

Patterns of occurrence of the sub-Antarctic fur seal *Arctocephalus tropicalis* (Gray, 1872) in Southern Brazil: climatic and environmental associations

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Abstract: This study presents the pattern of occurrence of sub-Antarctic fur seals (SAFS), *Arctocephalus tropicalis*, in the southern Brazilian coast and evaluate its association with climatic variability and anomalies in the concentration of chlorophytes and sea surface temperature in the reproductive colonies of Gough and Tristan da Cunha Islands. Date, sex, and age class of 254 stranded SAFS recorded between 1992 and 2013 were analyzed. Representative indexes of the patterns of climatic variability and environmental variables were obtained between four and five months before the records, the assumed interval of displacement for species between their closest breeding colonies and the southern Brazilian coast. The species was observed in southern Brazil between May and November each year, and most individuals were adult males. The records of SAFS on the southern Brazilian coast were associated with low concentration of chlorophytes interacting with negative sea surface temperature anomalies, and positive events of South Annular Mode, South Atlantic Ocean Dipole and Indian Ocean Dipole. Climatic variability is influencing the ecology SAFS, because it affects the environmental factors, that act as a driver of dispersion of the species. These variables had been interacting together in the region of the breeding colonies, and possibly during the fur seals' journey towards the Brazilian coast. Considering the current scenario of global climate change, we expect that SAFS will continue to disperse to areas beyond their regular distribution, not only in the direction of the coasts of southern continents, but also further south, towards higher latitudes.

Keywords: concentration of chlorophytes, climatic variability patterns, pinnipeds, extra-limital distribution, sea surface temperature.

INTRODUCTION

Climatic variability can be understood as an intrinsic property of the Earth's climatic system, responsible for natural oscillations in climatic patterns, observed at the local, regional, and global levels (Confalonieri 2003). These patterns of climatic variability associated with teleconnections and environmental variables, such as chlorophyll-a concentration and sea surface temperature (SST), can directly or indirectly affect marine diversity (Georges et al. 2000; Guinet et al. 2001; Beauflet et al. 2004; Ream et al. 2005; Campagna et al. 2006; Seyboth et al. 2016). Determining the link between individual or population behavioral responses and environmental factors is critical to understand the impact of climate variability on species, communities and ecosystems diversity and functioning (Guinet et al. 1994; Georges et al. 2000; Guinet et al. 2001; Beauflet et al. 2004; Forcada et al. 2005; Oliveira et al. 2006, 2009; Forcada and Hoffman 2014; Bost et al. 2015; Atkinson et al. 2019).

Among some of the main climatic patterns that influence the South Atlantic Ocean are the El Niño/Southern Oscillation (ENSO) (Trenberth 1997) and the Southern Annular Mode (SAM) (Marshall 2003). ENSO is the main mode of interannual variability in the tropics and fluctuates between warm phases, relates to El Niño (and indicated by positive numbers of its index) and cold phases, associated to La Niña (LNSO) periods (and negative numbers of the index), with an abnormal increase and decrease in SST specifically in the central-eastern/eastern Equatorial Pacific, respectively (Trenberth 1997).

The effects of climatic events such as ENSO are well known on the Pacific coast, such as increased SST resulting in reduced productivity and changes in the Humboldt current (Majluf 1992). The influence of ENSO on other ocean basins occurs through changes in the Walker and Hadley circulation, which are associated with changes in atmospheric wind, humidity, cloud cover, and so on. These changes, in turn, influence surface heat fluxes, wind and ocean circulation, resulting in SST variations in the other oceans (Wang 2019). In the South Atlantic Ocean, its effects are best known for equatorial and coastal regions, such as ENSO causing increased precipitation, freshwater discharges, and consequently increasing productivity in some areas as the Rio de la Plata plume (Franco et al. 2020).

