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Trevor A. Branch, Cole C. Monnahan,, Emmanuelle C. Leroy,, Fannie W. Shabangu,, Ana Širović, Suaad Al Harthi, Cherry Allison, Naysa Balcázar Cabrera, Dawn R. Barlow, Susannah V. Calderan, Salvatore Cerchio, Michael C. Double, Richard Dréo, Alexander

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TREVOR A. BRANCH[1], COLE C. MONNAHAN[1,2], EMMANUELLE C. LEROY[3],[4], FANNIE W. SHABANGU[5,6], ANA ŠIROVIĆ[7], SUAAD AL HARTHI[8], CHERRY ALLISON[9], NAYSA BALCÁZAR CABRERA[10], DAWN R. BARLOW[11], SUSANNAH V. CALDERAN[12], SALVATORE CERCHIO[13], MICHAEL C. DOUBLE[14], RICHARD DRÉO[15], ALEXANDER N. GAVRILOV[16], JASON GEDAMKE[17], KRISTIN B. HODGE[18], K. CURT S. JENNER[19], MICHELINE N.-M. JENNER[19], ISHMAEL S. LETSHELEHA[20],[21], ROBERT D. MCCAULEY[16], JENNIFER L. MIKSIS-OLDS[22], BRIAN S. MILLER[23], DIVYA PANICKER[24], CHRIS PIERPOINT[25], ZOE R. RAND[26], TRACEY ROGERS[3], JEAN-YVES ROYER[27], FLORE SAMARAN[28], KATHLEEN M. STAFFORD[11], KAROLIN THOMISCH[29], LEIGH G. TORRES[11], MAËLLE TORTEROTOT[27], JOY S. TRIPOVICH[30], VICTORIA E. WARREN[31], ANDREW WILLSON[32] , MAÏA S. WILLSON[33]

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[1] *School of Aquatic and Fishery Sciences, Box 355020, University of Washington, Seattle, WA 98195, USA, email: tbranch@uw.edu*
[2] *Resource Ecology and Fisheries Management, Alaska Fisheries Science Center, National Oceanic and Atmospheric Administration, Seattle, WA 98115, USA*
[3] *Evolution and Ecology Research Centre, and School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW, 2052, Australia*
[4] *GLOBICE Réunion, 7 Lot. Lelievre, Saint-Leu 97436, Réunion Island, France*
[5] *Fisheries Management, Department of Forestry, Fisheries and the Environment, Foreshore, Cape Town, South Africa*
[6] *Mammal Research Institute Whale Unit, University of Pretoria, Private Bag X20, Hatfield, Pretoria 0028, South Africa*
[7] *Trondheim Biological Station, Norwegian University of Science and Technology, Trondheim, Norway*
[8] *Environment Society of Oman, P.O. Box 3955, Ruwi 112, Oman*
[9] *International Whaling Commission, The Red House, 135 Station Road, Impington, Cambridge, CB4 9NP, UK*
[10] *COPAS Sur-Austral, University of Concepcion, Barrio Universitario s/n, Concepción 4030000, Chile*
[11] *GEMM Lab, Marine Mammal Institute, Department of Fisheries, Wildlife, and Conservation Sciences, Oregon State University, Newport, OR 97365, USA*
[12] *Scottish Association for Marine Science, Oban PA37 1QA, Argyll, Scotland*
[13] *African Aquatic Conservation Fund, P.O. Box 366, Chilmark, MA 02535, USA*
[14] *Australian Marine Mammal Centre, Australian Antarctic Division, 203 Channel Hwy, Kingston, TAS 7050, Australia*
[15] *Institut de Physique du Globe de Paris, Sorbonne Paris Cité, UMR 7154 CNRS, Paris, France*
[16] *Centre for Marine Science and Technology, Curtin University, GPO Box U1987, Perth, Western Australia 6845, Australia*
[17] *NOAA Fisheries Office of Science & Technology, Ocean Acoustics Program, 1315 East West Highway, Silver Spring, MD 20910, USA*
[18] *K. Lisa Yang Center for Conservation Bioacoustics, Cornell Lab of Ornithology, Cornell University, 159 Sapsucker Woods Road, Ithaca, New York 14850, USA*
[19] *Centre for Whale Research (WA) Inc., PO Box 1622, Fremantle, Western Australia 6959, Australia*
[20] *Cape Peninsula University of Technology, PO Box 652, Cape Town 8000, South Africa*
[21] *Institute for Maritime Technology, PO Box 181, Simons Town, 7995, Western Cape, South Africa*
[22] *Center for Acoustics Research and Education, University of New Hampshire, 24 Colovos Road, Durham, New Hampshire 03824, USA*
[23] *Australian Antarctic Division, 203 Channel Highway, Kingston, Tasmania, Australia*
[24] *School of Oceanography, University of Washington, Seattle, WA 98195, USA*
[25] *Seiche Ltd, Bradworthy Ind. Est., Langdon Rd., Bradworthy, Devon, EX22 7SF, UK*
[26] *Quantitative Ecology & Resource Management, Box 357941, University of Washington, Seattle, WA 98195, USA*
[27] *CNRS, University of Brest, Lab Geosciences Ocean, Rue Dumont d'Urville, F-29280 Plouzane, France*
[28] *ENSTA Bretagne, UMR CNRS 6285 Lab-STICC 29806 Brest Cedex 9, France*
[29] *Alfred-Wegener-Institut Helmholz-Zentrum für Polar- und Meeresforschung, Ocean Acoustics Group, Klussmannstr. 3d, 27570 Bremerhaven, Germany*
[30] *Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, University of New South Wales, Biological Sciences Building (D26), Randwick, Sydney, New South Wales 2052, Australia*
[31] *JASCO Applied Sciences (Australia), Unit 1, 14 Hook Street, Capalaba, Queensland 4157, Australia*
[32] *Future Seas Global SPC, PO Box 286, PC 116, Mina al Fahal, Oman*
[33] *Environment Society of Oman, P. O. Box 3955, Ruwi 112, Oman*

ABSTRACT

Blue whale populations each produce distinctive repeated songs that are stable over periods of decades, and can be used to identify where each population resides and moves. In the Southern Hemisphere and northern Indian Ocean, there are at least seven distinct populations based on their songs, some of which inhabit distinct areas (south-east Pacific, and the Antarctic), while five populations in the "pygmy blue whale" grouping overlap in their ranges. Here we use contemporary song detections from a broad compilation of data to predict where each pygmy population resides, and use these fitted spatial surfaces to separate historical catches of these populations, as a first step required to conduct population assessments. The five populations are in the north-west Indian Ocean (NWIO, Oman song type), central Indian Ocean (CIO, Sri Lanka), south-west Indian Ocean (SWIO, Madagascar to Kerguelen), south-east Indian Ocean (SEIO, Australia to Indonesia), and south-west Pacific Ocean (SWPO, New Zealand). Almost all pygmy blue whale catches (97% of 12,043) were taken by Japanese and Soviet pelagic whalers during 1959/60 to 1971/72, with a few taken in earlier years from opportunistic pelagic whaling or shore-based whaling in temperate regions. Generalized additive models based on latitude and longitude, plus a factor for month, were fitted to the song data for each population, using beta-binomial likelihoods to account for overdispersion, except for the NWIO where binomial likelihood produced better predictions. These fitted surfaces were used to estimate the probability of individual catches belonging to each population, and these probabilities were applied to annual pygmy blue whale catch totals for each whaling expedition and season. Estimated catches were highest from the SWIO and SEIO populations and lowest from the SWPO population, with total catches of 827 (NWIO), 1,729 (CIO), 6,723 (SWIO), 2,651 (SEIO), and 561 (SWPO).

INTRODUCTION

The assessment of the status of whale populations requires information on catches, abundance, and trends. Each of these is heavily dependent on defining the population of interest and where it resides, and on separation of these data from other similar populations. Blue whales present an interesting challenge for assessment, because while catches from some populations are easily separated, catches from others are not.

There is a long-standing debate over the higher-order classification of blue whales into subspecies. The Committee of Taxonomy for the Society for Marine Mammalogy recognizes four subspecies (Committee on Taxonomy 2022): Antarctic blue whales (*Balaenoptera musculus intermedia*), pygmy blue whales in the southern Indian Ocean (*B. m. brevicauda*), northern Indian Ocean blue whales (*B. m. indica*), and northern blue whales in the North Pacific and North Atlantic (*B. m. musculus*), but there are substantial issues with this assessment. First, North Pacific and North Atlantic blue whales are unlikely to be closely related given the geographic barriers between them. Second, Chilean blue whales are not mentioned, but are distinct from other populations genetically (LeDuc et al. 2007, LeDuc et al. 2017), morphologically (Branch et al. 2007a, Pastene et al. 2020), geographically (Branch et al. 2007b), and by song type (McDonald et al. 2006). Third, there is little evidence that northern Indian Ocean blue whales are a separate subspecies from southern Indian Ocean pygmy blue whales. There are two blue whale song types (indicating two populations) in the northern Indian Ocean: one recorded off Oman, Madagascar, and Diego Garcia (Cerchio et al. 2020a,b), and the other recorded off Sri Lanka and India (Panicker & Stafford 2021) and in the southern Indian Ocean (Samaran et al. 2013). Furthermore, length frequencies and length at maturity differ little in the northern Indian Ocean compared to the southern Indian Ocean (Branch & Mikhalev 2008), although fetal lengths in three regions of the northern Indian Ocean suggest a breeding season six months out of phase with the southern Indian Ocean (Mikhalev 2000).

Given these complexities, we adopt a pragmatic approach here and separate blue whales into four groupings: Antarctic blue whales, northern blue whales, Chilean blue whales, and the pygmy grouping (combining pygmy and northern Indian Ocean subspecies). In this paper we focus on assessing the distribution and historical catches of the pygmy grouping, since the status and trends of these populations is the least well known among all blue whale populations.

Song type is the primary method used to separate populations of blue whales (McDonald et al. 2006, Fig. 1), since there is currently no reliable biological or genetic method to separate populations (but see Barlow et al. 2018). Song characteristics of each population are stable over periods of decades (McDonald et al. 2006), although the tonal frequency of songs in all examined populations is declining over time for unknown reasons (e.g. McDonald et al. 2009, Leroy et al. 2018). Based on song type, the pygmy grouping consists of five known populations: north-west Indian Ocean (NWIO) detected off Oman, north-west Madagascar, and Diego Garcia (Cerchio et al. 2020a,b); central Indian Ocean (CIO) recorded from Sri Lanka to the southern Indian Ocean (Panicker & Stafford 2021, Stafford et al. 2011, Samaran et al. 2013); south-west Indian Ocean (SWIO) including Madagascar (Ljungblad et al. 1998); south-east Indian Ocean (SEIO) including Indonesia and western and southern Australia (e.g. McCauley et al. 2018); and south-west Pacific Ocean (SWPO) from New Zealand to Tonga (e.g. Barlow et al. 2023). It should be noted that in this region, one additional song type, the Diego Garcia downsweep ("DGD") recorded most frequently at Diego Garcia (Sousa & Harris 2015), but also in three other sites in the north-eastern Indian Ocean, have been proposed to be a blue whale song (Leroy et al. 2021), but were not included in this analysis.

All five populations in the pygmy grouping have unknown status, because despite some abundance estimates for these populations, it has not been possible to separate historical catches among the populations. Blue whale catch time series have been developed for Antarctic blue whales (Branch et al. 2004); for pygmy, Antarctic, North Pacific, and North Atlantic blue whales (Branch et al. 2008); and for eastern North Pacific vs. western and central North Pacific blue whale populations (Monnahan et al. 2014). The work here builds on previous efforts to separate catches in the pygmy grouping (Branch et al. 2018, 2019, 2021), which in turn build off the methods in Monnahan et al. (2014). In short, data are compiled for the proportion of hours with song of each population from different locations by month; spatial smoothers are fit to these data separately for each population; and then the resulting predictions are used to estimate the probability that a given catch comes from each population. Here we expand the number of passive acoustic datasets, and find more reliable spatial smoothers fit to these data to separate the catches.

METHODS

The overall problem is how to separate catches in the Southern Hemisphere and northern Indian Ocean between Antarctic blue whales and the pygmy grouping, and how to separate catches from the pygmy grouping among the five populations. Catches in the North Pacific and North Atlantic are not considered since they are a separate subspecies; while those in the South-East Pacific are also not considered since they are a separate subspecies or population.

Catch data: catches were obtained from the International Whaling Commission (IWC) in the form of two databases: an individual database containing date, location, length, sex and other information for each whale caught (Allison 2020a), and an annual database with annual summaries of total whales caught each year by "expedition code"—a land station or pelagic whaling expedition (Allison 2020b). The annual database is authoritative for total catch numbers since individual data are not available for all catches. Both databases list blue whales as being either "pygmy blue whales" or "true blue whales". The former code includes catches specifically listed as being pygmy blue whales in the northern and southern Indian Ocean, off Australia, and off New Zealand; while "true blue whales" is used for all other blue whale catches, including in the Antarctic, North Pacific, North Atlantic, and south-east Pacific. One of the problems we address in this paper is that some catches recorded as "true blue whales" were actually pygmy blue whales.

Catches from temperate land stations: whaling was conducted from a variety of land stations north of 40°S in the Southern Hemisphere, but not in the northern Indian Ocean. Length data from catches from each land station were examined to determine whether the catches were pygmy or Antarctic blue whales. Catches were assigned to Antarctic blue whales if a substantial portion of the whales were longer than 24.2 m (the maximum length for pygmy blue whales, Omura 1984), and if few mature females were shorter than 22 m. Seasonal timing of catches was also considered: land station catches in May-September were likely to be Antarctic blue whales (Mackintosh & Wheeler 1929); while land station catches peaking in December-March were likely to be pygmy blue whales, since Antarctic blue whales are generally south of 52°S during these months (Branch et al. 2007a, b). Catch rates were also taken into account (e.g. Best 1998, 2003): land stations with extreme declines in blue whale catch rates were considered to have caught Antarctic blue whales, since Antarctic blue whales had declined by 0.5% of pre-whaling levels by 1963 (Branch et al. 2004), whereas substantial whaling on pygmy blue whales only started in 1959/60 (Japan) and 1962/63 (USSR).

A standardized set of plots that tested each of these metrics was created for each land station in the Southern Hemisphere (location map, length frequencies, catches by month, catches by year), and used to assign catches to either pygmy or Antarctic blue whales. For land stations determined to be catching pygmy blue whales, all catches were assigned to the pygmy grouping. For land stations catching Antarctic blue whales, only catches confirmed to be pygmy blue whales by published papers (e.g., Gambell 1964), or evidenced by small lengths of sexually mature females, were included in the pygmy grouping.

Pygmy blue whale boundaries for pelagic catches: during pelagic whaling (November to April), the vast majority of Antarctic blue whales are in the Southern Ocean (Kato et al. 1995, Branch et al. 2007a, Branch et al. 2009), and pygmy grouping catches further north. We plotted length frequencies of blue whales catches (all blue whales combined, and sexually mature females only) in latitude and longitude bands to create a complex polygon defined as the boundary between Antarctic and pygmy blue whales. Pygmy blue whales never exceed 24.2 m (79.4 ft) (Omura 1984), while many Antarctic blue whales are longer than this threshold (Branch et al. 2007a). Furthermore, 50% of Antarctic blue whale females are sexually mature at 23.4 m (76.8 ft), but the corresponding length is 19.2 m (63.0 ft) for pygmy blue whales, thus sexually mature blue whales shorter than about 22 m (72 ft) are highly likely to be pygmy blue whales (Branch & Mikhalev 2008).

Combining annual and individual databases: The annual catch database has reliable totals of blue whale catches for each expedition by whaling season ("expedition-season"). Pelagic whaling seasons are 1 July to 30 June; while land stations seasons are 1 January to 31 December. We used for example 1960 to refer to both 1960/61 pelagic and 1960 land station seasons. All totals listed as "pygmy blue whales" in the annual totals were assigned to pygmy our grouping.

The individual catch database was also assigned to either pygmy or Antarctic blue whales in the following order: (1) All catches listed as pygmy blue whales were considered to be in the pygmy grouping; (2) all catches in the pygmy blue whale boundaries were considered to be pygmy blue whales; unless (3) they were longer than 24.2 m, in which case they were considered to be Antarctic blue whales. The boundaries chosen were consistent with previous analyses lengths of sexually mature females (Branch et al. 2007a), ovarian corpora accumulation by length (Branch et al. 2009), and length at sexual maturity (Branch & Mikhalev 2008) that also concluded that >99% of blue whales caught in this region were pygmy blue whales.

In the earlier years (1908/09–1958/59), catches from pelagic expeditions and the Kerguelen Islands, Australia, and New Zealand, were listed as "true blue whales" in the annual database, but we consider these to be pygmy blue whales, thus for these expedition-season combination, revised catch totals for pygmy blue whales are higher than (and replace) the totals in the annual database for "pygmy blue whales".

In the later years (1959/60-1972/73) pygmy blue whales were directly targeted by Japanese fleets mainly in 1959/60–1962/63 (*Tonan Maru*, *Tonan Maru II*, *Tonan Maru III*, *Nisshin Maru*, *Nisshin Maru II*, *Nisshin Maru III*, *Kinjo Maru*, *Kyokuyo Maru II*, and *Kyokuyo Maru III*), and by Soviet fleets *Slava* (1962/63-1965/66), *Sovetskaya Ukraina* (1962/63-1972/73), *Yuri Dolgoruky* (1962/63-1969/70), and *Sovetskaya Rossia* (1963/64-1972/73). For these expeditions, annual totals for pygmy blue whales are usually equal to or higher than the individual catch totals because not all whales have individual data recorded.

