Notes

Movement and diving patterns of juvenile male South American sea lions off the coast of central Chile

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Despite its wide distribution along both coasts of South America and a large population (>300,000 individuals, Werner and Campagna 1995) the South American sea lion (*Otaria byronia*) remains one of the world's least studied pinniped species. While limited information exists on the diving behavior of South American sea lions in the Atlantic (Werner and Campagna 1995, Thompson *et al.* 1998, Riet-Sapriza *et al.* 2013), there is no information on their behavior in the Pacific, where the oceanography is very different. Most sea lion species are benthic foragers, and South American sea lions foraging in the Atlantic appear to be no exception. Along its Atlantic range, South American sea lions forage in waters over the continental shelf, and dives of >300 m have been recorded (Werner and Campagna 1995, Thompson *et al.* 1998, Campagna *et al.* 2001, Riet-Sapriza *et al.* 2013). This diving pattern is likely related to the depth of the continental shelf. For instance, the deepest dives recorded for female South American sea lions (>60 m) off Patagonia, Argentina, are similar to the depth of the shelf in that area (Campagna *et al.* 2001). Further, females from Isla Lobos, Uruguay, exhibited benthic diving behavior reaching an average depth of only 21 m (Riet-Sapriza *et al.* 2013).

With a local population of over 16,000 individuals the South American sea lion is the only year-round resident pinniped found in Central Chile (32º–39ºS) (Sepúlveda *et al.* 2011). Given the considerable differences in the oceanography of the Pacific and Atlantic coasts of South America we would expect significant differences in the

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diving behavior of South American sea lions. The continental shelf off Argentina is not only shallower (*ca.* 100 m depth) but considerably wider (up to 400 km) than the shelf off the Chilean coast (200 m depth, <66 km wide in central Chile). Further, despite the high biological productivity that characterizes both systems, the oceanographic processes governing each one are radically different. The biological productivity in the South Western Atlantic is determined by the location and movement of water masses in the complex and dynamic confluence of the Brazil and Falkland Currents, together with the abundant runoff of La Plata River (Willson and Rees 2000, Milaslovich *et al.* 2011). Contrastingly, the Pacific coast of South America features the Humboldt Current System (HCS), one of the major upwelling systems of the world with intense seasonal productivity and highly productive fisheries, accounting for 16%–20% of the world's global catch (Shaffer *et al.* 1995, 2004; Miloslavich *et al.* 2011).

Considering the aforementioned differences in the habitat of sea lions, we would not necessarily expect to observe benthic foraging off Chilean waters as reported off Argentina and Uruguay. Indeed, Hückstädt and Krautz (2004) reported observations of sea lions in offshore waters as far as 300 km from the coast (>5,000 m depth), and over 250 km past the break of the continental shelf. Furthermore, the foraging range of the South American sea lion from the Pacific Ocean has yet to be determined, although circumstantial evidence from fisheries interactions suggests the sea lions may have similar ranges in the Pacific and Atlantic (Werner and Campagna 1995, Thompson *et al.* 1998, Campagna *et al.* 2001, Hückstädt and Krautz 2004).

Here, we present the first observations of the foraging behavior of juvenile South American sea lions off central Chile. Our goal was to describe at-sea distribution, movements, and foraging patterns of juvenile South American sea lions along the Chilean coast, and to identify the habitat used by foraging juvenile sea lions.

We captured male juvenile sea lions in July 2009 ($n = 4$) (Table 1), around the Cobquecura National Marine Sanctuary (36°07′S, 74°48′W) (Fig. 1a), a year-round rookery for the South American sea lion (~3,000 individuals, Sepúlveda *et al.* 2011), and one of the largest sea lion breeding colonies in central Chile. Animals were captured in the water, just outside the sanctuary using small purse seiner vessels from the sardine fleet. We developed a new capture technique taking advantage of animals that were naturally attracted to the boat. Animals were initially surrounded by the purse seine and lassoed with a rope in the water and then transferred to a hoop net. Once safely secured in the net, they were transferred to the fishing boat, then to a smaller boat and taken to land where instruments were attached. Capture time (first capture with the lasso to securing the animal in the small boat) lasted 20 min or less. Transit time, from the capture location to our field site, took roughly 15 min. Throughout the procedure animals were monitored by a veterinarian. We selected animals that appeared healthy.

