

Short Note

Southern Elephant Seals (*Mirounga leonina*) in the Galapagos Islands and the Eastern Tropical Pacific Amid Ocean Environmental Changes: Towards a Habitat Suitability Index

Juan José Alava,^{1,2} Marjorie Riofrío-Lazo,³ Gabriel Reygondeau,^{1,4}
Patricia Rosero,⁵ Isabel C. Avila,^{6,7} Daniel Lara,⁸
Fernando Gil,⁸ Carlos F. Yaipen-Llanos,⁹
Fernando R. Elorriaga-Verplancken,¹⁰ and Diego Páez-Rosas³

¹Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, Canada
E-mail: j.alava@oceans.ubc.ca

²Fundación Ecuatoriana para el Estudio de Mamíferos Marinos (FEMM), Guayaquil, Ecuador

³Galapagos Science Center, Universidad San Francisco de Quito, Islas Galápagos, Ecuador

⁴Department of Ecology and Evolutionary Biology, Max Planck Institute, Yale Center for Biodiversity Movement and Global Change, Yale University, New Haven, CT, USA

⁵Universidad de Las Américas, Quito, Ecuador

⁶Grupo de Ecología Animal, Universidad del Valle, Cali, Colombia

⁷Institute for Terrestrial and Aquatic Wildlife Research, University of Veterinary Medicine Hannover, Foundation, Germany

⁸Dirección Parque Nacional Galápagos, Unidad Técnica Operativa Isabela, Islas Galápagos, Ecuador

⁹Organization for Research and Conservation of Aquatic Animals – ORCA PERU, San Bartolo, Lima, Perú

¹⁰Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas, La Paz, Baja California Sur, México

The southern elephant seal (SES; *Mirounga leonina*) is the largest, sexually dimorphic pinniped species in the global ocean (Le Boeuf & Laws, 1994; Hindell, 2018). The distinctive feature for males is the proboscis; the maximum development of this feature occurs in adults over 10 years of age (Sanvito et al., 2007). The growth of females ceases after they reach maturity (i.e., ~5 y of age) at a body length of ~2.5 m and 400 to 600 kg body weight (Fedak et al., 1994). Adult males are physiological and socially mature after ~7 years of age when they reach up to 5 m body length and weigh 3,000 kg (Campagna & Lewis, 1992; Pistorius et al., 2005; Hindell, 2018). They are distributed throughout the circumpolar region, sub-Antarctic waters, and Antarctic ecosystems of the Southern Hemisphere (Hofmeyr, 2015; Jefferson et al., 2015; Hindell, 2018). Four genetically different populations are currently recognized, including subpopulations from Peninsula Valdés and the Falkland Islands, the Atlantic sector (South Georgia, South Orkney Islands, South Shetland Islands, and Bouvetøya and Gough Islands), the Indian sector (Iles Kerguelen, Iles Crozet, Heard Island, and the Prince Edward Islands), and the Pacific sector (Macquarie Island, Campbell Island, and Antipodes Island) (Slade

et al., 1998; Hofmeyr, 2015; Jefferson et al., 2015; Corrigan et al., 2016). The Atlantic populations, including South Georgia, Peninsula Valdés, and the Kerguelen Islands, are either currently stable or increasing slightly (Hindell et al., 2016), while the populations on Macquarie Island in the South Pacific are declining (van den Hoff et al., 2014; Hofmeyr, 2015). While the SES is currently classified as “Least Concern” by the International Union for Conservation of Nature’s (IUCN) *Red List of Threatened Species* (Hofmeyr, 2015), this pinniped species is affected by several anthropogenic threats such as bycatch, chemical and biological pollution, and human-induced environmental changes (Hofmeyr, 2015; Alava & Auriolles-Gamboa, 2017; Hindell, 2018).

Several pinniped species show a high dispersion capability during their feeding trips and oceanic distribution. This mobile capacity includes extralimital movements of vagrant adult and subadult individuals at sea and in coastal regions, hundreds or even thousands of kilometers away from their typical feeding or breeding areas in oceanic–coastal regions (e.g., Avila et al., 2014; Elorriaga-Verplancken et al., 2016; Alava & Auriolles-Gamboa, 2017; Quintana-Rizzo et al., 2017; Orr et al., 2018; Páez-Rosas et al., 2020; de Vos, 2021). These behavioral

dispersions and movements have allowed researchers in recent years to document numerous records of SES adult and subadult males resting and hauling out on the Eastern Tropical Pacific (ETP) coasts, including in México, El Salvador, Panamá, Colombia, Ecuador, Perú, and Chile (Alava & Carvajal, 2005; Sepúlveda et al., 2007; Acevedo et al., 2016; Páez-Rosas et al., 2018; Redwood & Félix, 2018; Elorriaga-Verplancken et al., 2020; Avila et al., 2021; Rosero & Alava, 2021; López et al., 2022; Figure 1). The increasing number of individuals from the Atlantic populations, including South Georgia, Peninsula Valdés, and Kerguelen Islands (Lewis et al., 1998; Galimberti et al., 2001; Hofmeyr, 2015; Hindell et al., 2016), and the influence of oceanographic conditions such as El Niño Southern Oscillation (ENSO) events, ocean temperature, and productivity affecting prey availability and distribution (Alava & Carvajal, 2005; Páez-Rosas et al., 2018; Avila et al., 2021; Rosero & Alava, 2021; López et al., 2022) have been suggested as possible factors driving the movement and arrival of the SES to these regions from its normal distribution range.