It is well known that Soviet expeditions originally misreported catch locations, seasons, and species during the later period (Yablokov 1994, Zemsky et al. 1995, Mikhalev 1996, Zemsky et al. 1996, Mikhalev 1997, Yablokov et al. 1998, Mikhalev 1999, Mikhalev 2000, Yablokov & Zemsky 2000, Mikhalev & Gill 2002). Annual totals for these expeditions are considered accurate, but individual catch locations have not been completely recovered. Most important, there are no location data in the individual catch database for the 1965/66 and 1968/69 *Sovetskaya Rossia* expeditions. For those expeditions, we obtained copies of the voyage summary maps (Y. Ivashchenko, pers. comm.), determined positions of blue whale catches from the maps, and augmented the individual catch database with these locations.

Combining these efforts, for every expedition-season combination we had (1) location data for some or all catches, and (2) total pygmy catches. For each expedition-season, spatial models could then be applied to the individual location data, to calculate the proportions in each of the five populations, and then these proportions could be applied to the season catch totals.

Passive acoustic data for spatial models: passive acoustic data were located originally using prior compilations (McDonald et al. 2006, Branch et al. 2007b, Miller et al. 2014, Širović et al. 2018), from published papers, and provided by the authors of this study (Table 1). Where possible, data were requested from the authors in the desired format, although in a few instances, data were obtained from published papers. Data were collected in a common format comprising the location, month, year, unit examined (hour or day), number of units examined, and the number of those units that included blue whale song from each of the populations of interest (NWIO, CIO, SWIO, SEIO, SWPO, and Antarctic, see Fig. 1 for diagnostic songs from each). Some studies searched for songs from only particular populations, and those cases the authors were asked whether the lack of detections should be recorded as a true zero (absence of the population) or as not examined (NA). In the models zeros are included in the analysis and NAs are omitted.

One data point was excluded from the model fits: CIO songs were heard off northern Angola (~6°S 12°E) on one day in October 2008 (Cerchio et al. 2010). This rare vagrant proved influential in spatial model fitting for CIO in October since this location was far from all other CIO song locations, and the location was outside the pygmy region.

Conversion of daily data to hourly data: the compiled data were either analysed in units of days or hours (i.e., number of hours with song out of total number of hours examined), with most analyses in hours (Table 1). The daily data cannot be converted by hours by multiplying by 24, because in the same dataset the proportion of days with detections will always be higher than the proportion of hours with detections. Therefore, we developed a method to convert daily data into hourly data. A large dataset of hourly data collected in a consistent manner around Australia (SEIO song) by authors A.G. and R.M. was used to calculate for each month both the proportion of hours with songs, and the proportion of days with songs. The best relationship between the two came from using the cumulative distribution function of a beta distribution (two parameters α and β), with beta-binomial likelihood that allows for overdispersion. A Bayesian model was fitted to the data to assess the uncertainty around the model fits, and the mean of 1000 posterior predictions was used to convert from days to hours for datasets with day units.

Spatial models: For each population we assumed that song detection is a smooth, continuous surface in space, that is modified up and down in each month. Models were developed and explored using the highly flexible GAMLSS R package (Rigby & Stasinopoulos 2005), which allows for beta-binomial likelihood, and terms predicting both the mean and the variance. The beta-binomial estimates an additional overdispersion parameter compared to the binomial, which makes sense for the assembled dataset: successive hours of data are not independent, and the wide variety of passive acoustic recorders and their placement relative to the sound channel will result in more variable proportions of hours with detections than expected from a binomial (which assumes each event is independent and identical). In Monnahan et al. (2014), the beta-binomial was far superior to a binomial likelihood.

A wide variety of models for the mean (proportion of hours with detections) were explored, consisting of the following elements: (1) binomial vs. beta-binomial likelihood, (2) generalized additive models (GAMs, using cubic splines) vs. generalised linear models (GLMs), (3) models based on latitude only, longitude only, or latitude and longitude, (4) models including an interaction term between latitude and longitude, (5) models with an interaction term between month and latitude or longitude, and (6) models with month treated as numeric, as a factor, and as a cyclic smoother.

In addition to these predictive surfaces for the mean, we also explored a set of simpler predictive models for the variance parameter in the beta-binomial: (1) constant, (2) linear with latitude, (3) linear with longitude, (4) linear with latitude and longitude, (5) GAM on latitude, (6) GAM on longitude.

Models were compared using the Akaike Information Criterion (AIC, Akaike 1973), where models that are within 2 units are considered similar, while those more than 10 units higher can be discarded. However, within the GAMLSS package, many of the tested models proved to be too complex to fit, and failed with errors, failed to converge, or occasionally produced predicted fits that were nonsensical (Table 2).

The spatial models predict the probability of song detection of each population at a given location in one hour. We recognize that this is not the probability of occurrence of actual whales since songs are produced only by males (e.g. Oleson et al. 2007), song production varies by month within the mating cycle (Barlow et al. 2023), and time of the day (e.g. Samaran et al. 2013), and is influenced by the type of passive acoustic recorder, the bathymetry around the recorder, the loudness and tonal frequency of songs made by each population, and many other factors. The use of the beta-binomial likelihood allows for data types to vary widely, but it was not possible to directly account for these other factors within the model.

Catch assignments to each population: from the selected model for each population, we predicted the detection probability for each catch (based on latitude, longitude and month), and then calculated the probability that a particular catch was from one of the five populations by dividing by the total. For example, if detection probabilities were 1.00, 0.50, 0.20, 0.001, and 0.001 for the populations then the probability a catch belongs to each 0.59, 0.29, 0.12, 0.00, and 0.00. In doing thus we assume that each population sings at the same rates and is equally detectable. Insufficient data exist to estimate and account for any differential detectability of the songs produced by each pygmy population, although evidence suggests that Antarctic blue whale song is louder and hence more easily detected than SWPO song (Warren et al. 2021). Our second major assumption is that distribution inferred from acoustic detections (in recent decades) is similar to the historical distribution of each population during whaling (largely in the 1960s). We cannot rule out changes in distribution over time due to depletion from whaling, climate change, and other factors. However, historical blue whale catches were taken in similar places to recent sightings, strandings, and acoustic detections across the entire Southern Hemisphere and northern Indian Ocean, with no obvious areas of extirpation or colonization (Branch et al. 2007b).

RESULTS

Defining pygmy blue whale boundaries for catches: there is a clear spatial separation in length frequencies of blue whales in pelagic catches, with catches south of 52°S including substantial numbers of whales greater than 80 ft, while catches in the Indian Ocean north of 52°S are nearly all shorter than 80 ft (Fig. 2). An even more marked geographic separation is seen in the lengths of sexually mature females, albeit based on fewer length data (Fig. 3). Similar analyses at a finer spatial scale shows that there is a slightly different southernmost latitude for pygmy blue whales depending on longitude, justifying a dividing line between pelagic catches of pygmy vs. Antarctic catches (Fig. 4), with pygmy blue whales comprising virtually none of the catches west of 20°E, but 100% of catches north of 46°S (20-30°E), north of 52°S (30-70°E), north of 53°S (70-80°E), and north of 52°S (80°E-180°). Within this pygmy region, catches longer than 80 ft were assigned to Antarctic blue whales, while outside this region some individual catches specifically recorded as being pygmy blue whales were assigned to the pygmy grouping.

Land station catches: catch characteristics at each land station are summarised here, together with the determination of whether these catches were likely to be in the pygmy grouping or Antarctic blue whales.

South-East Pacific Ocean (SEPO): In Peru, catches were highest in November-March, were nearly all caught in 1936 and 1937, and showed lengths typical of SEPO blue whales (Branch et al. 2007a). In Chile, catches increased over time, peaking in 1965, and remained high as a percentage of all species. Catches were primarily in austral summer months (November to April), and showed lengths typical of SEPO blue whales (Branch et al. 2007a). In the Galapagos, catches peaked in September, were caught in only two years (1926, 1954) and displayed small lengths, with the only two recorded sexually mature females being anomalously small (<60 ft) even for pygmy blue whales. All of these catches were considered to be SEPO blue whales.

Falkland Islands, South Georgia, South Shetland, South Orkneys: catches here were all south of 52°S in the Antarctic, declined precipitously to near zero by mid-century, had catches which peaked in November to February, and displayed lengths typical of Antarctic blue whales. In the earlier years up to 1929, a larger portion of sexually mature females were recorded between 60 and 75 ft, but these early data were also characterized by high proportions of rounding to the nearest 5 ft or 10 ft (Branch et al. 2007a), reports of dubious recording practices, and a lack of standardized length measurement techniques. Previous analyses of lengths of sexually mature females had estimated 8-10% were pygmy blue whales in the earlier years but only 1.9% in later years (Branch et al. 2007a). Since carefully standardized measurements found no small sexually mature females (Mackintosh & Wheeler 1929) and defined South Georgia as part of the canonical region inhabited by Antarctic blue whales, these catches were all assumed to be Antarctic blue whales.

Brazil: only two blue whales were caught from land stations, in June and September, and their lengths (65-70 ft) and unknown maturity status preclude assignment to subspecies. In addition, a 23.1 m female that stranded in 1992 could not be assigned to Antarctic or pygmy blue whales (Dalla Rosa & Secchi 1997), although this would be longer than almost all pygmy blue whales. Given the months, the location far to the east of SEPO blue whales, and far to the west of pygmy blue whales, these were assumed to be Antarctic blue whales.

West coast of Africa: Saldanha Bay, Hangklip, Namibia, Angola, and Congo: catches peaked in July to September, declined to around 1% of original catch levels, and sexually mature females were of sizes typical of Antarctic blue whale. Substantial portions of all catches were longer than 79 ft, but many small individuals were caught in these land stations compared to elsewhere, especially in Angola where the modal length was just 60 ft. At Saldanha Bay, the smaller individuals were sexually immature, and their lengths and bodily proportions were similar to those in South Georgia (Mackintosh & Wheeler 1929). Only one individual was caught in Congo and was in poor condition. Previous analysis of the lengths of sexually mature females indicated that 0.6-10.7% (95% CIs) of these catches could be pygmy blue whales after removing dubious lengths from early Hangklip catches, but this was based on a small number of sexually mature females (n = 56) (Branch et al. 2007a). These catches were all assumed to be Antarctic blue whales.

Durban: at least one pygmy blue whale was caught by the companies operating out of Durban: a 66 ft pregnant female caught on 21 September 1963, with a note that "this appears to be the first record" (Gambell 1964). Catch indicators point toward Antarctic blue whales dominating at this location: blue whale catches declined from 10-20% of all species in 1918-1932 to <2% from 1946 onwards; catches peaked in May to August; and substantial proportions of blue whales were longer than 24.2 m (79.3 ft). Only 14 sexually mature females were noted in the records, and 10 were typical of lengths for Antarctic blue whales. However, after 1937, although catches were still taken in June to August, fewer catches exceeded 24.2 m (9% instead of 24%), and all three sexually mature females were short (65, 66, 72 ft). Catch per unit effort data here declined to 2.8% of the level in 1920-28 (Best 2003) instead of the 0.3% expected if these later catches were Antarctic blue whales (Branch et al. 2007b). Thus, some later catches may have been pygmy blue whales. We assumed that Durban catches were Antarctic blue whales, except for four short sexually mature females that were assumed to be pygmy blue whales: 72 ft (12 July 1924), 72 ft (22 April 1937), 66 ft (21 Sept 1963), and 65 ft (3 May 1965).

West coast of Australia (Carnarvon, Point Cloates): scattered blue whale catches (22 in total) were made here among the target humpback whales when stations were operating (1925-28, 1956-63). Other whales were caught mainly in June to September, but blue whales were mainly caught in May, September, and October, and were unlikely to be Antarctic blue whales. Catch rates were similar over time (2.3/yr in 1925-28, 1.6/yr in 1956-63), and were typical lengths for pygmy blue whales (58-76 ft) except for one 84 ft mother caught on 1 October 1926, which was accompanied by a calf. Two pregnant females were 66 and 72 ft long. Five blue whales caught at Carnarvon are noted as being pygmy blue whales in the IWC's annual catch records (4 in 1962, 1 in 1963). We assumed these catches were pygmy blue whales except for the 84-ft blue whale caught in 1926, which we assumed to be an Antarctic blue whale.

West coast of Australia (Albany and Vasco da Gama): four blue whales were caught at Vasco da Gama during 1912-14 (individual information only available for one), and eight blue whales were caught at Albany (1959-60). All catches were in May or June, and were small (62-70 ft), including one small pregnant female (66 ft 2 in). One blue whale stranded dead at Albany (May 1973) and was processed for oil, but is excluded here since it was not a catch. Blue whale catches here were assigned to pygmy blue whales.

East coast of Australia (Tangalooma): one sexually mature female (66 ft 10 in) was captured on 11 June 1954 at Tangalooma on Moreton Island near Brisbane (27.2°S 153.4°E), and is assumed to be a pygmy blue whale.

East coast of Australia to New Zealand: The factory ship *Loch Tay* operated by the Australia Co caught 33 blue whales in 1912 and 93 blue whales in 1913, operating in New Zealand waters and the south coast of New South Wales (Southland Times, 11 December 1913). In addition, one blue whale was caught by the company *New Zealand Wh* in Rakiura. Individual locations and lengths are not available for these catches, which were assigned to pygmy blue whales.

Pelagic expeditions: There are four groupings of pelagic pygmy blue whale catches (Fig. 5): catches around Kerguelen Islands (that did not include data for individual whales); scattered catches with location and length data; directed catches by Japanese expeditions; and directed catches by Soviet expeditions.

Kerguelen Islands: 125 blue whales were caught off Kerguelen by three expeditions: the *A/S Kerguelen* (n = 8 in 1908/09, n = 1 in 1909/10), the *Mangoro* (n = 3, 1909/10), and the *Radioliene* (n = 113, 1929/30). These are assumed to be pygmy blue whales since they come from 47-53°S and 67-73°E, which is well within the boundaries of pygmy blue whales. Ichihara (1966) reports 113 pygmy blue whales here in 1928/29, but these were taken in July-Nov 1929. These catches were assumed to be pygmy blue whales (location 50°S 70°E).

Scattered catches: occasional pelagic expeditions ventured into the pygmy blue whale region (Fig. 5), headlined by the 1934/35 season when three Norwegian expeditions combined to catch 13 blue whales: *Solglimt* caught 2, *Skytteren* caught 10, and *Sir James Clark Ross* caught 1. In addition, *Skytteren* caught 1 more the following season; *UniWaleCo* (South Africa) caught 1 in 1937/38; and the *Willem Barendsz* (Netherlands) caught 2 in 1961/62. Individual catch locations were available for all of these pygmy blue whale catches.

Japanese expeditions: pelagic whaling by the Japanese on pygmy blue whales started in 1959/60 and essentially ended in 1962/63 except for the *Kyokuyo Maru III* in 1963/64 (n = 27) and 1966/67 (n = 3, by special permit); and by *Nisshin Maru* in 1969/70 (n = 2, by special permit). Targeted whaling by Japan ended with the IWC ban on catching all blue whales in the Southern Hemisphere. Japanese pygmy blue whale catches were confined to 0-80°E and 40-54°S for all expeditions and seasons (Fig. 5). For these expedition-season combinations, individual catch totals closely match the annual totals, and these catches are all recorded as pygmy blue whales in the individual catch database.

Soviet expeditions: the primary period of Soviet whaling on pygmy blue whales was 1962/63 to 1971/72, with the exception of 3 blue whales caught by *Yuri Dolgoruky* in 1961/62, and 2 caught by each of *Sovetskaya Ukraina* and *Sovetskaya Rossia* in 1972/73, which was the season that international observers were first introduced to the Soviet fleet (Fig. 5). Generally, annual totals are similar to the numbers in the individual database, except that three expeditions listed as being SH pelagic (i.e. all whaling south of 0°) have no individual catch locations: *Yuri Dolgoruky* in 1967/68 (7 pygmy blue whales and 43 total blue whales in annual catch data); *Sovetskaya Rossia* in 1965/66 (88 pygmy blue whales, 93 total blue whales); and *Sovetskaya Rossia* in 1968/69 (94 pygmy blue whales, 113 total blue whales). For these three expeditions, printed maps of catch locations were obtained from the IWC, and digitized to obtain approximate locations for individual catches, and those locations north of 54°S were used to predict which population those catches came from.

Conversion of acoustic data to a common unit of time: the best model fit to predict proportion of hours with songs from proportion of days with songs, was the cumulative distribution function of a beta distribution with $\alpha = 0.9533$ and $\beta = 0.1771$ (Fig. 6).

Acoustic data: passive acoustic data shows clear spatial separation in songs made by the six populations (Fig. 7a-f). NWIO song was recorded from only three regions, and at low detection rates. CIO song was recorded in the northern Indian Ocean, together with locations in the central and southern Indian Ocean. SWIO song was recorded around Madagascar stretching east to 75°E where it overlapped with CIO and SEIO songs, especially south of 30°S. SEIO song was recorded throughout north-western, western and southern Australian waters, with occasional song detections on the east coast of Australia, and also stretched west to waters almost directly south of Madagascar in waters south of 40°S. SWPO song was largely confined to New Zealand waters, but with records stretching to Tasmania, the east coast of Australia, and Tonga.

