



## Research

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# Decadal changes in blood $\delta^{13}\text{C}$ values, at-sea distribution, and weaning mass of southern elephant seals from Kerguelen Islands

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Changes in the foraging environment and at-sea distribution of southern elephant seals from Kerguelen Islands were investigated over a decade (2004–2018) using tracking, weaning mass, and blood  $\delta^{13}\text{C}$  values. Females showed either a sub-Antarctic or an Antarctic foraging strategy, and no significant shift in their at-sea distribution was detected between 2004 and 2017. The proportion of females foraging in sub-Antarctic versus Antarctic habitats did not change over the 2006–2018 period. Pup weaning mass varied according to the foraging habitat of their mothers. The weaning mass of sub-Antarctic foraging mothers' pups decreased by 11.7 kg over the study period, but they were on average 5.8 kg heavier than pups from Antarctic foraging mothers. Pup blood  $\delta^{13}\text{C}$  values decreased by 1.1‰ over the study period regardless of their sex and the presumed foraging habitat of their mothers. Together, these results suggest an ecological change is occurring within the Indian sector of the Southern Ocean with possible consequences on the foraging performance of southern elephant seals. We hypothesize that this shift in  $\delta^{13}\text{C}$  is related to a change in primary production and/or in the composition of phytoplankton communities, but this requires further multidisciplinary investigations.

## 1. Introduction

Global climate change triggers deep modifications in a broad range of terrestrial and marine ecosystems, and across a great variety of species [1,2]. Of particular concern are polar environments as climate change models predict that ocean warming should be especially intense at high latitudes with some likely large-scale consequences on the related marine ecosystems [3–5]. In the Southern Ocean (water masses south of the Subtropical Front), these predictions are supported by an increasing number of empirical observations, related to the melting of coastal glaciers [6,7], a reinforced wind regime modifying nutrient vertical advection and therefore influencing primary production [3,8], and an increase in surface chlorophyll-a biomass [9]. Quantifying and integrating the behaviour of top and wide-ranging predators is an especially informative way to monitor ecosystem changes. Due to their upper trophic

position, their vital rates integrate spatial and temporal variation of the underlying trophic levels—from phytoplankton to their prey that are generally difficult to monitor—across broad ocean basins [10]. Consequently, these animals can act as environmental sentinels by providing critical information about ongoing changes in components of the ecosystem that cannot otherwise be measured [10–12] and this is particularly true for the remote and poorly sampled Southern Ocean [13–16].

Among such upper predators, southern elephant seals (*Mirounga leonina*, hereafter SES) have been extensively studied. Adult females haul-out twice a year for approximately one month each time [17], to breed during the austral spring (September–October), and again to moult during summer (December–January). They can be monitored and sampled during these two terrestrial phases to quantify their at-sea performance by measuring mass and equipped with instruments to study their at-sea behaviour including distribution, foraging behaviour, and success. Because of their large body mass and abundant populations, SES are important consumers of resources in the Southern Ocean [18]. Therefore, variations in their vital rates and demography are likely to reflect large-scale changes in food availability. In that context, the Kerguelen, Crozet, and Marion Islands populations from the Indian sector of the Southern Ocean are now recovering following a marked decrease in numbers between the 1960s and early 1990s [19–22], suggesting that foraging conditions have been improving over the last decades. On the other hand, the population on Macquarie Island from the Pacific sector of the Southern Ocean is still decreasing, presumably because of a lack of available resources [10,19]. The status of the largest population of South Georgia is currently unknown [10]. Poor foraging efficiency by a female results in a decrease in pup weaning mass and first-year survival [23,24], ultimately leading to lower recruitment into the reproductive population [25,26]. Therefore, monitoring simple parameters such as pup weaning mass provides information on the foraging performance of their mother [25,27].

Biotelemetry tags provide critical information for monitoring animals' at-sea movements and identifying foraging habitats [11,12,28], but are generally deployed on a small number of individuals due to their cost. They enable the detection of possible changes over time in the at-sea distribution of marine predators. Complementary to biotelemetry, stable isotope analysis from individual tissues provide an indication of diet/trophic levels ( $\delta^{15}\text{N}$  [29,30]) and foraging habitat ( $\delta^{13}\text{C}$ ), and can be easily conducted on a large number of individuals. A Southern Ocean latitudinal gradient in  $\delta^{13}\text{C}$  values [29,31] enables the delineation of broad-scale latitudinal foraging habitats of female SES according to their blood  $\delta^{13}\text{C}$  values [32,33]. Long-term monitoring of the  $\delta^{13}\text{C}$  values can be a powerful way to quantify longitudinal foraging distribution and/or environmental conditions. If changes in  $\delta^{13}\text{C}$  values take place over time without a change in where individuals are distributed at-sea, this suggests that physical, biogeochemical, and/or ecological changes are taking place at the ecosystem scale.

Earlier studies revealed temporal variation in the  $\delta^{13}\text{C}$  values of metabolically inert tissues in a range of Arctic marine mammals including Steller sea lions [34], bowhead whales [35], northern fur seals [36], beluga whales, and killer whales [37]. The lack of  $\delta^{13}\text{C}$  baseline information and animal movement data prevented these authors from disentangling the driving mechanisms of trends in  $\delta^{13}\text{C}$  values. However, they suggested that  $\delta^{13}\text{C}$  variations were linked to changes in

primary productivity, combined with the release of anthropogenic  $\text{CO}_2$  [38,39]. Isotopically light  $\text{CO}_2$  released during anthropogenic fossil fuel burning causes a dilution of atmospheric  $^{13}\text{C}/^{12}\text{C}$  and ultimately decreases marine  $\delta^{13}\text{C}$  values. This process is referred to as the 'Suess effect'.

