Marine Ecosystems

Offshore migratory movement of southern right whales: informing critical conservation and management needs

Alice I. Mackay, Frederic Bailleul, Simon Childerhouse, David Donnelly, Robert Harcourt, Guido J. Parra, Simon D. Goldsworthy

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EXECUTIVE SUMMARY

The southern right whale (*Eubalaena australis*) (SRW) has a southern hemisphere circumpolar distribution between latitude 16°S and 65°S. Between May and October, a portion of the Australasian population aggregates at calving grounds in coastal Australian waters before migrating to offshore feeding grounds. However, the timing and route taken to these feeding grounds is unknown.

Satellite tracking provides a means of collecting critical information on the distribution, migration and seasonal movements of SRW that will contribute directly to two High Priority Actions of the Conservation Management Plan for the Southern Right Whale 2011-2021 (DSEWPaC 2012); 1) understanding offshore distribution and migration, and 2) characterising behaviour and movements.

Nine individual adult SRW were satellite tagged at the Head of Bight (HOB), South Australia, in September 2014. There was high variability in tag performance, but sufficient data were received to describe the migratory movements of three adult females accompanied by calves. Two whales migrated directly south from HOB, while one, after a period without data transmissions, moved west from Albany, Western Australia, into the Naturalist Plateau. Individual movement tracks were related to oceanographic features associated with areas of upwelling or high productivity. The identification of these likely offshore feeding sites can be used to help assess the impacts of climate variability on the population dynamics of SRW, as reproductive success has been linked to both oceanographic and anomalies climate associated ecosystem changes in prey abundance.

All three whales moved through areas of exposure to potential human impacts such as fishing, offshore oil and gas exploration and shipping. This study highlights the need for further information on offshore movements of SRW from Australia, to inform the conservation of this species and management of anthropogenic activities, particularly as populations continue to recover.

1. INTRODUCTION

1.1. Background

Southern right whales (*Eubalaena australis*) (SRW) are listed as Endangered under the *Commonwealth Environment Protection and Biodiversity Act 1999* (EPBC Act) and Vulnerable under the *South Australian National Parks and Wildlife Act (1972)*. Monitoring of the species in Australian waters is required to meet the objectives of the Conservation Management Plan for the Southern Right Whale (DSEWPaC 2012).

The species has a southern hemisphere circumpolar distribution between latitude 16°S and 65°S, and between May and October, a portion of the Australasian population migrates between offshore feeding grounds (between 40°S and 65°S) and calving/nursery grounds in coastal Australian waters. However, the time and route taken to return to the feeding grounds is unknown, and baseline information on migratory corridors between feeding grounds and coastal calving and breeding grounds is required to assess and manage potential threats. A deeper understanding of the offshore distribution of this species is also required, as only a section of the population migrates to coastal calving grounds each year.

Until recently, SRW in Australian waters have been managed as a single population estimated at approximately 3,500 individuals (DSEWPaC 2012). A recent genetic study has proposed the presence of two Australian populations; the south-western population (Western Australia and South Australia) and the south-eastern population (Carroll et al. 2011). However, the precise geographic delineation of these two populations, and amount of genetic interchange both within and between populations remains unclear due to the small sample sizes used in the study. Additional research indicates that each population is experiencing different rates of recovery from historical whaling. Estimated recovery and re-occupancy rates for the south-eastern population, including eastern South Australia, Victoria, Tasmania and New South Wales, remain low, while the south-western population is increasing at ~7% per annum (Bannister 2011), which is near or at maximum population growth.

During each Austral summer a portion of the south-western SRW population is distributed between Cape Leeuwin, Western Australia (WA) and Ceduna, South Australia (SA) (Bannister 2011), with established large coastal aggregation and calving grounds in the Doubtful Island Bay and Israelite Bay areas in WA, and the Head of Bight (HOB) in SA. Current population estimates put the south-western population at 2,900 individuals (Bannister 2011), or about 83% of the total estimated Australian SRW population.

Female SRW show strong fidelity to calving grounds (e.g. Burnell 2001, Patenaude et al. 2007), although movement of calving and non-calving adults between Australian and New Zealand calving grounds has been recorded between breeding seasons (Prizl et al. 1999). Photo-ID studies have provided information on coastal movement patterns of SRW, particularly for the south-western population, with resights of unaccompanied whales made between locations in Western Australia and the HOB (Burnell 2001). However, there is no information on the movement of whales from coastal Australia to offshore feeding grounds. Current knowledge on the probable location of SRW feeding grounds and movement from and to coastal areas is based on historical whaling data (Townsend 1935), Discovery marks[1] (Tormosov et al. 1998), photo-ID matches (Bannister 2001) and satellite tracks of three SRW from the Auckland Islands, New Zealand (Childerhouse et al. 2010), and one SRW from Tasmania (AMMC and DSEWPaC 2012).

The deployment of satellite telemetry devices has provided critical information on the distribution, migration and seasonal movements of many species of large whales (Baumgartner and Mate 2005, Wade et al. 2006, Bailey et al. 2010, Gales et al. 2010, Mate et al. 2010, 2011, 2015, Zerbini et al. 2011). Data collected through the judicious use of satellite telemetry can address a number of action areas identified under the Conservation Management Plan for the Southern Right Whale 2011-2021 (DSEWPaC 2012) and inform two High Priority Actions; 1) understanding offshore distribution and migration, and 2) characterising behaviour and movements. While satellite telemetry have provided important data for the conservation and management of large whale species, the use of implantable tags has raised a number of concerns with respect to possible short and/or long-term adverse effects of these devices on tagged individuals (Weller 2008, Moore et al. 2013). Recent studies utilising implantable satellite tags on large whales have therefore also aimed to assess the short- and medium-term physiological effects of tagging on the individual (Robbins et al. 2013).

[1] 'Discovery' marks were used to mark individual whales. They consisted of individually numbered stainless steel tubes that were fired into the muscle and designed to be retained inside the whale. The mark would then be 'discovered' if that individual was later killed and processed during commercial whaling. Data would then be available on the date and location the individual was marked and the date and location when it was killed, providing some information on movement patterns.

Data on the distribution and movement patterns of SRW can be used to improve our knowledge of habitat use between their calving and feeding grounds and to quantify the potential overlap in the habitat use of SRW with fisheries, offshore and inshore developments, and shipping. Telemetry data from SRW may also help to identify the locations of offshore feeding areas and be used to assess the influence of climate-linked changes in prey availability and quality on SRW calving success and population dynamics. This information will help to inform management strategies to mitigate potential threats to different components of the Australasian population, particularly the south-east population where recovery is slow.

The project aims to provide data on the offshore movements and migration patterns of adult SRW from the south-western population that will enable management of potential impacts to this population, inform marine bioregion assessment, and assist in informing management objectives of State and Commonwealth MPAs.

Objectives

1. To collect baseline satellite telemetry data on the offshore migratory routes of adult SRW from the HOB breeding aggregation in South Australia.

2. To monitor the short-, medium- and long-term effects of satellite tagging on whales.

2. METHODS

Study area

Satellite tagging and biopsy sampling of SRW was conducted between 6 September and 8 September 2014 at Head of Bight (HOB), South Australia. The HOB is a significant winter calving/aggregation site for a portion of the south-western SRW population and is encompassed by the Far West Coast Marine Park.

Satellite tag deployment

The satellite tags comprised Spot 5 (location only) satellite transmitters (Wildlife Computers Ltd) encased in an implantable housing designed by the Australian Antarctic Division (AAD) in conjunction with Sirtrack Ltd, New Zealand. The stainless steel satellite housing is 320 mm in length, and upon implantation the tag penetrates the skin and blubber where it is retained by the spring-loaded anchor and passively deployed petals (Figure 1). Prior to deployment, tags were sterilised and petals were held in place by dissolvable tape. On immersion, the salt-water switch is activated and the tag location is transmitted through the ARGOS satellite network. In order to maximise battery life and ensure that the offshore migratory movement of tagged individuals would be transmitted, satellite tags were programmed with a duty cycle of three hours on, three hours off.

Figure 1: Implantable satellite transmitter showing a) spring loaded anchor, b) passively deployed petals, c) ring to retain tag in projectile carrier – both ring and projectile carrier fall way when tag is implanted and d) the antenna. Cable tie is removed prior to deployment.