Spatial model fitting: for mean predictions, all of the models with lowest AIC were of the form (det, nodet) ~ cs(Lat) + cs(Lon) + factor(Month): the number of hours with detections vs. no detections were best explained by a cubic spline on latitude and longitude, and month as an additive factor. Models assuming beta-binomial likelihoods were always better than those assuming binomial likelihoods (9,860–197,934 units worse, Table 2). More complex models of the mean often failed to converge. Most notably, beta-binomial models of the NWIO population frequently predicted high probabilities of song along the east coast of Africa and down to 52°S (gray cells in Table 2) in regions with zero detected NWIO songs. Therefore, instead of using beta-binomial likelihood for NWIO, we chose to use a binomial model for this population, which predicted song only in the north-western Indian Ocean, despite the much higher AIC values for this model. For the remaining populations (CIO, SWIO, SEIO, SWPO, and Antarctic), we used beta-binomial likelihoods.

For the remaining populations, we chose the model with the lowest AIC value out of the six models with different predictors for the variance of the beta-binomial. However, it should be noted that three models with sigma ~ cs(Lon) failed, and the model with sigma ~ Lat + Lon for the CIO population was excluded since it predicted high song detection rates around Australia where no CIO song has been detected. The chosen models were binomial for NWIO, and beta-binomial for the others, with sigma ~ cs(Lat) for CIO, sigma ~ Lon for SWIO, sigma ~ cs(Lon) for SEIO, and constant sigma for SWPO (bold models in Table 2).

All of the selected models included Month as an additive factor in the predictions, which estimates the amount that detections increase or decrease compared to the average, by month (Fig. 8). Detection rates peaked in April (NWIO & SWPO), May (SWIO, SEIO), July (Antarctic) and in both June and December (CIO).

Spatial predictions fit the data well for the selected models (Fig. 9a-f). Note that since only one model was fit for each population, the predicted distributions do not shift in latitude or longitude to follow migration patterns, as they did when each month was fitted separately (Branch et al. 2021). Instead, the spatial distributions are similar for each month but the song detection rate shifts up and down by month, following the pattern in Fig. 8. The fits for NWIO seem reasonable, and no longer display the high probabilities of detections seen in the previous analysis (Branch et al. 2021). For CIO, all models predicted strong detections in the longitudinal center of the Indian Ocean, with a small probability of being detected throughout the north-western Indian Ocean. For SWIO, the detections are highest in the south-western Indian Ocean. For SEIO, the main distribution is around the western side of Australia and extending westward and southward into an area of high catches. For SWPO, the distribution is from Tasmania northwards and eastward and around New Zealand. Finally, Antarctic blue whales have some predicted detection throughout the Southern Hemisphere, with especially high probabilities in winter months (May-August), and low probabilities in summer (December-March).

Catch assignments to each population: model predictions for catches generally seem reasonable assuming that each population should be geographically separate, but do reveal some interesting patterns (Fig. 10). The most surprising predictions are catches from the CIO population coming the expected Sri Lanka and India, but also in the southern Indian Ocean, and with a moderate probability in the core range of the NWIO and SWIO populations. Furthermore, the SEIO catches range far west and south of Australia, with similar assignment probability to CIO, SWIO and SEIO in the region 30–50°S and 60–80°E. Also of interest is the abrupt cleaving of catches between SEIO and SWPO populations at Tasmania, with SEIO catches west of Tasmania and SWPO catches east of Tasmania.

Total catches by population: after applying the catch separation algorithm to each expedition-season combination (Appendix 1) and expanding to the season total catch of pygmy blue whales, we obtain the annual catch totals for each population (Table 3). Most catches (97.4%) came during 1959/60 to 1971/72 during the Japanese and Soviet whaling operations that were targeted on pygmy blue whales. In total we estimated 827 catches from NWIO, 1,729 from CIO, 6,273 from SWIO, 2,651 from SEIO, and 561 from SWPO, out of the total of 12,041 pygmy blue whale catches. It should be noted that 101 of 561 (18%) SWPO catches were taken in 1912/13–1913/14 by the factory ship *Loch Tay*.

DISCUSSION

The catch separation presented here builds on previous efforts, revealing great differences in whaling impacts on each of the five populations in the pygmy grouping: with 11 times more catches being taken from the SWIO population than from the SWPO population. It should be noted that even the 12,041 catches from all pygmy populations combined are dwarfed by the estimated 345,775 Antarctic blue whales caught by whalers (Branch et al. 2008). Total catches for all pygmy blue whales here are lower than the 13,022 estimated using different methodology (Branch et al. 2008), largely because those efforts assumed that 3.9% of blue whales caught on the west coast of Africa were pygmy blue whales and that 30-50% of the Durban catches were pygmy blue whales, whereas we consider those catches to be almost exclusively Antarctic blue whales. Our estimates also differ from previous assessments using similar methodology (Table 4), because of new data and a more refined selection of models, but these differences also suggest that considerable uncertainty surrounds our mean allocation of catches. Further work is needed to characterise the uncertainty surrounding these estimates, with bootstrapping being a promising approach (Monnahan et al. 2014).

The predicted surface for CIO requires more discussion. This population was originally assumed to occur only in the northern Indian Ocean, but is predicted here to be also present in the southern Indian Ocean, and with some probability in the core range of both the NWIO and SWIO populations. These predictions do follow the data: CIO song has been detected recently off Oman in March-October 2020 (Cerchio et al., unpubl.), while further back in time CIO song has been detected far south of the equator (Samaran et al. 2013). In addition, a vagrant CIO blue whale was detected on a single day off northern Angola (Cerchio et al. 2010), although this data point is not included in our analyses.

The fitted surfaces here do not incorporate the satellite tag data on SEIO blue whales (Double et al. 2014, Thums et al. 2022), which were included in Branch et al. (2019) by assuming that 1 in every 5 points was equivalent to an acoustic "detection", and the remainder a non-detection—feeding and migrating north-east Pacific blue whales only sing in 20-30% of hours (Lewis et al. 2018, Ostreich et al. 2020). Our spatial predictions of SEIO blue whales do not include high probabilities of detection in the Banda Sea, Indonesia, where satellite tags show that migrating SEIO blue whales go to in winter. Conversely, satellite tag data do not predict SEIO presence in the regions far to the west of Australia, where passive acoustic monitoring reveals their presence.

The current analysis builds on earlier, similar work (Branch et al. 2018, 2019, 2021): expanding the input data to include new data sources and refining the model structure toward greater model stability. The key for stability was to model all data together and allow month to be an additive factor in shifting detection up and down by month. Of interest is that the peak in detection rates in April-July for five of the six populations appears to coincide with the period between calving and conception, as has been reported in SWPO blue whales (Barlow et al. 2023). However, further work is needed to confirm this result, since the current compilation of data includes a wide variety of data sources including many that are not year-round.

The catches presented here can form the basis of stock assessments for the five pygmy blue whale populations. Partial abundance estimates are available for the CIO, SWIO, and SEIO populations; and a more complete abundance estimate is available for SWPO blue whales (Barlow et al. 2018). Stock assessments of these populations are thus possible to, at a minimum, assess a lower bound on status, as done for Chilean blue whales (Williams et al. 2011). While the spatial models do open up the potential to extrapolate survey abundance estimates in small areas out to broader regions, such extrapolations (as always) bring both promise and peril.

DISCLAIMER

Due to insufficient time for co-author review before the SC paper deadline, the full list of coauthors were not able to review the results and writeup before submission, and therefore the lead author (T.A.B.) takes full responsibility for typos, errors, and omissions in this paper.

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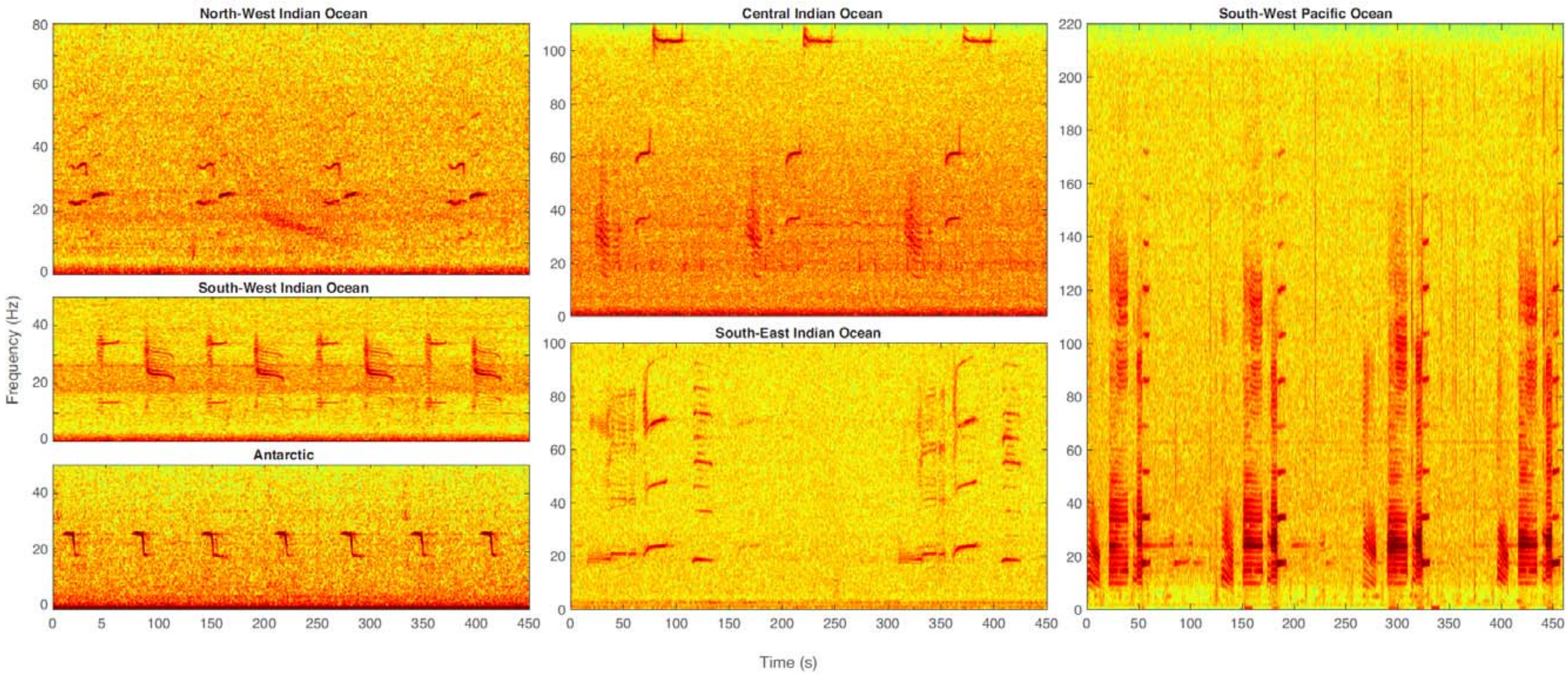

Fig. 1. Spectrograms showing song types associated with blue whale populations that are heard in the Indian Ocean and south-western Pacific Ocean. The Antarctic song is associated with Antarctic blue whales, while the other songs have been referred to as Oman song (North-West Indian Ocean, NWIO), Madagascar song (South-West Indian Ocean, SWIO), Sri Lanka song (Central Indian Ocean, CIO), Australia-Indonesia song (South-East Indian Ocean, SWIO), and New Zealand song (South-West Pacific Ocean, SWPO).

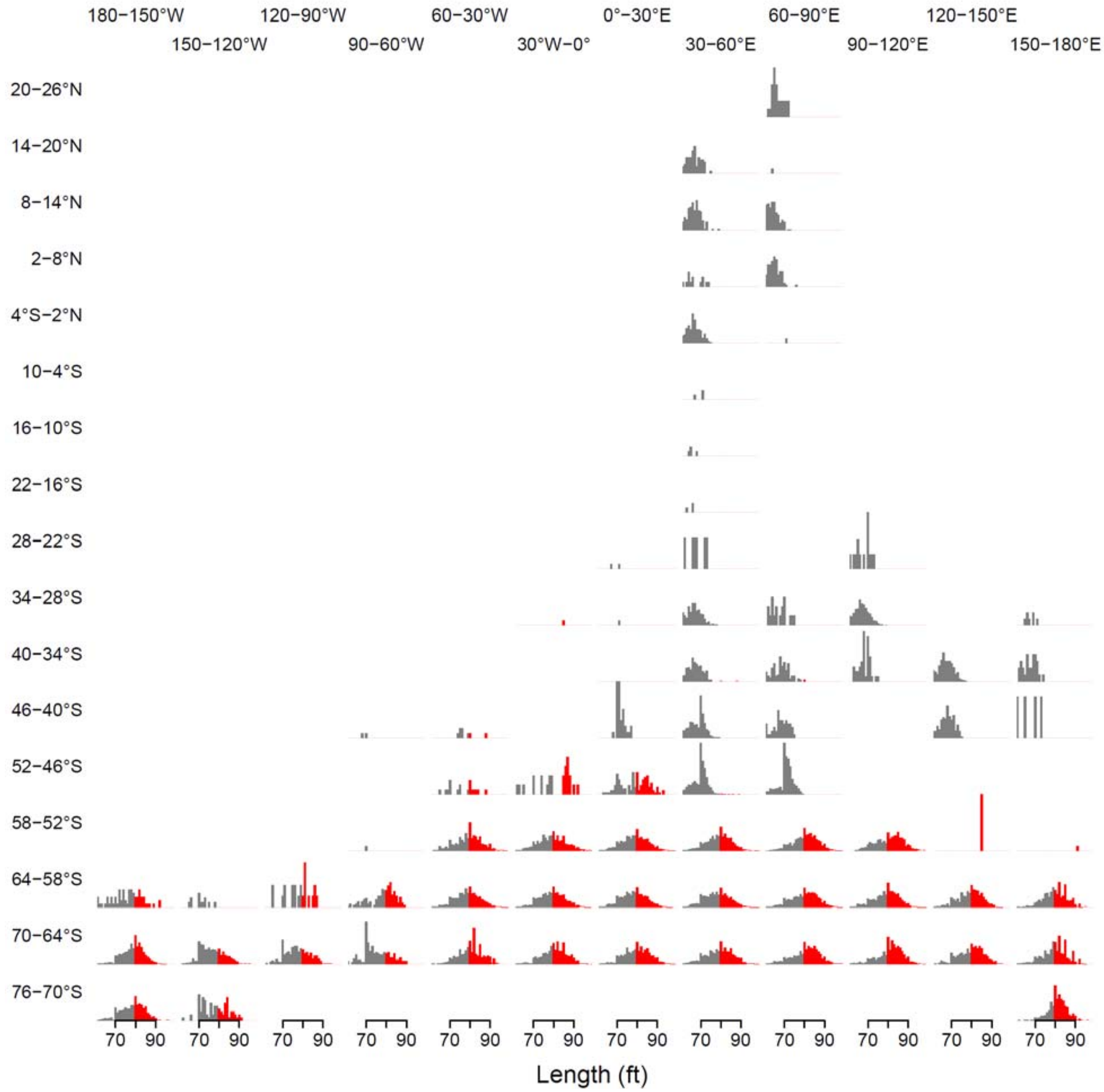

Fig. 2. Length frequencies of **all** blue whale catches in the Southern Hemisphere and northern Indian Ocean in the region 76°S–26°N and 180°W–180°E. South American catches are not included. Red indicates lengths ≥80 ft, i.e., longer than the maximum pygmy blue whale length.

