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Satellite tracking of blue whales (Balaenoptera musculus) from Patagonia (Chile) to Galapagos (Ecuador): novel insights into migratory pathways along the Eastern South Pacific

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Satellite tracking of blue whales (*Balaenoptera musculus*) from Patagonia (Chile) to Galapagos (Ecuador): novel insights into migratory pathways along the Eastern South Pacific

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ABSTRACT

Despite whaling records suggest that blue whales migrate to and from the Southern Ocean in a regular fashion, the seasonality, routes used, and perhaps more importantly, the location of wintering destinations remain virtually unknown. This lack of information compounds the design and implementation of effective conservation measures to allow their recovery. This research programme aims at unveiling important habitat for blue whales through a satellite tagging and tracking program that will deliver key ecological and conservation information on a regional context. Here we report the results of the 2015 fieldwork, when seven blue whales were instrumented in northern Patagonia, Chile, during mid-April. The minimum distance travelled by the blue whales ranged between 80 and 4,010 nm and the longevity of the tags stretched between 21 and 162 days. Upon departing the feeding ground during mid to late austral autumn, blue whales moved in a wide array of directions which further on coincided on a general movement direction (NW) but along a wide corridor exceeding 1,000 nm on occasions. Area Restricted Search (ARS) behavior was exhibited within protected waters of Chiloe inner sea and also along open waters of the Corcovado Gulf and W of Guafo Island. Interestingly, ARS behavior (together with deep dives (350 m)) was also exhibited South of Galapagos Islands by one whale who remained in the area since mid-July to late-September, when transmissions ceased. Some transit behavior was noted between feeding areas in the Chiloense Ecoregion feeding ground, but most notably became evident during offshore and alongshore movements, indicative of migration.

KEYWORDS: CHILOENSE MARINE ECOREGION, FEEDING AND BREEDING GROUNDS; MIGRATION; CETARTIODACTYLA: BALAENOPTERIDAE

INTRODUCTION

In general, most baleen whales (Mysticeti) spend summers feeding in productive waters at high latitudes and over-wintering in warmer waters at lower latitudes where whales calve and mate, but rarely feed (Mackintosh and Wheeler, 1929; Mackintosh 1965). Despite whaling records suggest that blue whales (*Balaenoptera musculus*) migrate to and from the Southern Ocean in a regular fashion (Mackintosh, 1966), the seasonality, routes used, and perhaps more importantly, the location of wintering destinations (prospective breeding grounds) remain virtually unknown.

The first report of southern hemisphere blue whale movements using satellite telemetry came from Hucke-Gaete and Mate (2005). Of five whales tagged in the fjords off southern Chile in January 2004, two travelled north as far as the Nazca Ridge (*ca.* 800km from shore, ~25°S). The only other available information of a satellite-monitored blue whale population in the southern hemisphere comes from Gales *et al*. (2010) and Double *et al*. (2014) who reported movements of blue whales from the Perth Canyon and Naturaliste Plateau, along the western coast of Australia to Indonesia (Banda and Molucca Seas).

In order to further describe the migratory movements of eastern South Pacific blue whales, we present the satellite telemetry derived movements of seven individuals tagged off southern Chile during 2015.

METHODS

Study area

This study was performed during mid-April 2015 in the waters of eastern Chiloe and the Gulf of Ancud, located in the northern portion of Chiloe Inner Sea, in northern Patagonia (Chiloense Marine Ecoregion), Chile (~42°S; 73°W).

Satellite tracking

A 17m motherboat (L/M Noctiluca) was used as the main searching platform while towing the tagging platform, a 7.6 m rigid-hulled inflatable boat (R/V Musculus) equipped with a 150hp outboard engine. Satellite tags were deployed from R/V Musculus on seven blue whales during the austral summer and early autumn of 2015, at their reported feeding ground off Southern Chile (Hucke-Gaete *et al*. 2004). The satellite tags employed are comprised of a custom-designed, anchor section joined to a stainless steel housing containing a location-only Spot 5 (n=3) or dive depth and location MK10 (n=4) transmitter manufactured by Wildlife Computers (Redmond, Washington, USA) as described in detail by Double et al. (2014). Satellite tags were deployed using a modified version of the Air Rocket Transmitter System (ARTS, Restech) at a pressure of 10-14 bar. All tags were programmed to transmit on a daily basis, every hour of the day up to a maximum of 500 messages per day. Tag delivery procedure was designed such that a biopsy skin sample was collected simultaneously when a whale was tagged using a Paxarms system. Biopsies will later on be used for DNA extraction and sex determination of each individual.