Satellite tags were deployed from a 5.5 m inflatable vessel launched from the RV Ngerin. For safety reasons, the total number of personnel on the inflatable vessel was restricted to three (tagger, biopsy sampler and driver). Strict protocols developed by the Australian Antarctic

Division (AAD) were employed to avoid undue disturbance to whales during deployments, and tags were deployed in as short a time as possible to reduce any stress to the animal from the close proximity of the vessel. A tagging approach was halted if an individual showed a highly evasive response to the vessel.

Tags were deployed using a modified pneumatic line-thrower (ARTS; Air-Rocket-Transmitter-System – see Heidi-Jorgenson et al. 2001 for details) set at 11 bar of pressure and fired at distances ranging from 2-5 m from the individual. Transmitters were aimed to be deployed at the highest point on the whale's back, close to the dorsal midline between the pectoral fins and where the dorsal fin would be (if the species had one), to minimise physiological responses to implantation and ensure good antenna exposure. Where possible, biopsy samples were taken concurrently to tagging using a biopsy dart fired from a modified .22 calibre rifle (Paxarms). Biopsy samples collected during this study are being used in a global SRW research project to increase our understanding of the role of behavior in shaping population structure and connectivity in this species. This work is led by Dr E. Carroll and Prof O. Gaggiotti of the University of St Andrews, Scotland, and includes a global collaboration of right whale researchers.

All approaches to whales were video recorded from the inflatable vessel either by a helmet mounted camera and/or a camera mounted on a pole attached to the centre console. As it was not possible to have a dedicated photo-ID person on the small vessel, individual whale IDs were collected where possible using this footage. An approach was defined as commencing when the small inflatable vessel was first within 20 m of the whale(s) until the vessel left the whale(s). After the successful deployment of a satellite tag, the small vessel returned to the RV Ngerin to re-pressurise the ARTS and collect the next tag. Data on the start and end time of the approach, GPS track line, and group composition and behaviour of individuals were recorded.

Analysis of individual movement post tag deployment

The short-term response of individuals to satellite tag deployment was assessed by: 1) calculating the mean distance that each individual moved in the 12 hours following tag deployment; and 2) calculating the time spent by each individual in the tagging area after tag deployment. The tagging area within the HOB region was defined by the movement of the animals between the tagging location, and where applicable, the point where offshore movement from the aggregation area began. This corresponded to an area of 1400 km^2 (approximately a 70 x 20 km rectangle).

Filtering of location data

Location data of satellite tagged SRW were collected through the Argos system. Argos-derived locations are received at irregular intervals and are based on 7 levels of accuracy, or location classes, that range from ~ 150 m to greater than 1000 m. The accuracy of Argos-derived locations is dependent on the satellite coverage at the time of transmission and prevailing conditions. Raw location data were filtered using the function “sdafilter” (package “argosfilter” – R core team 2014) based on the algorithm described in Freitas et al. (2008). The filter first removes all points for which the location process failed (location class Z), and then uses the McConnell et al. (1992) algorithm to remove any point for which an unrealistic swimming speed would have been required, with the exception of those points located within 5 km of the previously transmitted location. The maximum speed threshold was 3 m/s. Finally, the algorithm filters any improbable locations based on distance and turning angle between locations.

Analysis of migratory tracks

Bearings between filtered Argos locations were calculated for each track and a circular diagram produced to illustrate the main direction of trajectory for each individual. A trade-off in using a duty cycle to prolong battery life is that information gaps between transmitted locations can lead to under-estimation of the mean horizontal swimming speed of each track. Such under-estimation biases the results of classical methods based on an increase in track tortuosity and a decrease in speed (e.g. State Space Models; Jonsen et al. 2005) to identify behavioural states (transit vs. area restricted searching or ARS) along the path. Therefore, analysis of filtered offshore migratory tracks was restricted to investigating whether individual movements were related to environmental characteristics. To do this, location data were superimposed on dynamic oceanic conditions that were averaged over the 3 weeks prior to the last location transmitted for each track. Sea surface temperature data were extracted using NOAA Optimum Interpolation Sea Surface Temperature data (https://www.ncdc.noaa.gov/oisst), while sea surface height and current data were extracted from AVISO Satellite Altimetry Data (www.aviso.altimetry.fr). Results are presented for those covariates that showed a temporal and spatial overlap with the movement patterns of tagged individuals.

Post-tagging assessment of individuals

Due to inclement weather conditions, dedicated post-deployment focal follows of tagged individuals could not be conducted. Immediate assessment of tag implantation and behavioural response was assessed in the field, and by reviewing tagging videos. A dedicated aerial survey was conducted on 25 September 2014, 18 days after completion of tag deployments, as part of a SRW monitoring project in the Far West Coast Marine Park conducted by DEWNR and SARDI. Photographs collected during this survey provided resights of tagged individuals and were used to assess, where possible, the tag site on the individual. Full details of the aerial survey methodology are provided in Mackay and Goldsworthy (2015).

3. RESULTS

In total, 45 approaches to suitable whales were made, resulting in 9 successful satellite tag deployments (with 6 concurrent biopsy samples) and a further 13 biopsy samples collected from non-tagged adult SRWs. Approaches lasted 4.6 minutes on average (range 1 – 13 minutes). GPS tracks of all approaches are provided in Figure 2.

Figure 2: GPS tracks of small vessel approaches to SRWs. Tracks in yellow indicate approaches when a satellite tag was successfully deployed.

Satellite tags were deployed on eight adult females accompanied by a calf and one unaccompanied adult. Photo-IDs were successfully obtained from video footage for six of the nine individuals. Details of each tagging event are provided in Table 1, and for each individual whale in Appendix 1.

Table 1: Start time, length and group composition for all approaches that resulted in the successful deployment of a satellite tag on an adult southern right whale at the Head of Bight in September 2014.

Date	Tag and Individual ID	Time	Approach length (mins)	Group composition	Biopsy sample taken	Reaction	Photo-ID
6/09/2014	123225	15:26	2	2 adults 2 calves	N	2	N
6/09/2014	112725	15:58	2.5	1 adult 1 calf	Y	2	Y
6/09/2014	121202	18:24	5.5	1 adult 1 calf	N	3	N
7/09/2014	112729	9:50	1.0	1 adult 1 calf	Y	2	Y
7/09/2014	121199	10:05	1.0	1 adult 1 calf	Y	2	Y
7/09/2014	120944	11:47	3.0	1 adult 1 calf	N	1	N
7/09/2014	121209	12:19	6.0	1 adult 1 calf	Y	1	Y
7/09/2014	120945	12:54	1.0	1 adult 1 calf	Y	3	Y
7/09/2014	120949	14:47	2.0	1 adult 1 calf	Y	3	Y

* reaction (1-3) 1 = negligible, 2 = mild (shudder or immediately evasive), 3 = extreme (tail slapping, lunging at boat)

Offshore migratory movement

Only three of the nine tags transmitted location data for a sufficient length of time to provide offshore movement patterns (Figure 4). All were deployed on adult females accompanied by a calf.