The ongoing dispersion and recurring records of the SES to the ETP, with a potential geographical expansion towards the Northern Hemisphere as far as 10,000 km from the closest SES populations in the Southern Hemisphere, underscore the notion that the current SES movements may no longer be limited to the circumpolar distribution range around the Southern Ocean and sub-Antarctic regions (Alava & Carvajal, 2005; Acevedo et al., 2016; Páez-Rosas et al., 2018; Elorriaga-Verplancken et al., 2020; Avila et al., 2021; Rosero & Alava, 2021). The influence of ENSO events in tandem with La Niña cold episodes were suggested as possible factors triggering the dispersion and increasing number of SESs to these ETP coastal regions (Alava & Carvajal, 2005; Páez-Rosas et al., 2018; Avila et al., 2021; López et al., 2022). However, questions remain about the influence of other environmental and climate change factors (e.g., ocean heat waves, primary productivity changes, prey availability, and redistribution) in the ocean exacerbating the extralimital dispersions of SESs and the plausible emergence of potential habitat suitability niches in the ETP.

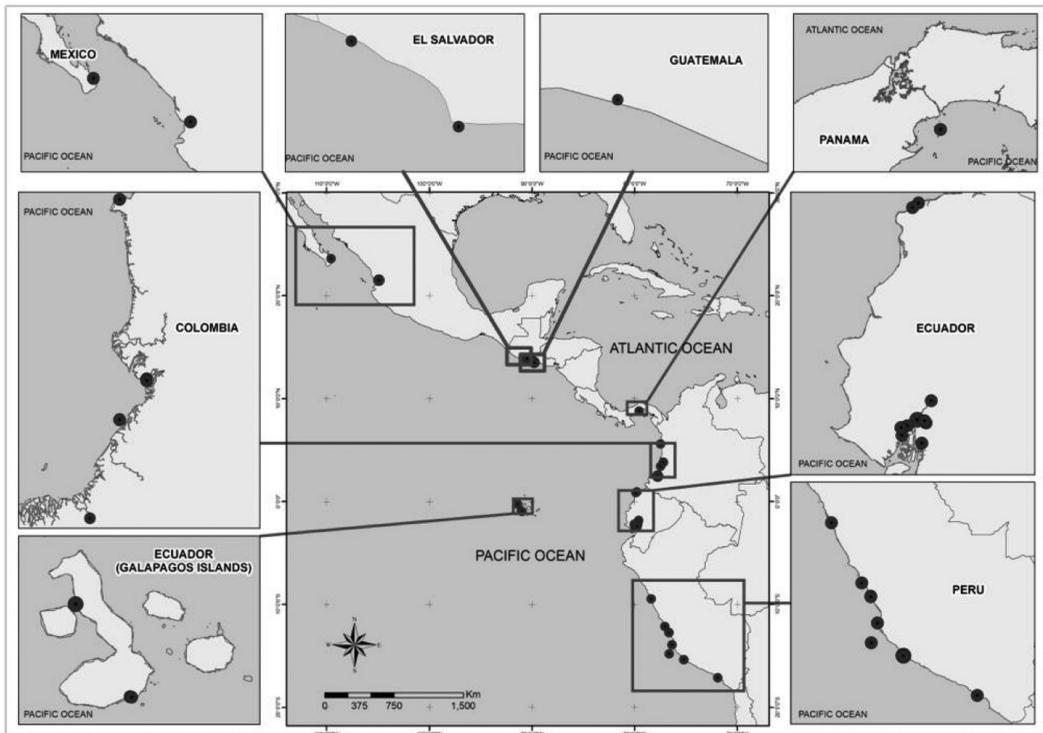


Figure 1. Map showing the records of southern elephant seals (*Mirounga leonina*) and geographical location of sightings along the Eastern Tropical Pacific (México, El Salvador, Guatemala, Panamá, Colombia, Ecuador, Galapagos Archipelago, and Perú) from 1989 to 2022 (see Table 1). The records along the coastal and insular regions of Chile are referred to in the distribution maps available in Acevedo et al. (2016) and Cárcamo et al. (2019).

To enhance our understanding regarding extralimital records in the Galapagos Archipelago and the recent dispersion and records of SESs across the ETP, we compiled 40 nonsystematic observations from 1989 to mid-2022. In doing so, we reviewed the existing peer-reviewed literature, technical reports, and conference papers, as well as personal observations and/or communications from the authors and regional expert colleagues in regards to confirmed records of this species in the Galapagos and across the ETP. When possible and available, online photos and social media sources with information reporting the presence of SESs were also collected and considered in the analyses. The photographic records used for identifying and confirming the species allowed us to differentiate each individual observed due to the low numbers of SESs sighted along the coastal and insular regions assessed in the ETP.

The data collected included date, country, location, geographical coordinates, number of individuals, age, and sex categories (Table 1). The studied regions included the Galapagos Archipelago (Vargas & Steinfurth, 2004; Rosero & Alava, 2021), Ecuador's continental coast (Alava & Carvajal, 2005; Páez-Rosas et al., 2018; Rosero, 2019; Rosero & Alava, 2021), and records from the Pacific coasts of México, Panamá, Colombia (Figure 2e & f), and Perú (Figure 2g & h) (Acevedo et al., 2016; Redwood & Félix, 2018; Stepchew & Yaipen-Llanos, 2019; Elorriaga-Verplancken et al., 2020; Avila et al., 2021), as well as the first sightings from Salvador (López et al., 2022) and Guatemala in 2021 (Figure 1; Table 1). Data for SES records and distribution in Chile were not included in Table 1 to avoid repetition as this information has already been described by other authors (Sepúlveda et al., 2007; Acevedo et al., 2016; Cárcamo et al., 2019); however, the Chilean distribution records were included in modelling projections (i.e., HSI and SDM) as explained later.