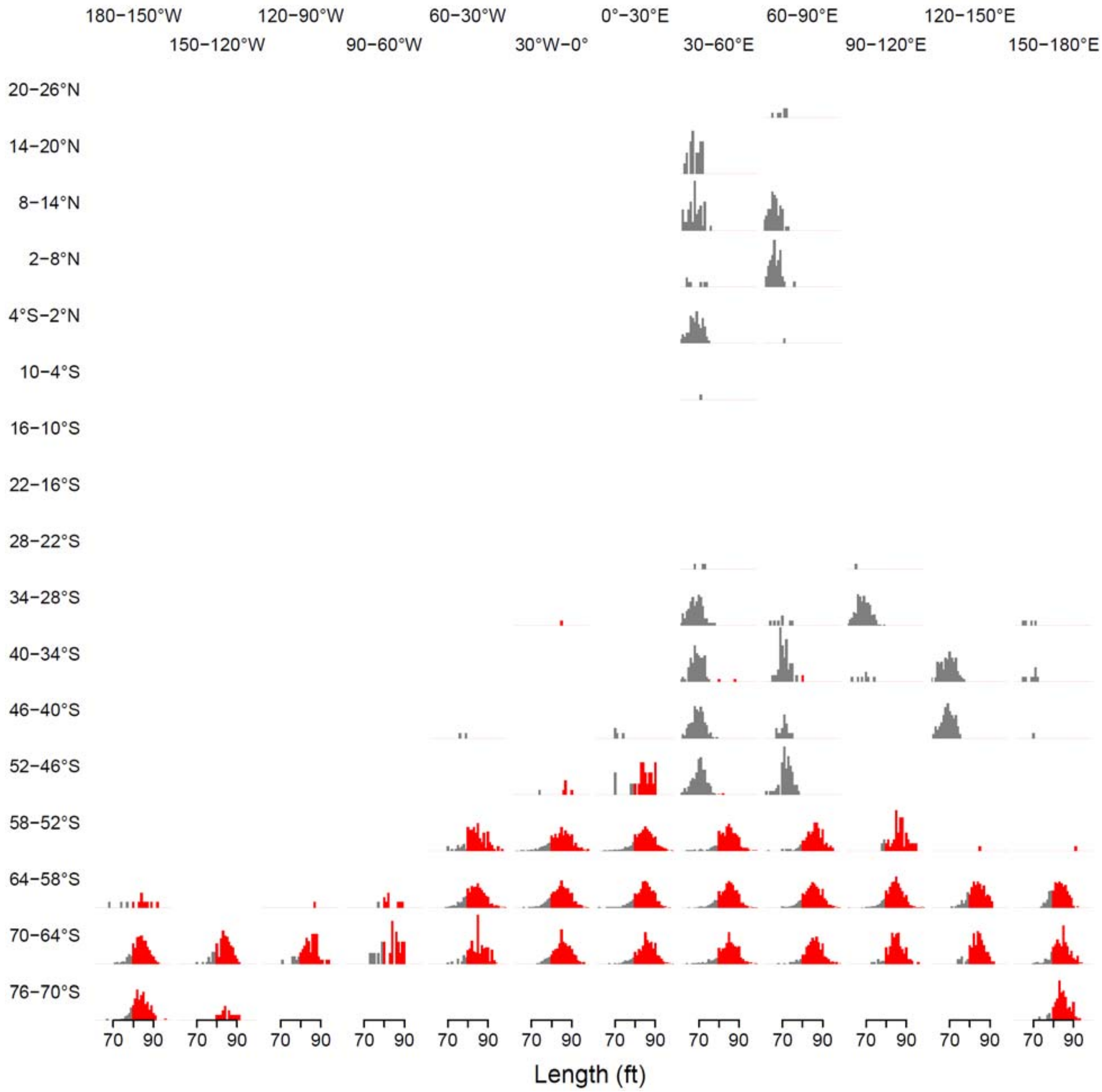

Fig. 3. Length frequencies of **sexually mature female** blue whales in the Southern Hemisphere and northern Indian Ocean in the region 76°S–26°N and 180°W–180°E. South American catches are not included. Red indicates lengths ≥80 ft, i.e., longer than the maximum pygmy blue whale length.

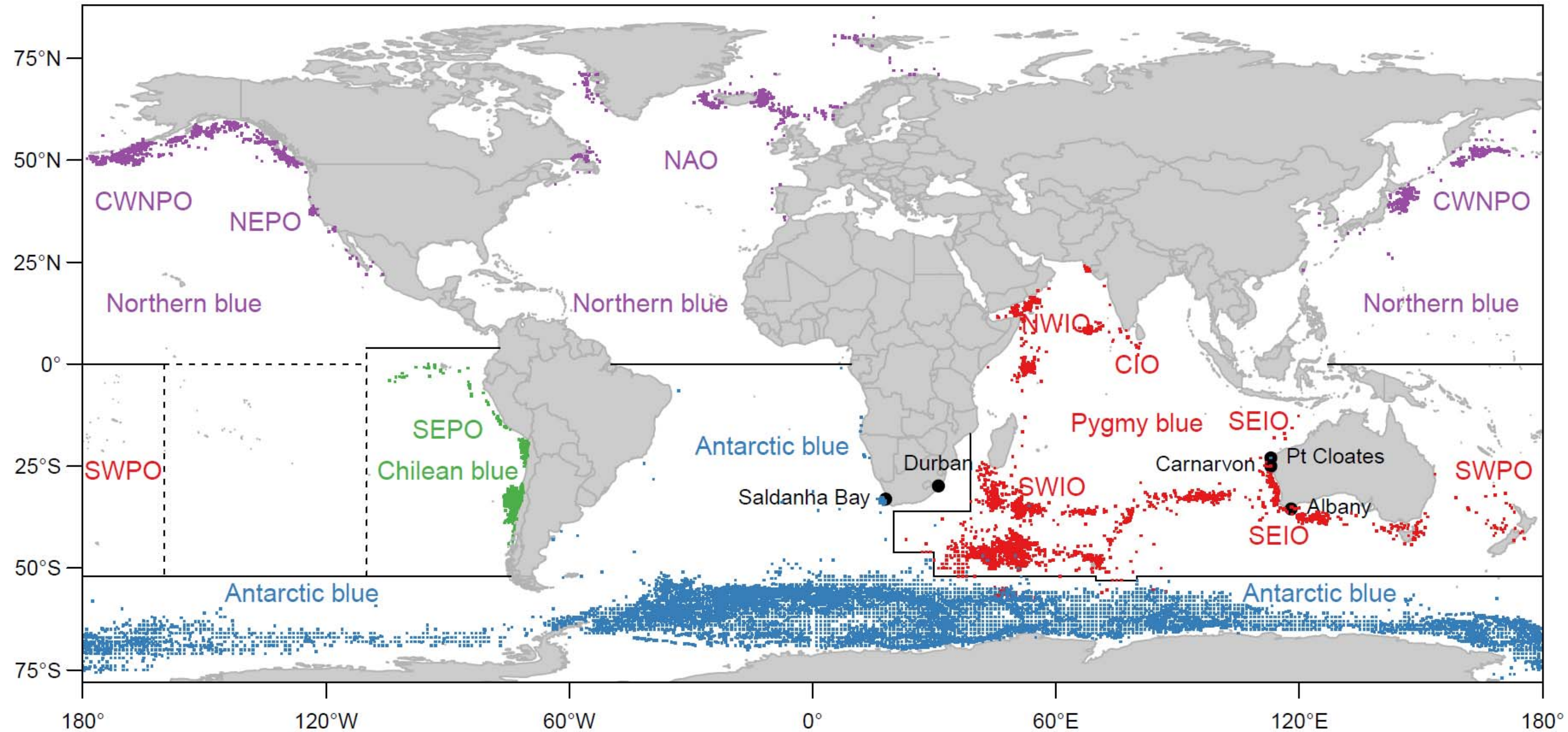

Fig. 4. Blue whale catches worldwide of each of the generally accepted major groupings (northern blue, Chilean blue, Antarctic blue, and pygmy blue), with assumed boundaries in black between each. Dashed boundaries enclose an area in the South Pacific with no known catches. Acronyms denote each of the currently assumed blue whale populations, with common names for song types in parentheses: north-west Indian Ocean (NWIO, Oman), central Indian ocean (CIO, Sri Lanka), south-west Indian Ocean (SWIO, Madagascar), south-east Indian Ocean (SEIO, Australia/Indonesia), south-west Pacific Ocean (SWPO, New Zealand), south-east Pacific Ocean (Chilean blue whales), north-east Pacific Ocean (NEPO, California/Mexico), central and western north Pacific Ocean (CWNPO, Japan to Gulf of Alaska), and north Atlantic Ocean (NAO). Key land stations in and near the pygmy blue whale region are labelled.

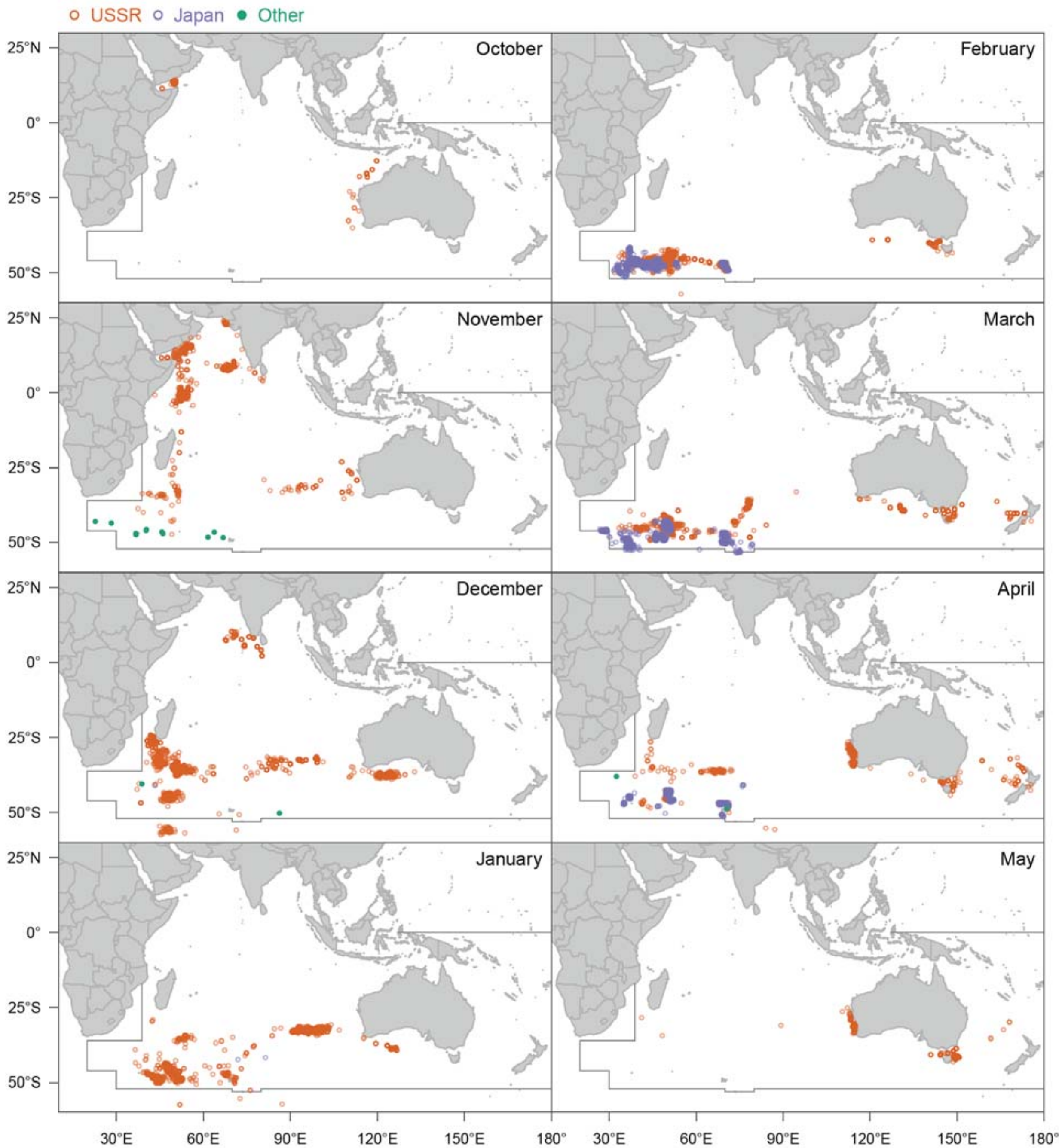

Fig. 5. Locations of assumed pygmy blue whale catches from pelagic expeditions in each month that includes catches (October to May), showing the distribution of catches by Japanese expeditions (blue, almost all 1959/60 to 1963/64), Soviet expeditions (red, almost all 1962/63 to 1971/72), and scattered catches from other expeditions (green). Catch locations rounded to the nearest degree are jittered here to represent this uncertainty.

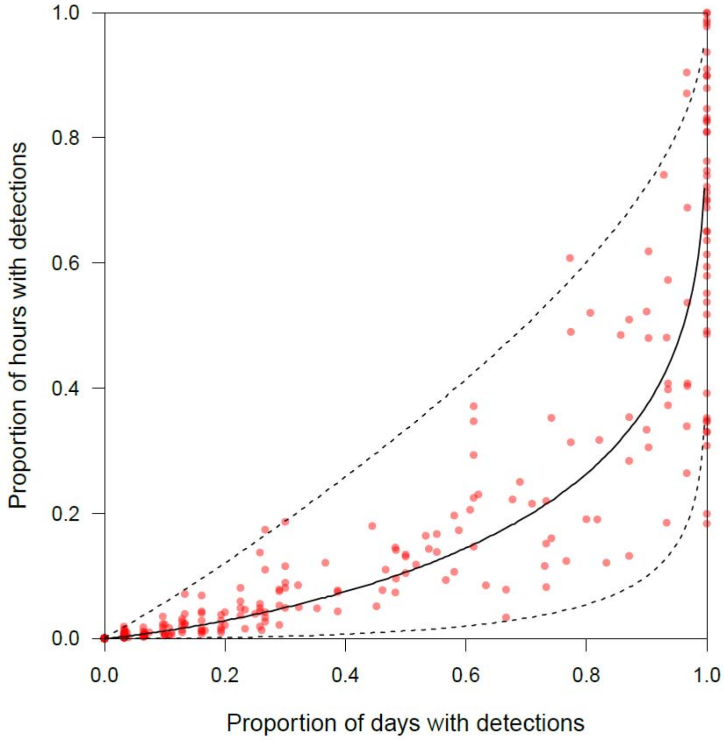

Fig. 6. Conversion between acoustic data recorded daily to an hourly equivalent. Each red point shows the proportion of hours with songs and proportion of days with songs, for one month of data. The fitted curve (median and 95% credibility intervals) is the posterior distribution of the model fits, assuming the fitted function is the cumulative distribution function of a beta distribution with binomial likelihood.

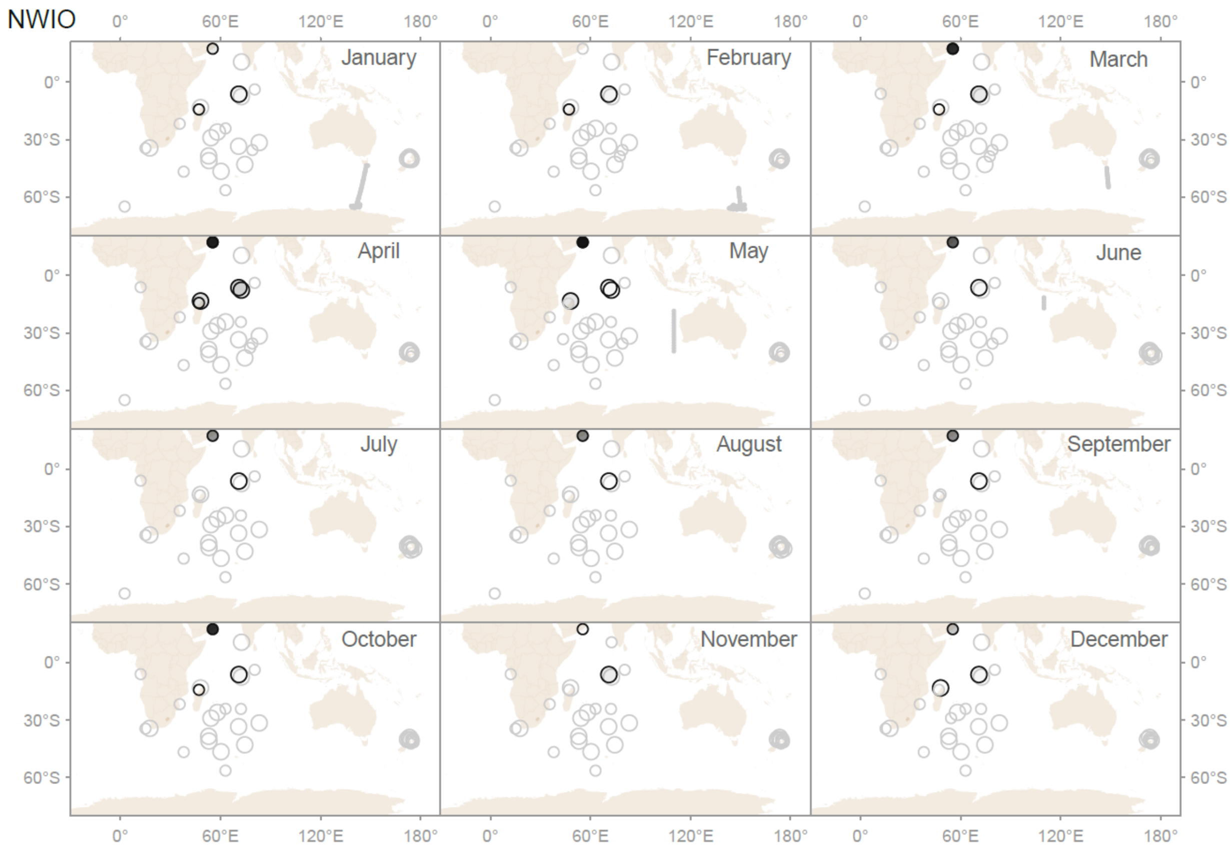

Fig. 7a. Monthly song data available for **NWIO blue whales**. Each circle represents one location at which acoustic data were collected. Small circles are short recording events, usually during cruises; medium circles represent a fixed deployment for one year; and large circles a multi-year fixed deployment. If there were no detections, the circle is gray, otherwise the outer circle is in color. Greater interior color represents a higher proportion of hours with detections.