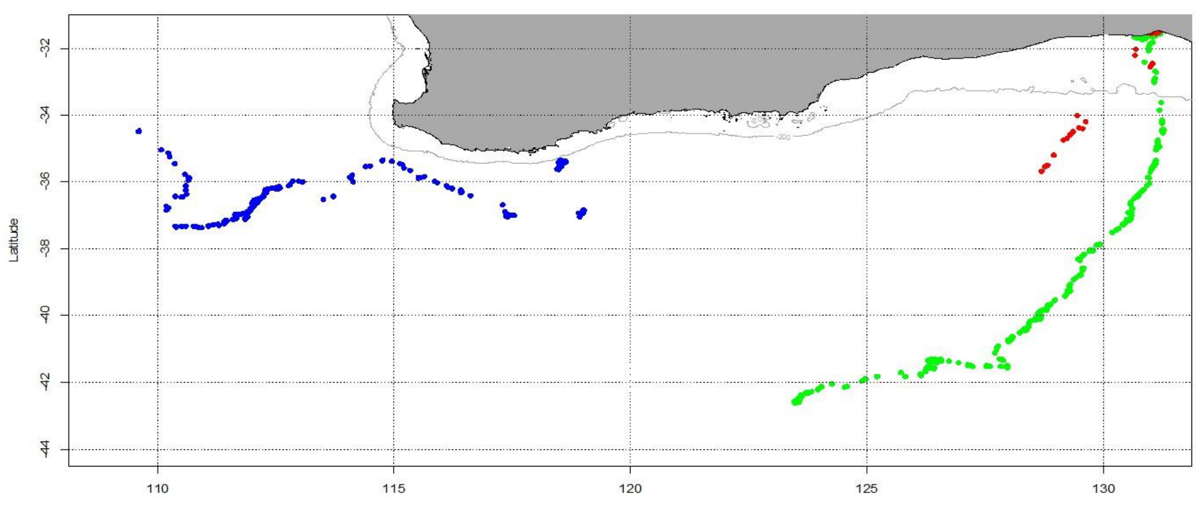

Figure 4: Filtered Argos locations for Tag 120944 (Blue), Tag 120949 (Red) and Tag 120945 (Green)

The predominant direction of migration of individuals 120945 and 120949 was south-westerly (Figure 5), reflecting the southerly offshore movement of these individuals from the HOB between 1 and 5 October 2014. The coastal residency periods of these adult females at the HOB aggregation area post tag deployment were 24 and 28 days, respectively. It was not possible to determine the date that individual 120944 left the HOB, as no transmissions were received from the tag between 9 September and 6 October 2014. When transmissions of this tag restarted, the individual was approximately 1,320 km west of the HOB, just east of Albany, Western Australia. This individual displayed a wider range of directional travel, although overall the predominant direction of travel was west-south-westerly (Figure 5).

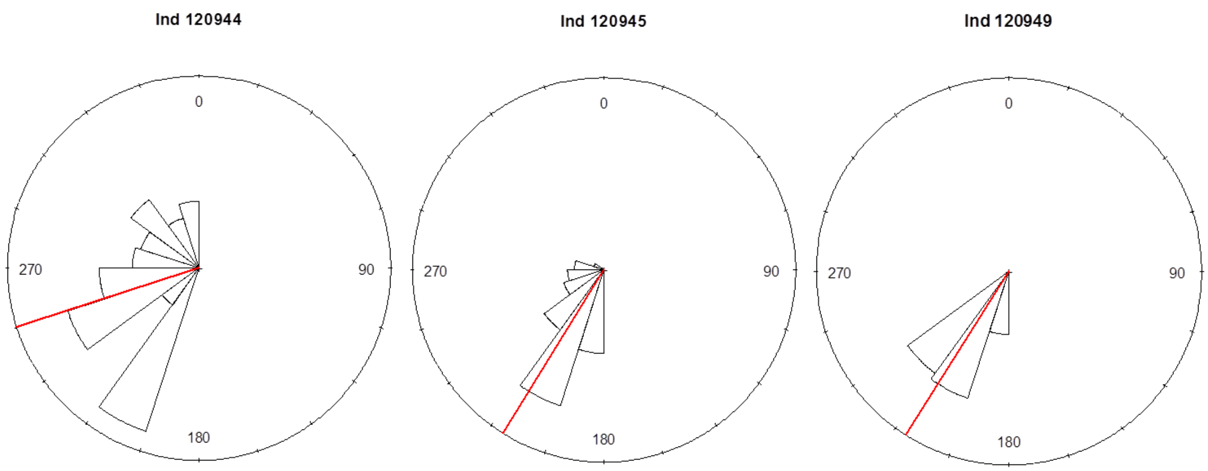

Figure 5: Distribution of headings calculated between filtered Argos locations for each of the three tagged whales. The red line represents the median bearing of the individual.

Mean and median swim speeds were similar for the three individuals (Table 2). Overall minimum and maximum swim speeds recorded were 0 and 5.89 km/h, respectively. Swim speed varied during travel, with all individuals displaying prolonged periods where swim speeds were consistently lower or higher than their medians. Figure 6 displays the filtered track lines for these individuals, with location data categorised as being above or below median swimming speed.

Table 2: Summary of mean and median speeds of each satellite tagged southern right whale calculated from filtered Argos data.

Id	Mean speed (km/h)	Median speed (km/h)
120944	3.19 ± 2.70	2.2
120945	2.93 ± 2.45	2.2
120949	2.87 ± 2.87	2.16

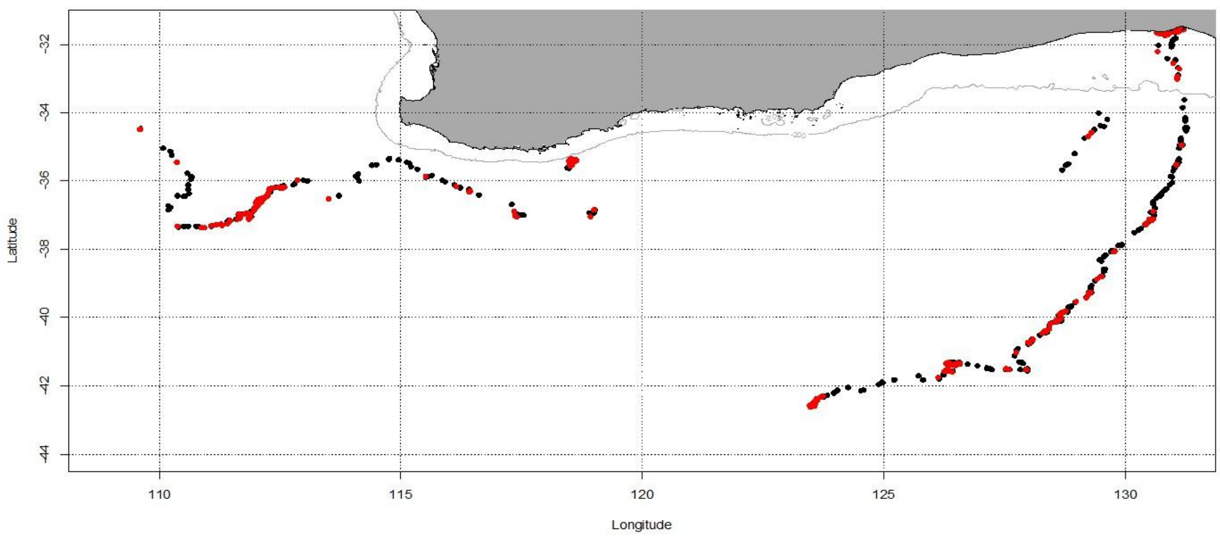

Figure 6: Filtered Argos locations of all three satellite tagged southern right whales showing periods of swimming that were lower (red) or higher (green) than the median speed of all individuals combined.

Association with environmental variables

Individual 120949 consistently moved in a southerly direction until the tag ceased transmitting at approximately 35°S, however the amount of transmitted data was not sufficient to investigate any associations with environmental variables.

Individual 120945 also showed consistent directed southerly movement after leaving the HOB until reaching approximately 41ºS at which point directionality became more westerly. Figure 7 shows the filtered track of individual 120945 superimposed on sea surface temperature (SST) averaged for the three weeks prior to the last transmission received from this tag. These data show a change in directionality and association within an area with an average temperature band of 11.5 ºC. This temperature band and longitude coincides with the subtropical front (STF) within the subtropical convergence (STC).