As adult SES display fidelity to their foraging sites [40–43], SES are likely to be affected by ongoing environmental changes at their foraging grounds propagated through the food web. This will be reflected in population-level demographic responses to environmental variations [23,44,45]. As part of a long-term study, the Kerguelen SES population has been censused annually since the late 1950s, and recent analyses reveal a 20% increase in the size of the Kerguelen SES population (J Laborie 2019, *et al.*, unpublished data). At-sea movement data are available from satellite tracking studies since 2004 as well as the blood  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of tracked individuals. In addition, weaning mass of pups and their  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values have been monitored every year since 2006. Because pups exclusively feed on their mother's milk until weaning, pup blood isotopic values indicate the isotopic values of their mothers [46]. The concomitant study of foraging performance indices (such as pup weaning mass) and isotopic values may highlight regional differences in foraging performances with potential demographic consequences.

The first and main objective of this study was to investigate if a change in seal  $\delta^{13}\text{C}$  values took place over the study period and whether this variation reflects a change in the at-sea foraging distribution of female SES or changing  $\delta^{13}\text{C}$  isoscapes in the Indian sector of the Southern Ocean. We assessed whether this shift in  $\delta^{13}\text{C}$  values reflects environmental changes such as the Suess effect and/or other broad-scale ecological mechanisms [38]. The second objective of this study was to determine if pup weaning mass varied according to the estimated foraging habitat of their mothers and over the study period. Such changes could be used as an index of female breeding success and have implications for population size and growth at Kerguelen Islands. Finally, we discuss the observed changes in the Kerguelen SES population over the last 15 years and the underlying potential environmental drivers of such changes.

## 2. Material and methods

Fieldwork took place on Kerguelen Islands from 2004 to 2018, as part of long-term scientific programs led by CEBC. All animals used were cared for in accordance with the French Polar Institute Paul Emile Victor (IPEV) ethics committee guidelines. Data processing and statistical analyses were performed under the R v. 3.6.1 software [47], and the *ggplot2* package was used for graphical representations [48].

### (a) Satellite telemetry

From 2004 to 2017, 154 post-moult adult female elephant seals were captured and anaesthetized with an intravenous injection of Zoletil100 (1:1 combination of tiletamine and zolazepam; [49,50]). They were equipped with a glued head-mounted satellite-relayed-data-logger (CTD-SRDL,  $10.5 \times 7 \times 4$  cm, Sea Mammal Research Unit, St Andrews, UK). Individual seals were measured from snout to tail and tagged on land during the breeding (austral spring) or moulting period (austral summer). Seals carrying such devices were not affected in either the short-term (growth rates) or long-term (survival) [51]. Seals at-sea movements were determined using the ARGOS satellite tracking system (<http://www.argos-system.org>).

The raw tracking data were filtered by first removing class Z locations (the lowest location quality index provided by the ARGOS service). Then the McConnell *et al.* [18] speed filter was applied to remove successive locations implying an unrealistic speed (20 km h<sup>-1</sup>; [52]). The resulting tracks were mapped to identify the main foraging habitats and used to investigate changes in mean latitudinal distribution. A mixture model set up on the density of satellite locations with respect to latitude using the Rmixmod R package [53] was used to determine the main latitudinal foraging habitats. Only locations for the months of May, June, and July were retained to calculate the trip's mean latitude of each individual and allow for inter-annual comparisons. Those three months were chosen as they are included in the core foraging area of SES during their post-moult trip, and are the best correlated to the blood  $\delta^{13}\text{C}$  isotopic values of SES sampled during the breeding period [32]. Linear models of the mean latitude of each individual trip (for May, June, and July) according to the year were performed for each foraging habitat.

### (b) Pup weaning mass

Each year from 2006 to 2018, between 57 and 275 pups were tagged at birth with a flipper-tag set in the interdigital space of the hind-flipper. This tag allowed pup identification for recapture at weaning approximately three weeks later, when it moved out of the harem. These known-age pups were weighed to the nearest 0.1 kg before removing the flipper-tags. Pup data collected in 2017 were excluded from the analyses to remove spatial variability because they were sampled at another sub-colony. Females from that sub-colony foraged in a different location compared to females from the east Courbet sub-colony (C Guinet 2019, unpublished data).

### (c) Stable isotope analyses

Blood samples were taken from the extradural intervertebral venous sinus for all elephant seals regardless of their age and sex. All pups were sampled at weaning, whereas adult females were sampled when satellite tags were deployed and recovered. Whole blood samples (hereafter blood) were stored in 70% ethanol until laboratory analyses. Females were considered sexually mature if they were longer than 1.89 m (i.e. the length of the smallest female observed with a pup within our dataset). Female seals of unknown length or those smaller than 1.89 m were excluded from stable isotope analyses.