The taxonomic identification to differentiate the SES from the northern elephant seal (NES; *Mirounga angustirostris*) was based on morphological traits such as body size and coloration, the ratio of neck to head size, and the shape and size of the proboscis (i.e., the proboscis of the NES is larger, while the neck, skin, and chest are more developed in the SES male; Reeves et al., 1992; Laws, 1993; Jefferson et al., 2015; Hindell, 2018). The age category was based on external characteristics such as prominent elongated proboscis in adult males vs the lack of proboscis in juvenile males, and larger size in adult males vs smaller size in juvenile males (Sanvito et al., 2007; Jefferson et al., 2015; Hindell, 2018). For pinniped species identification, we followed identification guides and morphological information as documented by Reeves et al. (1992),

Laws (1993), Boyd et al. (1994), and Jefferson et al. (2015). Individual identification was assessed and corroborated by the senior authors (i.e., JJA, MR-L, ICA, PR, CFY-L, FE-V, and DP-R), who have concerted field expertise and training to identify pinniped species. Identification was also based on the assumption that the geographical distribution of NESs is limited to the Northern Hemisphere with little overlapping with the current distribution and recent extralimital records of SESs (i.e., a vagrant SES was both morphologically and genetically identified in La Ribera, near Los Cabos in Baja California Sur, México, in 2019 by Elorriaga-Verplancken et al., 2020; Table 1).

Moreover, we analyzed the sightings compiled with a Habitat Suitability Index (HSI), which is based on the species distribution and ecological niche to project the recent regional movements and plausible migration of SESs throughout the ETP (Reygondeau, 2019). We applied a Species Distribution Model (SDM) statistical approach (Reygondeau, 2019) to develop a current HSI, with HSI anomaly maps computed as the average distribution over the 1960 to 2010 period relative to the reference period 1970 to 2000. This methodology relies on the concept of ecological niche theory, first defined by Hutchinson (1957), stating that a species can occur in a multidimensional environment dictated by evolutionary processes shaping their physiological characteristics to compete for resources and survive. The SDM consists of quantifying the relationship between occurrence and environmental condition in which the species has been observed to delineate its ecological niche in a set of environmental dimensions (Reygondeau & Beaugrand, 2011). This methodology can identify the potential distribution of a species based on the quantified ecological niche and predict changes in distribution in agreement with environmental temporal and spatial variation (Reygondeau & Beaugrand, 2011; Reygondeau, 2019). The methodology for the HSI and SDM modelling projections is described below.

Occurrence Database

The database was populated with spatially informed occurrences data and an expert range map originated from the Ocean Biogeographic Information System (OBIS; www.iobis.org), the Intergovernmental Oceanographic Commission of UNESCO (IOC; ioc-unesco.org), the Global Biodiversity Information Facility (GBIF; www.gbif.org), Fishbase (www.fishbase.org), and the expert range map from the IUCN (www.iucnredlist.org/technical-documents/spatial-data). From the initial dataset, we removed records with spatial location as "Not Assigned" (NA) or null values, and replicated among databases (i.e., records with the same coordinates and sampling details).

Table 1. Documented observations and unpublished records of southern elephant seals (*Mirounga leonina*) in the Eastern Tropical Pacific coast, including México, El Salvador, Guatemala, Panamá, Colombia, Ecuador and its Galapagos Archipelago, and Perú, from 1989 to mid-2022

Records in chronological order	Date	Location	Geographical coordinates	Age/sex class	Source/reference
1	1989	Punta San Juan, Perú	15° 21' 59" S, 75° 11' 31" W	Juvenile male	Acevedo et al., 2016
2	1994	Punta San Juan, Perú	15° 21' 59" S, 75° 11' 31" W	Juvenile male	Acevedo et al., 2016
3	December 1998	Babahoyo River, Los Ríos, Ecuador	2° 05' S, 79° 48' W	Subadult male	Alava & Carvajal, 2005
4	February 2002	Estero Salado, Guayas, Ecuador	2° 10' S, 79° 56' W	Subadult male	Alava & Carvajal, 2005
5*	May 2004	Playa Tortuga Negra, Isabela Island, Galapagos, Ecuador	0° 14' 53" S, 91° 23' 14" W	Juvenile male	Vargas & Steinfurth, 2004; Lewis et al., 2006
6	May 2004	Playa Tortuga Negra, Isabela Island, Galapagos, Ecuador	0° 14' 53" S, 91° 23' 14" W	Subadult males	Vargas & Steinfurth, 2004
7	December 2007	Punta San Juan, Perú	15° 22' 03" S, 75° 11' 22" W	Juvenile male	Acevedo et al., 2016
8	August 2009	Punta San Juan, Perú	15° 22' 01" S, 75° 11' 33" W	Juvenile/ unidentified	Acevedo et al., 2016
9	February 2010	Punta San Juan, Perú	15° 22' 01" S, 75° 11' 33" W	Juvenile/ unidentified	Acevedo et al., 2016
10	April 2012	Punta San Juan, Perú	15° 21' 45" S, 75° 11' 30" W	Juvenile male	Acevedo et al., 2016
11	2013	Comuna de Pimocha, Los Ríos, Ecuador	1° 49' S, 79° 36' W	Subadult male	Rosero, 2019; Rosero & Alava, 2021
12	2015	Babahoyo River, Los Ríos, Ecuador	2° 05' S, 79° 48' W	Subadult male	Rosero, 2019; Rosero & Alava, 2021
13	March 2016	Makaha Beach, Lima, Peru	12° 07' 40" S, 77° 02' 14" W	Juvenile male	Stepchew & Yaipen- Llanos, 2019
14	December 2016	Taboga Island, Panama	08° 47' 40" N, 79° 33' 17" W	Subadult male	Redwood & Félix, 2018
15	October 2017	Milagro River, Guayas, Ecuador	2° 07' 34" S, 79° 40' 16" W	Adult male	Páez-Rosas et al., 2018
16	December 2017	Yaguachi River, Guayas, Ecuador	2° 5' 48" S, 79° 41' 41" W	Subadult male	Páez-Rosas et al., 2018
17	December 2017	Casma Port, Ancash, Perú	9° 27' 26" S, 78° 23' 09" W	Subadult male	Stepchew & Yaipen- Llanos, 2019
18	January 2018	Tonsupa, Esmeraldas, Ecuador	0° 53' 12" N, 79° 48' 46" W	Adult male	Páez-Rosas et al., 2018
19	January 2018	Piangüita and Magüipi, Valle del Cauca, Colombia	3° 50' N, 77° 11" W	Juvenile male	Avila et al., 2021
20	January 2018	Paracas, Ica, Perú	13° 54' 58" N, 76° 20' 18" W	Subadult male	Stepchew & Yaipen- Llanos, 2019
21**	February 2018	Atacames, Esmeraldas, Ecuador	0° 52' 00" N, 79° 21' 43" W	Adult male	Páez-Rosas et al., 2018
22***	February 2018	Guachalito, Chocó Pacific, Colombia	5° 36' N, 77° 27' W	Juvenile male	Avila et al., 2021
23	February 2018	Motobomba Beach, Arequipa, Perú	17° 07' 35" N, 71° 53' 28" W	Subadult male	Stepchew & Yaipen- Llanos, 2019
24	July 2019	La Chorerra, Los Ríos, Ecuador	1° 78' 00" S, 79° 53' 98" W	Subadult male	Rosero, 2019; Rosero & Alava, 2021