On land, animals were anesthetized using isofluorane gas (0.5%–2.5%) administered with 100% oxygen *via* a cone shaped mask and intubation, using a portable field vaporizer (Gales and Mattlin 1998). Once the animals were quiescent, morphometric measurements (length and girth ±1 cm) (Table 1) were collected and SPLASH satellite tags (Wildlife Computers, Redmond, WA) were attached to the dorsal pelage between the shoulder blades using 5 min Quick Set epoxy (Loctite, Westlake, OH). At the end of the procedure animals were taken off the isofluorane, weighed using a stretcher and tripod with a digital scale (±0.1 kg), and then allowed to recover while being monitored and once awake released.

Table 1. Tracking data, morphometric measurements, and movement variables (mean ± SD) of juvenile South American sea lions (*Otaria byronia*) off central Chile.

ID	Date	Mass (kg)	Standard length (m)	Days transmitting	Trip duration (d)	Transit rate (km/h)	Maximum distance from colony (km)	Total distance traveled (km)
OFCL1	20 July 2009	78.2	1.43	70.5	2.65 ± 2.18	1.2 ± 0.9	315.5	2,782.9
OFCL2	20 July 2009	90.8	1.47	44.5	1.29 ± 0.83	1.6 ± 1.5	153.1	1,133.9
OFCL3	21 July 2009	68.6	1.43	15.7	1.73 ± 1.07	1.3 ± 1.6	86	309.3
OFCL4	21 July 2009	116.2	1.57	68.6	2.56 ± 1.75	2.5 ± 1.8	289.6	2,693.7
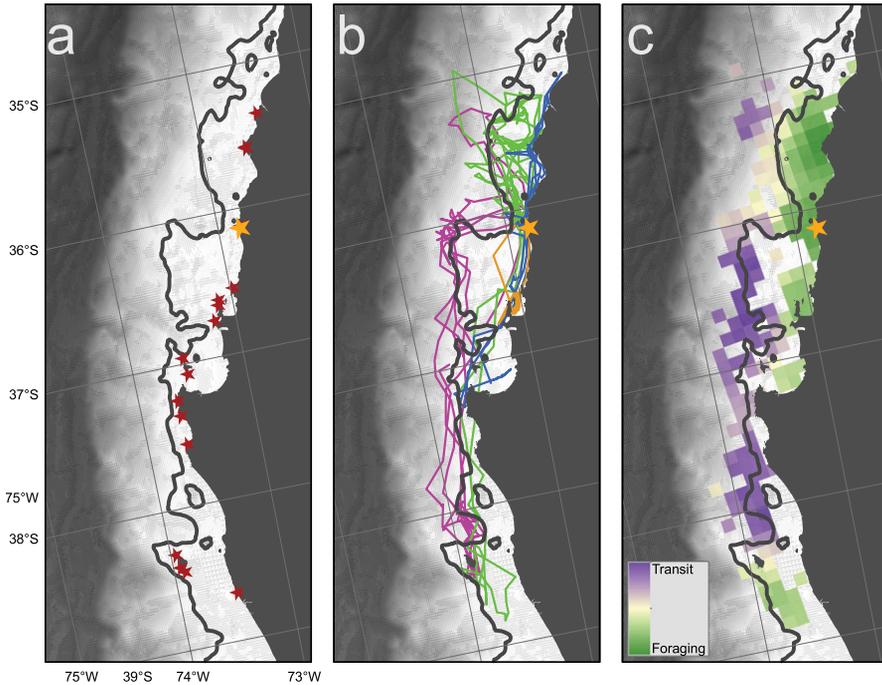
Figure 1. (a) Location of colonies and haul-out sites of South American sea lion (*Otaria byronia*) along central Chile (red stars). The yellow start indicates the capture site at the Cobquecura colony. (b) Satellite locations from four juvenile male sea lion instrumented in central Chile. Each color indicates the track for an individual sea lion. (c) Spatial distribution of hot spots of foraging behavior (green) and transit behavior (purple), as identified from a Switching State Space Model. The thick gray line represents the shelf break, indicated by the 200 m isobath. The bathymetric depth is depicted in a gray color scale, with lighter colors indicating shallow depths, while darker shades indicate deeper depths.