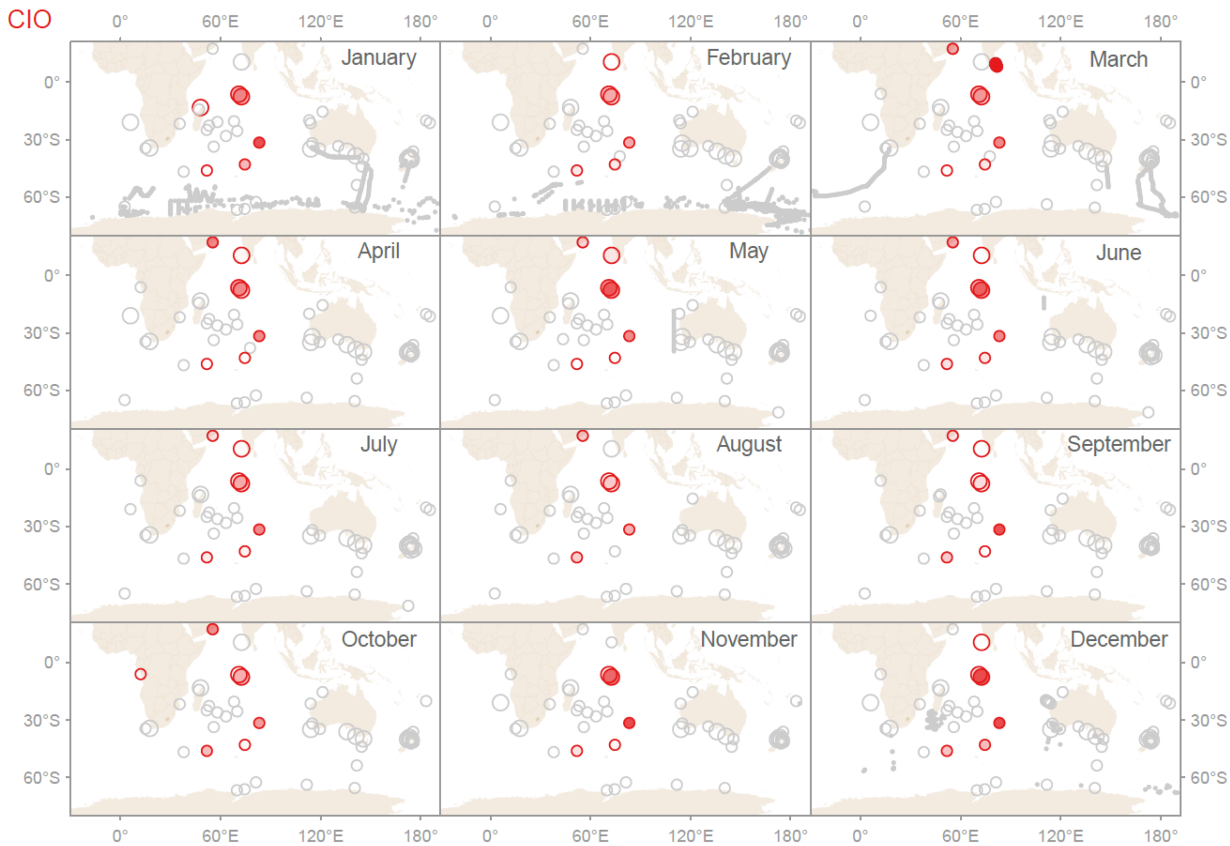

Fig. 7b. Monthly song data available for **CIO blue whales**. Each circle represents one location at which acoustic data were collected. Small circles are short recording events, usually during cruises; medium circles represent a fixed deployment for one year; and large circles a multi-year fixed deployment. If there were no detections, the circle is gray, otherwise the outer circle is in color. Data are not plotted if the song type was not looked for in the data. Greater interior color represents a higher proportion of hours with detections.

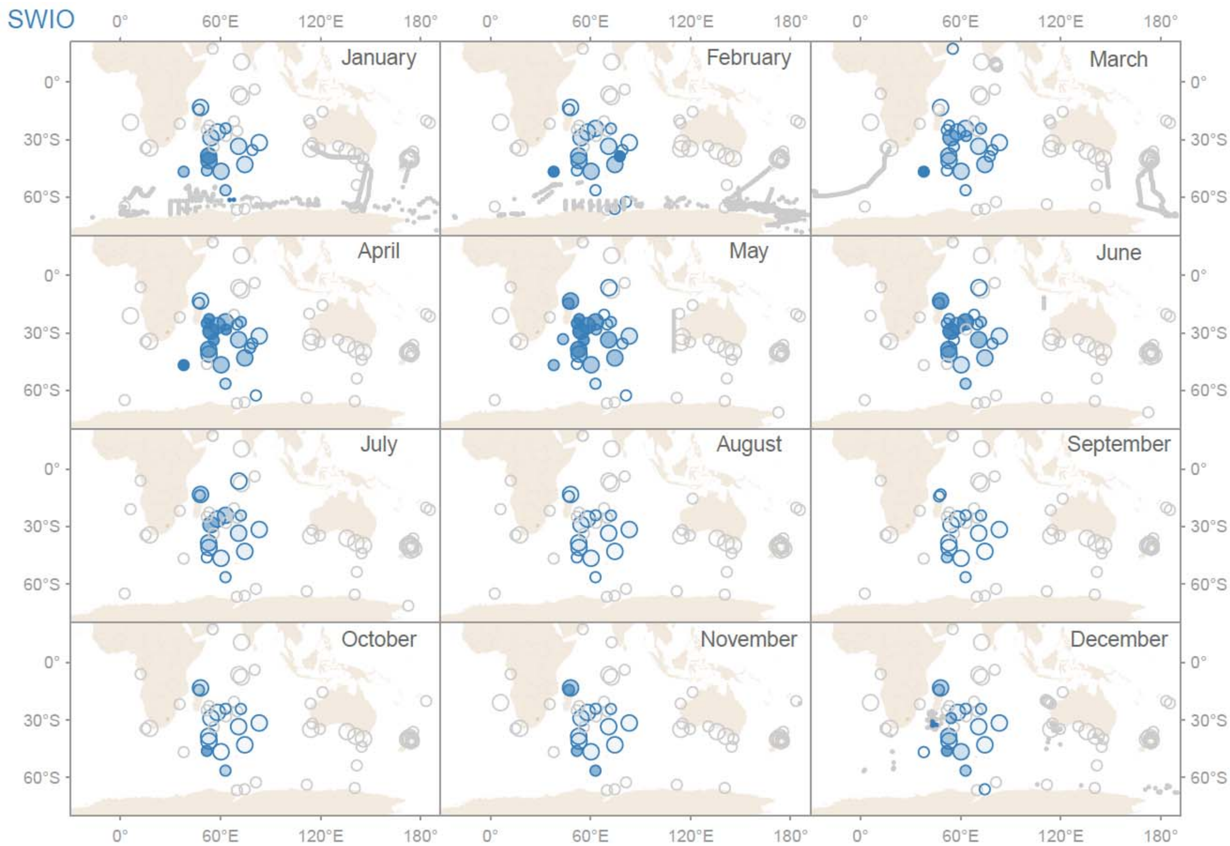

Fig. 7c. Monthly song data available for **SWIO blue whales**. Each circle represents one location at which acoustic data were collected. Small circles are short recording events, usually during cruises; medium circles represent a fixed deployment for one year; and large circles a multi-year fixed deployment. If there were no detections, the circle is gray, otherwise the outer circle is in color. Data are not plotted if the song type was not looked for in the data. Greater interior color represents a higher proportion of hours with detections.

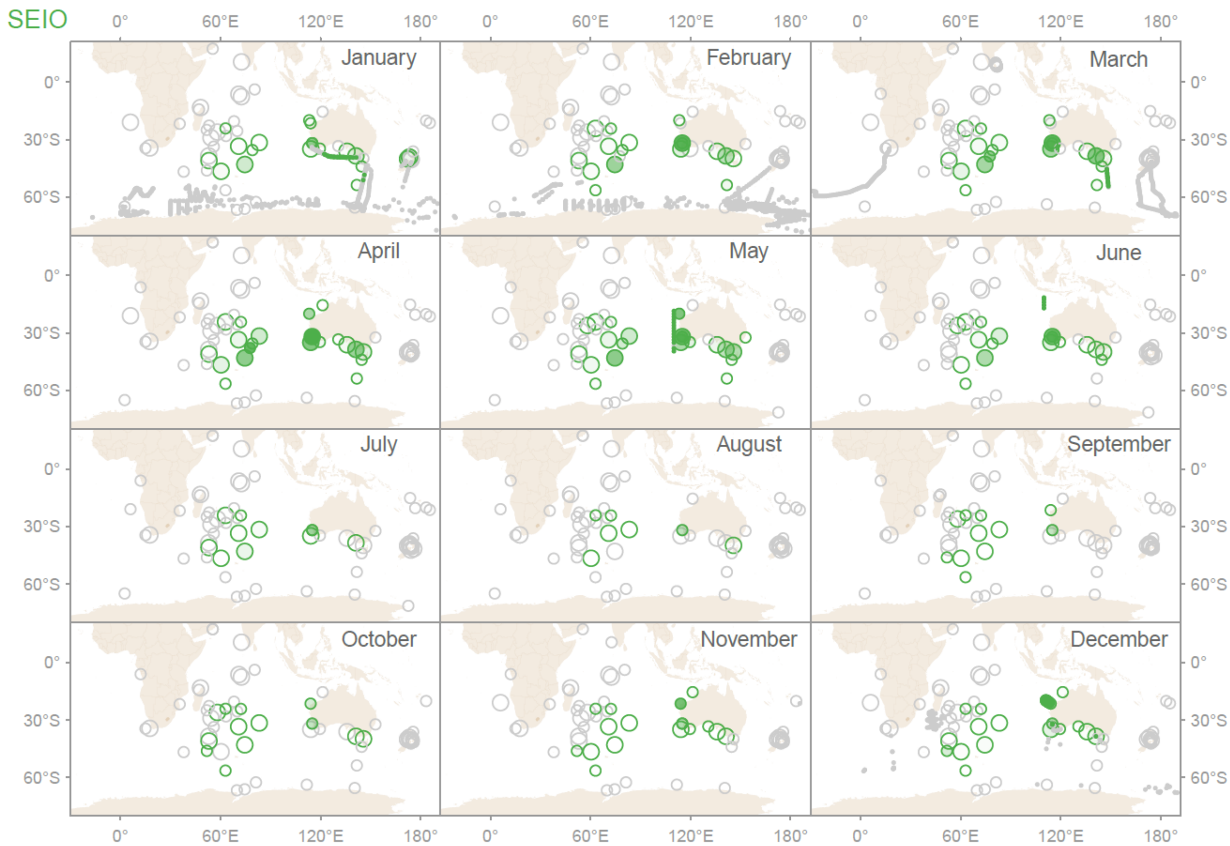

Fig. 7d. Monthly song data available for **SEIO blue whales**. Each circle represents one location at which acoustic data were collected. Small circles are short recording events, usually during cruises; medium circles represent a fixed deployment for one year; and large circles a multi-year fixed deployment. If there were no detections, the circle is gray, otherwise the outer circle is in color. Data are not plotted if the song type was not looked for in the data. Greater interior color represents a higher proportion of hours with detections.

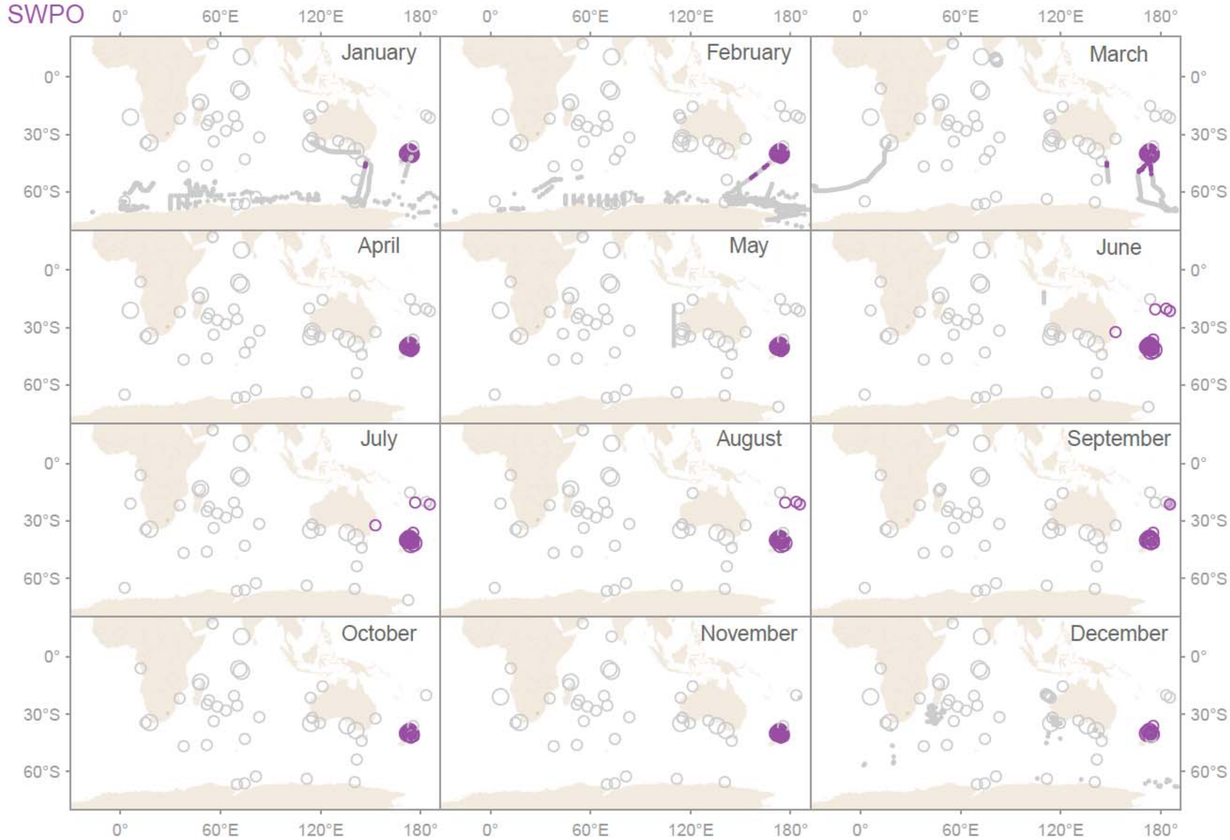

Fig. 7e. Monthly song data available for **SWPO blue whales**. Each circle represents one location at which acoustic data were collected. Small circles are short recording events, usually during cruises; medium circles represent a fixed deployment for one year; and large circles a multi-year fixed deployment. If there were no detections, the circle is gray, otherwise the outer circle is in color. Data are not plotted if the song type was not looked for in the data. Greater interior color represents a higher proportion of hours with detections.

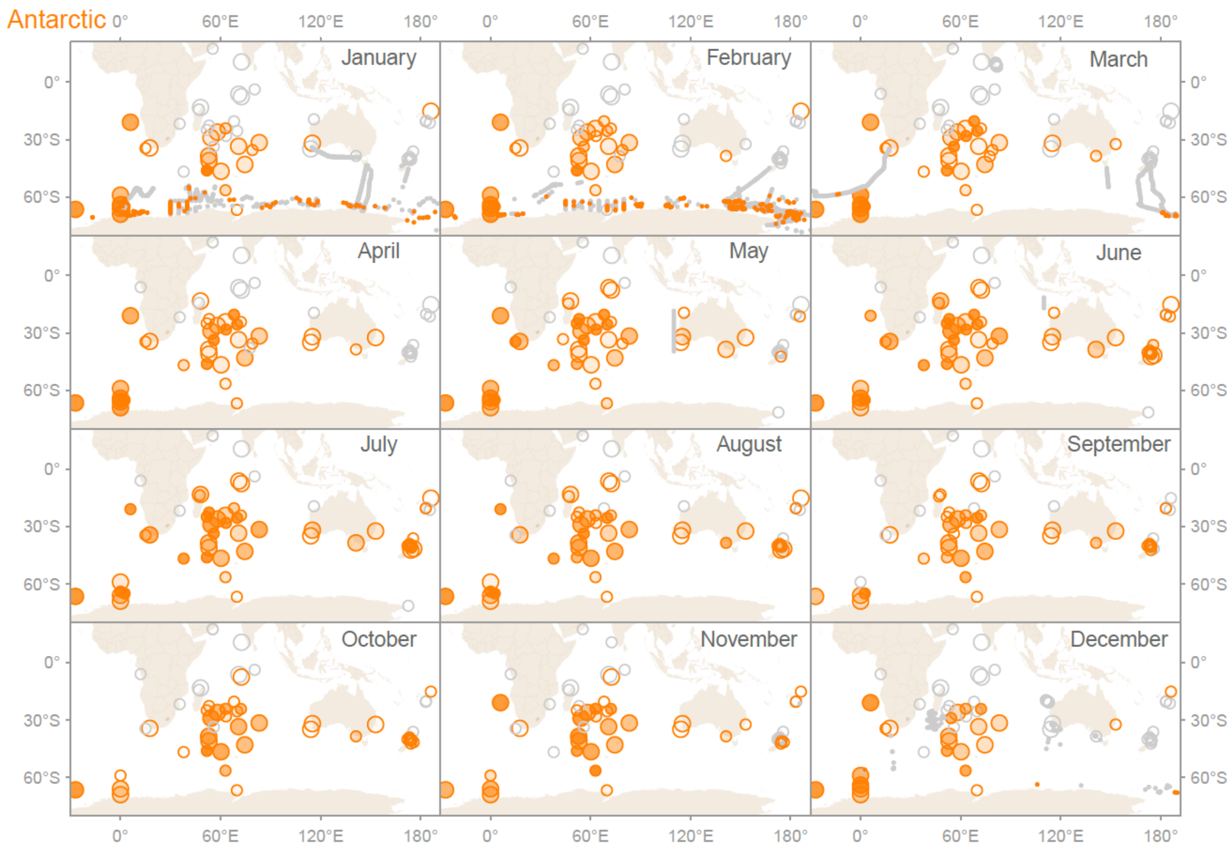

Fig. 7f. Monthly song data available for **Antarctic blue whales**. Each circle represents one location at which acoustic data were collected. Small circles are short recording events, usually during cruises; medium circles represent a fixed deployment for one year; and large circles a multi-year fixed deployment. If there were no detections, the circle is gray, otherwise the outer circle is in color. Data are not plotted if the song type was not looked for in the data. Greater interior color represents a higher proportion of hours with detections.

