vessels, b) <50 m, c) 51-100 m, d) >101 m.

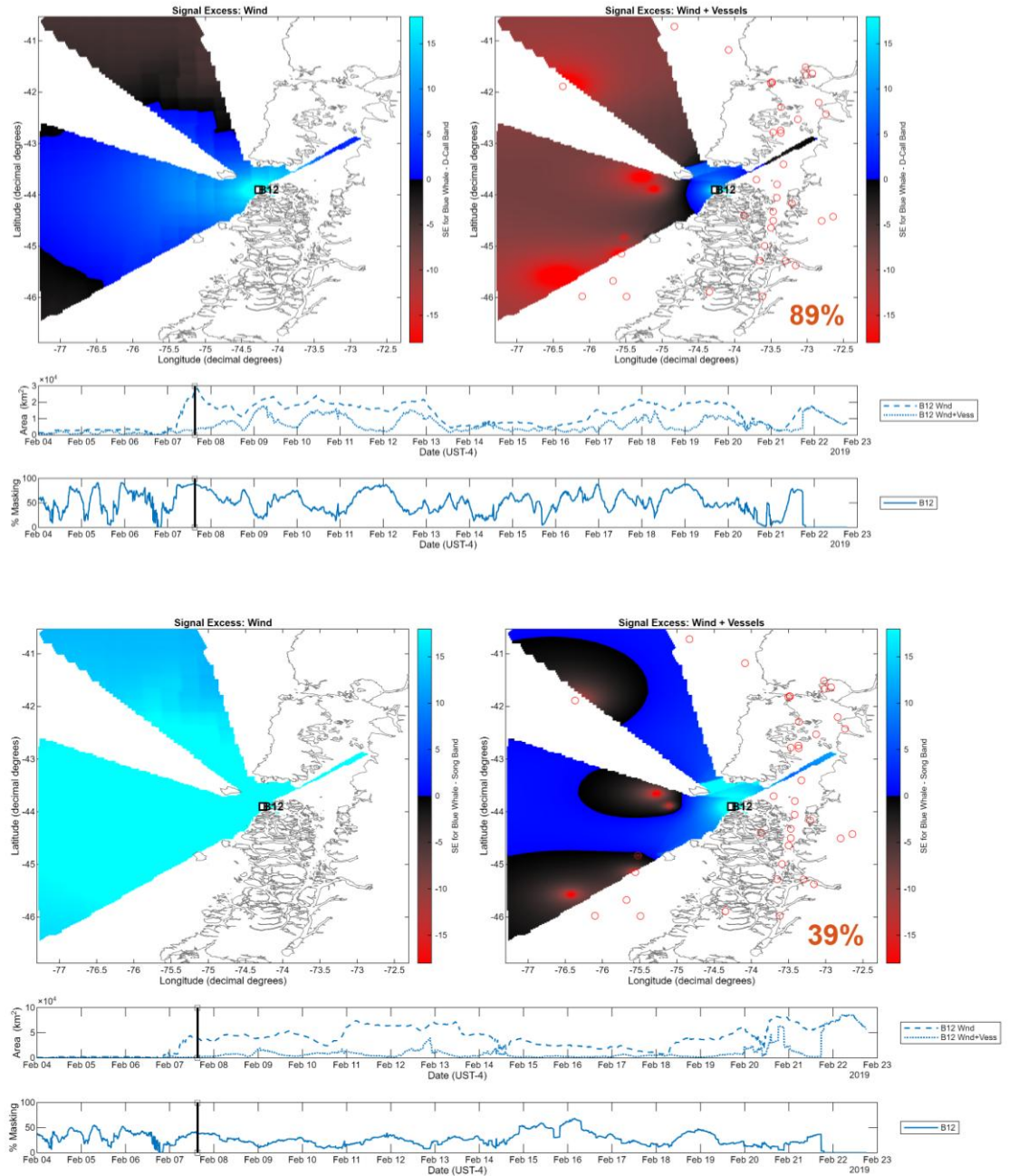


Figure 4. Spatial representation of changes in communication for A) blue whale D-calls and B) blue whale song calls at 15:10 on February 7th 2019, during the track of blue whale B12. Left panels show CSwind+vessel noise, and right panels show CSwind. The “CSwind+vessels under a 10 kt speed limit” scenario is not shown here. The red colour scale shows signal excess below 0, and the blue colour scale shows signal excess above 0. Percentage masking is shown on each plot.