State-space modelling

We used a switching first-difference correlated random walk (DCRWS) model described in Jonsen et al. (2005), with modifications at the priors previously used for other satellite-tagged marine mammals (Breed et al., 2009; Silva et al., 2013). As this approach have been extensively described elsewhere (Jonsen et al., 2007, 2005; Morales et al., 2004; Patterson et al., 2008) we will only briefly describe the rationale. As satellite tags provides location information with error in space and at irregular time intervals, DCRWS couple two stochastic models: a process model that predicts the future state of an animal given its current state, and an observation model that relates the unobserved location states (true locations) predicted by the process model to the observed data (locations obtained from ARGOS). As animals are expected to switch their behaviour along their paths, the process model to describe movement dynamics allows movement parameters to change between two discrete behavioural states by including a process model for each one (Morales et al., 2004).

Metrics used for the process model were mean turning angle, with a descriptive parameter θ_b extracted from a beta distribution and, autocorrelation between speed and direction, with a descriptive parameter γ_b extracted from a gamma distribution. Subscript *b* indicates the two possible behavioural states. In order to quantify discrete behavioural modes, the DCRWS model incorporated an index based on mean turning angle and speed/direction autocorrelation parameters. Behavioural modes are estimated from the means of the MCMC samples within the model, producing continuous variables between 1 and 2; higher values represent higher turning angle and speed/direction variability. Modes are then classified (conservatively) as follows: behavioural mode 1 (1−1.25) assumes a low turning angle and speed/direction variability and is classified as transit behaviour while behavioural mode 2 (1.75−2) corresponds to higher turning angles and speed/direction variability, and is classified as area-restricted search (ARS). Unclassified behaviour mode values fall between 1.25 and 1.75.

Raw ARGOS data was used, with the exception of a few exceptionally extreme locations that were removed in order to improve fitting, these were never more than 4% of the total raw data. As migratory movements and wintering destinations of blue whales at the Eastern South Pacific have never being described previously, the duty cycle used in order to save battery, lead to the existence of some gaps in our data that prevented us from using a regular time-step of less than 48 hours (Breed et al., 2011). The model was fit in R (R Development Core Team 2015) and JAGS (Plummer, 2003) for the Markov Chain Monte Carlo (MCMC) estimation methods. Two chains were run in parallel, producing a total of 120,000 MCMC samples each. The first 100,000 samples were discarded as burn-in, and 1 out of every 20 remaining samples was retained, for a total of 2,000 samples to form the posterior distribution of model parameter estimates. Model convergence was assessed by ascertaining whether posterior samples were stationary, the individual MCMC chains were wellmixed, within-chain sample autocorrelation was relatively low, and the Brooks-Gelman-Rubin potential scale reduction factors were ≤ 1.1.

RESULTS

During the 2015 field campaign, weather conditions tended to be impeccable on most surveys days, allowing a good proportion of searching days and provided an increased probability of finding whales. We departed from Dalcahue in Chiloe Island on 08 April and tagged our first blue whale on 09 April near the town of Tenaun. The second tag was deployed on 13 April near Quemchi, another four the next day when finding ca. twenty blue whales in the Gulf of Ancud, and a final one on 15 April. As summarized in Table 1, six out of seven tags provided detailed information on how blue whales use their feeding ground in northern Patagonia during austral autumn and winter of 2015; and of these four provided valuable information on the migratory timings, routes and behavior on their northbound migration (Figs. 3 & 4). The minimum distance travelled by the whales ranged between 80 and 4,010 nm and the longevity of the tags ranged between 21 and 162 days.

Table 1: Summary of blue whale satellite tracking information obtained during 2015.