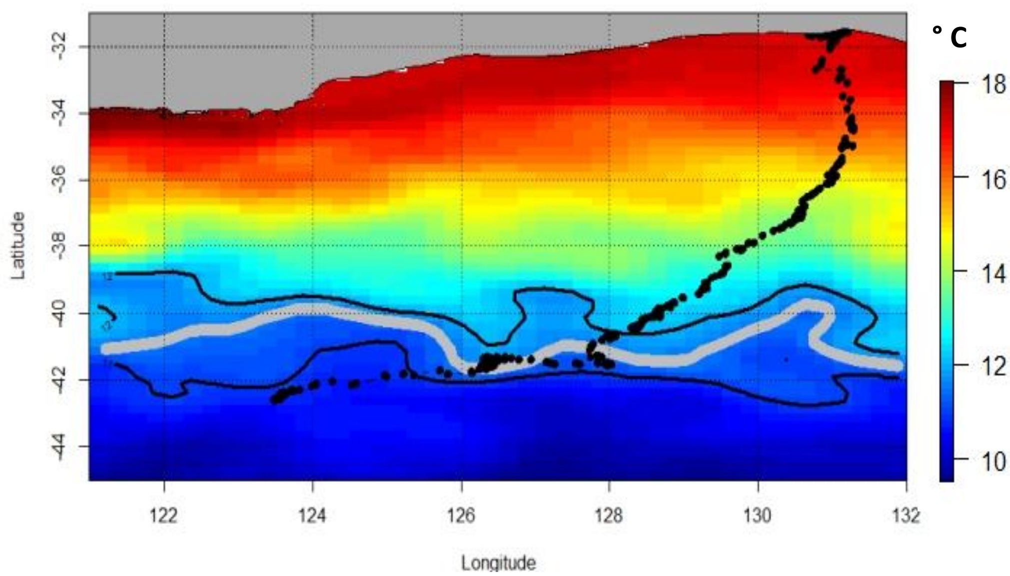

Figure 7: Filtered Argos locations of Tag 120945 superimposed on sea surface temperatures (degrees Celsius) averaged for the three weeks prior to the last location data received from this tag. Grey line indicates average temperature contour of 11.5 ºC, bounded by 12 ºC and 11 ºC contours (black lines).

Investigation of temporal and spatial relationships between location data received for individual 120944, and environmental variables, showed strong associations with sea level height anomalies (Figure 8a) and current data (Figure 8b). Low sea level height anomalies and high current flow are indicative of low pressure eddies which result in areas of localised upwelling. The current flow in these eddies is anti-cyclonic, and the track indicates that individual 120944 moved around the edge of the eddy facing into the current. While the geographic location of these two individuals differed, both showed movement patterns related to oceanographic features that are associated with high productivity.

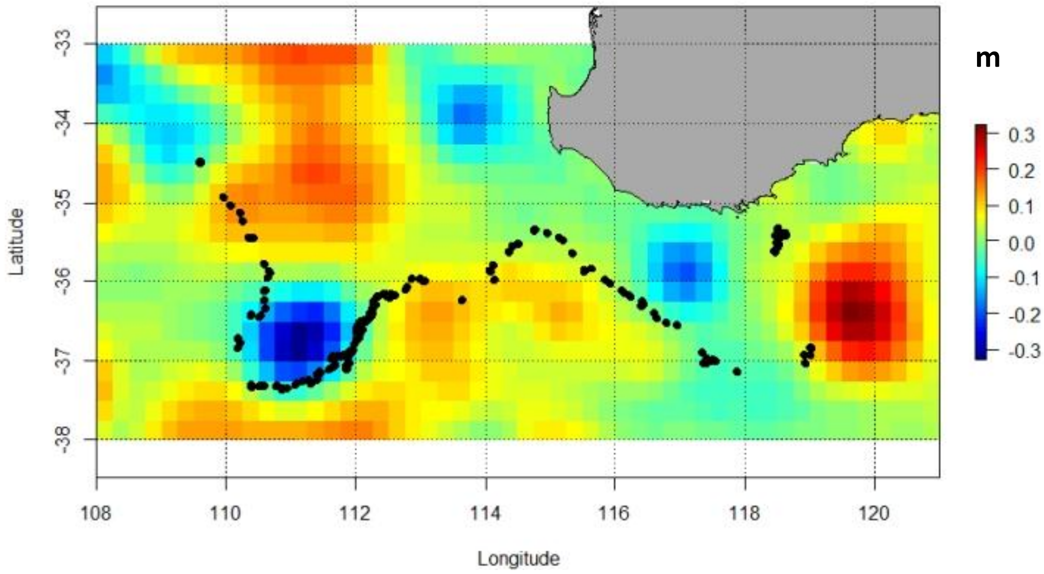

Figure 8a: Filtered Argos locations of Tag 120944 superimposed on sea level height anomaly (m) averaged for the three weeks prior to the last location data received from this tag.

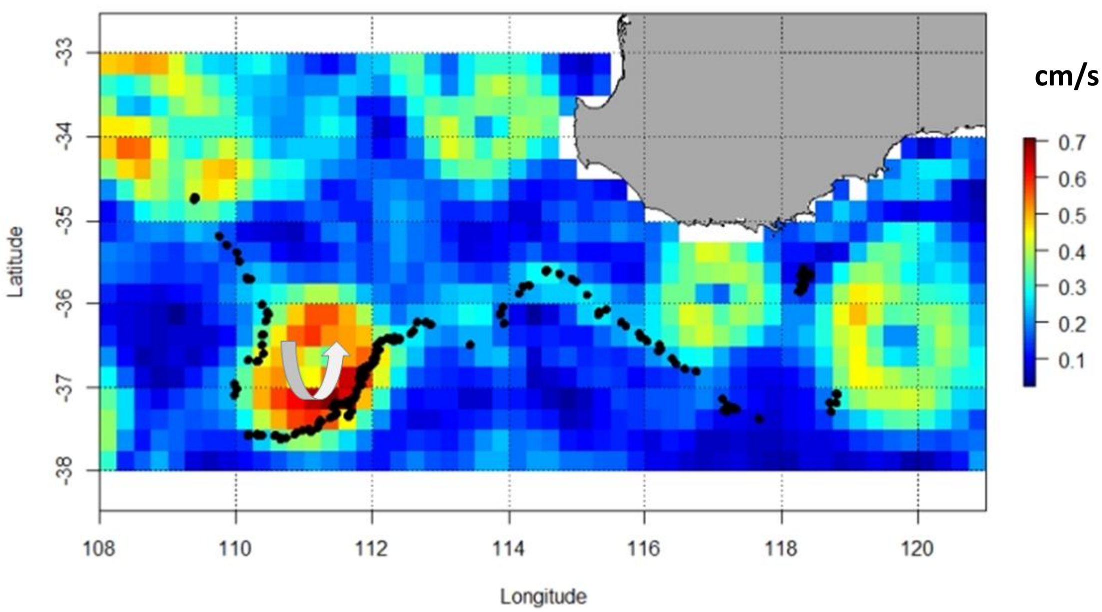

Figure 8b: Filtered Argos locations of Tag 120944 superimposed on current data (cm/s) averaged for the three weeks prior to the last location data received from this tag. The white arrow indicates direction of current in the eddy.

Movement through areas of potential risk

The total amount of time spent within current petroleum exploration permit areas in the Great Australian Bight Basin was calculated for each of the three female-calf pairs. The two females who followed a southerly migration from the HOB aggregation spent 2.04 (120945) and 1.08 (120949) days, respectively, transiting through current exploration permit lease areas (Figure 9). The third female-calf pair (120944) spent 1.69 days travelling through an exploration permit area in Western Australia (Figure 9). However, this female-calf pair could have potentially spent an additional 6.12 days in the lease area based on linear interpolation between the time it was tagged at the HOB and the position where that individual's tag resumed transmissions in Western Australia (Figure 9).