Prior to isotopic analyses, blood samples were stood in a fume hood to evaporate ethanol, and then freeze-dried for 48 h. The resulting blood powder was weighed (0.3–0.5 mg) into tin cups before combustion in an elemental analyser (Flash 2000, Thermo Scientific, Milan, Italy) coupled to a continuous flow mass spectrometer (ConFlo IV, Thermo Scientific, Bremen, Germany). Isotopic analyses were conducted in LIENSs Stable Isotope Facility (La Rochelle, France). Carbon to nitrogen (C:N) mass ratios were carefully checked because lipids are depleted in <sup>13</sup>C relative to proteins and carbohydrates [54]. When C:N ratios were above 3.7, lipids were extracted from blood using cyclohexane and new stable isotope analyses were conducted. Stable isotope values are presented in the usual  $\delta$  notation with units expressed as parts per thousand (‰) relative to Vienna Pee Dee Belemnite and atmospheric N<sub>2</sub> for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ , respectively. Precisions for isotopic measurement were 0.15‰ for  $\delta^{13}\text{C}$ , and 0.20‰ for  $\delta^{15}\text{N}$ , respectively. In addition to C:N mass ratios, replicate measurements of laboratory standards (USGS-61 and USGS-62) were checked to ensure that inter-annual comparisons of stable isotopes measurements would not be skewed.

Stable isotope values were compared inter-annually for monitored pups and tagged adults in order to detect any trends in foraging habits over the study period. Proportions of individuals using either the Antarctic or sub-Antarctic habitats were studied

using mixture models, which are typically used to determine hidden groups of individuals inside a population of some known parameters. SES blood  $\delta^{13}\text{C}$  values follow a bimodal distribution [33]. We thus assumed that a  $\delta^{13}\text{C}$  bimodal distribution reflects the two foraging strategies of female SES (i.e. lower blood  $\delta^{13}\text{C}$  values in the Antarctic zone versus higher  $\delta^{13}\text{C}$  values in the sub-Antarctic zone). Mixture models were run for  $\delta^{13}\text{C}$  values of blood-sampled pups, taking into account the effect of year and a potential trend in  $\delta^{13}\text{C}$  to avoid any bias in the formation of groups through time. We modelled  $\delta^{13}\text{C}$  as a mixture of two Gaussian distributions:

$$\delta^{13}\text{C} = p(\delta^{13}\text{C}_{\text{sub-Antarctic}} + \varepsilon_{\text{sub-Antarctic}}) + (1 - p)(\delta^{13}\text{C}_{\text{Antarctic}} + \varepsilon_{\text{Antarctic}}),$$

where  $p$  is the probability of seals having foraged in the sub-Antarctic zone,  $\varepsilon$  the residuals, and  $\delta^{13}\text{C}_{\text{sub-Antarctic}} > \delta^{13}\text{C}_{\text{Antarctic}}$ . Models were fitted in a Bayesian framework (see electronic supplementary material S3 for model specification) with the R package rstan [55], which runs Stan software [56] through R. Unless specified, blood isotopic values were raw values of pups. Because pup stable isotope values reflect those of their mothers ([46], updated in electronic supplementary material S2), the two groups of pups assigned according to their  $\delta^{13}\text{C}$  value enabled a comparison of weaning mass according to the estimated foraging habitat targeted by their mother (i.e. sub-Antarctic versus Antarctic). Those two habitats relate to broad-scale foraging zones, and do not correspond to the water masses the SES passed through.

## 3. Results

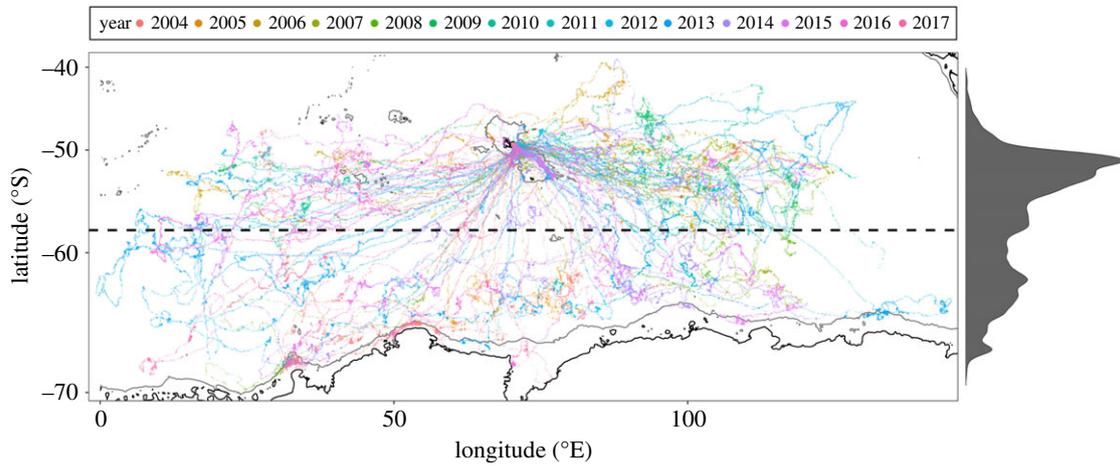
### (a) Satellite telemetry to investigate at-sea distribution

From 2004 to 2017, 64 complete post-moult foraging trips (approx. 180 days) were collected from the 154 equipped adult females. Most females travelled southeast of Kerguelen Islands (figure 1). A mixture model of the number of latitudinal satellite locations suggested that a threshold at 58°S could be used to split individuals according to their foraging habitat (sub-Antarctic north of 58°S, and Antarctic south of 58°S; electronic supplementary material S1, figure S1). No significant shifts in the latitudinal distribution of female SES was found for any of the foraging habitats (lm: mean latitude<sub>[May–July], sub-Antarctic habitat</sub> =  $-0.21 \times \text{year} + 363.83$ ,  $n = 38$ ,  $p\text{-value} = 0.12$ ,  $R^2 = 0.07$ ; lm: mean latitude<sub>[May–July], Antarctic habitat</sub> =  $0.10 \times \text{year} - 271.26$ ,  $n = 22$ ,  $p\text{-value} = 0.37$ ,  $R^2 = 0.04$ ).