25	September 2019	La Ribera, Baja California Sur, México	23° 36' N, 109° 35' W	Subadult male	Elorriaga-Verplancken et al., 2020
26	November 2019	Puerto Hondo, Guayas, Ecuador	2° 11' 33" S, 80° 01' 26" W	Subadult male	Rosero, 2019; Rosero & Alava, 2021
27	November 2019	Puerto Villamil, Isabela Island, Galapagos, Ecuador	0° 57' 31" S, 90° 57' 59" W	Subadult male	This study
28	November 2019	San Pablo River, Los Ríos, Ecuador	1° 83' 93" S, 79° 44' 02" W	Subadult male	Rosero, 2019; Rosero & Alava, 2021
29	December 2019	Yurumanguí River, Valle del Cauca, Colombia	3° 26' N, 77° 27' W	Three subadult males	Avila et al., 2021
30	December 2019	Los Delfines Beach, Lima, Perú	12° 43' 45" S, 76° 37' 52" W	Adult male	C. Yaipen-Llanos, pers. obs., 2019
31	December 2019	Chocalla Beach, Lima, Perú	12° 44' 33" S, 76° 38' 08" W	Juvenile male	C. Yaipen-Llanos, pers. obs., 2019
32****	January 2020	Yurumanguí River, Valle del Cauca, Colombia	3° 26' N, 77° 27' W	Three subadult males	Avila et al., 2021
33	January 2020	Asia Island, Lima, Perú	12° 47' 22" S, 76° 37' 10" W	Subadult male	C. Yaipen-Llanos, pers. obs., 2020
34	January 2020	Puerto Villamil, Isabela Island, Galapagos, Ecuador	0° 57' 40" S, 90° 57' 18" W	Juvenile male	This study
35	May 2020	Punta San Juan, Perú	15° 22' 09" S, 75° 11' 28" W	Subadult male	Programa Punta San Juan, 2020†
36	July 2020	San Pancho/ San Francisco de Nayarit, México	21° 30' 55" N, 104° 55' 5" W	Subadult male	Grupo de Investigación de Mamíferos Marinos (GRIMMA Social Media), Cruz de Huanacastle, Nay, México, 2020††
37	January 2021	Guapi, Guapi River, Colombia	2° 27' N, 77° 44' W	Dead subadult male in moderate decomposition state	Avila et al., 2021; I. Avila, pers. comm., 2021
38*****	January 2021	Salvador (Los Cobanos and Barra de Santiago)	13° 31' 34.0" N, 89° 48' 11.6" W; 13° 42' 19.4" N, 90° 01' 41.3" W	Subadult male	López et al., 2022; this study
39*****	January 2021	Guatemala (Monterico Beach)	13° 53' 32.2" N, 90° 29' 09.9" W	Subadult male	This study
40	July 2022	Playa El Coyote, municipality of Mulege (Cortez Sea, Baja California, México)	26° 53' N, 112° 03' W	Subadult male	F. R. Elorriaga- Verplancken, pers. obs., 2022; this study†††

*One of the individuals observed was a young animal that had a blue tag in the flippers.

**This individual is likely to be the same adult male observed in Tonsupa (Esmeraldas, Ecuador) on 24 January 2018 (Páez-Rosas et al., 2018).

*** This animal is likely to be the same subadult observed in Pianguita and Magtipi in January 2018 (Avila et al., 2021).

**** These three subadult males were the same individuals observed in the Yurumanguí River on December 2019. The animals stayed in the area from December 2019 to January 2020 (Avila et al., 2021).