The SAM dominates Southern Hemisphere climate variability and is based on the zonal pressure difference between six meteorological stations at latitude 40°S and six stations at latitude 65°S (Marshall 2003). A positive phase of SAM occurs when pressures at mid-latitudes (30°S-50°S) are above average (Marshall 2003). This corresponds to stronger than average westerly winds at sub-Antarctic latitudes (50°S-70°S) and weaker winds at mid-latitudes (30°S-40°S) (Marshall 2003; NCAR 2019), including the South Atlantic Ocean region. Ayers and Strutton (2013), demonstrated the influence of positive SAM and wind stress swell anomalies on nutrient variability and dynamics in the subantarctic region of the Pacific sector. In addition to these, several other climatic phenomena can influence the South Atlantic Ocean, but their effects are still not well understood. Among them are the South Atlantic Ocean Dipole (SAOD) (Venegas et al. 1997), the Subtropical Indian Ocean Dipole (SIOD) (Behera and Yamagata 2001), and the Indian Ocean Dipole (IOD) (Saji et al. 1999).

SAOD corresponds to the heating of surface waters on the coasts of West/Central Equatorial Africa, between 10°20'E, 0°15'S and simultaneous cooling of similar magnitude on the coast between Argentina, Uruguay, and Brazil, between 10°40'W, 25°40'S (Venegas et al. 1997). The positive phase is equivalent to

SST in Equatorial Africa being above the average compared to the southwest region, while its negative phase is below the average.

SIOD is represented by the difference in SST anomaly between the western subtropical Indian Ocean south of Madagascar, in the domain between 55°65'E, 37°S27'S, and eastern subtropical Indian Ocean west of Australia, 90°100'E, 28°18'S (Behera and Yamagata 2001). In its positive phase, the SST south of Madagascar is anomalously hot in relation to Western Australia. The IOD is characterized by the difference in SST anomalies in the southeastern Equatorial Indian Ocean located north of Australia, 10°10'N, 50°70'E, and SST anomalies in the western part of the Equatorial Indian Ocean north of Madagascar at 10°0'S, 90°110'E (Saji et al. 1999). The IOD positive and negative phases occur when the SST in northern Madagascar is above or below average compared to the northern region of Australia, respectively.

The influence of Indian Ocean modes on the South Atlantic Ocean is still unclear, although Indian Ocean-induced atmospheric waves and/or atmospheric circulations could be candidates (Zhang and Han 2021). The Indian Ocean may influence the South Atlantic Ocean by the Agulhas Current and its leakage from the Agulhas vortices to southern Africa (Schouten et al. 2000; Lutjeharms 2006). On interannual timescales, a negative IOD strengthens the tropical and subtropical gyres of the southern Indian Ocean, as observed in satellite data (Schouten et al. 2002), while a positive IOD weakens the same gyres. These spin changes increase or decrease the sources of the Agulhas Current, affecting the frequency of vortex shedding and therefore the influence of the Indian Ocean in other areas. Vortices in general can carry different concentrations of chlorophyll-a on their edges (Dower and Lucas 1993), which can influence the foraging behaviour of marine predators (Wege et al. 2019).

In marine ecosystems, these climatic events described above can drastically change environmental conditions, with direct or indirect impacts on the abundance and distribution of top predator species, such as birds and marine mammals (Oliveira et al. 2006, 2009; Bost et al. 2015; Atiknson et al. 2019; Krüger et al. 2021). Acute and long-term exposure to warmer waters, for example, can impact species distribution through direct physiological and indirect ecological pathways (O'Connor et al. 2009). Pinnipeds (elephant seals, fur seals, sea lions and walruses) distribution and demography can be strongly influenced by the variability patterns of climate. For example, Oliveira et al. (2006, 2009) demonstrated that a population decrease of South American fur seals, *Arctocephalus australis* in Peru, along the Pacific coast, has led to genetic bottleneck as a result of starvation mortality due to the disappearance of their main prey Peruvian anchoveta, *Engraulis ringens*, in 1997/1998 during the strongest El Niño event in history. Testa et al. (1991) reported demographic fluctuations in Antarctic phocids possibly related to the effects of ENSO. Guinet et al. (1994) observed annual variations in pup production of Antarctic fur seal, *Arctocephalus gazella*, on Possession Island (Southern Austral Indian Ocean), which was significantly lower in years following the events ENSO. Seyboth et al. (2016) analysed the effects of Oceanic Niño Index, Antarctic Oscillation and Antarctic sea ice area on krill, *Euphausia superba* density in the Atlantic feeding grounds, and consequently their relation with the reproductive success of southern right whale, *Eubalaena australis*. According to the authors, if krill abundance continues to reduce its number due to global warming, southern right whales will most likely reduce their current recovery rate. Several other studies have demonstrated the influence of SAM on nutrient variability, dynamics on krill availability and the survival of females of *A. gazella* until reproductive age (e.g. Ayers and Strutton 2013; Coulson and Clegg 2014; Forcada and Hoffman 2014).