### (b) Insights into the foraging habitat through stable isotopes

Linear models were established for adult females that were blood-sampled during tag deployment or on retrieval (during either the moult,  $n = 244$  or breeding period,  $n = 153$ ). The blood  $\delta^{13}\text{C}$  values of adult females decreased significantly with time ( $\delta^{13}\text{C} = -0.11 \times \text{year} + 206$ ;  $n = 396$ ,  $p\text{-value} < 0.001$ ,  $R^2 = 0.12$ ), highlighting a mean overall decrease of  $-1.4\text{‰}$  over the 2004–2017 period.

A multiple linear model on females which were fitted with satellite tags and blood-sampled on their return ashore following their post-moulting trip ( $\delta^{13}\text{C} = 0.13 \times \text{mean latitude} - 0.09 \times \text{year} + 181.10$ ;  $n = 60$ ,  $p\text{-value} < 0.001$ ,  $R^2 = 0.59$ ) revealed a significant effect of year (negative effect) and mean latitude of trips from May to July (positive effect) on the blood  $\delta^{13}\text{C}$  values of female SES. As expected, the  $\delta^{13}\text{C}$  value of a female was also strongly correlated to the mean



**Figure 1.** Satellite tracking of 64 complete post-moult foraging trips of adult female southern elephant seals from Kerguelen Islands. Trip colours represent the year of tracking. Black lines indicate the coastline of adjacent landmasses (Antarctica, Kerguelen Islands, and Australia), and grey lines the 1000 m isobath. The marginal plot depicts the density of satellite locations, and the dashed black line the  $-58^{\circ}\text{S}$  latitudinal threshold. (Online version in colour.)

**Table 1.** Blood  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of southern elephant seal pups from 2006 to 2018 at Kerguelen Islands. Female-predicted values after [46] are displayed in the last row.

	year	n	blood $\delta^{13}\text{C}$ (‰)			blood $\delta^{15}\text{N}$ (‰)		
			min	mean $\pm$ s.d.	max	min	mean $\pm$ s.d.	max
pup raw values	2006	214	-23.4	$-21.2 \pm 0.9$	-18.9	10.3	$11.3 \pm 0.4$	12.6
	2007	57	-23.6	$-20.9 \pm 0.9$	-19.0	10.4	$11.1 \pm 0.4$	12.3
	2008	231	-23.0	$-20.9 \pm 0.8$	-19.1	10.2	$11.5 \pm 0.5$	12.8
	2009	275	-23.9	$-21.3 \pm 0.9$	-18.8	10.1	$11.4 \pm 0.4$	12.7
	2010	204	-23.2	$-21.1 \pm 0.9$	-19.2	10.5	$11.4 \pm 0.4$	12.8
	2011	110	-23.7	$-21.5 \pm 0.8$	-19.0	10.7	$11.4 \pm 0.3$	12.6
	2012	96	-23.4	$-21.7 \pm 0.8$	-19.9	10.8	$11.5 \pm 0.4$	12.7
	2013	85	-23.1	$-21.5 \pm 0.7$	-19.9	11.0	$11.5 \pm 0.3$	12.6
	2014	112	-23.6	$-21.6 \pm 0.8$	-20.0	10.8	$11.5 \pm 0.3$	12.6
	2015	123	-23.3	$-21.7 \pm 0.8$	-19.8	9.4	$11.3 \pm 0.5$	12.8
	2016	77	-23.3	$-21.8 \pm 0.7$	-20.0	9.7	$11.3 \pm 0.4$	12.0
	2018	100	-23.9	$-22.1 \pm 0.9$	-20.2	10.5	$11.2 \pm 0.3$	12.2
	2006–2018	1684	-23.9	$-21.4 \pm 0.9$	-18.8	9.4	$11.4 \pm 0.4$	12.8
female estimated values	2006–2018	1684	-24.4	$-21.8 \pm 0.9$	-19.2	9.2	$10.2 \pm 0.2$	10.9