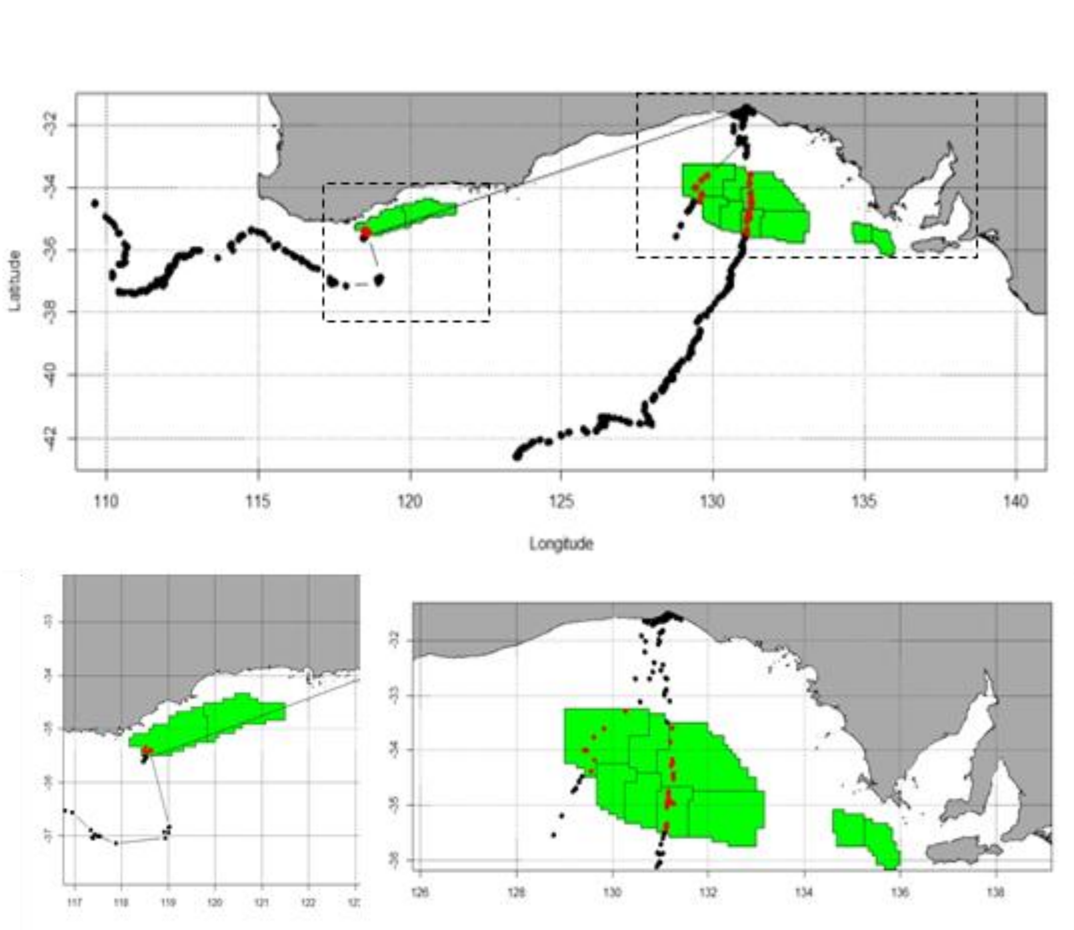

Figure 9: Filtered Argos locations of all three satellite tagged southern right whales and current petroleum exploration permit lease areas in the Great Australian Bight. Red dots indication whale location is within a permit lease area.

Post-tagging behavioural response

The immediate behavioural response of individuals to tag deployment, recorded in the field and assessed from video footage, ranged from negligible to extreme, as defined by Australian Marine Mammal Centre categories, with extreme behaviour involving a rapid movement away from the tagging vessel or a tail slap from the individual.

Three tags failed to transmit post-deployment, but data from the six other tags showed that in the 12 hours following implantation, individuals remained on average within 2.8 (S.D. ± 2.0) km of the location where they were tagged. For the tags which did not transmit long enough to provide migratory data, all individuals were within the tagging area when tag transmissions ceased (0.03 – 4.6 days). Although most tags stopped transmitting within five days of deployment, an aerial survey conducted by SARDI and DEWNR resighted four of the nine individuals with their calves within 18 days of tag deployment and at distances between 0.42 – 3.35 km from the location where they were tagged (Table 3). Two of these individuals had level 2 reactions and the others level 3 reactions to tag deployment, indicating that an immediate-strong reaction to the tag being deployed did not result in longer term displacement of the individuals from the area where they were tagged.

Table 3: Summary of time spent in tagging area (70 x 20 km) by each individual after tag deployment, and the distance from the location of initial tag deployment for those individuals resighted during an aerial survey conducted in late September 2014. * indicates the tag stopped transmitting after this time.

Id	Time spent in the area after tagging (days)	Distance between tagging and resight location (km) during aerial survey
112729	2.3*	0.42
120944	1.7*	Not resighted
120945	23.9	1.66
120949	26.7	3.35
121199	4.6*	0.59
123225	0.03*	No photo-ID of individual

Tag performance

Tag performance was highly variable; three tags failed to transmit post-deployment while transmission length of the six other tags ranged from 1 hour to 48 days. Figure 3 presents a schematic diagram showing when the location data were received from each tag.

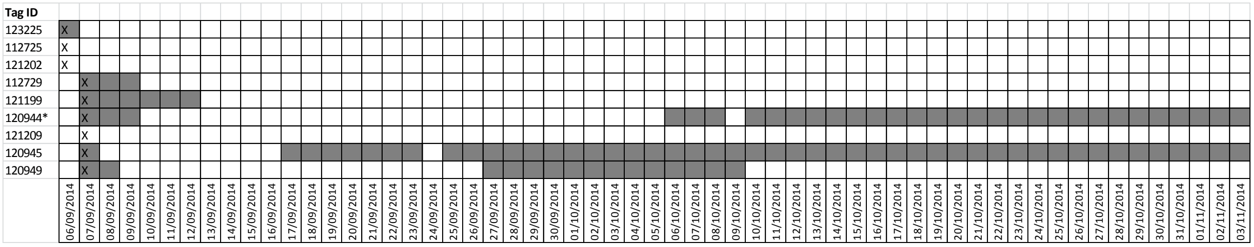

Figure 3: Summary of transmission histories for each of the 9 satellite tags. X = tag deployment, grey shading indicates dates when at least one location was received. * = a single additional location was received from this tag on 18 November, 2014.

Video footage of each tagging event, and photographs taken of the four tagged whales resighted during the dedicated aerial survey, were assessed to see if possible causes of tag transmission variability or failure could be determined for each individual. Video footage indicated that Tag 123225 passed through the water during deployment and may not have implanted fully into the individual. Tag implantation was low on the right flank of the animal and two location positions were received from this tag in the hour after deployment before the tag ceased transmitting. Photo-ID was not obtained of this individual due to failure of one of the video cameras to record.

During the deployment of Tag 112725, the adult female rolled over on her right side, resulting in the tag implanting low on her left flank around the midline of the side of her body (Fig A2 Appendix 1). Given the position of this tag, it is unlikely the antenna would have broken the surface of the water during normal surfacing behaviour of the individual. Photo-ID was successfully obtained for this mother calf pair, but they were not resighted during the aerial survey.

Tag 121202 hit the water prior to implantation and assessment of the video from the deployment indicates the tag did not implant properly, with approximately 2/3 of the tag protruding from the surface of the skin (estimate). No photo ID was obtained for this individual.

Tag 112729 fully implanted on the female’s upper right flank. Photographs taken of this female during the aerial survey showed that the tag was still present and in a good position for the antenna to be exposed during normal behaviour. Although deployed in an optimal position, this tag ceased transmitting 2 days after deployment.

Implantation of Tag 121199 was impeded by the tag hitting the water during deployment. The tag ceased transmitting 5 days after deployment and was not present when this female calf pair was resighted during the aerial survey. It is likely that the tag fell out of the animal on 12 September when transmissions ceased.

Tag 120944 implanted fully on the upper right flank of the individual in a good position to ensure the antenna was exposed during normal behaviour. Location data were received from the tag for three days after deployment after which there was a gap of 26 days before transmissions were received again. It was not possible to obtain a photo ID of this individual and so no resight data are available.

Tag 121209 implanted fully on the upper left flank of the individual and was in a good position for the antenna to be exposed during normal behaviour. However, no locations were transmitted from this tag. A photo ID was successfully obtained, but this individual was not resighted during the aerial survey.

Tag 120945 was deployed on the left flank of the individual. Video shows it implanted almost fully but was at a slight angle, so the posterior end was not flush with the skin. Location data was received intermittently from this tag, which ceased transmitting 3 hours after deployment and began transmitting again 9 days later. Photographs taken during the dedicated aerial survey on 25 September show what appears to be a blubber extrusion covering the aerial of the tag.

Tag 120949 fully implanted in the upper left flank of the individual. This tag stopped transmitting location data after 18 hours, but was still implanted when the female-calf pair were resighted during the aerial survey. Photographic resolution was not high enough to determine if the antenna of the tag was fouled. The tag restarted transmitting two days after the aerial survey and continued to transmit until 9 October 2014.

The three tags which transmitted for the longest periods (15, 31 and 48 days) had periods without any transmission being received that ranged from 9 to 26 days.

4. DISCUSSION

This study provides the first description of the offshore movement patterns of satellite tagged adult female SRW from the HOB aggregation, South Australia. These data inform two High Priority Actions listed in the Conservation Management Plan for the SRW (DSEWPaC, 2012): 1) understanding offshore distribution and migration, and 2) characterising behaviour and movements. These data will also help to assess and manage potential interactions between SRW and human activities.