PTT #	Name	Type	Date and time of deployment and last transmission	Deployment Lat/Long	# locs	Data span	Distance travelled (km/nm)
84481	Tenaun	MK10	09 April 2015 – 17:34 14 June 2015 – 19:55	42.33°S/73.39°W	361	61d 16h	5,150/2,781
84485	Flaca	MK10	13 April 2015 – 13:38 05 May 2015 – 10:53	42.26°S/73.31°W	293	21d 15h	148/80
84484	Madre	MK10	14 April 2015 – 12:51 26 Sept. 2015 – 14:53	41.94°S/73.25°W	1336	162d 8h	7,427/4,010
84494	Golfo	MK10	15 April 2015 – 11:42 26 July 2015 – 20:18	41.86°S/73.24°W	93	103d	3,943/2,129
112696	Loca	SPOT5	14 April 2015 – 18:15 07 July 2015 – 23:49	41.90°S/73.27°W	294	89d 3h	314/170
112719	Orca	SPOT5	14 April 2015 – 15:33 02 Sept. 2015 – 13:53	41.89°S/73.24°W	4	145d 17h	NA
120948	Quemchi	SPOT5	14 April 2015 – 09:36 07 July 2015 – 20:31	41.09°S/73.38°W	864	89d	7,092/3,829

Tag #112719 (named Orca) emitted just four signals over a long period (April-Sept.) but no locations could be fixed. This was probably due to the fact that the tag was probably implanted too low on the left flank of the animal (as shown in Fig. 1).

Fig. 1: Blue whale named Orca (tag #112719) showing the implanted tag location, which was apparently too low to allow for sufficient transmissions to the satellite.

Better results were obtained from the rest of the tags, such as #84481 (named Tenaun) which remained in the same place it was originally tagged for a couple of days while apparently searching for food. Tenaun then commenced moving slowly southwards and from mid-April onwards rapidly moving SW and then some 150 nm to the West. During late April, Tenaun moved steadily north past the Nazca ridge and ceased transmitting in mid-June when reaching offshore waters off Lima, Peru (*ca*. 500 nm offshore).

Another tagged blue whale (#120948 named Quemchi) showed intense use of the immediate foraging spot where she was tagged and later showed a southward movement towards the mouth of Guafo (southern Chiloe Island) and departed the area moving SW for ca. 1,000 km, where she changed course NW for a further 600 nm. She maintained this course until reaching the Galapagos Rise and ceased transmitting around the Bauer Basin, some 700 nm WSW off Isabela Island in the Galapagos Archipelago (or ca. 1,400 nm off mainland Ecuador).

Two other tagged blue whales (#84485 named Flaca & #84484 named Madre) remained performing ARS behavior (most likely foraging) near the same original spot where they were tagged for several weeks. While the former ceased transmissions on May 5, the latter continued moving throughout the Chiloense Ecoregion until early June, when she exhibited a northward transit behavior or migratory movement along coastal Chile (within 30nm from shore). When reaching the vicinity of the coastal city of La Serena (30°S-71°W) by mid-June she changed course NW and started aiming for the Galapagos Islands, which she actually reached by mid-July. She remained within the Ecuadorian Galapagos EEZ until transmissions ceased during late September. Perhaps this whale performed one of the most interesting movements as a whole as she resumed performing ARS behavior in the Galapagos together with deep dives (350 m).

Tag #112696 (named Loca) was deployed successfully on a very large blue whale which extensively used the waters of the Chiloe inner sea as well the Gulf of Corcovado and the Moraleda Channel to the South. She appeared to depart the feeding area roaming SSW some 500 nm from the place it was tagged, but soon returned and ceased transmissions during early July while exhibiting ARS behavior within the narrow fjords of Chiloe’s inner sea.

Finally, tag #84494 was the last placed on a blue whale during the 2015 fieldwork (Fig. 2). The whale (named Golfo) remained in the feeding area for a couple of weeks but later on moving S and departing the area due W some 500 nm and then roaming NE directly due and past the Nazca Ridge. This tag ceased transmitting in mid-June when the whale was reaching the latitude of Lima (Peru), some 400 nm offshore.

Fig. 2: Satellite tag implanted on a blue whale (tag #84494), just anterior to its dorsal fin.

As expected, very slow speeds are used by blue whales when possibly searching for food (Fig. 5) with general mean speeds of 0.4 ± 0.5 knots when exhibiting ARS behavior (range: 0.005-3.1 knots). In contrast, mean speeds of 2.1 ± 0.9 knots were achieved during transit/migration (range: 0.2-5.9 knots).

Upon departing the feeding ground during mid to late autumn, blue whales moved in a wide array of directions but further on coincided on a general movement direction (NW) but along a wide corridor exceeding 1,000 nm on occasions (Fig. 6). ARS behaviors were exhibited within protected waters of Chiloe inner sea and also along open waters of the Corcovado Gulf and W of Guafo Island. Interestingly, ARS behavior was also identified S of Galapagos Islands in one whale (tag #84484) (Fig. 6). Some transit behaviors were noted between feeding areas in the Chiloense Ecoregion, but most notably during offshore and alongshore migratory behaviors.