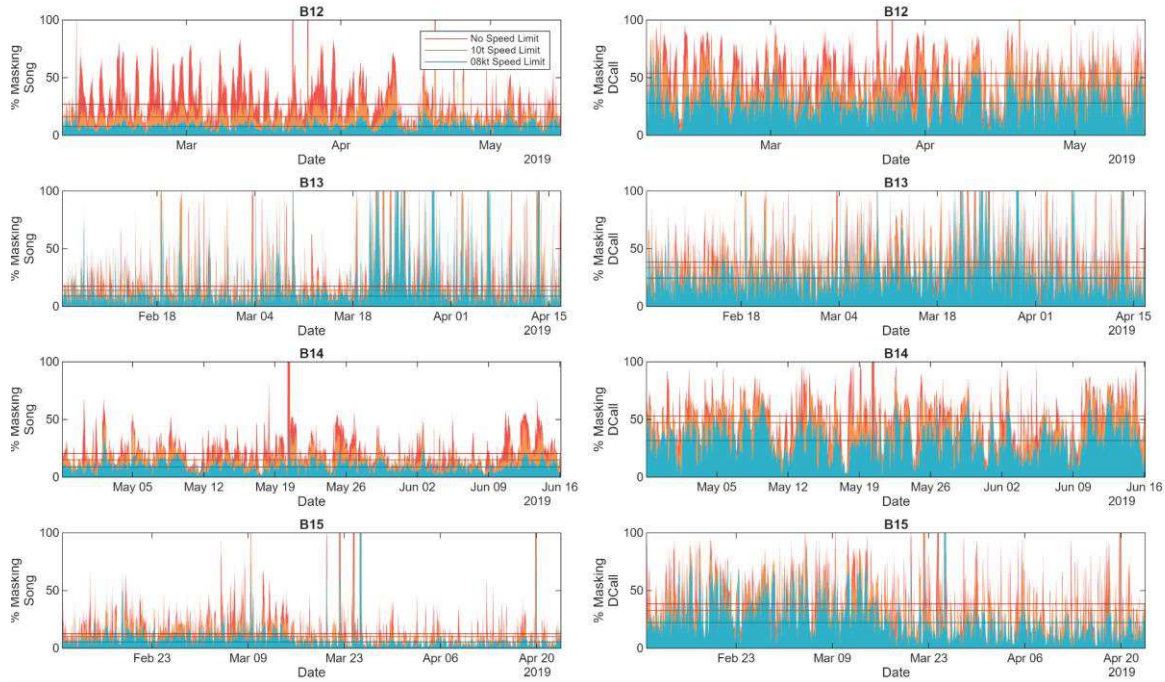


Figure 5. Time series of percentage masking at a 10-minute sample resolution of blue whale D-calls (right panels) and song calls (left panels) under current No Speed Limit conditions (i.e. wind + vessel noise; in red) and under potential 10 kt Speed Limit conditions (i.e. wind + vessel noise under 10 kt speed limit; in orange) and for 8 kt Speed Limit conditions (i.e. wind + vessel noise under 8 kt speed limit; in blue), for blue whales B12, B13, B14 and B15. Horizontal lines indicate median masking.