Offshore migratory movements and association with environmental covariates

Three tags transmitted for sufficient periods to provide data on the migratory movements of SRW female-calf pairs. Mean swimming speed of the three whales during offshore movement was 2.87 to 3.1 km per hour, although swim speed was not consistent along the trackline, with all three individuals exhibiting extended periods of travel above mean swim speeds interspersed with periods of travel below mean swim speeds. Mean swim speeds are similar to those reported for 5 satellite tagged adult SRW during offshore migration from the coast of South Africa (mean = 3.3 km/h; Mate et al. 2011).

Individuals 120945 and 120949 both exhibited strong south-westerly directional movement from the HOB, which continued until transmissions ceased from Tag 120949 at approximately 35 degrees south and continued for 120945 until approximately 41 degrees south, when the female started moving in a westerly direction. Averaged sea surface temperature data indicates that the change in direction of movement of 120945 was likely associated with the occurrence of the Subtropical Front (STF), within the Subtropical Convergence (STC), which is characterised by an area of high of elevated primary production (Moore and Abbott 2000) and typically occurs between latitudes 39° - 42°S. The Subtropical Front is a major ocean boundary and is a continuous, but relatively weak, feature to the south of Australia where areas of primary production are likely patchy (Tomczak et al. 2004). Such oceanographic fronts in the Southern Ocean are important foraging areas for a range of marine predators (Bost et al. 2009).

There are a number of information sources that indicate the STF may be an important feeding area for SRW that calve in Australian and New Zealand waters. Historical whaling data show catches of SRW occurring in the region of the STF south of Australia in the Austral summer months (Townsend 1935), and 75 and 35 individual SRW were recorded in this area during dedicated whale sighting surveys between 41-44°S and 116-124°E in December-January

1981/82 and 1995/96 (reported in Bannister 2001). Two individually photo-identified SRW were matched from 43°S in December 1995, one that had previously been photographed in South Australia in June 1994, the other off Western Australia in September 1995 (Bannister 2001). Three adult SRW tagged at the Auckland Islands, New Zealand, also travelled westwards during the Austral summer 2008/09 (Childerhouse et al. 2010) to a similar location as Tag 120945, while eastward movement of two SRW between latitudes 40-47° south was reported through the recovery of discovery marks during illegal Soviet whaling in the late 1960s and early 1970s (Tormosov et al. 1998). Three SRW satellite tagged in South Africa also showed an association with the Southern Tropical Convergence in the South Atlantic during the Austral summer months (Mate et al. 2011), and recent data from SRW tagged off Peninsula Valdez, Argentina, showed migratory movement of one female accompanied by a calf to latitudes associated with the STC (Zerbini et al. 2015).

In contrast, individual 120944 did not show the same initial directed southward offshore movement towards the STF, although no data were received from this tag for 26 days, at which point the individual was south-west of Albany, Western Australia. Overlaying this individual's satellite track on averaged sea surface height and current speed showed an association between this female's movements and a low pressure anti-cyclonic eddy off the south-west tip of Western Australia. These quasi-periodic eddies occur annually in the region during the Austral summer, and are driven by the interaction between a weakening in the southerly flowing Leeuwin Current and persistent seasonal southerly winds that results in localised upwelling (Waite et al. 2007). Final location data received from this tag were transmitted from the southwest edge of the Naturaliste Plateau, where SRW were historically whaled in the Austral summer (Townsend 1935). The Naturaliste Plateau was also recently shown to have high residency periods of satellite tracked pygmy blue whales (Double et al. 2014).

Movement data from this, and previous studies, indicate at least three likely foraging grounds for SRW that breed and or calve in Australia and New Zealand: south-west Western Australia, Sub-tropical Front (this study, Childerhouse et al. 2010, Bannister 2001), and Antarctic waters (AMMC and DSEWPaC 2012). The utilisation of different within-ocean basin foraging grounds has also been observed for satellite tracked SRW from the South African and Argentinean populations (Mate et al. 2011, Zerbini et al. 2015).

While the diet and foraging behaviour of SRW is not well understood, stomach samples analysed from whaling records indicate that the prey found in SRW diets are specific to different feeding locations and that foraging likely occurs over wide latitudes (Tormosov et al. 1998). Analysis of stomach contents of SRW harvested at latitudes below 40°S indicated that their diet was dominated by copepods, whilst those taken above 50°S were dominated by krill, with a mixture of both prey items in stomachs from animals taken from intervening latitudes (Tormosov et al. 1998). Analyses of stable isotopes, in combination with genetic data, indicate that maternally directed site fidelity to specific feeding areas may exist for SRW (Valenzuela et al. 2009). Such maternally transmitted fidelity to feeding grounds has been proposed for other whale species including humpback whales (*Megaptera novaengila)* in the Southern Hemisphere (Barendse et al. 2013) and North Pacific gray whales (*Eschrichtius robustus*) (Lang et al. 2014). Reproductive success in SRW calving in Argentina has been linked to sea surface temperature anomalies (Leaper et al. 2006) and changes in calf production in north Atlantic right whales (NARW) has been linked to climate associated ecosystem changes in prey abundance (Meyer-Gutrod et al. 2014). Slow recovery of the south-east Australian population relative to the south-west population, likely reflects the high historical hunting pressure on the former, and the potential that cultural memory of calving grounds was lost resulting in slow recolonization of these areas. Although SRW generally show fidelity to a particular calving ground, interchange of females between calving grounds at HOB and the Auckland Islands, New Zealand, has been recorded (Pirzl et al. 2009, E. Carrol *unpublished data*), and there is some genetic evidence of mixing of maternal lineages (Patenaude et al. 2007). One female SRW in the current study moved to the same general region of the STF as three SRW tagged at the Auckland Islands providing evidence that overlap in the offshore distribution of SRW from different calving grounds is likely to occur.

Potential overlap with human activities

Movement patterns of the three SRW satellite tracked in the current study also showed overlap with areas of human activity and highlight some of the potential risks this species is exposed to. A number of threats to the recovery of SRW populations in Australasian waters are identified in the Conservation Management Plan for the species (DSEWPaC 2012). For the south-west population, the most likely threats are entanglement, shipping noise, seismic surveys and whale watching. For the south-east population, which is recovering more slowly than the south-west population, likely threats also include the development of coastal infrastructure such as ports. It is likely that the risks posed to SRW population recovery will be greatest during the Austral winter when SRW are utilising coastal areas for breeding and calving.

All three tagged females in the current study passed through areas leased for oil and gas exploration and development. Movements of SRW through these areas makes them potentially susceptible to vessel strike, and negative impacts associated with marine noise from vessels, seismic surveys, and drilling. Vessel strike is one of the major anthropogenic causes of death to cetaceans, and has been recorded for at least 11 species worldwide (Laist et al. 2001, Redfern et al. 2013). Vessel collisions have been reported as one of the two main sources of anthropogenic mortality to North Atlantic right whales (Laist et al. 2014), with individuals found to show no response to the sound of approaching vessels (Nowacek et al. 2004). Ship strikes of SRW have been recorded throughout the southern hemisphere (Van Waerebeek et al. 2007), although records are likely to be underestimated due to limited stranding data or lack of awareness for reporting. To date, four fatal, and three non-fatal vessel collisions with SRW have been recorded in Australian waters between 1950 and 2006 (Kemper et al. 2008), with a further fatal and non-fatal collision reported in annual Scientific Committee progress reports submitted by Australia to the International Whaling Commission between 2007 – 2014 (https://iwc.int/scprogress). As SRW numbers continue to recover in Australasian waters, the risk of vessel strike and increased disturbance to whales will increase, particularly in areas where the intensive development of coastal or offshore activities lead to changes in the distribution and intensity of vessel traffic.

Vessel noise in low-frequency bands can overlap with the frequency range of acoustic signals produced by large whales. Parks et al. (2007) found a positive correlation between the call rate, signal frequency and magnitude of NARW vocalisations and vessel noise (Parks et al. 2011). Noise associated with ship traffic has also been shown to result in the acoustic masking of right whale signals over large areas (Hatch et al. 2012). Whale physiological responses may also be affected. A study of NARW in the Bay of Fundy, Canada, linked decreases in their baseline stress hormones to decreases in underwater noise associated with reduced ship traffic post September 2011 (Rolland et al. 2012).