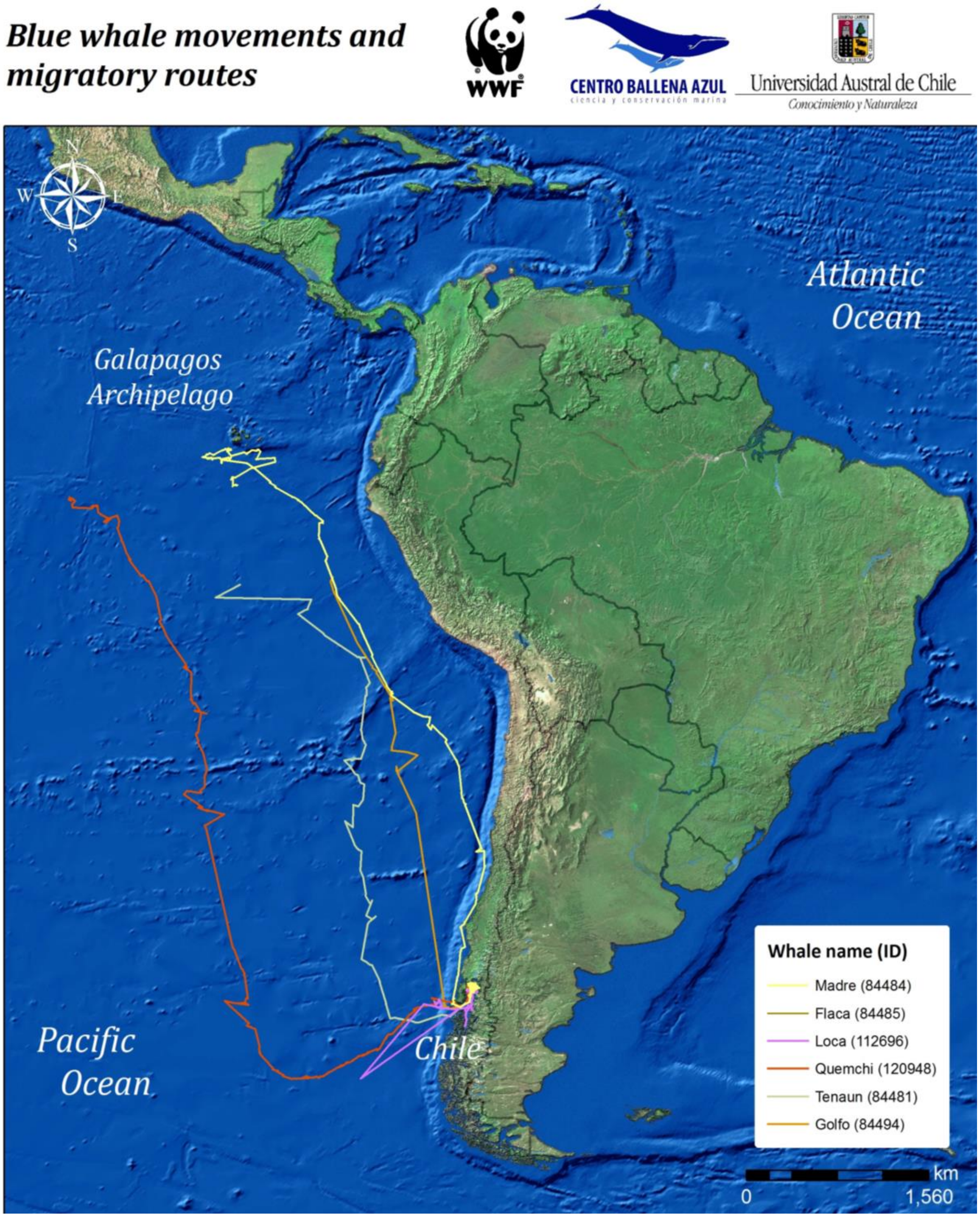

Fig. 3: Long range movements of six satellite-tagged blue whales off southern Chile during 2015.