*****The subadult male was the same individual observed (photo-identified by two scars on the upper posterior-dorsal side of the back) in Salvador on 15-16 January 2021 and in Guatemala on 17-18 January 2021 in less than one week.

†Programa Punta San Juan: <https://www.facebook.com/watch/?v=164823964947104>

†† GRIMMA: <https://www.facebook.com/GRIMMA.ORG/posts/3147563538613155>

††† Cable News Network (CNN): <https://cnnespanol.cnn.com/video/elefante-marino-california-playa-cnn-primera>



Figure 2. Examples of original photos of subadult and juvenile male southern elephant seals recently observed on Isabela Island (Galapagos Archipelago), Colombia, and Perú from 2016 to 2020, respectively. Galapagos Islands: (a, b & c) a subadult male was first observed resting on the sandy-lava beach on 18 November 2019 and remained in the area for a few days according to local people from the nearby community (*Photo credits:* F. Gil and D. Lara); and (d & e) juvenile male (i.e., the penial or penile opening is clearly visible on the ventral region as pinpointed by the white arrow in [e]) observed resting on mangroves in January 2020 (*Photo credit:* D. Lara). Colombia: (f) juvenile observed in Guachalito Beach, Chocó, on 22 February 2018 (*Photo credit:* V. A. Quintero); and (g) subadult male found at the Yurumanguí River mouth, Valle del Cauca, on 29 December 2019 and 20 January 2020 (*Photo credit:* M. E. Arroyo). Perú: (h) juvenile male recorded for the first time on the central coast of Perú at Makaha Beach within Lima Bay on 11 March 2016; and (i) subadult male recorded for the first time at Casma port, Ancash, on 5 December 2017 (*Photo credit:* ORCA PERU's Stranding Network Archive). Note either the very short proboscis or absence of a proboscis, which is a typical age dimorphic trait found in subadult and juvenile males, respectively.

Then, each record was rasterized based on its geographical location on a 0.5° per 0.5° regular global grid extracted from the CMIP6 consortium (<https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6>). Similarly, the expert range was intersected using the *MATLAB* geospatial toolbox on the same global grid. This allows us to have the full extent of observed distribution of the species.

Abiotic Database

Sea surface temperature (SST), sea surface salinity, surface pH, surface oxygen concentration, and vertically integrated (0 to 100 m) net primary production (NPP) were selected as indicators of changes in ocean physics and biogeochemistry. These oceanographic variables were selected because changes in these variables are likely to have large impacts

on marine species through either direct effects on physiology or alterations of the trophodynamics of marine ecosystems (Asch et al., 2018; Reygondeau, 2019). For the specific case of the SES, the selection of these oceanographic variables is considered important as they readily influence the foraging ecology, ecological niche, and distribution of this species in the ocean (Bailleul et al., 2007; Biuw et al., 2010; Hofmeyr, 2015; Albouy et al., 2020).

Data on these variables were derived from the National Oceanic and Atmospheric Administration's (NOAA) Geophysical Fluid Dynamics Laboratory's Earth System Model (GFDL ESM2G; Dunne et al., 2012, 2013), the Institute Pierre Simon Laplace Earth System Model (IPSL-CM6A-LR), and the Max Plank Institute Earth System Model (MPI ESM1 HR). These climate models were selected since they were developed independently, include all ocean biogeochemical variables of interest, and represent the full spectrum of equilibrium climate sensitivities among models included in the latest Intergovernmental Panel on Climate Change (IPCC) assessment report (Andrews et al., 2012). The Earth System Model has a nominal 1° latitudinal/longitudinal ocean resolution and 63 depth layers. This earth system model uses the TOPAZ2.0 biogeochemical submodel to examine dynamical changes in pH, O₂, and NPP. The IPSL model has a latitudinal/longitudinal ocean resolution that varies between 0.5 to 2° and contains 31 depth layers. It uses the PISCES submodel to track the dynamics of the biogeochemical variables reported upon herein. The MPI model has a latitudinal/longitudinal ocean resolution of 0.4° with 40 depth layers. Ocean biogeochemistry is tracked in the MPI model using the HAMOCC5.2 submodel. To account for variability between different climate models, our analysis averaged data from these three models together to create a composite projection of future changes.

Data from these models were extracted for three time periods: a baseline period (1980 to 2000), a mid-century period (2040 to 2060), and an end-of-century period (2080 to 2100). We extracted data for 20-year periods to minimize the likelihood that a climate change signal would be masked by naturally occurring interannual or decadal climate variability (e.g., ENSO, Pacific Decadal Oscillation).

Species Distribution Model

We used the gridded occurrence and environmental data in a multi-model approach following established methodologies to best approximate the environmental niche of each species using four SDM approaches: Bioclim and Boosted Regression Trees from the 'biomod2' R package®, Maxent®, and Non-Parametric Probabilistic Ecological Niches. We used

the average of multi-model environmental response to quantify the suitability of a given geographical cell for each species (i.e., HSI). Gridded occurrences were used as a training set for the modelling. Projected species distribution is computed for all geographical cells in the ocean, but a native range was identified using the expert range map gathered. SDM was evaluated using a cross validation (30% of the training set), and only models with an Area Under the Curve index of 0.5 were considered for model averaging between spatially unfiltered model output and the expert range map. Projected distribution is then applied with validated ensemble models and represented in Figures 3 and 4.