Seismic surveys are often undertaken as part of offshore marine oil and gas exploration. Changes in behaviour due to airgun noise associated with seismic surveys have been reported for a number of whale species (see Gordon et al. 2003 for review), including changes in diving (Robertson et al. 2013) and foraging behaviour (Miller et al. 2009), and movement out of the area of seismic activity (Castellote et al. 2012). Extensive seismic surveys for oil and gas reserves have been conducted in the Great Australian Bight in recent years and will continue in the near future. The migratory movements of all three individuals in the current study show the potential for overlap between migration pathways and areas of seismic activity.

Entanglements of large whales in fishing gear are a leading cause of mortality for some species (Moore 2014). Disentanglement of gear from whales is not straightforward to achieve and an individual may remain entangled for many days or months before shedding gear. A total of 82% of 626 individually identified NARW showed evidence that they had been non-fatally entangled at least on one occasion (Knowlton et al. 2007). Disentanglement will be dependent on the complexity of the entanglement and the ability of individuals to break through fishing gear if it is encountered. An increase in the severity of observed NARW entanglement injuries since the mid-1990s may be related to changes in the manufacturing of rope, and that the breaking strength of rope played a role in the severity of the entanglement (Knowlton et al. 2015). Where entanglements cannot be shed, or the individual is restricted in its ability to forage, fatally entangled right whales can take an average of six months to die, with serious individual welfare consequences (Moore 2014).

As the Australasian SRW population continues to recover, there will be increased risk of individuals encountering and becoming entangled with fishing gear. The extent to which whales are at risk from entanglement risk is dependent on the number of whales overlapping in areas used by fishing. For example, an increase in the number of SRW reported entangled in fixed fishing gear in South Africa has been attributed to both increasing population size and increased spatial overlap of fishing effort and whale distribution (Meyer et al. 2012). In Australia, 13 entanglements of SRW have been reported between 1987 and 2006. Of these, one whale was recorded as a fatal entanglement in a longline (Kemper et al. 2008), two whales were recorded as disentangled, and the fate of nine others is unknown. These entanglements have predominantly been with ropes and/or floats, and in five cases gear was attributed to that used in crustacean fisheries, although one individual was also non-fatally entangled in gear used by a fish farm.

In South Australia, southern rock lobster (*Jasus edwardsii*) is fished between October and May, with 80% of the annual catch taken within 30 km of the coast (Linanne and Crosthwaite 2009). Research is currently being undertaken to assess the viability of fishing for rock lobster in winter in the northern zone (PIRSA Fisheries and Aquaculture *pers comm*). If winter fishing is permitted, there may be a higher risk of entanglement of SRW with fishing gear while migrating to winter calving grounds. In Victoria, where the rock lobster fishery operates in coastal waters between November and September, an industry code of practice is currently in place that aims to minimise the risk of entanglement to whales. This includes measures such as reducing excessive slack in ropes attached to rock lobster pots. Recorded entanglements of humpback whales in the West Coast Rock Lobster Managed Fishery (WCRLMF) in Western Australia have led to trials aimed to mitigate the risk of entanglement to whales, and include modifications of fishing gear such as placing limits on rope length and the use of negatively buoyant ropes. These management and research measures may be necessary in SA should winter fishing be permitted in the future

In order to obtain long-term baseline movement data of SRW between their breeding and feeding grounds, current telemetry attachment technology requires the use of deep implantable satellite tags. Implantable satellite tags have provided important data on movement patterns, migration, distribution and ecology of a number of large whale species (e.g. Baumgartner and Mate 2005, Wade et al. 2006, Gales et al. 2009, Bailey et al. 2010, Gales et al. 2010, Mate et al. 2010, 2011, Zerbini et al. 2011). However, due to the invasive nature of the attachment used in such tags, concerns remain over the possible short- and long- term physiological effects of these devices (e.g. Moore et al. 2013).

Robbins et al. (2013) conducted focal follows of tagged humpback whales for a minimum of one hour after tag deployment and found that tagged individuals returned to normal behaviour after a few minutes and up to 4.5 hours post-tag deployment. Although focal follows could not be conducted in the current study due to weather conditions, location data received from 6 tags which transmitted post-deployment showed that in the 12 hours following tag implantation, these individuals remained an average distance of 2.8 km from the tagging location. Four tagged individuals were resighted during a SARDI/DEWNR aerial survey 18 days after tag deployment, all within 3.35 km of the location where they were tagged, and were also opportunistically resighted at the HOB between 9 and 21 days post tag deployment during cliff-top surveys conducted by the Curtin University Great Australian Bight Right Whale Study (GABRWS) (Charlton and Ward 2015). While information on the movement patterns in the hours and days after deployment are not available for three of the individuals, satellite location and resight data indicate that behavioural impacts on tagged whales were likely minimal as they did not leave the aggregation area in the hours and days after tag deployment.

The failure of three tags to transmit, and the variability in transmission performance of the other six tags, could be due to a number of factors. These include mechanical failure, electronic failure, sub-optimal position of tag deployment, or post-deployment damage to the tag caused by the behaviour of the individual or conspecifics (calves).

Cessation of transmissions from Tag 121199 was caused by tag loss associated with the tag failing to fully implant, and may have been related to the tag hitting the water prior to implantation. This individual was opportunistically photographed a day after tag deployment (Charlton and Ward 2015), and 80-90% of the tag body was visibly protruding from the whale, indicating that full implantation had failed. The last transmission from this tag was received 5 days later and this is likely when the tag was shed. Opportunistic photographs of the individual taken 12 days after deployment indicate that the tag had fully shed from the whale by this point (Charlton and Ward 2015). Transmission failure due to rapid shedding of the tag may also be the cause of transmission failure for Tag 121202, which also did not implant fully on deployment.

Zerbini et al. (2015) found that two tags which achieved 10-15% implantation in SRW in Argentina were both shed within a day of deployment, and Robbins et al. (2013) found that tag transmission duration for humpback whales was significantly higher when full, rather than partial implantation of the tag had occurred.

Tags may have also electronically failed. In the current study, Tag 112729 ceased transmitting 2 days post-deployment but photographs taken of the individual during the dedicated aerial survey show that the tag was still implanted and in a good position 18 days later. Opportunistic photos taken of this individual on 22 September 2015 also show that the tag and antenna were still intact (Charlton and Ward 2015). Given the tag was still present in the whale at least 18 days after deployment, the lack of transmissions from this tag is most likely a result of electronic failure. Electronic failure may have been inherent to the tag, but may also be a result of damage to the tag post-implantation. Robbins et al. (2013) also recorded two instances where tags were implanted but not transmitting. Other telemetry studies on SRW have suggested that reduced transmission periods of tags deployed on females with a calf, relative to those deployed on unaccompanied whales, could be a result of tag damage caused by a calf's thigmotactic behaviour towards its mother (Mate et al. 2011, Best et al. 2014).

Three of the tags in the current study had periods where no location data were received prior to transmission resuming, and such breaks in transmission have been reported in other telemetry studies on SRW (Childerhouse et al. 2010, Zerbini et al. 2015). For example, Childerhouse et al. (2010) reported a 36 day period between tag deployment and the first data transmission received for one tag. In the current study, Tag 120944 had a 23 day period of silence before data transmission resumed, at which point the female was off the coast of Western Australia. There were no resights of this individual post tag deployment, so it is not possible to assess what may have caused this period without data transmissions. For the other two individuals, a photograph of Tag 120945 taken during the aerial survey, which coincided with a time when that tag was not transmitting, appears to show an extrusion of tissue covering the antenna. Opportunistic photographs taken by the Curtin University Great Australian Bight Right Whale Study also appear to show a plug of tissue and swelling around the site of Tag 120949 (Charlton and Ward 2015). It is possible that the periods without transmission for these tags were a result of tissue fouling the antennae, or caused by tissue swelling around the tag that affected the function of the tag’s salt water switch.