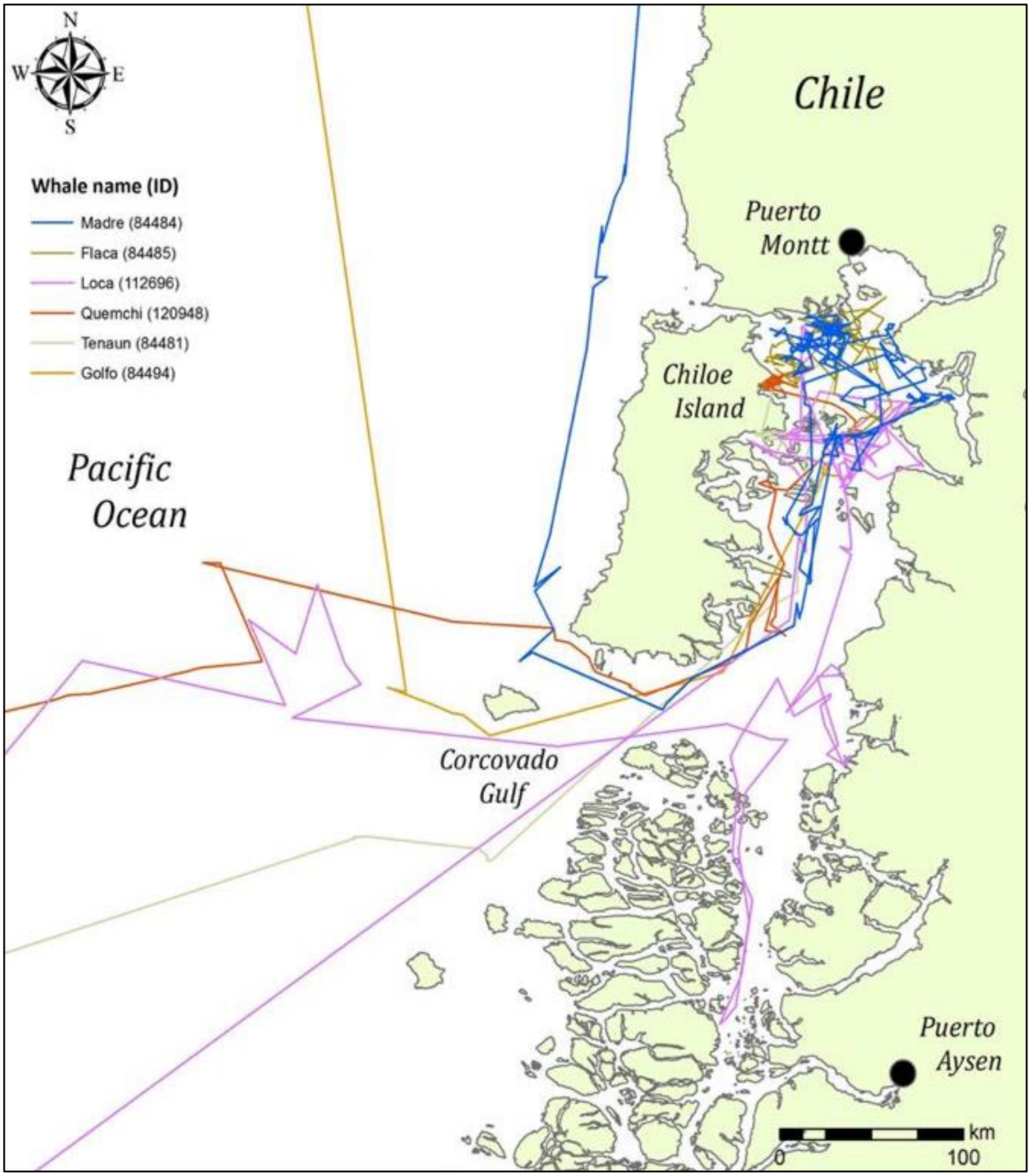

Fig. 4: Blue whale movements throughout the Chiloense Ecoregion.