SPLASH tags were programmed to collect and transmit data *via* the ARGOS system (Toulouse, France). Data on at-sea locations of sea lions, as well as summaries of diving depth (m), duration of the dive (s), and time spent at water temperature (°C) at predefined bins were collected and transmitted by the Argos transmitter on board the instrument. Diving and temperature data were collected every 2 s and summarized for 6 h periods, obtaining four histograms per day per animal for 14 predefined bins. We defined a dive as depth >4 m, while the tag entered haul-out mode (*i.e.*, battery saving mode) when the sensors were dry for a period of >10 min.

To define the bins for the summarized diving data, we took into consideration the available information for the species in the Atlantic (Thompson *et al.* 1998, Campagna *et al.* 2001, Werner and Campagna 2005), as well as the bathymetry in our study area. Hence, diving depth bins were defined every 20 m, with the last bin including dives of over 240 m in depth. SPLASH tags also process and transmit data on time-at-temperature (data not presented here), and time-at-depth (or time spent within the specified depth bin, as defined for diving depth). Diving depths reported in our analysis correspond to the deepest 20 m diving bin reached by the sea lions, while time-at-depth corresponds to the most used depth bin (m) used by sea lions in

each 6 h period. Due to an error when programming the instruments, data on dive duration were not included in this analysis.

Raw ARGOS location data were preprocessed using a forward/backward speed filter to remove aberrant positions (Patterson *et al.* 2010) using a conservative speed of 10 m/s, and then further processed using a Switching State Space Model (SSSM) (Jonsen *et al.* 2005). A State Space Model (SSM) provides positions estimates that incorporate errors associated with each ARGOS location class as well as the dynamics of the movement process (Jonsen *et al.* 2005, McConnell *et al.* 2010, Patterson *et al.* 2010). A "Switching" SSM (SSSM) includes a model of two behavioral states: traveling (periods of sustained faster and directed movements) and foraging (nondirected and slow movements) as a binary distribution using Markov chain Monte Carlo (MCMC) (Breed *et al.* 2009, McConnell *et al.* 2010).

A haul-out period was defined as the time an animal spent within 5 km of a colony or haul-out site that lasted at least 4 h. We then defined a foraging trip as the time between haul-out periods. We limited our analysis to foraging trips lasting longer than 12 h, and used these periods to calculate the maximum distance from the colony (km), transit rate (km/h), and total traveled distance (km). An analysis of the spatial distribution of the two behavioral states obtained from the SSSM (foraging *vs.* transit behavior), was carried out using the hot spot analysis (Getis-Ord Gi* statistic, ArcGIS v10) to identify clusters of either behavior using a grid cell of 10 × 10 km (Fig. 1c).

To assign a bathymetric depth to each diving bin, we first estimated a location for the midpoint of each 6 h period summarized in the transmitted histograms from the SSSM-filtered track, to then proceed to extract the bathymetric depth (m) at that location from the ETOPO 1-min data set. With this, we were able to calculate the dive index for each 6 h period (diving depth/bathymetric depth), a dimensionless index that ranges between 0 (indicating pelagic foraging) and 1 (indicating benthic foraging).

We captured juvenile males, which ranged in mass between 68.6 and 116.2 kg (Table 1). The instruments deployed on these sea lions transmitted data for a period that varied between 16 and 71 d per individual, and we obtained diving data from three individuals (OFCL3, with the shortest telemetry record, did not render usable diving data) (Table 1).

The tracking data (Fig. 1b) showed a marked directionality in the movement of juvenile sea lions, which followed the characteristic north-south orientation of the Chilean coast, with very few intrusions into deeper, off-shelf waters. Despite the rather limited longitudinal extent in their movement, the sea lions showed a wide spatial range, reaching distances of over 310 km from the capture site (OFCL1, Fig. 1b). Adult male South American sea lions have been observed to reach distances of up to 300 km from the coast, both in Argentinean and Chilean waters (Campagna *et al.* 2001, Hückstädt and Krautz 2004), yet juvenile sea lions in our study rarely ventured into offshore waters, reaching a mean distance from the coastline of 20 km, with a maximum of only 80.2 km.