According to the dataset (Table 1), the first SES sighting in the ETP occurred in Punta San Juan in Perú in 1989 (Acevedo et al., 2016), while the first sighting along the continental coast of Ecuador was in the Gulf of Guayaquil in 1998 (Alava & Carvajal, 2005). An increasing number of opportunistic SES sightings have occurred in Ecuador–Galapagos ($n = 15$) and Perú ($n = 14$) over the last three decades (1989 to 2020), increasing the frequency of sightings from 2015 to 2020 with five sightings in each country (Páez-Rosas et al., 2018; Stepchew & Yaipen-Llanos, 2019; Rosero & Alava, 2021). The observations recorded from 2017 to early 2020 accounted for 50 and 60% of the total sightings reported for Perú and Ecuador, respectively. In comparison, a smaller number have been recorded in Panamá ($n = 1$ in 2016), Colombia ($n = 5$ between 2018 and 2021; Figure 2e & f), México ($n = 3$ in 2019, 2020, 2022), and in Salvador and Guatemala ($n = 2$; same animal recorded in these Central American neighbor countries in mid-January 2021) over the 2016 to 2022 period (Redwood & Félix, 2018; Elorriaga-Verplancken et al., 2020; Avila et al., 2021; Table 1).

In the Galapagos Archipelago, following a period of 15 years when the first record of a SES was observed in Playa Tortuga Negra on Isabela Island (Vargas & Steinfurth, 2004; Table 1), a couple of SES individuals ($n = 2$) were sighted on the coast of Isabela Island on November 2019 and January 2020 (Figure 2). On 18 November 2019, a subadult male SES (Figure 2a-c), with an estimated length of > 3 to 4 m, was sighted resting at an islet near Puerto Villamil (0° 57' 31" S, 90° 57' 59" W) on Isabela Island (Figure 1). Subsequently, rangers from the Galapagos National Park (GNP) monitored the animal, which exhibited apparently healthy body conditions and an absence of injuries or trauma (Figures 2a-c). Remarkably, about 2 months later, from 2 to 10 January 2020, a juvenile male SES was observed in the wetland complex "El Estero" (0° 57' 40" S, 90° 57' 18" W), close to Puerto Villamil (Figure 1). This animal was monitored by GNP rangers, who estimated the animal at a length of ~2 to 2.5 m (Figure 2d & e).

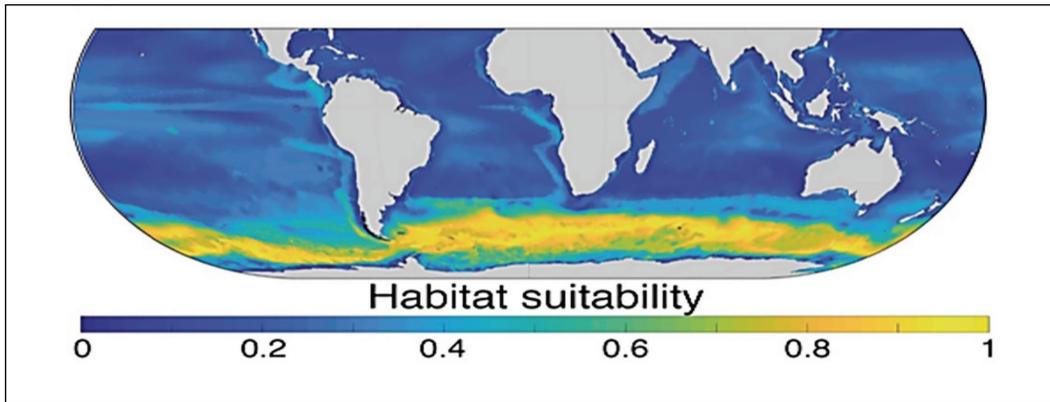


Figure 3. Projection of the baseline Habitat Suitability Index (HSI) for the current distribution of the southern elephant seal. In the HSI scale bar, a value of 0 (dark blue color) indicates lack of habitat suitability for the species to exist, while a HSI of 0.4 to 0.6 (light blue to blue-green) and 0.8 to 1 (orange-yellow) stands for 40 to 60% and 80 to 100% habitat suitability available for this pinniped species to occur, respectively.

Similar to the subadult male, this animal exhibited healthy body conditions and no signs of emaciation, stress, or presence of injuries.

Twenty percent (3/15) of the total number of sightings ($n = 15$) in Ecuador's main coast ($n = 11$) and the Galapagos Archipelago ($n = 4$) coincided with the timing of the SES breeding season in the Southern Hemisphere. The dispersal capacity and emigration of some subadults and of older adult males reaching reproductive senescence towards other marine regions may well be triggered by competition with territorial adult males (alpha males) during the breeding season, or it may be due to a lack of haul-out sites for resting and food availability in foraging grounds as some populations reach their carrying capacity (McMahon et al., 2005).

Based on the first Galapagos Archipelago record, a light blue tag (Jumbo Rototag) was observed (Vargas & Steinfurth, 2004), resembling the color and model of tags used for tagging SESs from the Peninsula Valdés population (Lewis et al., 2006). Although NESs at Guadalupe Island, México, were also tagged with identical blue tags during that time period, phenotypic features of the juvenile sighted in 2004 on Isabela Island, Galapagos, were unmatched in age to the tagging schedule of NESs in Guadalupe Island in 2003 (Lewis et al., 2006; Acevedo et al., 2016). This observation may well serve as an indication that at least one of the SESs observed in the Galapagos Islands originated from one of the SES populations found within the species' regular distribution range in the Atlantic.