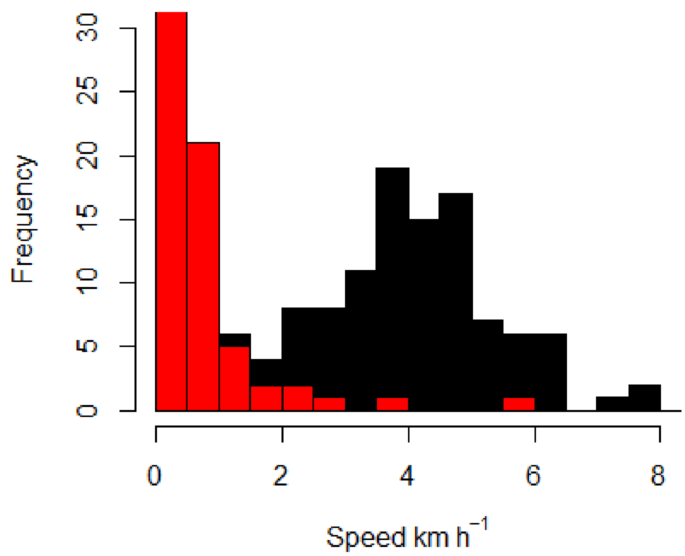

Fig. 5: Blue whale movement speeds during two contrasting behavioral modes (ARS (red) and transit (black).

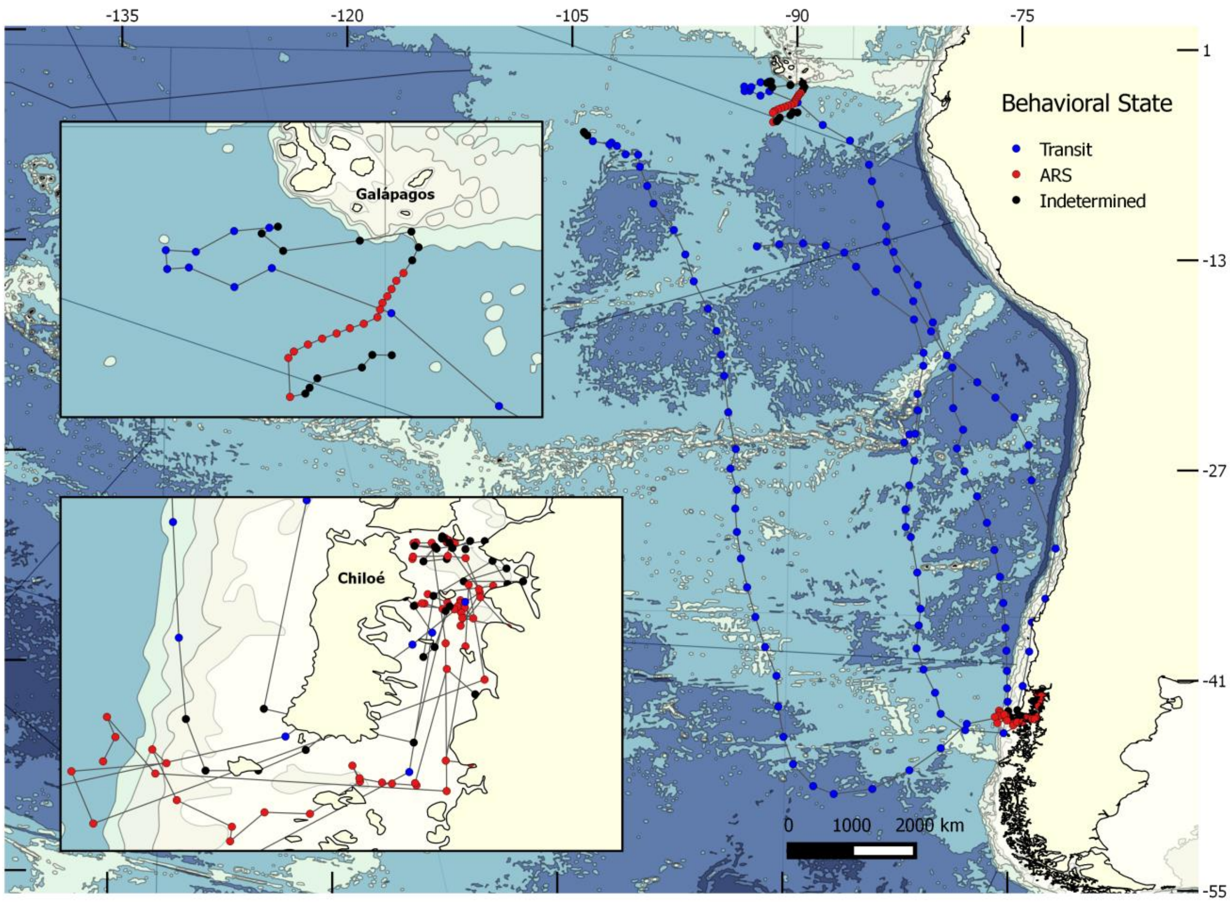

Fig. 6: State-space model derived locations of all tagged blue whales off Chile, transmitting from April to September 2015. Area-Restricted search (ARS) behavior is indicated by red dots, transit by blue dots and undetermined behavior by black dots.