Our definition of foraging trips based on a distance from land haul-out sites and colonies was rather conservative. We identified between 5 and 24 foraging trips for each animal, which depended on the length of the tracking record. Foraging trips in our sample ranged in duration between 0.6 and 7.3 d, with a mean of 2.32 d, and mean transit rate (±SD) was 1.89 ± 1.04 km/h (Table 1). Juvenile sea lions in our study traveled farther than adult animals from Patagonia, Argentina (Campagna *et al.* 2001), some traveling >300 km from their capture site at Cobquecura, and

traveling total distances well over 2,000 km during the study period (Table 1). However, their transit speeds during their foraging trips were considerably slower than those reported for adult males and females in the Atlantic (Campagna *et al.* 2001).

Raum-Suryan *et al.* (2004) reported an increase in traveled distance of juvenile Steller sea lions (*Eumetopias jubatus*) with age; however, our small sample size and the large variation in length of transmissions for sea lions makes comparisons difficult. As reported for Steller sea lions (Raum-Suryan *et al.* 2004), juvenile sea lions in our study also did not display fidelity to the colony but hauled out at several other rookeries along the coast (Fig. 1a, b). This behavior of low fidelity to particular colonies or haul-out sites has been reported for male California sea lions (*Zalophus californianus*), which display large scale movements of hundreds of kilometers visiting multiple haul-out sites (Weise *et al.* 2006). Similarly, juvenile male Steller sea lions are also capable of moving over long distances (>500 km) and use multiple haul out sites (Raum-Suryan *et al.* 2004). On the other hand, female otariids are generally central-place foragers during their lactation period, returning to their colony to rest and feed their pup while lactating (Costa 1991, Chilvers *et al.* 2005, Womble *et al.* 2009), although some exceptions have been described for species such as the Galapagos sea lions (*Z. wollebaeki*) that also haul out at locations other than the colony where their pup is located (Villegas-Amtmann *et al.* 2008).

The utilization of the SSSM approach allowed us to assign behavioral categories (foraging *vs.* transit) to sea lions at sea based on the characteristics of their movement pattern (see Jonsen *et al.* 2005, Breed *et al.* 2009, McConnell *et al.* 2010). Overall, juvenile sea lions in our study spent 76.1% of their time at sea in foraging behavioral mode, whereas the remaining 23.9% of their time was identified as transit. The hot spot analysis (Fig. 1c) revealed an interesting spatial pattern: sea lions concentrated their foraging on shelf waters; yet a few foraging grounds can be detected in off shelf waters (yellow-green tones, Fig. 1c), with animals transiting back and forth between them (transit hot-spots, purple tones, Fig. 1c). It is important to notice that the hot spot analysis does not indicate spatial segregation in the behavioral modes, but rather it identifies spatially significant clusters of each behavior.

Juvenile sea lions in our study showed a clear pattern of epipelagic foraging, as it is evident from the diving index, which ranged between 0.1 and 0.9, with a mean of 0.45 (Fig. 2a). 82.4% of the dives by sea lions in our study were shallower than 20 m, whereas only 1.9% of the dives were deeper than 200 m in depth (Fig. 2b, c). Likewise, sea lions spent most of their time diving in the 0–20 m interval (Fig. 2d, e). Our data also showed evidence of some benthic foraging with dives >240 m for some individuals over the shelf break region (200 m isobath) (Fig. 2b). No clear differences were evident in the distribution of diving depths between the behavioral modes (Figs. 2b–e), although there is a relatively higher frequency of dives to the deeper depths (>100 m) associated with the foraging (Figs. 2b, c). Benthic diving was mostly associated with shallow-coastal locations, although some benthic diving was observed over deeper shelf waters. The shallow diving depth and relatively higher diving index observed for foraging dives is likely explained by the high occurrence of this behavior on shelf waters (<200 m in depth) as opposed to transit dives, which were concentrated spatially along the shelf break, as identified from the hot-spot analysis (Fig. 1).