The majority of sightings of the SES along the ETP were recorded after, or at the end of, its normal reproduction period (September to mid-November) and coincided with the moulting season on land (mostly from December to February), transitioning

within the timing of ocean life stages (i.e., post-moulting and post-reproduction) of this species (Campagna et al., 1993; Le Boeuf & Laws, 1994; Acevedo et al., 2016; Hindell, 2018). Since field observations of individuals have been recorded opportunistically, the increase in SES sightings in the ETP did not follow an increased observation effort in the field as systematic monitoring periods in quest of this species were not deployed in the study regions. Thus, the recent occurrence of SESs across the ETP warrants an investigation of the intrinsic and extrinsic ecological factors modulating the species' populations in tandem with the changing ocean environment and climatic conditions (e.g., Freund et al., 2019).

The increase in some of the SES populations in circumpolar regions cannot be ruled out as a density-dependent factor influencing the extralimital dispersion of the species, which shows a high capacity in this regard under normal conditions—that is, absence of ENSO events (Hindell, 2018; Elorriaga-Verplancken et al., 2020)—especially for immature individuals (i.e., subadult animals). These age classes do not seem to choose hauling sites as selectively as older and more experienced animals (Mulaudzi et al., 2008). In this context, the continental edge of the southern ETP is narrow and relatively closer to the coast, which favors juveniles and subadults to follow this edge and its productive waters, dispersing towards distant latitudes further north along the ETP coast in South America (i.e., Chile, Perú, and Ecuador; Acevedo et al., 2016). Based on the most recent assessment of the IUCN's *Red List of Threatened Species*, the global abundance of the SES is estimated to be stable as it has increased over the past three generations or 28.5 years (i.e., generation length: 9.5 y; Pacifici

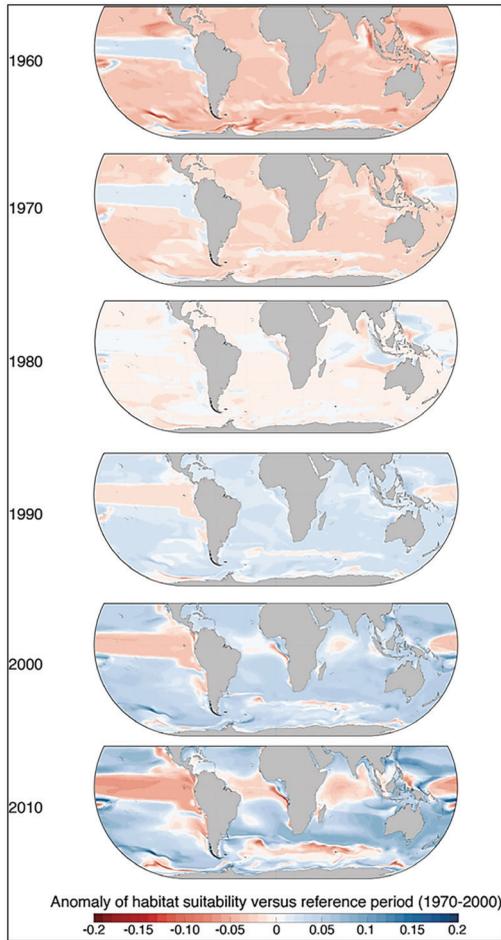


Figure 4. Projections of the HSI anomalies for the southern elephant seal relative to the 1970 to 2000 period and computed for each decade from 1960 to 2010 to evaluate if the HSI increases or decreases with time. The HSI scale bar shows negative anomalies in red colors and positive anomalies in blue colors.

et al., 2013) from 1982 to 2009 (Hofmeyr, 2015). Recovery has been associated with the positive growth rates of the Atlantic and Peninsula Valdés populations (Lewis et al., 1998; Galimberti et al., 2001; Hofmeyr, 2015). As it stands, the SES population serving as a potential source of all migrant and vagrant individuals observed in the ETP is currently unknown thus far.

The projection of the baseline HSI for actual SES distribution is presented in Figure 3 along with the projections of the HSI anomalies of SES distribution computed for each decade (from 1960 to 2010) relative to the reference period (Figure 4). The HSI anomaly maps of SES distribution illustrate that

the species' distributional pattern increased from its known distribution ranges further north to tropical and subtropical latitudes in the ETP, mainly in coastal waters. This is particularly apparent towards subequatorial and equatorial latitudes throughout the Pacific coasts of South America upward to the Mexican Pacific and Gulf of California (Figures 3 & 4). The projected species' distribution range shifts into these new regions are corroborated by recent field observations of this species in Perú, Ecuador, Colombia, Central America (Panamá, Guatemala, and Salvador), and México as aforementioned (Table 1; Figure 1).

The past and present HSI-modelling projections (Figure 4) suggest the ocean-coastal environment throughout the ETP would be a plausible biological corridor suitable for potential dispersion of SESs not only during the non-breeding season or oceanic life stage of this species but likely during hunting as already shown with bluefin tuna (*Thunnus thynnus*) in the southern Atlantic (Fromentin et al., 2014). As some SES populations continue to increase, the potential for novel foraging grounds in this emerging environmental niche can also increase as indicated by the HSI (Figures 3 & 4). The oceanographic environment, particularly the temperature of the water masses, may determine the successful foraging zones of SESs in the ETP (Bailleul et al., 2007; Biuw et al., 2010; McIntyre et al., 2011). While, on a large scale, SESs feed in frontal zones to obtain highly abundant preys, at a finer scale, within the frontal zones, the foraging areas show specific gradients of temperature and bathymetry conditions that determine the distribution of their prey (Bailleul et al., 2007).