Dispersion to areas far from their breeding colony sites, and outside the known limits of their usual distribution, is a phenomenon widely reported for pinnipeds, especially for Antarctic and subantarctic species (for a review, see Prado et al. 2016; Frainer et al. 2018; Milmann et al. 2019; Bester 2021a, b; Sousa-Lima et al. 2022). However, the reasons for the distribution of the vagrants are still unknown. In this context, studies that directly associate climate variability patterns with the dispersion of pinnipeds in regions beyond the limit of their traditional distribution are needed.

Of the three species of fur seals recorded on the coast of Rio Grande do Sul in southern Brazil, the *A. australis* and the sub-Antarctic fur seal (SAFS), *A. tropicalis* are the most frequently observed (Pinedo 1990; Simões-Lopes et al. 1995; Oliveira et al. 2001; Prado et al. 2016; Procksch et al. 2020). The breeding colonies of SAFS are widely distributed in the Southern Hemisphere, mainly on sub-Antarctic islands north of the Antarctic Convergence, in the southern parts of the Atlantic and Indian Oceans, including Amsterdam Island and neighbouring Saint Paul Island, the Crozet group of islands (Guinet et al. 1994), Tristan da Cunha Islands and Gough Island (Hofmeyr et al. 2016), Macquarie Island (Shaughnessy 1993), and the Prince Edward Islands (Marion and Prince Edward Islands) (Bester et al. 2003; Hofmeyr et al. 2016; Wege et al. 2019). They also breed on Heard Island (Goldsworthy and Shaughnessy 1989). All occurrences of SAFS outside these regions are considered extra-limital and such individuals are called vagrants (Bester 1989; Hofmeyr 2015; Bester 2021a, b). Vagrants specimens of SAFS were recorded on the Antarctic coasts (Shaughnessy and Burton 1986), southern South America (Pinedo 1990; Bastida et al. 1999; Oliveira et al. 2001, Prado et al. 2016), northern South America (Milmann et al. 2019; Sousa-Lima et al. 2022), Southern Africa (Bester 1989; Shaughnessy and Ross 1980), Madagascar (Garrigue and Ross 1996), Australia (Gales et al. 1992) and New Zealand (Taylor 1990), Bouvetøya (Hofmeyr et al. 2006), Comores (David et al. 1993), Juan Fernandez Islands (Torres and Aguayo 1984), Kerguelen Islands (Wynen et al. 2000), Mauritius Islands (David and Salmon 2003) and South Georgia Islands (Payne 1979).

The extra-limital occurrences of SAFS in the southern Brazilian coast has often been considered occasional or the result of erratic movements and its mortality probably was not related to specific causes, such as fisheries interactions (Oliveira et al. 2001; Ferreira et al. 2008). Molecular markers analyses have indicated that specimens of SAFS found dead in the region had multiple origins Ferreira et al. (2008). The vast majority were from Gough Island, which together with the northern group of the Tristan da Cunha Islands are the breeding colonies of SAFS closest to southern Brazil, between 3,800 km and 4,200 km distant. According to Hofmeyr (2015), SAFS presented the greatest dispersion among pinnipeds in the Western South Atlantic, including the tropical region.