Studies collecting diet and direct observational data have suggested that South American sea lions forage in the epipelagic zone throughout their range in the Pacific (Huckstadt and Krautz 2004, Soto *et al.* 2006, Hückstädt *et al.* 2007). Our data
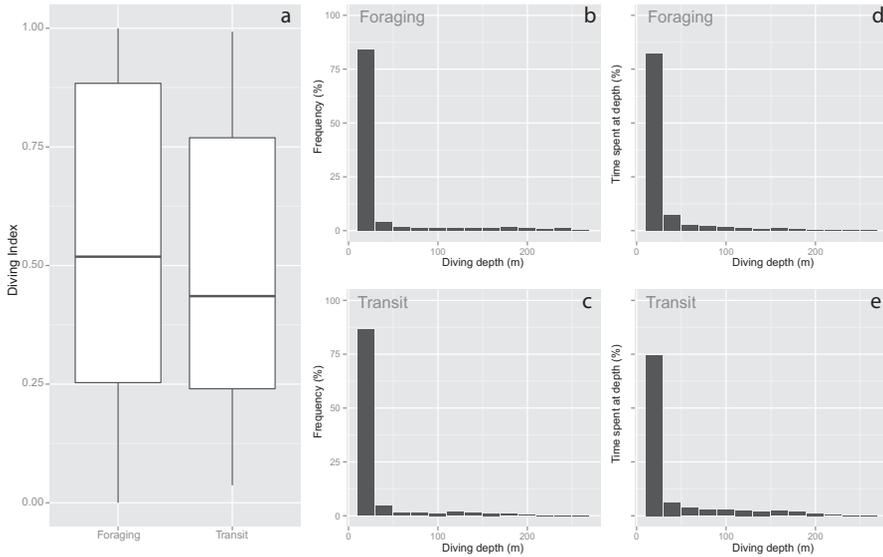
Figure 2. Diving behavior of juvenile male South American sea lions (*Otaria byronia*) according to behavioral state as identified from the Switching State Space Model: (a) diving index according to the at-sea behavioral state; (b) distribution of diving depths (m) associated with foraging behavior; (c) distribution of diving depths (m) associated with transit behavior; (d) Time spent at depth, associated with foraging behavior; and (e) Time spent at depth, associated with transit behavior.

provide empirical evidence from diving behavior consistent with the diet and observational data, departing from the benthic foraging observed for this species in the Atlantic (Werner and Campagna 1995, Thompson *et al.* 1998, Riet-Sapriza *et al.* 2013). The difference in foraging behavior found for juveniles in our study suggests further descriptions of the foraging behavior of South American sea lions throughout their range are necessary. If these patterns persist, differences in foraging behavior should be considered as a factor related to the slow recovery that the Atlantic stock has experienced after the intense human harvest compared with the healthier Pacific stock.

In summary, our study showed that juvenile sea lions in central Chile, despite being mainly limited to shelf waters as their Atlantic counterparts, display an epipelagic foraging behavior. However, they are capable of reaching depths in excess of 240 m when diving. Animals did not show fidelity to any specific colony, instead individuals moved among several haul-out sites along the coast. Finally, our data showed some evidence of environmental differences between areas that are used for foraging *vs.* transit areas, as identified from the SSSMs.

LITERATURE CITED

Breed, G. A., I. D. Jonsen, R. A. Myers, W. D. Bowen and M. L. Leonard. 2009. Sex-specific, seasonal foraging tactics of adult grey seals (*Halichoerus grypus*) revealed by state-space analysis. Ecology 90:3209–3221.

Campagna, C., R. Werner, W. Karesh, M. R. Marin, F. Koontz, R. Cook and C. Koontz. 2001. Movements and lactation at sea of South American sea lions (*Otaria flavescens*). Journal of Zoology (London) 257:205–220.

Chilvers, B. L., I. S. Wilkinson and P. J. Duignan. 2005. Summer foraging areas for lactating New Zealand sea lions *Phocarctos hookeri*. Marine Ecology Progress Series 304:235–247.

Costa, D. P. 1991. Reproductive and foraging energetics of high latitude penguins, albatrosses and pinnipeds: Implications for life history patterns. American Zoologist 31:111–130.

Gales, N. J., and R. H. Mattlin. 1998. Fast, safe, field-portable gas anesthesia for otariids. Marine Mammal Science 14:355–361.

Hückstädt, L. A., and M. C. Krautz. 2004. Interaction between southern sea lions *Otaria flavescens* and jack mackerel *Trachurus symmetricus* commercial fishery off Central Chile: A geostatistical approach. Marine Ecology Progress Series 282:285–294.