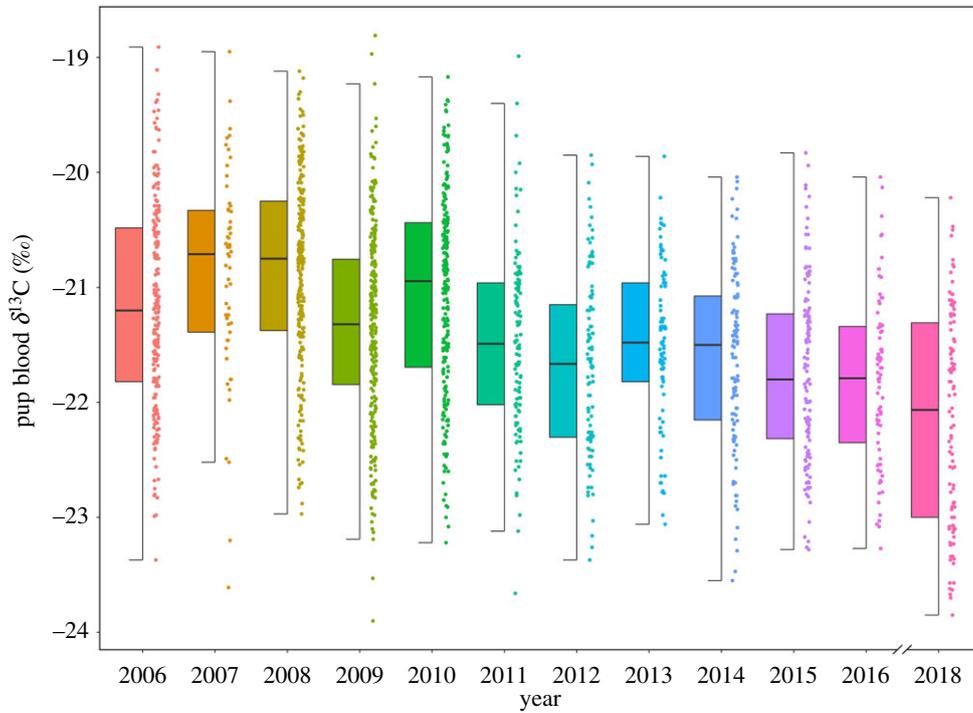
latitude of its trip for the months of May, June, and July ( $\rho = 0.69$ ,  $p$ -value  $< 0.0001$ , Spearman's rank correlation). Importantly, blood  $\delta^{13}\text{C}$  values decreased over the study period for a given latitude visited by female SES.

Pup blood  $\delta^{13}\text{C}$  values range from  $-18.8\text{‰}$  to  $-23.9\text{‰}$ , with annual means between  $-20.9\text{‰}$  and  $-22.1\text{‰}$ . Pup blood  $\delta^{15}\text{N}$  values are less scattered, ranging from  $9.4\text{‰}$  to  $12.8\text{‰}$  with average annual means between  $11.1\text{‰}$  and  $11.5\text{‰}$  (table 1).

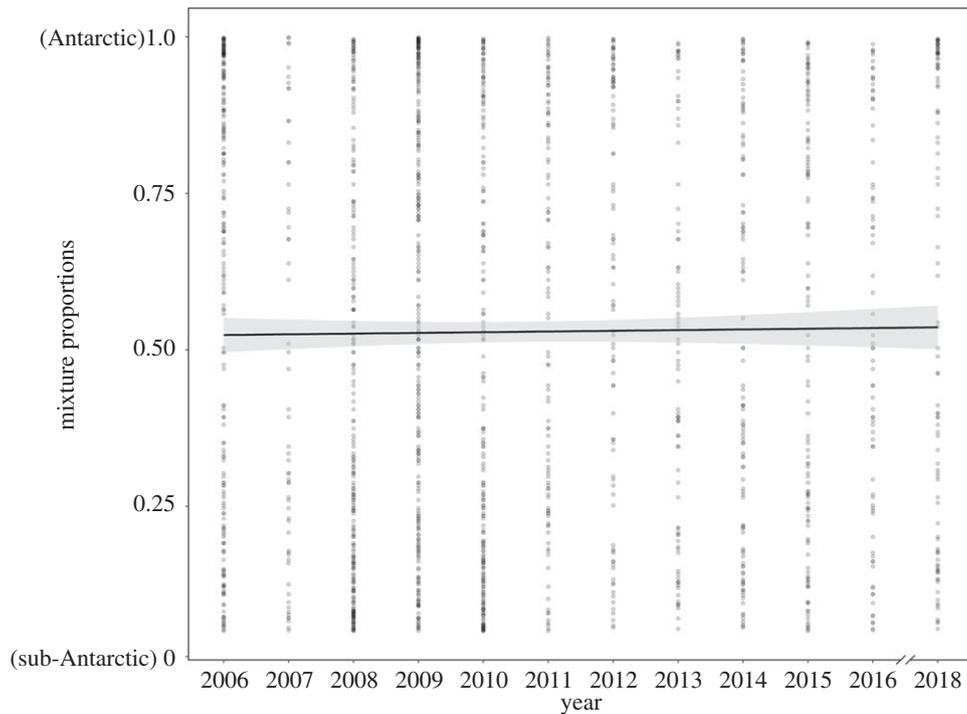
From 2006 to 2018, an annual decrease in  $\delta^{13}\text{C}$  was found (linear model:  $\delta^{13}\text{C} = -0.09 \times \text{year} + 160$ ;  $n = 1684$ ,  $p$ -value  $< 0.001$ ,  $R^2 = 0.11$ ) resulting in an overall  $1.08\text{‰}$  decrease in the mean  $\delta^{13}\text{C}$  value of pups (figure 2). A second linear model applied on  $\delta^{15}\text{N}$  values suggested a decrease over time ( $\delta^{15}\text{N} = -0.006 \times \text{year} + 23$ ;  $n = 1684$ ,  $p$ -value  $= 0.04$ ,  $R^2 = 0.002$ ). Considering the poor significance of the linear model

for  $\delta^{15}\text{N}$ , and because a  $\beta$  coefficient of  $-0.006$  is irrelevant regarding the precision of isotopic measurements and biological meaning, only  $\delta^{13}\text{C}$  values were kept for further analyses (see electronic supplementary material S2, figure S3).