Studies on movements and migrations of pinnipeds revealed that most species disperse in the oceans shortly after the end of the breeding season or after moulting (Ridgway and Harrison 1981). In southern Brazil, SAFS is found mainly in the winter, with an apparent predominance of adult males (Pinedo 1990; Simões-Lopes et al. 1995; Oliveira 1999; Prado et al. 2016). This pattern likely results from differential parental care investment. Adult males are not involved in the care of offspring after the end of the breeding season (Bester 1981, 1990), as opposed to lactating females during the 10 - 11 months lactation period (Bester 1987, 1995), which may allow large post-breeding season displacements of adult males (Bester 1981). However, the predominance of adult males of SAFS specimens in southern Brazil must be seen with caution due to the lack of more comprehensive datasets.

Annual variation in the occurrence of SAFS, with a high frequency of occurrence of the species on southern Brazilian coast (precisely between 1993 and 1998 to the northern coast of Rio Grande do Sul) and other parts of the Atlantic coast of South America in specific years, between 1982 and 1998 have been observed (Oliveira 1999). Usually, these records were considered to be a result of increased population sizes owing to their protection after the end of sealing in the Antarctic and sub-Antarctic waters (Pinedo 1990; Hofmeyr et al. 1997; Shaughnessy et al. 2014) and the increased effort in monitoring of the Brazilian coast for pinnipeds, especially in southern Brazil (Oliveira et al. 2001). However, Oliveira (1999) suggested a potential influence of oceanographic events on the arrival of the species in the Atlantic coast of South America, because the number of vagrant SAFS oscillates and eventually increases in several special years (*e.g.* 1984 = 19 specimens, 1988 = 15 specimens, 1992 = 32 specimens, 1994 = 16 and 1998 = 18). Oliveira et al. (2001) proposed that the increase in records could also be related to anomalies in ocean currents due to oceanographic and climatic events, such as ENSO. Later, Prado et al. (2016) observed low stranding rates during the strong El Niño episodes of 1982/1983, 1997/1998 and 2009/2010 and high stranding rates that coincided with a strong La Niña event in 2000 and a moderate El Niño event in 2002, suggesting that the main factors influencing the occurrence patterns of SAFS occurrence in Brazilian coastal waters deserve further investigation.

More data and analyses are still necessary to understand the association of the oceanographic and atmospheric variables with the dispersion of SAFS into areas beyond their usual distribution. Thus, the main objective of the present study was to characterize the patterns and drivers of the occurrences of SAFS on the southern Brazilian coast through testing the following hypothesis: (i) subadult and adult males are the predominant age categories and sex of the individuals arriving in southern Brazil. We expect that non-reproductive subadults and adult males may disperse more and consequently they can use more frequently extra-limital areas, since the adult females are the sole responsible for the parental care; (ii) there are years and months of greater occurrence of the species in the study region; and (iii) the seasonal and annual patterns of variation in the occurrence of SAFS in southern Brazil are influenced by climate variability patterns and environmental parameters. We assume that the last two hypothesis, ii and iii, are influenced by patterns of climate variability and environmental parameters, mainly related to climate variability such as ENSO and LNSO as proposed by Oliveira (1999), and to environmental parameters (chlorophyte concentration and SST) in the breeding colonies on Gough and Tristan da Cunha Islands. We expect that these climatic conditions in the breeding colonies act as triggers for the dispersal of these SAFS towards the south coast of Brazil, thus explaining the irregular pattern of annual occurrence, as proposed by Oliveira (1999).

METHODS

Study area

Two areas were analysed to understand the patterns of occurrences (temporal, age, and sex) of SAFS on the southern Brazilian coast and test the potential association of these records with the environmental variables and the patterns of climatic variability. The first area was the coast of Rio Grande do Sul state, in southern Brazilian coast, where the occurrence of the species was monitored and its records collected. The second area was around the Tristan da Cunha and Gough islands, in the South Atlantic

Ocean, from where chlorophytes concentration and sea surface temperature (SST) data were obtained (Fig. 1).