Hückstädt, L. A., C. Rojas and T. Antezana. 2007. Stable isotope analysis reveals pelagic foraging by the Southern sea lion in central Chile. Journal of Experimental Marine Biology and Ecology 347:123–133.

Jonsen, I. D., J. M. Flemming and R. A. Myers. 2005. Robust state–space modeling of animal movement data. Ecology 86:2874–2880.

McConnell, B. J., M. A. Fedak, S. Hooker and T. Patterson. 2010. Telemetry. Pages 222–242 *in* I. L. Boyd, W. D. Bowen and S. J. Iverson, eds. Marine mammal ecology and conservation. Techniques in Ecology and Conservation Series. Oxford University Press, Oxford, U.K.

Miloslavich, P., E. Klein, J. M. Diaz, *et al*. 2011. Marine biodiversity in the Atlantic and Pacific coasts of South America: Knowledge and gaps. PLoS ONE 6(1):e14631.

Patterson, T. A., B. J. Mcconnell, M. A. Fedak, M. V. Bravington and M. A. Hindell. 2010. Using GPS data to evaluate the accuracy of state–space methods for correction of Argos satellite telemetry error. Ecology 91:273–285.

Raum-Suryan, K. L., M. J. Rehberg, G. W. Pendleton, K. W. Pitcher and T. S. Gelatt. 2004. Development Of dispersal, movement patterns, and haul-out use by pup and juvenile Steller sea lions (*Eumetopias jubatus*) in Alaska. Marine Mammal Science 20:823–850.

Riet-Sapriza, F. G., D. P. Costa, V. Franco-Trecu, *et al*. 2013. Foraging behavior of lactating South American sea lions (*Otaria flavescens*) and spatial–temporal resource overlap with the Uruguayan fisheries. Deep Sea Research Part II: Topical Studies in Oceanography 88–89:106–119.

Sepúlveda, M., D. Oliva, A. Urra, *et al*. 2011. Distribution and abundance of the South American sea lion *Otaria flavescens* (Carnivora: Otariidae) along the central coast off Chile. Revista Chilena de Historia Natural 84:97–106.

Shaffer, G., S. Salinas, O. Pizarro, A. Vega and S. Hormazabal. 1995. Currents in the deep ocean off Chile (30 degrees S). Deep Sea Research Part I: Oceanographic Research Papers 42:425–436.

Shaffer, G., S. Hormazabal, O. Pizarro and M. Ramos. 2004. Circulation and variability in the Chile Basin. Deep Sea Research Part I: Oceanographic Research Papers 51:1367–1386.

Soto, K. H., A. W. Trites and M. Arias-Schreiber. 2006. Changes in diet and maternal attendance of South American sea lions indicate changes in the marine environment and prey abundance. Marine Ecology Progress Series 312:277–290.

Thompson, D., C. D. Duck, B. J. Mcconnell and J. Garrett. 1998. Foraging behaviour and diet of lactating female southern sea lions (*Otaria flavescens*) in the Falkland Islands. Journal of Zoology, London 246:135–146.

Villegas-Amtmann, S., D. P. Costa, Y. Tremblay, S. Salazar and D. Aurioles-Gamboa. 2008. Multiple foraging strategies in a marine apex predator, the Galapagos sea lion *Zalophus wollebaeki*. Marine Ecology Progress Series 363:299–309.

Weise, M. J., D. P. Costa and R. M. Kudela. 2006. Movement and diving behavior of male California sea lion (*Zalophus californianus*) during anomalous oceanographic conditions of 2005 compared to those of 2004. Geophysics Research Letters 33:L22S10.

Werner, R., and C. Campagna. 1995. Diving behaviour of lactating southern sea lions (*Otaria flavescens*) in Patagonia. Canadian Journal of Zoology 73:1975–1982.

Willson, H. R., and N. W. Rees. 2010. Classification of mesoscale features in the Brazil-Falkland Current confluence zone. Progress in Oceanography 45:415–426.

Womble, J. N., M. F. Sigler and M. F. Willson. 2009. Linking seasonal distribution patterns with prey availability in a central-place forager, the Steller sea lion. Journal of Biogeography 36:439–451.