DISCUSSION

In particular, we consider the 2015 field season as a complete success. This means we have fine-tuned field procedures, particularly satellite tag deployment techniques which are always a challenge with this fast-moving species, in sometimes unforgiving sea-conditions. Accordingly, tag duration increased considerably in contrast to a 2013 trial. This allowed us to grasp blue whale movements and migratory routes in detail for the first time in the Eastern South Pacific.

Whales departing from the Chiloense Ecoregion feeding ground travelled along widely dispersed migratory paths spread longitudinally over ca. 1,000 nm. By contrast, the most studied blue whale population in the world, the Eastern North Pacific population behaves apparently different. Bailey et al. (2009) used data from 128 tags deployed between 1993 and 2007 (the largest cetacean tagging dataset to date) and concluded that migratory routes were primarily close to the continental margin, with occasional movements offshore. Further tagging efforts are needed to better understand inter-annual variability and identify more robust migratory patterns.

The broad-scale accounts of ARS behaviors presented here for a mid-latitude feeding ground should be complemented with finer scale studies that allow the identification of potentially important feeding habitat within northern Patagonia. This is part of an undergoing work focused on movement patterns within this particular area that will aim at using shorter regular time steps in the SSM analysis, as well as the incorporation of environmental covariates. Over the years these studies could allow us to understand the underlying mechanisms that determine important ecological processes, such as habitat selection, and thus focus adequately on efficient conservation measures. Migratory routes, other important feeding hotspots and breeding/calving areas remain unknown and thus our capacity to identify and quantify threats together with implementing appropriate conservation measures remains limited and should become a priority.

The ARS behavior identified in the tropical wintering grounds off Galapagos may be representative of reproductive behavior; however, preliminary analysis of diving behavior data derived from MK10 tags suggests that this might not necessarily be the exclusive case. Diving data from Galapagos suggests that the single animal monitored extensively enough (#84484 / Madre) might have also searched for prey performing deep dives. This information will be essential to identify and quantify threats and later recommend the implementation of appropriate conservation measures at multiple scales on a regional context.

Several blue whale sightings have been reported throughout the Eastern Tropical Pacific (ETP) and particularly in waters off the Galapagos Islands (1,000 km West of Ecuador), chiefly along the west side where upwelling is strong and almost exclusively during the austral winter and spring months (Reilly and Thayer 1990; Palacios 1999; Denkinger et al. 2013). Recently, a first confirmation of the purported link between southern Chile and Galapagos, among the Eastern Southern Pacific (ESP) was reported by Torres-Florez et al. (2015) from a single female blue whale photo-identified and genetically matched 10 years apart. Based on this evidence and further genetic and acoustic studies (Buchan et al. 2014, Torres Florez et al. 2014), Torres-Florez et al. (2015) proposed that the Galapagos region could serve as a wintering destination of the ESP blue whale population. Here we provide further evidence that supports this hypothesis.

Over the past decade or so, several feeding hotspots have been auspiciously discovered in the Southern Hemisphere: southern Australia (Gill 2002), southern Chile (Hucke-Gaete et al. 2004), the Indian Ocean (Samaran et al. 2010, Stafford et al. 2011) and New Zealand (Torres 2013). Probably one of the most important ones is found along the coastal waters of southern Chile where hundreds of blue whales gather in the Chiloense Marine Ecoregion each year to nurse their calves and feed on abundant krill (Hucke-Gaete 2004). But threats to blue whales are mounting and are manifold. From ship collisions, to increasing underwater noise, coastal habitat degradation, plastic debris and the unknown effects of climate change are all a matter of concern and might be precluding full recovery of the species. The Chiloense Ecoregion is well known for its intense maritime shipping, fisheries and salmon farming activities (Hucke-Gaete et al. 2004; 2010; 2013; Viddi et al. 2015), where important overlap with blue whale feeding activities occur. Therefore it appears essential to focus efforts on planning and coordinating efforts to mitigate any potential negative effects on whale populations. We expect to continue this research programme over the next years in order to identify and redirect efforts to those places that are in dire need of protection.

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