Climate change, mainly driven by ocean warming, produces changes in the Southern Ocean and Antarctic regions' climate that may have influenced migration patterns, prey availability, population dynamics, and phenology in marine mammals, including the SES (McMahon & Burton, 2005; Pistorius et al., 2005, 2008; McIntyre et al., 2011; Hindell et al., 2020). These marine ecosystems have been changing in the last 30 years in response to large-scale changes in the physical environment and circulation, including increasing ocean temperatures and changes in the extent and seasonality of sea-ice mass (Croxall et al., 1992; Constable et al., 2014; Hindell et al., 2020; Rogers et al., 2020). However, the degree of impact of climate change varies throughout the Southern Ocean as it is particularly significant and accelerating faster in the western Antarctic Peninsula and around the sub-Antarctic islands (Elliott & Simmonds, 2007; Hindell et al., 2020; Rogers et al., 2020). These changes are propagated and are driving shifts throughout all trophic levels of Antarctic marine food webs (Rogers et al., 2020).

The development of the SES's global distribution pattern along with the HSI supports the projection of different temporal occurrence and distribution scenarios for the species, mainly in a climate change and oceanographic context (Figure 4). The analysis of HSI anomaly scenarios allows us to assess whether this species is redistributing or partially migrating into new habitats and areas (i.e., gain and loss of areas) in response to climate change. This is of paramount importance as climate change is altering marine food webs towards restructuring or eliminating lower trophic-level organisms and biomass in the oceans (Adame et al., 2020). This plausible redistribution can lead to regionally reduced food resources for migratory and highly mobile predators such as fish, large whales, and pinnipeds in their regular foraging habitats, triggering dispersion to other previously uninhabited and either suitable or sub-suitable habitats to search for food (Elliott & Simmonds, 2007; Simmonds & Elliott, 2009; Constable et al., 2014; Ramp et al., 2015).

At the global level, the intrinsic sensibility and exposure (i.e., vulnerability) of marine mammals to global warming is scarcely known (Albouy et al., 2020). For instance, the NES is one of the most vulnerable marine mammals under a worst-case scenario of climate change (i.e., Representative Concentration Pathway [RCP] 8.5 = high greenhouse emissions) within its geographical range (Albouy et al., 2020), with the potential to cause abundance changes along its whole distribution (García-Aguilar et al., 2018). Conversely, our understanding of mobile SES sensitivity and vulnerability to the accumulative impacts of climate change (including the increasing frequency of El Niño in recent decades; Freund et al., 2019), changing food supply, and other environmental risks is limited.

In response to changing environmental conditions, marine top predators from the Southern Ocean and Antarctic ecosystems feed in regions where physical climatic forcing and specific oceanographic features such as increasing SST and changes in primary production and ice mass coverage are responsible for increased availability of prey. Among these predators are pinnipeds (e.g., SESs, NESSs, crabeater seals [*Lobodon carcinophaga*], and weddell seals [*Leptonychotes weddelli*]) and baleen whales (e.g., humpback whales [*Megaptera novaeangliae*]) (Costa et al., 2010; Avila et al., 2020). While top marine predator species in the Southern Ocean and Antarctic have adapted to extreme living conditions in the face of changing climate, the expected changes for marine mammals are mainly associated with their capabilities of adapting to warmer seasonal shifts and foraging behavior plasticity in moving

to alternative locations for prey (Simmonds & Elliott, 2009; McIntyre et al., 2011; Schuman et al., 2013; Constable et al., 2014; Lescroël et al., 2014; Ramp et al., 2015). This ecophysiological adjustment obviously involves energetic costs for more prolonged or complex foraging trips to accommodate the impacts of climate variability and environmental forcing.

For example, previous observations in the western Antarctic Peninsula show sightings of Weddell seals have declined, and sightings of Antarctic fur seals (*Arctocephalus gazella*) and SESs have increased as a response to the effects of environmental change (Siniff et al., 2008). However, the Antarctic fur seal populations in South Georgia in the Atlantic sector currently show a strong negative response to increased ocean warming (Forcada et al., 2005, 2008). Comparably, SESs invest most of their time and energy sea diving and feeding in close association with frontal systems, ocean currents, and shifting marginal ice-edge zones (Hofmeyr, 2015). They are sensitive to fine-scale variations in bathymetry and oceanographic variables such as sea-ice concentration and sea temperature profiles in foraging grounds (Bailleul et al., 2007; Biuw et al., 2010; McIntyre et al., 2011). Thus, current and future changes in these regions are expected to alter either the foraging habitats of pinniped species or their tolerance and adaptation to abiotic conditions (Constable et al., 2014).

Similarly, current shifts in the migration timing of humpback whales from Antarctic feeding grounds to breeding grounds in the ETP (waters off Colombia) are in response to changes in sea-ice coverage during the austral fall (Avila et al., 2020). The sea-ice pack mass changes due to ocean warming are influencing food availability for humpback whales in Antarctica along with their increasing population size over the past decades, which may have promoted the phenological changes in this highly migratory cetacean species; however, it has not been possible to determine which factor is more important in relation to this trend (Avila et al., 2020).

As research efforts continue to unravel the undetermined impacts of global climate change on the largest pinniped species, we further hypothesize that the presence of SESs outside their regular feeding or reproduction grounds would be associated with the possible extralimital dispersion and partial emigration of individuals from some increasing populations. Changing climate conditions in the Southern Ocean and Antarctic ecosystems may well be impacting the distribution of prey and environmental niche of this species as shown by the HSI assessment. A call out to develop appropriate management response and conservation actions

for roaming pinnipeds washing ashore (Rosero & Alava, 2021), and to increase monitoring and field research on the ongoing dispersion and extralimital distribution of this species towards the tropical/subtropical zones (i.e., Tropic of Cancer in the Northern Hemisphere and Tropic of Capricorn in the Southern Hemisphere, as well as subtropics) and north regions at higher latitudes is strongly advocated.

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