The probability that a pup was born from a mother which foraged in sub-Antarctic or Antarctic waters was estimated using a mixture model on pup  $\delta^{13}\text{C}$  values between 2006 and 2018. The  $\delta^{13}\text{C}$  trend of  $-0.09\text{‰}$  per year was included in the model (electronic supplementary material S3, §§1 and 2). No change in the distribution of probability to belong to either group (sub-Antarctic versus Antarctic) was detected over the study period (linear model,  $p$ -value  $> 0.05$ ; electronic supplementary material S3, figure S5), suggesting that the balance between the two foraging habitats remained stable from 2006 to 2018 (figure 3). From 40.2% to 63.1% of individuals were attributed to the Antarctic strategy, whereas



**Figure 2.** Hybrid box- and scatterplot of inter-annual blood  $\delta^{13}\text{C}$  values of southern elephant seal pups at Kerguelen Islands. (Online version in colour.)



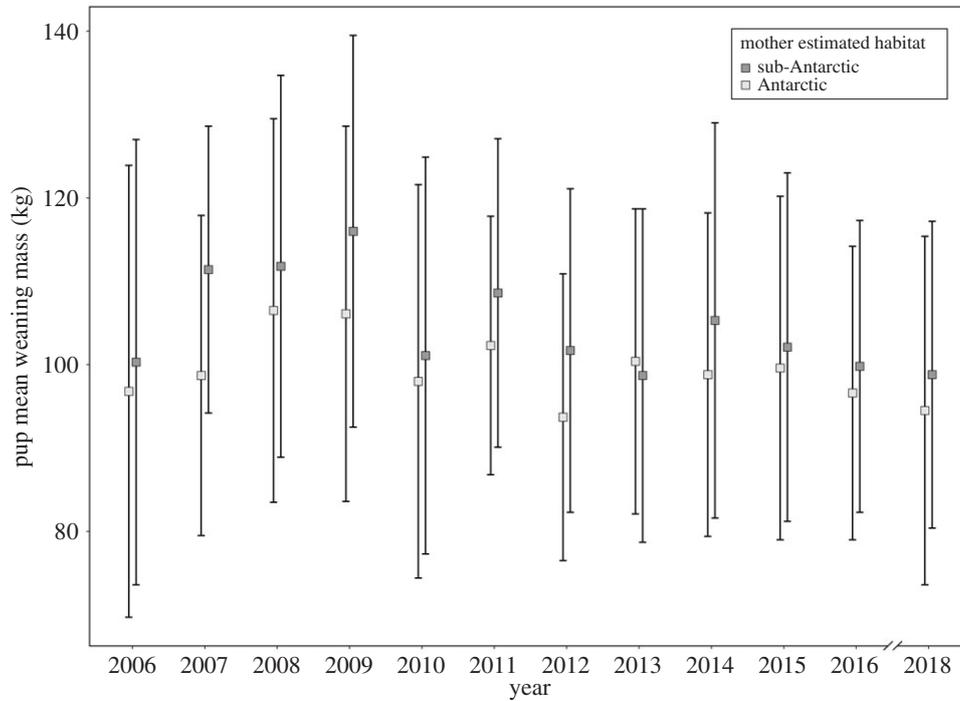
**Figure 3.** Marginal probabilities of southern elephant seal pups to be assigned to the Antarctic or sub-Antarctic group. Each dot represents a pup. A pup with a posterior mean of 1 is assigned to the Antarctic habitat with 100% confidence, whereas a posterior mean of 0 means that the pup belongs to the sub-Antarctic group. Pups whose probability is higher than 0.5 were assigned to the Antarctic group, whereas those with a probability lower than 0.5 were assigned to the sub-Antarctic group. The straight line represents the linear regression of the mixture proportions through years, and the shaded area highlights the 0.95% confidence interval.

36.5% to 61.5% were assigned to the sub-Antarctic one (electronic supplementary material S3, figure S6).

### (c) Pup weaning mass

Of the 1684 pups in the study, 1550 were weighed and of these, 1543 were sexed. The mixture model based on pup  $\delta^{13}\text{C}$

value indicated a sub-Antarctic group of 826 individuals whose mean weaning mass was  $105.9 \pm 23.0$  kg. By contrast, the mean weaning mass of the 858 pups assigned to the Antarctic group was  $100.1 \pm 22.3$  kg. Pups assigned to the sub-Antarctic group (i.e. with less negative  $\delta^{13}\text{C}$  values) were significantly heavier (+5.8 kg) at weaning than their conspecifics (linear model: weaning mass =  $100.1 + 5.8 \times$



**Figure 4.** Mean  $\pm$  standard deviation of pup weaning mass through time. Dark grey squares correspond to mean weaning mass of pups assigned to the sub-Antarctic group, and light grey ones represent pups assigned to the Antarctic group.

foraging habitat;  $n = 1550$ ,  $p$ -value  $< 0.0001$ ,  $R^2 = 0.016$ ; figure 4). A linear model revealed a decrease in pup weaning mass with time (weaning mass =  $-0.9 \times \text{year} + 1821$ ;  $n = 826$ ,  $p$ -value  $< 0.0005$ ,  $R^2 = 0.015$ ) in the sub-Antarctic habitat, corresponding to a mean decrease of 11.7 kg over the 2006–2018 period. No significant trend was detected in the Antarctic group.