Due to the reproductive cycle of SRW, where females breed approximately every three years, it is not possible to conduct a follow-up assessment of the health and wound healing for tagged individuals in the year after tagging. Resights of satellite tagged SRW in South Africa collected over an 11 year period post-deployment showed that most implantable tags were shed by 36 months and the majority of individuals appeared to have healed tag sites six years after tagging (Best et al. 2014). The study also found no difference in the calving rates of satellite tagged female SRW compared to untagged females, and so far observations of tagged humpback whales in the Gulf of Maine have not shown any difference in the number of tagged females returning to calve in the year following tagging compared to untagged females (Robbins et al. 2013). Photo-ID data of tagged individuals from the current study will be available for matching in the Australasian Right Whale Photo-identification Catalogue (ARWPIC), and given the fidelity of females to specific calving grounds, it should be possible to collect further resight data on these individuals in the future.

The study has generated the first offshore movement pattern of SRW from mainland Australia, and has provided important information for the assessment and management of threats identified in the Conservation Management Plan for this species (DSEWPaC 2012). The study highlights the need for further information on offshore movements of this species as populations continue to recover, and the ability of satellite telemetry to provide these data. While the use of satellite telemetry can provide invaluable information for the management of SRW in Australasian waters, the impacts of implantable tags on individuals needs to be considered. The inclusion of photo-ID of tagged individuals from the current study in ARWPIC will allow for the longer term monitoring of these whales, and is particularly important for reproductive females who are not expected to return to HOB for three years.

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APPENDIX 1

Appendix 1 – Details of satellite tag deployments

Tag deployment 1 – tag ID 123225

The tag was deployed on an adult whale accompanied by a calf on 6 September at 15:30. The adult and calf were resting at the surface prior to approach by the small vessel and the total time of approach until tagging was 2 minutes. On deployment of the tag the adult submerged, did a tail flick underwater and then swam away quickly. The position of the tag was about halfway along the length of the animal low on the right flank (Fig. A1). The biopsy gun failed to fire so no biopsy sample was taken of this animal. The satellite tag transmitted for one hour after deployment. No resight data is available for this individual.

Figure A1: position of satellite tag indicated by arrow

Tag deployment 2 – tag ID 112725

The tag was deployed on an adult whale accompanied by a calf on 6 September at 16:01. The adult and calf were resting at the surface prior to approach by the small vessel and the total time from initial approach to tag deployment was 2 ½ minutes. As the tag was being deployed the adult started to roll and turn away from the boat. The reaction to deployment was a rapid dive and then the adult and calf swam away quickly. The position of the tag was about halfway along the length of the animal on the left flank. Because the adult started to roll as the tag was being deployed, the position of the tag was low on the flank (Fig A2). A biopsy sample was successfully obtained from this individual. No transmissions were received from this tag post deployment, which may be due to the low deployment position as the aerial may not be exposed sufficiently to transmit. No resight data is available for this individual.

Figure A2: position of satellite tag indicated by arrow

Tag deployment 3 – tag ID 121202:

The tag was deployed on an adult whale accompanied by a calf on 6 September at 18:19. The adult and calf were slow travelling prior to approach and the total time from initial approach to tag deployment was 5 ½ minutes. On deployment of the tag the adult flicked its tail and both adult and calf swam away quickly. The position of the tag was about halfway along the length of the animal on the right flank and the tag hit the water prior to implantation (Fig A3). The biopsy dart stuck in the individual so no sample was obtained. No transmissions were received from this tag. Video footage was only recorded by one GoPro during this approach so it is not possible to determine how well the tag implanted. No resight data is available for this individual.

Figure A3: Satellite tag hitting water prior to implantation, indicated by arrow.

Tag deployment 04 – tag ID 112729:

The tag was deployed on an adult whale accompanied by a calf on 7 September at 09:50. The adult and calf were resting at the surface prior to approach and the total time from initial approach to tag deployment was 1 minute. On deployment of the tag the adult arched its back then moved off slowly. The position of the tag was about a third along the length of the animal on the right flank. A biopsy sample was successfully obtained from this individual. The tag stopped transmitting two days after deployment and it is unclear why this tag stopped working as resights of the individual showed the tag and aerial appeared to be intact. The adult and calf were resighted at Head of Bight during an aerial survey conducted by SARDI and DEWNR on 25 September 2014 (Fig. A5).

Figure A4: position of satellite tag indicated by arrow

Figure A5: Tagged individual with calf sighted at HOB aerial survey 25 September 2014. Location of tag indicated by arrow.

Tag deployment 5 – tag ID 121199

The tag was deployed on an adult whale accompanied by a calf on 7 September at 10:05. The adult and calf were resting at the surface prior to approach and the total time from initial approach to tag deployment was 1 minute. Prior to deployment of the tag the adult had started to dive, on deployment of the tag it continued to dive and swim away from the boat. Because of the movement of the adult just as the tag was deployed the tag ended up being shot through the water (Fig. A6). A biopsy sample was successfully obtained from this individual.

Figure A6: tag indicated by arrow

The tag was deployed about half way along the body on the right flank but it is not possible to determine the position or amount of implantation for the tag from the video footage. However, a photo taken of the individual by the GABRWS a day after deployment shows the tag did not implant properly (See Charlton et and Ward 2015 for further details).

The tag transmitted successfully for 5 days during which period the individual remained at Head of Bight. It is likely that the end of transmissions occurred when the tag fell out of the individual. This individual was re-sighted with its calf on 25 September at Head of Bight during the aerial survey conducted by SARDI and DEWNR (Fig A8)

Figure A8: arrow indicates wound after tag has fallen off of the individual.

Tag deployment 6 – tag ID 120944:

The tag was deployed on an adult whale accompanied by a calf on 7 September at 11:47. The adult and calf were resting at the surface prior to approach and the total time from initial approach to tag deployment was 3 minutes. On deployment of the tag the adult rolled away from the boat and moved off slowly showing a very mild reaction. The tag was deployed about one third along the animals length and high on the right flank (Fig. A9). Although a biopsy was taken, the sample fell out of the dart before it could be retrieved. No resight data is available for this individual.

Figure A9: arrow indicates position of tag, circle indicates biopsy dart

This tag transmitted for two days after implantation but then did not transmit for the following 26 days. When transmission started to be received again on 6 October the individual was off the coast of Albany, WA. The last transmission was received from this tag on 3 November 2014.

Tag deployment 7 – tag ID 121209:

The tag was deployed on an adult whale accompanied by a calf on 7 September at 12:13. The adult and calf were slow travelling prior to approach and the total time from initial approach to tag deployment was 6 minutes. When tagged the adult continued a normal dive and both adult and calf continued on slow travel away from boat after deployment. The tag was deployed about half way along the body on left flank with good tag implantation (Fig. A11). A biopsy sample was also obtained from this individual. Photo-ID collected during aerial surveys showed that the calf, which has distinctive white pigmentation on its back, was actually the calf of another individual and not that of the tagged whale. No transmissions were received from this tag. No resight data is available for this individual.


Figure A11: arrow indicates position of tag

Tag deployment number 8 – tag ID 120945

The tag was deployed on an adult whale accompanied by a calf on 7 September at 12:54. The adult and calf were resting at the surface prior to approach and the total time from initial approach to tag deployment was 1 minute. When tagged, the adult rolled and changed direction, and then both adult and calf swam away rapidly from the boat. The tag was deployed about half way along the body on the left flank (Fig. A12). A biopsy sample was successfully obtained from this individual.


Figure A12: arrow indicates position of tag

The tag transmitted for a few hours after deployment and then was silent for ten days. The tag began transmitting again on 17 September and continued to transmit for a further 50 days. The individual and calf were sighted at HOB during the aerial survey on 29 September. Final transmission of the tag was received on 6 November 2014.

Tag deployment number 9 – tag ID 120949

The tag was deployed on an adult whale accompanied by a calf on 7 September at 14:47. The adult and calf were resting at the surface prior to approach and then began travelling slowly. The total time from initial approach to tag deployment was 2 minutes. When tagged, the adult the adult gave a large tail slash and then swam rapidly away with the calf. The tag was deployed about one third of the way along the body on the upper left flank (Fig. A14). A biopsy sample was successfully obtained from this individual.

Figure A14: arrow indicates location of tag, circle shows biopsy dart.

The tag transmitted for 18 hours after deployment and then was silent for 19 days. The tag began transmitting again on 27 September and continued to transmit for a further 13 days. The individual and calf were sighted at HOB during the aerial survey on 29 September and the final transmission was received on 09 October 2014.