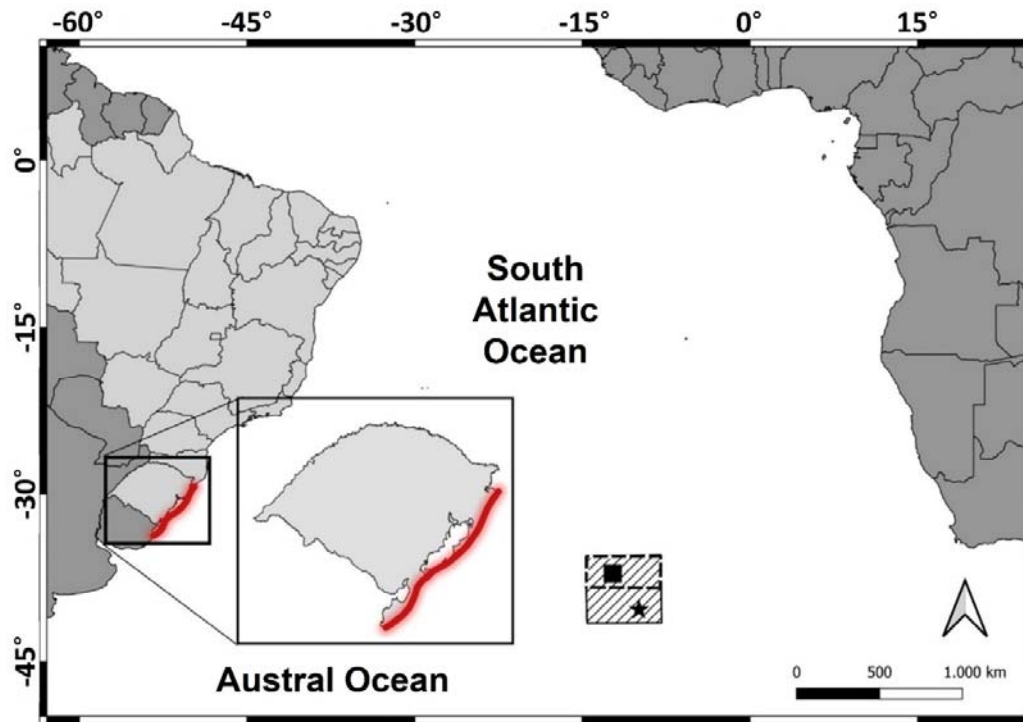


Fig. 1 Map of the studied areas. The coast of Rio Grande do Sul with a monitored area of 645 km (red line) for the occurrences of sub-Antarctic fur seal, *Arctocephalus tropicalis*, between the locations of Barra do Rio Mampituba and Barra do Chuí. Location of Gough Island (black star) and Tristan da Cunha Island (black square). The area with diagonal lines and the dashed rectangle indicates the regions surrounding of Gough and Tristan da Cunha Islands, the closest breeding colonies of the studied species, where chlorophyte concentration and temperature of the sea surface were estimated, respectively

The southern Brazilian coast in this study is represented by the coast of Rio Grande do Sul state, which comprises sandy beaches with flat and wide continental shelf (with width ranging between 100 km in the north to 180 km in the south), and soft slope (2m per km) to the shelf break, which begins near the 150 – 200 m isobath (Calliari 1998). This coastal area is influenced by the Subantarctic Shelf Water transported northward by the Malvinas/Falkland Current (MFC) and by the Tropical Water and South Atlantic Central Water transported southward by the Brazil Current (BC) (Möller et al. 2008). The Río de la Plata estuary (38°S) and the Patos Lagoon estuary system (32°S) are the two major freshwater input into the region. During austral winter the south-westerly winds displace the Plata/Patos plume far from the Cabo de Santa Marta Grande (28°S), while in summer it retracts to approximately 32°S (Möller et al. 2008). The influence of subantarctic waters and freshwater discharge makes the continental shelf of the region one of the most productive areas off Brazil (Calliari 1998).