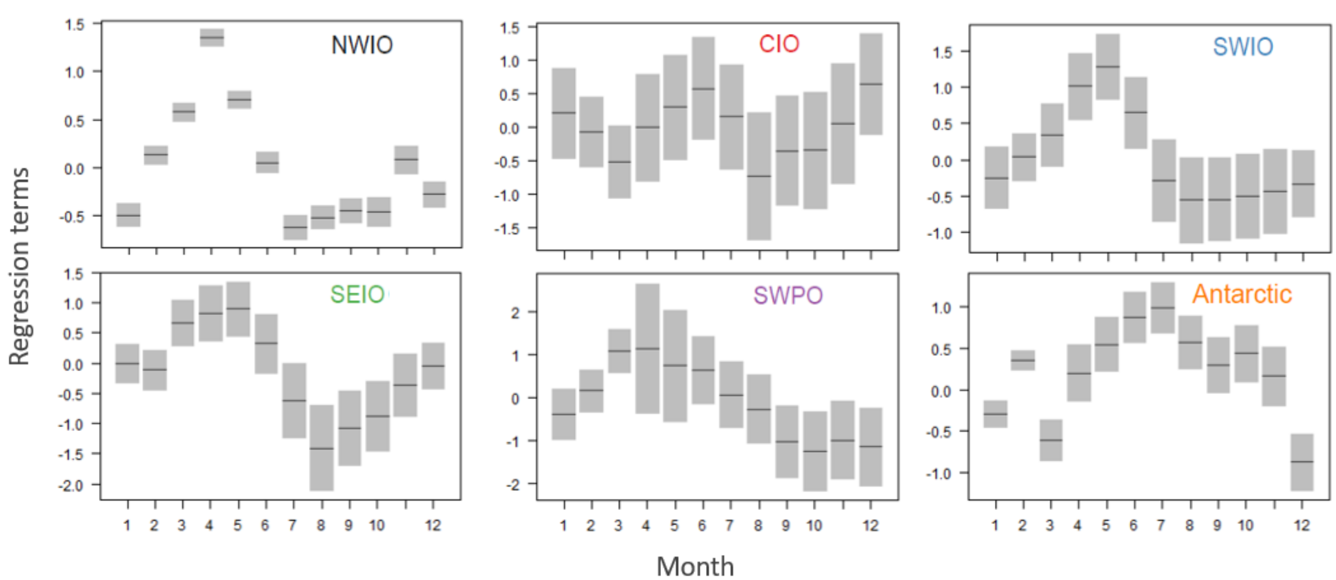

Fig. 8. Model predictions of the impact of month (an additive factor) on predicted song detection rate for each population.

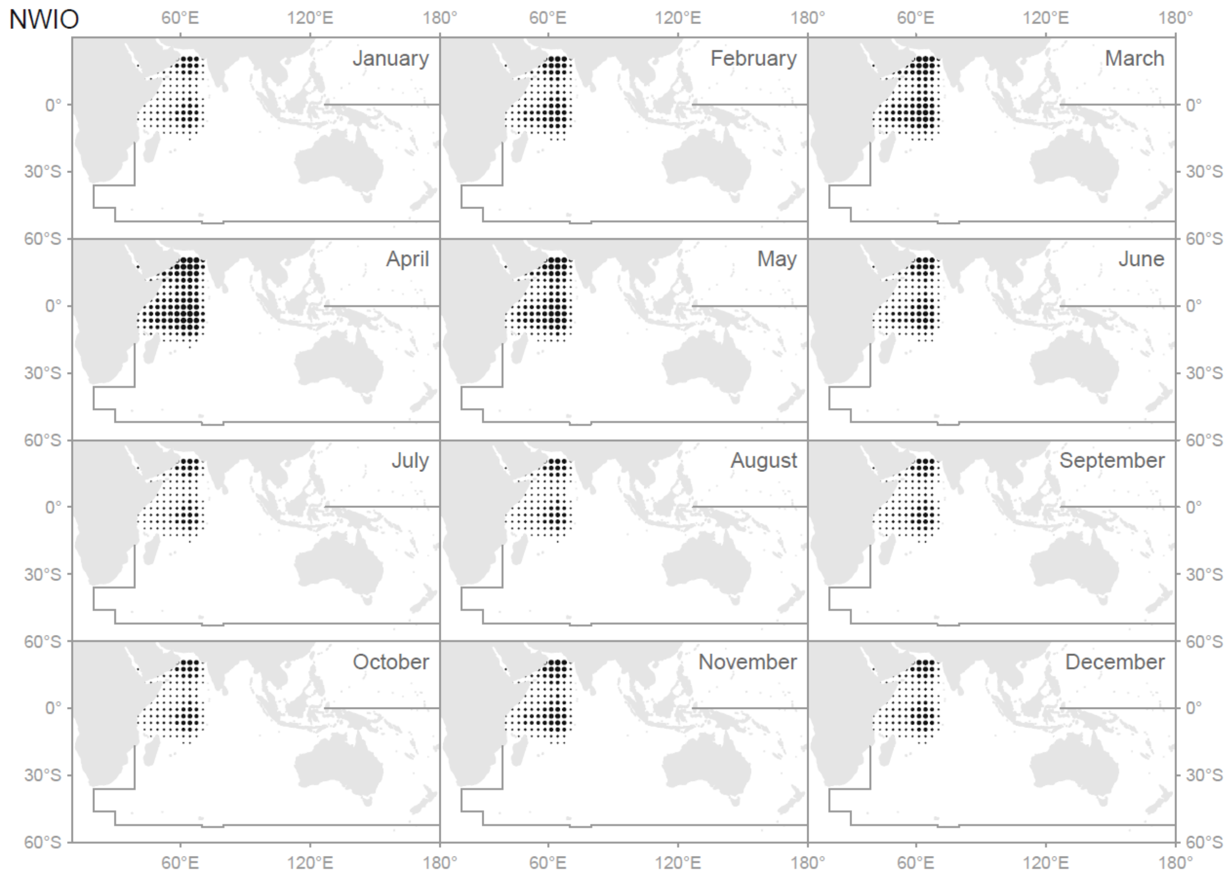

Fig. 9a. Spatial model predictions by month for the **NWIO population**, with circle size representing the predicted probability of detecting song from that population at each location. Probabilities are obtained independently for each month and population.

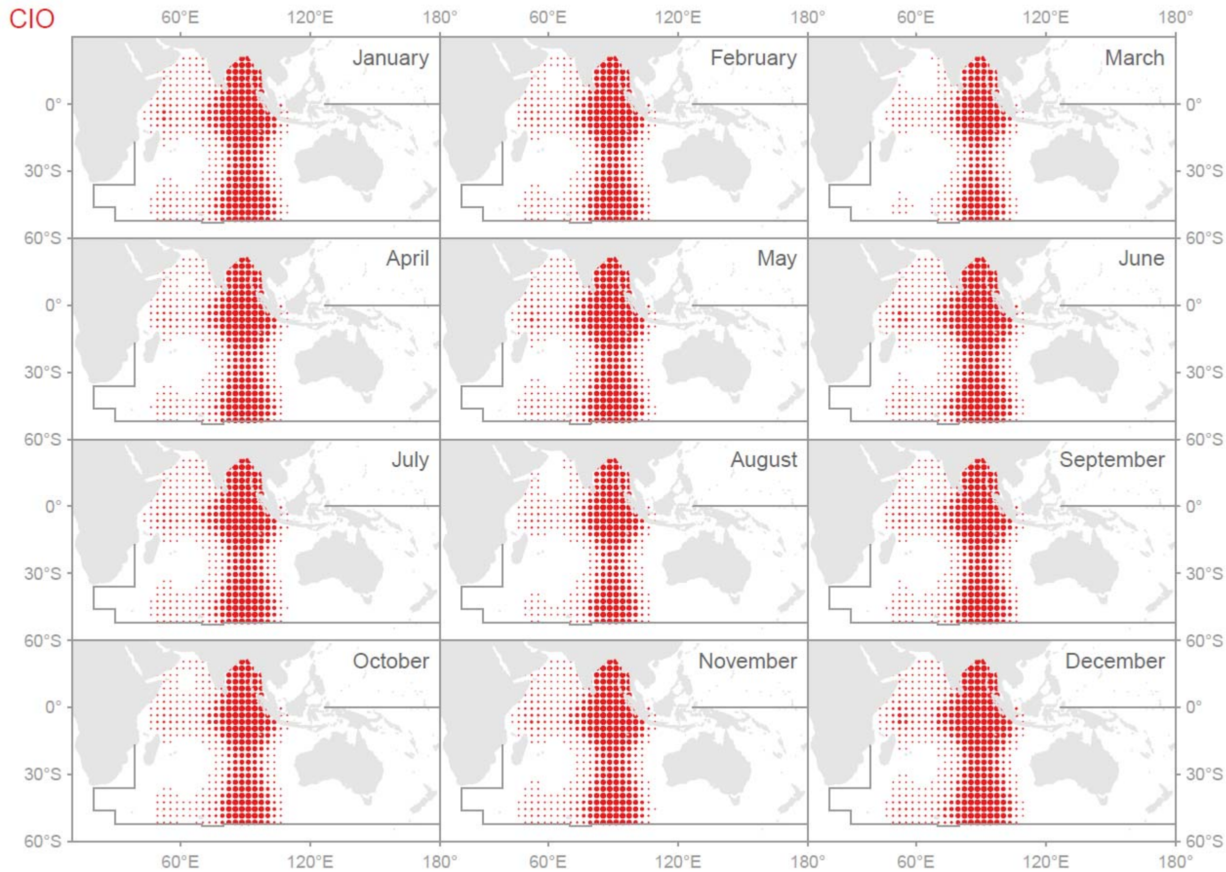

Fig. 9b. Spatial model predictions by month for the **CIO population**, with circle size representing the predicted probability of detecting song from that population at each location. Probabilities are obtained independently for each month and population.

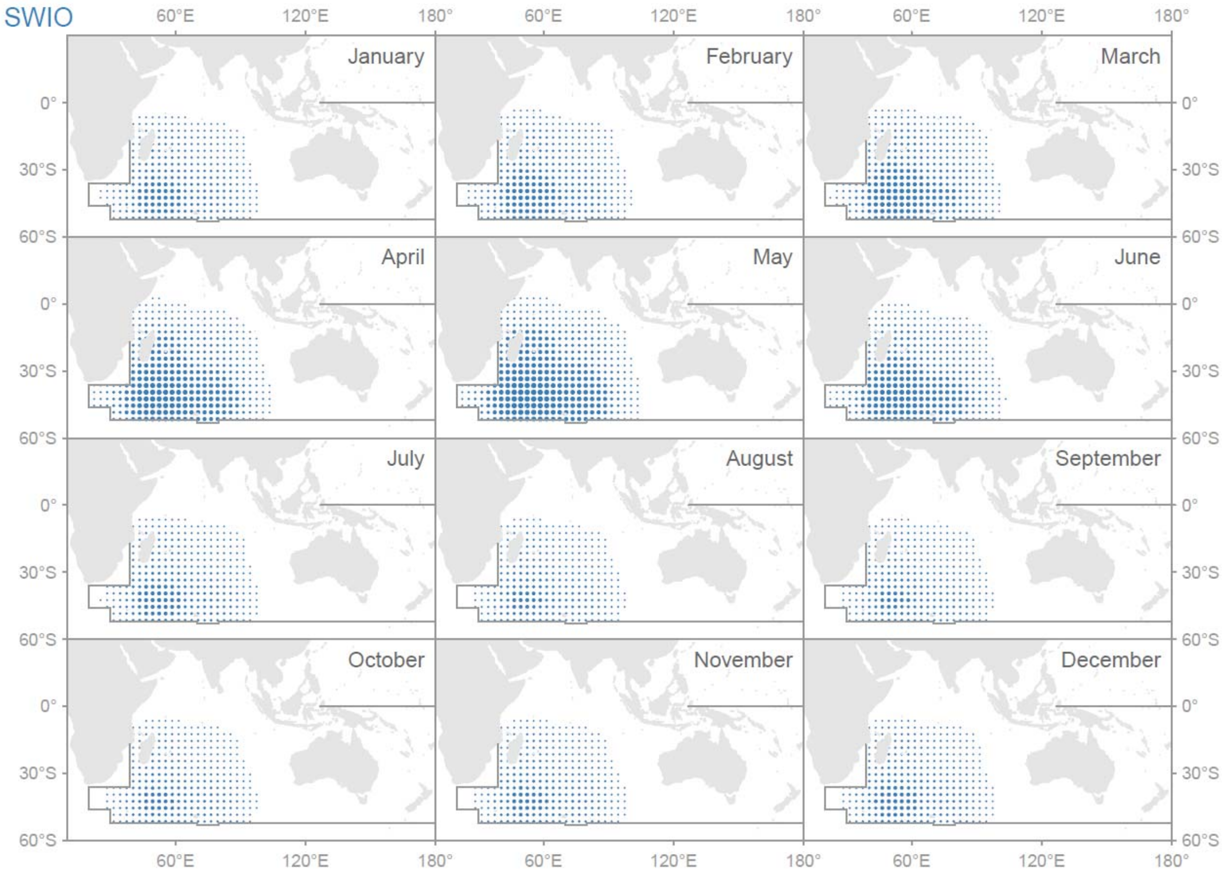

Fig. 9c. Spatial model predictions by month for the **SWIO population**, with circle size representing the predicted probability of detecting song from that population at each location. Probabilities are obtained independently for each month and population.

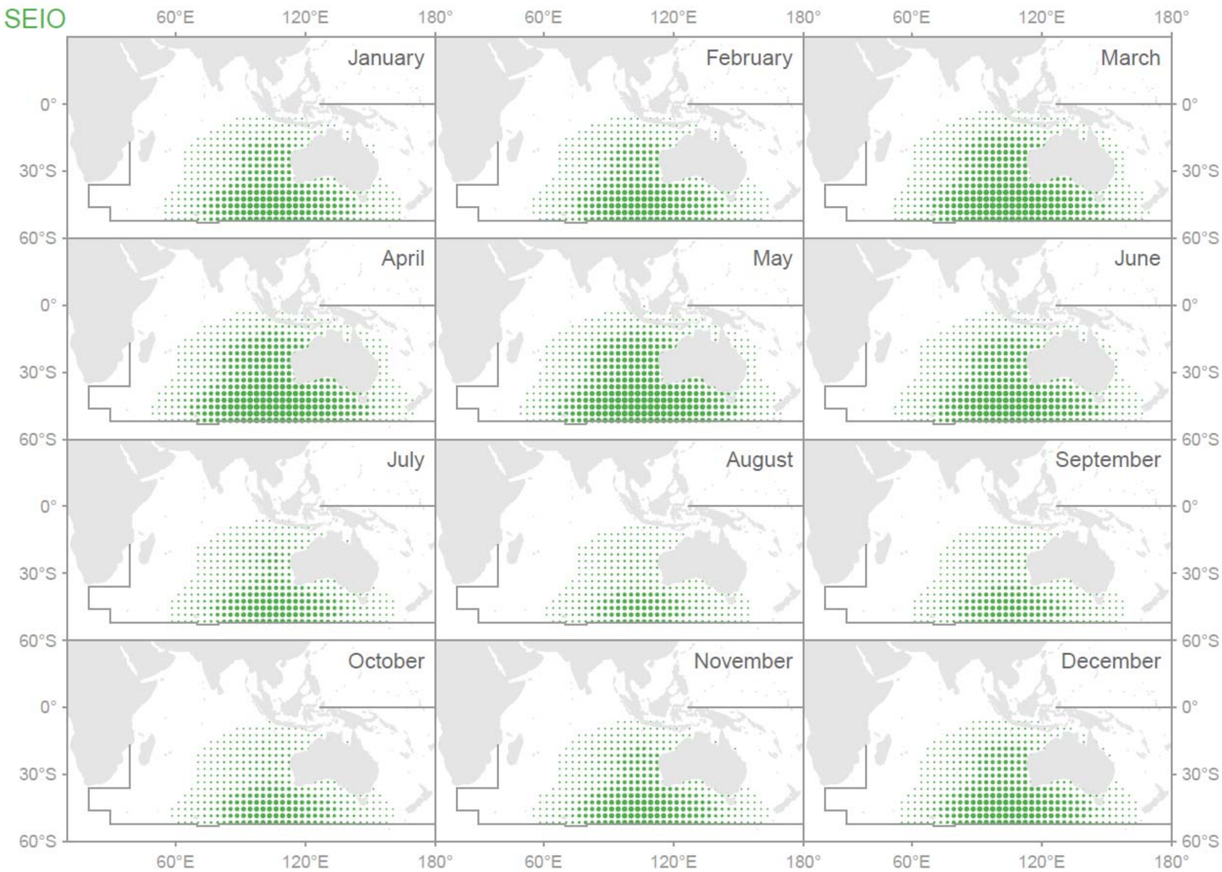

Fig. 9d. Spatial model predictions by month for the **SEIO population**, with circle size representing the predicted probability of detecting song from that population at each location. Probabilities are obtained independently for each month and population.