Those results were confirmed by a multiple linear model ( $p < 0.0001$ ,  $R^2 = 0.04$ ,  $n = 1543$ ) revealing that pup weaning mass was significantly influenced by their birth year ( $p < 0.0001$ ; negative effect), the probability of being assigned to a foraging group ( $p < 0.0001$ ; pups assigned to the sub-Antarctic group being on average heavier at weaning), and sex ( $p < 0.0005$ ; with male pups being on average heavier than females).

## 4. Discussion

### (a) Towards shifting foraging strategies or environmental-driven changes?

This study aimed to investigate female SES foraging strategies over 14 years, in order to detect any changes in behaviour. A mean annual decrease of  $-0.09\%$  in the blood  $\delta^{13}\text{C}$  values of pups was detected over the 2006–2018 period, corresponding to  $-1.2\%$  in 13 years. Smaller datasets obtained from blood-sampled adult females at moulting and breeding corroborated the values from pups with a mean blood  $\delta^{13}\text{C}$  decrease of  $-1.4\%$  over the 2004–2017 period. We explore several possible hypotheses to explain this decrease in seal blood  $\delta^{13}\text{C}$  values.

First, and perhaps most obviously, this decrease could have been related to an increase in the proportion of female SES using the Antarctic habitat compared to the sub-Antarctic one, and/or a global southward shift of their at-sea distribution. However, our findings do not support this hypothesis. A decrease in  $\delta^{13}\text{C}$  values with increasing latitude is well-documented in the Southern Ocean [29,31]. If females travelled further south

to forage, this would lead to a decrease in their  $\delta^{13}\text{C}$  values and those of their pups. The latitudinal distribution of adult females suggests two main habitats during their post-moult foraging trip (i.e. the Antarctic and the sub-Antarctic habitats), confirming earlier observations [32,33]. We found no change in the proportion of individuals foraging in the Antarctic versus the sub-Antarctic habitat over the study period. Inter-annual comparisons of the mean latitude of females' post-moulting tracks for the months of May, June, and July revealed a non-significant annually  $-0.21^\circ$  trend in the distribution of sub-Antarctic foraging females which corresponds to a 300 km southward shift in 13 years. However, a minor latitudinal shift such as this would not be sufficient to explain the decrease in the  $\delta^{13}\text{C}$  values (see electronic supplementary material S1, §2).

As the clear decrease in blood  $\delta^{13}\text{C}$  values cannot be explained by a change in SES at-sea distribution, it may be due to changes in abiotic conditions and/or other biotic components in the Indian sector of the Southern Ocean. Blood  $\delta^{15}\text{N}$  values strongly suggest that adult female SES from the Kerguelen Islands feed primarily on mesopelagic fish, including myctophids [57] with no indication of significant dietary shifts over the study period. Hence, the decrease in blood  $\delta^{13}\text{C}$  values is most likely unrelated to a change in SES foraging ecology, but rather to changes in the environment itself.

An alternative explanation of the observed  $\delta^{13}\text{C}$  decrease is a depletion in  $^{13}\text{C}$  at the base of the food web ( $\delta^{13}\text{C}$  baseline). Oceanic dissolved inorganic carbon (DIC)  $\delta^{13}\text{C}$  relies on atmospheric  $\text{CO}_2$  composition [58] and may be influenced by the Suess effect [39], whose magnitude varies with latitude and ocean basins [59]. Previous studies investigating metabolically inert tissues in Arctic marine mammals and seabirds, and in coral species in tropical ecosystems imputed a decrease in  $\delta^{13}\text{C}$  values to the Suess effect [37,60] at times combined with changes in primary productivity [35,38,39,61]. However, the Southern Ocean's Suess effect accounts for only approximately

−0.01‰ per decade [59,62], whereas our dataset showed a tenfold greater decrease in blood  $\delta^{13}\text{C}$  values (i.e. −1‰ per decade). DIC  $\delta^{13}\text{C}$  may also be influenced by remobilization of deep  $^{12}\text{C}$  because of the benthic-pelagic  $\delta^{13}\text{C}$  gradient [63], implying processes such as wind strengthening or upwelling. However, no changes in the vertical distribution of abiotic carbon have been detected south of the Polar Front over the last decade in the Indian sector of the Southern Ocean (N Metz 2019, personal communication).