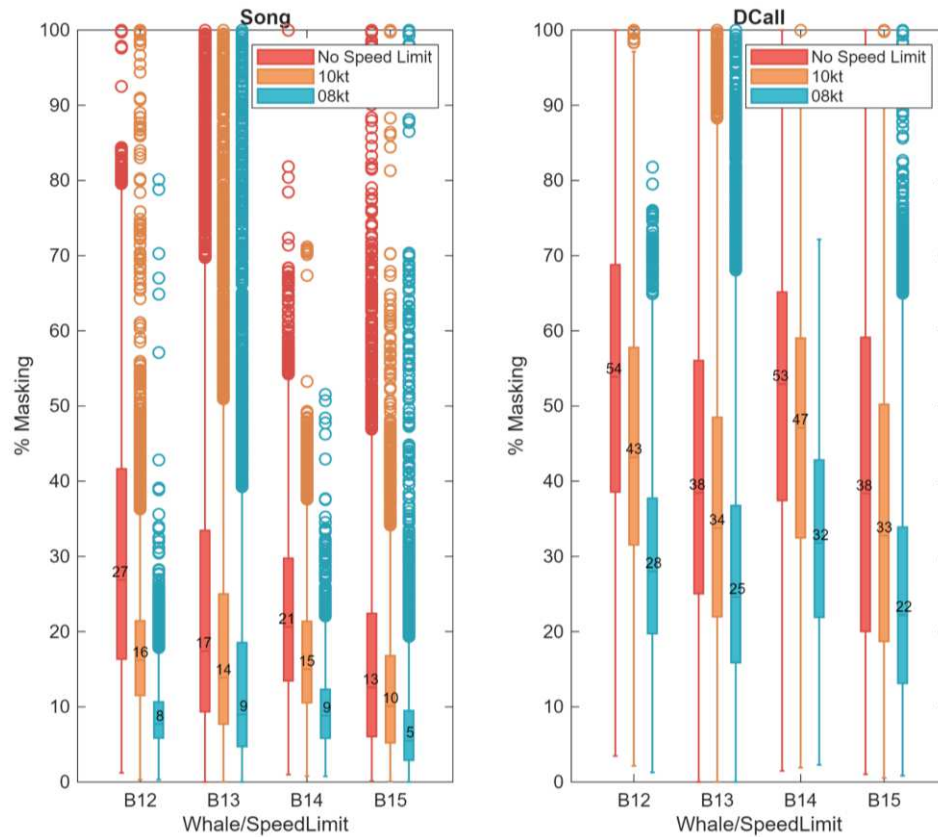


Figure 6. Box plot of percentage masking of blue whale D-calls (left panel) and song calls (right panel) under current No Speed Limit (NSL, red bars) conditions (i.e. wind + vessel noise) and under potential 8 kt (8kt, blue bars) and 10 kt Speed Limit (10kt, orange bars) conditions, for blue whales B12, B13, B14 and B15. Median values are shown on each bar.