Fig. 9e. Spatial model predictions by month for the **SWPO population** using a GAM with binomial likelihood, with circle size representing the predicted probability of detecting song from that population at each location. Probabilities are obtained independently for each month and population.

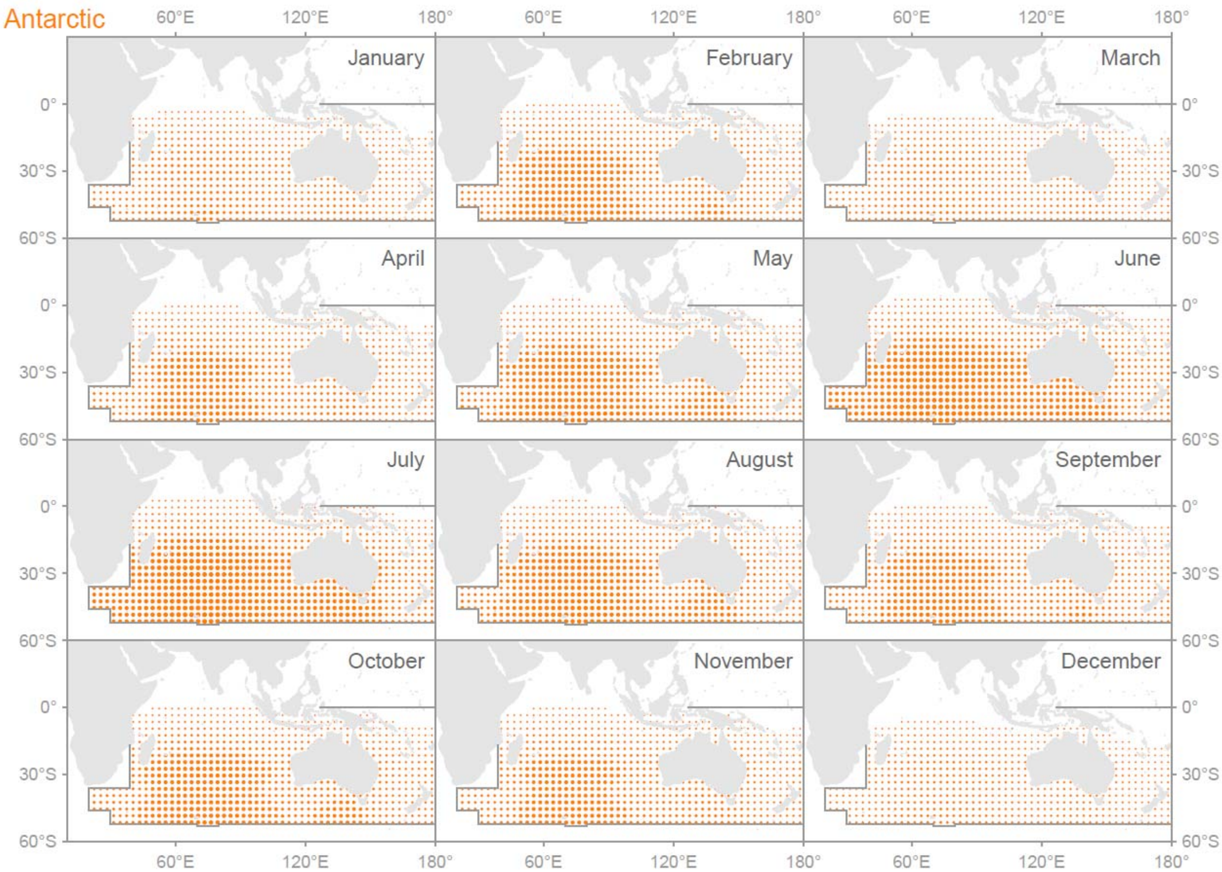

Fig. 9f. Spatial model predictions by month for the **Antarctic population** using a GAM with beta-binomial likelihood, with circle size representing the predicted probability of detecting song from that population at each location. Probabilities are obtained independently for each month and population.

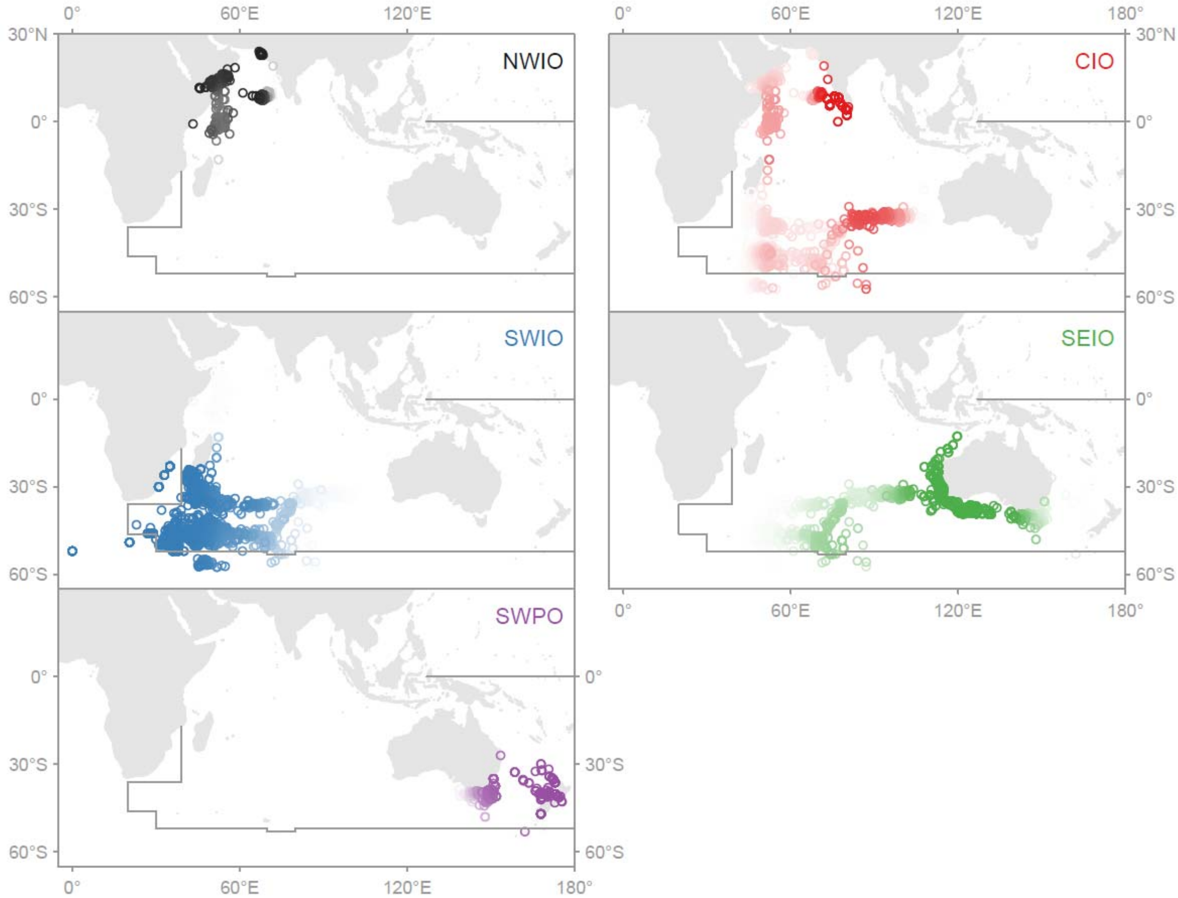

Fig. 10. Allocation of pygmy blue whale catches to each of the five pygmy blue whale populations. At each catch location, the color ranges from white (zero probability of belonging to that population) to a bright color (100% probability). These predictions are the probability of detecting song of that population at that location divided by the sum of the probabilities for all five populations. Colors may vary at nearby locations since predictions for each catch location are based on the monthly surfaces in Fig. 10.

Table 1. Sources of acoustic song data.

Source	Years	Latitudes	Longitudes	Units	Sample size
Alling et al. (1991)	1984	8-11°N	80-82°E	Hours	563
Balcazar et al. (2015)	2009-10	15-39°S	177°W-154°E	Days	1,064
Balcazar et al. (2017)	2009-11, 2013	15-39°S	177°W-154°E	Days	2,303
Barlow et al. (2018, 2023)	2016-18	39-41°S	172-175°E	Hours	80,063
Brodie & Dunn (2015)	2009-10	20-22°S	174-177°W	Days	626
Calderan et al. (2020)	2018, 2020	52-55°S	35-48°W	Hours	58
Calderan (unpubl.)	2022	53-55°S	35-40°W	Hours	12
Cerchio et al. (unpubl.)	2020	17-18°N	55-56°E	Hours	5,163
Cerchio et al. (2010)	2008	6-7°S	12-13°E	Days	550
Cerchio et al. (2020a,b)	2010-13, 2016-19	14°S-18°N	48-73°E	Hours	95,834
Double et al. (2015)	2015	41-75°S	162-186°E	Hours	285
Dréo et al. (2019)	2012-13	20-34°S	51-71°E	Days	2,384
Garcia-Rojas et al. (2018)	2013	34-40°S	114-144°E	Hours	100
Gavrilov & McCauley (2013)	2002-10	34-35°S	114-115°E	Hours	78,888
Gavrilov et al. (2012)	2002-11	34-35°S	114-115°E	Hours	87,792
Gavrilov et al. (2018)	2014	19-21°S	111-113°E	Hours	2,688
Gedamke & Robinson (2010)	2006	59-70°S	29-81°E	Hours	145
Gedamke et al. (2007)	2004-07	44-67°S	74-145°E	Days	900
Kibblewhite et al. (1967)	1964	34-35°S	172-173°E	Hours	1
Letsheleha et al. (2022)	2015-17	34-35°S	14-18°E	Hours	19,235
Ljungblad et al. (1996)	1995	31-43°S	114-144°E	Hours	55
Ljungblad et al. (1998)	1996	25-35°S	40-51°E	Hours	97
McCauley et al. (2018)	2004-05, 2009-17	15-40°S	113-146°E	Hours	124,310
McDonald (2006)	1997	36-37°S	175-176°E	Days	179
Miksis-Olds et al. (2018)	2002-12	6-7°S	71-72°E	Hours	95,592
Miller et al. (2014)	2013	41-70°S	140-190°E	Hours	349
Miller et al. (2017)	2017	34-74°S	180°W-180°E	Hours	294
Miller et al. (2020)	2019	43-67°S	138-153°E	Hours	281
Pangerc (2010)	2006-07	53-54°S	37-38°W	Days	60
Panicker & Stafford (2021)	2018-20	10-11°N	72-73°E	Hours	14,118
Pierpoint et al. (unpubl.)	2019-20	13-16°S	45-48°E	Hours	21,636
Samaran et al. (2010)	2003-04	46-47°S	51-52°E	Hours	8,052
Samaran et al. (2013)	2007	20-43°S	58-84°E	Days	1,095
Shabangu et al. (2017)	1997-2000, 2002-4, 2006-9	38-79°S	180°W-180°E	Hours	476
Shabangu et al. (2019)	2014-15	34-35°S	17-18°E	Hours	13,613
Shabangu et al. (2020)	2014	65-65°S	2-3°E	Hours	5,949
Shabangu et al. (unpubl. a)	2020	21-22°S	35-36°E	Hours	15,314
Shabangu et al. (unpubl. b)	2021-22	46-47°S	37-38°E	Hours	8,999
Širović et al. (2004)	2001-04	62-68°S	62-75°W	Days	4,190
Širović et al. (2006)	2003	52-63°S	26-57°E	Hours	107
Širović et al. (2009)	2003-04	60-72°S	52°W-173°E	Days	520
Sprogis et al. (2022)	2019	11-40°S	110-110°E	Hours	20
Stafford et al. (2011)	2002-03	6-35°S	71-115°E	Hours	29,880

Thomisch et al. (2016)	2008-13	59-69°S	27°W-0°	Days	5,157
Thomisch et al. (2019)	2011-13	20-21°S	5-6°E	Days	460
Torterotot et al. (2020)	2010-18	3-57°S	52-84°E	Hours	359,357
Torterotot et al. (2022)	2017	33-34°S	43-44°E	Hours	259
Torterotot et al. (2022)	2019	37-38°S	77-78°E	Hours	860
Tripovich et al. (2015)	2009-10	38-39°S	141-142°E	Hours	10,320
Warren et al. (2021)	2016-17	40-43°S	174-176°E	Hours	14,594

Table 2. Model selection for each population (bold and beige cells) was based on the lowest Akaike Information Criterion (AIC) values except as noted below. All examined models predicted the mean with (det, notdet) ~ cs(Lat) + cs(Lon) + factor(Month), where cs indicates a cubic spline. Alternative models for the mean, including those with interaction between latitude and longitude, and linear models, all had worse (higher) AIC values. Binomial likelihood was always far worse than beta-binomial likelihood, but for NWIO binomial likelihood was selected since beta-binomial models failed to run, failed to converge, or resulted in absurd predictions (high probabilities of song in southern areas with zero detections). The beta-binomial models below differ in how they model variance (sigma). The CIO model with sigma ~ Lat + Lon was also discarded since it predicted high detection rates in the eastern half of the Indian Ocean where zero CIO calls were detected.

Likelihood Sigma	Binomial –	Beta-binomial Const	Beta-binomial ~ Lat	Beta-binomial ~ Lon	Beta-binomial ~ Lat+Lon	Beta-binomial ~ cs(Lat)	Beta-binomial ~ cs(Lon)
NWIO	**9,860.44**	36.33	10.59	19.46	0.00	1,678.82	failed
CIO	23,076.60	5.84	2.54	1.60	0.00	**0.33**	failed
SWIO	72,841.85	46.12	48.19	**0.00**	0.26	31.40	failed
SEIO	56,332.60	71.30	46.54	31.02	17.12	42.43	**0.00**
SWPO	15,634.37	**0.00**	1.81	2.03	3.32	43.49	1.21
Antarctic	197,933.88	63.01	56.24	65.09	57.84	**0.00**	42.83

Table 3. Estimated total catches for each of the five populations in each whaling season (1 July to 30 June).

Pelagic season	NWIO	CIO	SWIO	SEIO	SWPO	Total
1908/09		1	4	3		8
1909/10		1	2	1		4
1912/13				8	27	35
1913/14			9	20	74	103
1914/15			3	4		7
1915/16			2	5		7
1926/27				5		5
1927/28				3		3
1928/29				1		1
1929/30		20	55	38		113
1930/31					1	1
1934/35		1	10	1		12
1935/36		1				1
1937/38			5		1	6
1938/39			1		1	2
1939/40					1	1
1947/48					1	1
1949/50			1			1
1950/51			1			1
1954/55					1	1
1958/59				2		2
1959/60		25	128	170		323
1960/61		39	1,004	86		1,129
1961/62		14	349	31		394
1962/63		107	1,222	78		1,407
1963/64	56	151	900	178	28	1,313
1964/65	535	1,029	102	1,286	171	3,123
1965/66	143	79	221	289	19	751
1966/67	31	27	4	59	85	206
1967/68		12	312	8	4	336
1968/69	62	56	424	31	5	578
1969/70		64	637	178	6	885
1970/71		92	481	75	114	762
1971/72		10	394	91	20	515
1972/73			2		2	4
Total	827	1,729	6,273	2,651	561	12,041

Table 4. Comparison of total catches for each population to previous studies. In the first two papers, the NWIO song type was not included, and catch totals were for the NIO (northern Indian Ocean).

Reference	NWIO	CIO	SWIO	SEIO	SWPO	Total
Branch et al. (2018)	1,228		6,889	3,646	421	12,184
Branch et al. (2019)	1,796		7,674	2,310	404	12,184
Branch et al. (2021)	1,118	822	5,677	3,953	473	12,043
This paper	827	1,729	6,273	2,651	561	12,041

Appendix 1: Whaling expedition codes in each whaling season that caught pygmy blue whales, and the allocation of pygmy blue whale catches to each of the five populations (NWIO, CIO, SWIO, SEIO, and SWPO). Blue whale catches in the annual catch database are listed either as "Blue db" and "Pygmy db", while "Pygmy" represents our estimate of total pygmy blue whale catches for that row. A single expedition code may be listed twice in one season in the annual database with two date periods. Due to rounding, the numbers in the final five columns may not add exactly to the total in the "Pygmy" column.