Population declines in a number of top predator species across several oceans, including the Southern Ocean and over the past few decades have been attributed to decreases in primary productivity of these ecosystems (e.g. Steller sea lions [34]; rockhopper penguins [64]). It was recently revealed that primary productivity has increased over the past 20 years in the Southern Ocean [9] and is supported by a change in phenology with blooms starting earlier in spring [65]. Changes in Southern Ocean productivity and/or in the composition of phytoplankton communities could contribute to the observed decrease in seal  $\delta^{13}\text{C}$  values. Photosynthesis drives  $\delta^{13}\text{C}$  baseline fluctuation for a given location through many biotic processes, and  $\delta^{13}\text{C}$  values then vary little throughout the food web [30,31]. The food chain  $\delta^{13}\text{C}$  value is mostly affected by primary producers through the rate of C incorporation [66], cell surface/volume ratio and cell growth rate [67–69], the timing of phytoplankton blooms, and phytoplankton types [70,71]. A change in the proportion of  $^{13}\text{C}$ -rich phytoplankton species such as diatoms versus  $^{13}\text{C}$ -depleted nano- and picophytoplankton could for example lead to a decrease in the observed  $\delta^{13}\text{C}$  values in our study [70]. Changes in diatom species composition can induce an approximately 10‰ isotopic shift in particulate organic carbon  $\delta^{13}\text{C}$  values [72,73], hence investigating the evolution of phytoplankton biomass and composition of the communities seems a promising line of investigation.

Interestingly, a recent study using scenario modelling and investigating  $\delta^{13}\text{C}$  trends and their causal links in three tuna species also supports the hypothesis of a global shift in the structure of pelagic phytoplankton communities [74]. Our study suggests that investigating changes in primary productivity and the composition of phytoplankton communities should be a research priority to help understand the functional links between physical oceanography and primary producers in the Indian sector of the Southern Ocean. Moreover, further multidisciplinary investigation across multiple species is needed to assess to what extent a decrease in food web  $\delta^{13}\text{C}$  baseline and associated changes may impact upper trophic levels in the context of global change.

### (b) From foraging habitat to reproductive success

Linking foraging behaviour to reproductive success in wide-ranging species, including SES, remains challenging. Between 1970 and 1987, the Kerguelen SES population underwent a significant decrease in the number of breeding females of 3.6% per annum [20]. Earlier studies suggested that this decline was due to poor female foraging conditions [20], implying a drop in maternal fitness and investment, leading to an overall decrease in pup weaning mass, survival, and subsequent recruitment [19,32]. It did identify that female foraging strategies (i.e. Antarctic versus sub-Antarctic habitat) are of critical importance for their pups' survival rate, and ultimately for the future of the population [44,75,76].

The influence of some abiotic factors such as sea ice extent and chlorophyll-a concentration on pup weaning mass has been suggested for SES breeding on Kerguelen, Macquarie, and Marion Islands [23,32,77–79]. A similar strong positive relationship was found between annual primary production in an Antarctic polynya and pup production in Weddell seals (*Leptonychotes weddellii*) [80]. This raises the question of the viability of SES foraging strategies in the context of global change, and the potential consequences for the SES population from Kerguelen Islands [43].

Numerous studies have revealed the existence of distinct foraging strategies among individuals from the same population (e.g. loggerhead turtles, [81]; Antarctic fur seals, [82]; northern fur seals, [83]). Adult SES display fidelity to their foraging site [40,41], and no significant change in the annual proportion of seals assigned to the two foraging strategies was detected over the study period. We suggest that both strategies may persist in the population because current environmental conditions in sub-Antarctic and Antarctic habitats provide sustainable foraging grounds. However, SES foraging success varies between individuals and with environmental conditions for a given foraging zone [84], hence generalizing the relationship between pup weaning mass and the foraging habitat of their mothers may be overly simplistic.

We found that pups born from mothers foraging in the sub-Antarctic habitat were on average 5.8 kg heavier than their conspecifics at weaning. Weaners that are 5 kg heavier could spend 10 more days fasting at-sea during their first foraging trip due to their higher energy stores [85,86], suggesting a benefit to sub-Antarctic foraging. However, we observed a decrease in pup weaning mass only in the sub-Antarctic group (−11.7 kg over the study period). A continuous decrease in pup weaning mass should impact population recruitment through reduced survival [19,26,85,86] and lead to a differing recruitment age [24]. However, density dependence predicts that weaning mass should decrease in growing populations inhabiting rich foraging areas, as individuals should breed at a younger age and thus be smaller [25]. A strong link between demographic trends and pup weaning mass has been found in multiple studies [75,77,79], and a link between pup weaning mass, the number and size of females ashore, and even harem size was demonstrated for SES at Marion [79] and Macquarie Islands [77]. The Kerguelen SES population is now increasing (J Laborie 2019, *et al.*, unpublished data) raising the question of the consequences of increased intraspecific competition.

The present work does not allow partitioning the variance to explain whether the decrease in weaning mass (only observed in pups from the sub-Antarctic group) is a consequence of a density dependence mechanism alone, or a density dependence mechanism combined with ecosystem changes. Hence, it is important to explore further the relationships between foraging strategies and reproductive success by maintaining this monitoring over a longer time scale.

**Ethics.** All animals used were cared for in accordance with the French Polar Institute Paul Emile Victor (IPEV) ethics committee guidelines.

**Data accessibility.** The tracking data were collected and made freely available by the International MEOP Consortium and the national programs that contribute to it (<http://www.meop.net>).

The SIA data underlying this study are available as part of the electronic supplementary material.

**Authors' contributions.** C.G., M.A.H., and R.H. designed data collection and provided the dataset. J.M. and C.G. conceived the study. J.M. and M.A. performed SIA and Y.C. helped with data validation. J.M. performed data analysis with substantial contributions from M.A. and C.G. J.M. wrote the paper and all authors contributed to the paper review, read and approved the final manuscript.

**Competing interests.** We declare we have no competing interests.

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