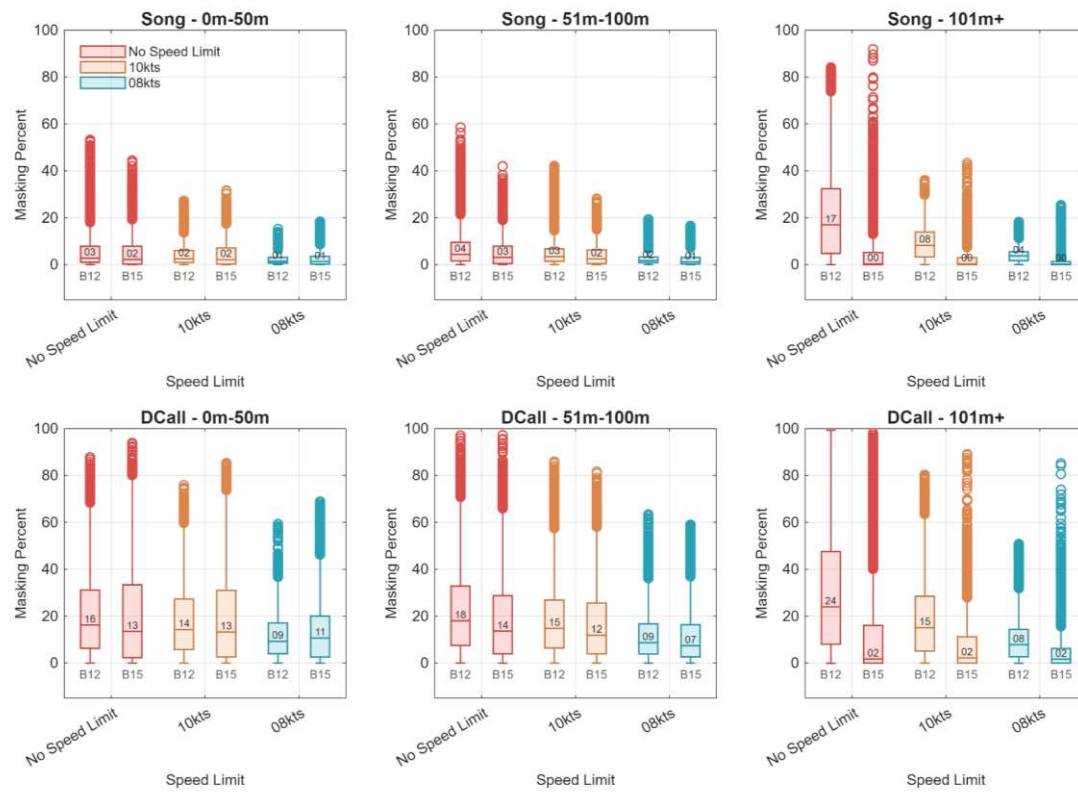
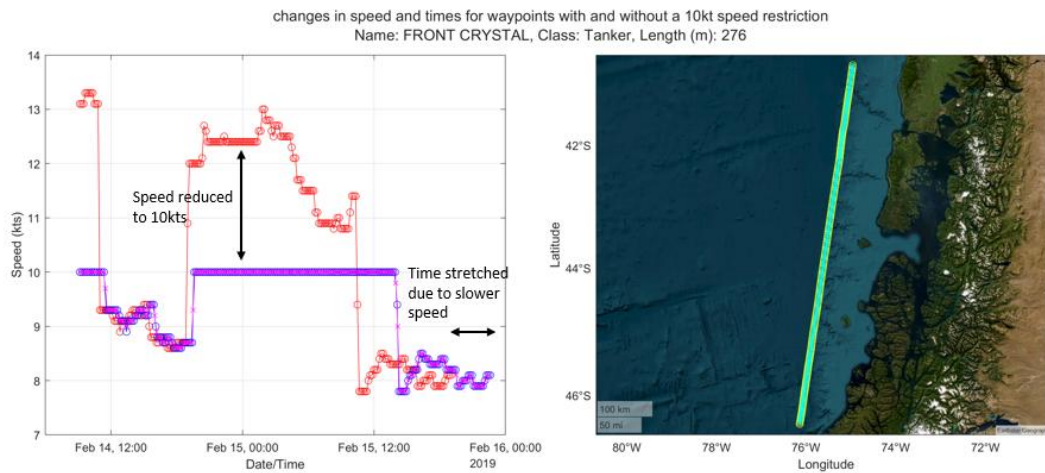


Figure 7. Boxplots of percentage masking for blue whales B12 & B15 comparing No Speed Limit compared with 10 kt Speed Limit, for three vessel size classes (0-50m n=179, 50-100m n=254, >100m n=379).

Supplementary Material:



Supplementary Material Figure 1. An example of the method used for determining changes in speed and times for waypoints (from AIS data) with and without a 10 kt speed restriction. Left panel: Time series of vessel speed showing the original speeds (red) and the modified speeds capped at 10 knots (purple). Periods where speeds exceed 10 knots are reduced, and the resulting slower transit leads to a stretching of travel time along the track. Right panel: Spatial representation of the vessel track along the Chilean coast, illustrating that the route remains unchanged. In contrast, the timing of movement along the track is modified under the speed restriction scenario.

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Data Availability Statement:

The AIS data that support the findings of this study are available from Whale Guardians (info@whaleguardians.org) but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. The satellite tag data that support the findings of this study are available from Centro Ballena Azul (contacto@ballenazul.org) but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available.

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