Season	Date range	Area	Exp code	Nation	Blue db	Pygmy db	Pygmy	NWIO	CIO	SWIO	SEIO	SWPO
1908/09	1908–1909	Kerguelen	280	Norway	8	0	8	0	1	4	3	0
1909/10	1909	Kerguelen	280	Norway	0	1	1	0	0	0	0	0
1909/10	Mar 1909–Jun 1910	Kerguelen	5303	Norway	0	3	3	0	1	1	1	0
1912/13	4 Nov 1912–1 May 1913	Australia W	5030	Norway	1	0	1	0	0	0	1	0
1912/13	7 Sep 1912–30 Nov 1912	Australia E	5035	Norway	33	0	33	0	0	0	7	26
1912/13	1912	Australia E/NZ	5039	Norway	1	0	1	0	0	0	0	1
1913/14	Jun 1913–3 Nov 1913	Mozambique	4500	Norway	7	0	7	0	0	7	0	0
1913/14	1913	Mozambique	4502	S.Africa	2	0	2	0	0	2	0	0
1913/14	27 May 1913–16 Sep 1913	Australia W	5030	Norway	1	0	1	0	0	0	1	0
1913/14	18 May 1913–27 Oct 1913	Australia E	5035	Norway	93	0	93	0	0	0	19	74
1914/15	Feb 1914–Jun 1914	Australia W	0	Norway	3	0	3	0	0	0	3	0
1914/15	Jun 1914–14 Nov 1914	Mozambique	4500	Norway	3	0	3	0	0	3	0	0
1914/15	12 Jul 1914–14 Oct 1914	Australia W	5030	Norway	1	0	1	0	0	0	1	0
1915/16	1915	Mozambique	4500	Norway	2	0	2	0	0	2	0	0
1915/16	1915	Australia W	4668	Norway	5	0	5	0	0	0	5	0
1926/27	28 Jun 1926–8 Oct 1926	Australia W	4610	Australia	5	0	5	0	0	0	5	0
1927/28	18 Jun 1927–10 Oct 1927	Australia W	4610	Australia	3	0	3	0	0	0	3	0
1928/29	26 Jun 1928–30 Sep 1928	Australia W	4610	Australia	1	0	1	0	0	0	1	0
1929/30	Jul 1929–Nov 1929	Kerguelen	5760	S.Africa	113	0	113	0	20	55	38	0
1930/31	1930	New Zealand	4820	N.Zealnd	1	0	1	0	0	0	0	1
1934/35	13 Nov 1934–31 Mar 1935	Antarctic	5681	Norway	684	0	2	0	0	1	1	0
1934/35	14 Nov 1934–30 Mar 1935	Antarctic	5710	Norway	780	0	8	0	0	8	0	0
1934/35	17 Nov 1934–31 Mar 1935	Antarctic	5940	Norway	613	0	1	0	0	1	0	0
1935/36	22 Nov 1935–4 Mar 1936	Antarctic	5710	Norway	758	0	1	0	1	0	0	0
1937/38	1937	New Zealand	4820	N.Zealnd	1	0	1	0	0	0	0	1
1937/38	11 Nov 1937–10 Mar 1938	Antarctic	6010	S.Africa	508	0	1	0	0	1	0	0
1937/38	10 Jun 1937–30 Sep 1937	Indian Oc S	6013	S.Africa	4	0	4	0	0	4	0	0
1938/39	1938	New Zealand	4820	N.Zealnd	1	0	1	0	0	0	0	1
1938/39	1938	Indian Oc S	6013	S.Africa	1	0	1	0	0	1	0	0

1939/40	1939	New Zealand	4820	N.Zealnd	1	0	1	0	0	0	0	1
1947/48	11 May 1947–6 Aug 1947	New Zealand	4820	N.Zealnd	1	0	1	0	0	0	0	1
1949/50	19 May 1949–10 Oct 1949	Indian Oc S	5815	UK	1	0	1	0	0	1	0	0
1950/51	28 May 1950–28 Sep 1950	Indian Oc S	5816	France	1	0	1	0	0	1	0	0
1954/55	3 Jun 1954–12 Sep 1954	Australia E	4700	Australia	1	0	1	0	0	0	0	1
1958/59	29 Apr 1958–18 Oct 1958	Australia W	4650	Australia	2	0	2	0	0	0	2	0
1959/60	17 May 1959–21 Sep 1959	Australia W	4650	Australia	6	0	6	0	0	0	6	0
1959/60	22 May 1959–19 Nov 1959	Australia W	4680	Australia	6	0	6	0	0	0	6	0
1959/60	27 Nov 1959–26 Mar 1960	Antarctic	5981	Japan	46	9	9	0	1	3	5	0
1959/60	26 Nov 1959–26 Mar 1960	Antarctic	6131	Japan	30	10	10	0	1	3	6	0
1959/60	28 Nov 1959–26 Mar 1960	Antarctic	6141	Japan	16	272	272	0	21	114	137	0
1959/60	25 Nov 1959–29 Mar 1960	Antarctic	6430	Japan	21	20	20	0	2	8	10	0
1960/61	30 Mar 1960–13 Dec 1960	Australia W	4680	Australia	2	0	2	0	0	0	2	0
1960/61	18 Nov 1960–17 Mar 1961	Antarctic	6131	Japan	2	311	311	0	6	302	4	0
1960/61	16 Nov 1960–16 Mar 1961	Antarctic	6141	Japan	8	114	114	0	19	53	41	0
1960/61	14 Nov 1960–15 Mar 1961	Antarctic	6410	Japan	0	273	273	0	12	225	36	0
1960/61	16 Nov 1960–3 Apr 1961	Antarctic	6430	Japan	1	202	202	0	1	200	1	0
1960/61	17 Dec 1960–5 Apr 1961	Antarctic	6450	Japan	0	226	226	0	1	224	1	0
1961/62	7 Nov 1961–30 Mar 1962	Antarctic	5981	Japan	32	25	25	0	3	10	12	0
1961/62	9 Nov 1961–2 Apr 1962	Antarctic	6062	Japan	3	5	5	0	0	5	0	0
1961/62	4 Nov 1961–3 Apr 1962	Antarctic	6131	Japan	2	9	9	0	0	9	0	0
1961/62	13 Dec 1961–3 Apr 1962	Antarctic	6141	Japan	26	55	55	0	1	54	1	0
1961/62	6 Dec 1961–15 Apr 1962	Antarctic	6281	Nethrlnd	45	0	2	0	0	2	0	0
1961/62	2 Nov 1961–8 Apr 1962	Antarctic	6430	Japan	6	182	182	0	6	174	2	0
1961/62	26 Nov 1961–7 Apr 1962	Antarctic	6450	Japan	28	36	36	0	4	18	15	0
1961/62	29 Nov 1961–19 Apr 1962	Antarctic	6461	USSR	35	2	2	0	0	1	0	0
1961/62	12 Nov 1961–2 Apr 1962	Antarctic	6480	Japan	2	78	78	0	0	78	0	0
1962/63	10 May 1962–15 Sep 1962	Australia W	4650	Australia	0	4	4	0	0	0	4	0
1962/63	20 Nov 1962–31 Mar 1963	Antarctic	5981	Japan	0	45	45	0	1	44	0	0
1962/63	2 Nov 1962–4 Apr 1963	Antarctic	6062	Japan	1	102	102	0	3	92	7	0
1962/63	21 Nov 1962–31 Mar 1963	Antarctic	6131	Japan	1	49	49	0	0	49	0	0
1962/63	18 Nov 1962–1 Apr 1963	Antarctic	6141	Japan	2	83	83	0	4	77	2	0
1962/63	9 Dec 1962–1 May 1963	Antarctic	6300	USSR	0	189	189	0	21	154	13	0
1962/63	28 Oct 1962–10 Apr 1963	Antarctic	6430	Japan	4	147	147	0	9	135	3	0

1962/63	1 Apr 1963–10 Apr 1963	Antarctic	6442	USSR	6	0	6	0	1	4	2	0
1962/63	1 April 1963–30 April 1963	Antarctic	6442	USSR	6	0	6	0	1	4	2	0
1962/63	30 Nov 1962–9 Apr 1963	Antarctic	6450	Japan	3	202	202	0	4	195	2	0
1962/63	2 Dec 1962–21 Dec 1962	Antarctic	6461	USSR	0	82	82	0	10	64	8	0
1962/63	6 Jan 1963–14 Apr 1963	Antarctic	6461	USSR	84	191	191	0	23	149	19	0
1962/63	Oct 1962–Apr 1963	Antarctic	6461	USSR	0	59	59	0	7	46	6	0
1962/63	22 Dec 1962–5 Jan 1963	Indian Oc S	6463	USSR	0	156	156	0	19	136	1	0
1962/63	7 Nov 1962–4 Apr 1963	Antarctic	6480	Japan	2	86	86	0	3	74	9	0
1963/64	13 Mar 1963–3 Oct 1963	Natal,SAfrica	4480	S.Africa	4	1	1	0	0	1	0	0
1963/64	7 Jun 1963–8 Jul 1963	Australia W	4650	Australia	0	1	1	0	0	0	1	0
1963/64	13 Nov 1963–18 Mar 1964	Antarctic	5981	Japan	4	2	2	0	0	2	0	0
1963/64	27 Nov 1963–14 Mar 1964	Antarctic	6131	Japan	0	1	1	0	0	1	0	0
1963/64	8 Dec 1963–1 May 1964	Antarctic	6300	USSR	12	140	140	0	16	87	10	26
1963/64	19 Nov 1963–7 Dec 1963	Indian Oc S	6302	USSR	0	20	20	0	2	18	0	0
1963/64	6 Nov 1963–18 Nov 1963	Indian Oc NW	6303	USSR	0	79	79	56	20	3	0	0
1963/64	14 Nov 1963–26 Nov 1963	Antarctic	6442	USSR	0	3	3	0	0	2	1	0
1963/64	8 Dec 1963–1 May 1964	Antarctic	6442	USSR	39	9	9	0	1	5	2	1
1963/64	27 Nov 1963–7 Dec 1963	Indian Oc S	6443	USSR	0	1	1	0	0	1	0	0
1963/64	29 Nov 1963–7 Apr 1964	Antarctic	6450	Japan	0	28	28	0	0	28	0	0
1963/64	4 Dec 1963–27 Mar 1964	Antarctic	6461	USSR	79	382	382	0	36	337	9	0
1963/64	21 Nov 1963–3 Dec 1963	Indian Oc S	6463	USSR	0	18	18	0	1	14	3	0
1963/64	28 Mar 1964–20 Apr 1964	Indian Oc S	6463	USSR	0	119	119	0	7	93	20	0
1963/64	16 Nov 1963–7 Apr 1964	Antarctic	6490	USSR	10	492	492	0	68	310	114	0
1963/64	9 Nov 1963–15 Nov 1963	Indian Oc S	6493	USSR	0	18	18	0	0	0	18	0
1964/65	5 Feb 1965–10 Apr 1965	Antarctic	6300	USSR	0	70	70	0	0	0	42	28
1964/65	19 Dec 1964–2 Feb 1965	Indian Oc S	6302	USSR	0	395	395	0	200	8	187	0
1964/65	5 Nov 1964–16 Dec 1964	Indian Oc NW	6303	USSR	0	329	329	174	152	3	0	0
1964/65	2 Feb 1965–6 Apr 1965	Antarctic	6442	USSR	0	264	264	0	0	0	155	109
1964/65	17 Dec 1964–1 Feb 1965	Indian Oc S	6443	USSR	0	880	880	0	312	10	557	0
1964/65	23 Oct 1964–16 Dec 1964	Indian Oc NW	6444	USSR	0	656	656	361	288	7	0	0
1964/65	11 Apr 1965–23 Apr 1965	Australia E/NZ	6445	USSR	0	34	34	0	0	0	0	34
1964/65	2 Dec 1964–6 Jan 1965	Antarctic	6461	USSR	18	55	55	0	4	47	3	0
1964/65	2 Feb 1965–10 Mar 1965	Antarctic	6461	USSR	1	19	19	0	1	16	1	0
1964/65	20 Nov 1964–1 Dec 1964	Indian Oc S	6463	USSR	0	4	4	0	1	0	3	0

1964/65	8 Jan 1965–31 Jan 1965	Indian Oc S	6463	USSR	0	163	163	0	28	4	131	0
1964/65	13 Mar 1965–18 May 1965	Indian Oc S	6463	USSR	0	247	247	0	43	6	199	0
1964/65	30 Oct 1964–21 Nov 1964	Indian Oc S	6493	USSR	1	7	7	0	0	0	7	0
1965/66	5 Jan 1966–15 Apr 1966	Antarctic	6300	USSR	119	18	18	0	2	15	1	0
1965/66	29 Nov 1965–3 Jan 1966	Indian Oc S	6302	USSR	0	225	225	0	18	205	2	0
1965/66	9 Nov 1965–27 Nov 1965	Indian Oc NW	6303	USSR	0	109	109	81	28	1	0	0
1965/66	30 Nov 1965–17 Dec 1965	Indian Oc S	6443	USSR	0	223	223	0	4	0	219	0
1965/66	13 Nov 1965–25 Nov 1965	Indian Oc NW	6444	USSR	0	88	88	63	25	0	0	0
1965/66	1965–1966	Antarctic	6490	USSR	5	88	88	0	1	0	68	19
1966/67	13 Dec 1966–12 Apr 1967	Antarctic	6442	USSR	66	4	4	0	0	0	0	4
1966/67	24 Nov 1966–12 Dec 1966	Indian Oc S	6443	USSR	0	2	2	0	1	1	1	0
1966/67	4 Nov 1966–22 Nov 1966	Indian Oc NW	6444	USSR	0	38	38	31	7	0	0	0
1966/67	13 Apr 1967–17 Apr 1967	Australia E/NZ	6445	USSR	0	2	2	0	0	0	0	2
1966/67	25 Dec 1966–17 Jan 1967	Antarctic	6450	Japan	0	3	3	0	1	2	1	0
1966/67	16 Dec 1966–18 May 1967	Antarctic	6490	USSR	35	118	118	0	0	0	38	80
1966/67	7 Oct 1966–15 Dec 1966	Indian Oc S	6493	USSR	0	39	39	0	19	1	19	0
1967/68	29 Dec 1967–23 Apr 1968	Antarctic	6442	USSR	8	13	13	0	0	8	1	3
1967/68	17 Nov 1967–28 Dec 1967	Indian Oc S	6443	USSR	0	297	297	0	8	288	1	0
1967/68	27 Apr 1968–16 May 1968	Indian Oc S	6443	USSR	0	1	1	0	0	1	0	0
1967/68	18 Dec 1967–12 Apr 1968	Antarctic	6461	USSR	36	2	2	0	0	2	0	0
1967/68	31 Oct 1967–12 Apr 1968	Antarctic	6461	USSR	0	5	5	0	0	5	0	0
1967/68	2 Jan 1968–7 May 1968	Antarctic	6490	USSR	13	1	1	0	0	0	0	0
1967/68	8 May 1968–12 May 1968	Australia E/NZ	6492	USSR	0	1	1	0	0	0	0	1
1967/68	11 Oct 1967–1 Jan 1968	Indian Oc S	6493	USSR	2	17	17	0	3	7	6	0
1968/69	22 Apr 1969–3 May 1969	Indian Oc S	6443	USSR	0	21	21	0	0	0	21	0
1968/69	26 Dec 1968–19 Apr 1969	Antarctic	6461	USSR	9	461	461	0	32	421	8	0
1968/69	13 Oct 1968–22 Apr 1969	Antarctic	6461	USSR	0	3	3	0	0	3	0	0
1968/69	1968–1969	Antarctic	6490	USSR	19	94	94	62	25	0	2	5
1969/70	9 Mar 1970–12 Mar 1970	Antarctic	6062	Japan	0	2	2	0	0	2	0	0
1969/70	15 Jan 1970–7 Apr 1970	Antarctic	6442	USSR	0	536	536	0	37	476	23	0
1969/70	8 Apr 1970–1 May 1970	Indian Oc S	6443	USSR	1	14	14	0	0	14	0	0
1969/70	9 Jan 1970–5 Apr 1970	Antarctic	6461	USSR	8	2	2	0	0	0	2	0
1969/70	Oct 1969–Apr 1970	Antarctic	6461	USSR	0	4	4	0	0	0	4	0
1969/70	18 Dec 1969–7 Jan 1970	Indian Oc S	6463	USSR	0	155	155	0	10	82	63	0

1969/70	7 Apr 1970–22 Apr 1970	Indian Oc S	6463	USSR	0	104	104	0	7	55	42	0
1969/70	7 Jan 1970–13 May 1970	Antarctic	6490	USSR	30	13	13	0	1	3	3	6
1969/70	31 Oct 1969–6 Jan 1970	Indian Oc S	6493	USSR	0	17	17	0	4	2	11	0
1969/70	18 May 1970–27 May 1970	Indian Oc S	6493	USSR	0	21	21	0	5	2	14	0
1969/70	26 Oct 1969–30 Oct 1969	Indian Oc NE	6497	USSR	0	17	17	0	0	0	17	0
1970/71	21 Dec 1970–31 Mar 1971	Antarctic	6442	USSR	37	562	562	0	43	470	50	0
1970/71	2 Apr 1971–26 Apr 1971	Indian Oc S	6443	USSR	0	8	8	0	0	7	1	0
1970/71	2 Jan 1971–21 Apr 1971	Antarctic	6490	USSR	33	90	90	0	0	0	6	83
1970/71	30 Apr 1971–21 May 1971	Antarctic	6490	USSR	0	33	33	0	0	0	2	30
1970/71	15 Nov 1970–1 Jan 1971	Indian Oc S	6493	USSR	0	69	69	0	48	4	16	0
1971/72	28 Dec 1971–25 Mar 1972	Antarctic	6442	USSR	8	61	61	0	1	60	1	0
1971/72	26 Mar 1972–16 May 1972	Indian Oc S	6443	USSR	5	2	2	0	0	2	0	0
1971/72	7 Jan 1972–12 Apr 1972	Antarctic	6490	USSR	2	164	164	0	5	54	89	16
1971/72	27 Apr 1972–31 May 1972	Australia E/NZ	6492	USSR	0	5	5	0	0	0	0	5
1971/72	15 Nov 1971–3 Jan 1972	Indian Oc S	6493	USSR	0	284	284	0	4	279	1	0
1972/73	13 Mar 1973–25 Mar 1973	Antarctic	6442	USSR	0	2	2	0	0	2	0	0
1972/73	24 Feb 1973–7 Mar 1973	Antarctic	6490	USSR	1	2	2	0	0	0	0	2