The records of SAFS found dead in the coast of Rio Grande do Sul were collected by the “Grupo de Estudos de Mamíferos Aquáticos do Rio Grande do Sul” (GEMARS) (Oliveira 1999), Universidade Federal do Rio Grande (FURG) and “Núcleo de Educação e Monitoramento Ambiental” (NEMA) and by

the “Laboratório de Ecologia e Conservação da Megafauna Marinha” (ECOMEGA), Universidade Federal do Rio Grande (FURG) (Prado et al. 2016) (Table 1) (see Online resource 1), during monthly coastal monitoring from 1992 to 2013, which combined covered over 645 km of coastline, between Barra do Rio Mampituba, in Torres (29°S, 49°43'W) and Chuí (33°45'S, 53°22'W) (Fig. 1). Since the regions surveyed by each institution do not overlap, double count was not an issue. Live individuals were not considered in this study, as they could move from one coastal region to another and thus be counted twice in the monitoring records. The data collected for each specimen included the date of sampling, standard body length, sex and the state of decomposition of each specimen collected (following Geraci and Lounsbury 2005). When an individual was in a very advanced stage of decomposition (code 5 = mummified or skeletal remains), we considered that the stranding had occurred 30 days earlier, as adopted by Prado et al. (2016).

Table 1 Sample size for each analysis performed on specimens of sub-Antarctic fur seal, *Arctocephalus tropicalis*, recorded by each institution on the coast of Rio Grande do Sul, southern Brazil. M = male specimens; F = female specimens; U = specimens of undetermined sex

Type of analysis	Total	Period
Temporal pattern	254 (132M+47F+75U)	
Age pattern	179	1992-2013
Sex ratio	(132M+47F)	
Modes of climatic variability	254 (132M+47F+75U)	
Environmental parameters	208 (126M+45F+37U)	1998-2013

The Tristan da Cunha and Gough Islands are a set of four volcanic islands located in the South Atlantic Ocean. Tristan da Cunha (37°6'S, 12°17'W) is situated in the warm temperate part of the Subtropical Atlantic Gyre, while Gough Island (40°19'S, 9°55'W) is in the Subtropical Convergence Zone. The southern limit of Gough is influenced by the Subantarctic Front, which is the northern limit of the Antarctic Circumpolar Current and carries cold and highly productive waters (Requena et al. 2020).

Experimental design

To verify the hypotheses of possible association between the occurrence of SAFS and the climatic patterns and the environmental, the values of some climatic variables (ENSO, SAM, SAOD, SIOD and IOD), a productivity proxy (chlorophyte) and SST anomalies were obtained for a period of two to seven months prior to the record of the stranding in Rio Grande do Sul (see Online resource 2 and statistical analyses section for details). However, we keep in the analyses and discussion sections only the models of four and five months, because these time lags were the most well-fitted models according the selection criteria and variables adopted in the study. Moreover, this lag period was assumed to be an estimate of the timing of departure and displacement of SAFS from their breeding colonies at the Tristan da Cunha Islands, South Atlantic Ocean, towards southern Brazil. Two adult female SAFS satellite-tracked post-lactation

(freed from attending a pup) took approximately two months to travel between 1,500 and 2,000 km from Tristan da Cunha Island (which include the three northern islands, including Tristan da Cunha, and the southernmost Gough Island) towards South America on the 45°S latitude line (Mammal Research Institute, University of Pretoria, unpublished results).

Timing, age class, and sex of SAFS sighted

The occurrence of SAFS on the coast of Rio Grande do Sul was monitored of the species in the area between 1992 and 2013. The records of specimens were grouped by month and year, sex and age categories. Age classes of the specimens were defined as yearlings, juveniles, subadults, and adults, based on the standard nose-tail length measurement (STDL in cm) (American Society of Mammalogists 1967) and their limits as proposed by Bester and Van Jaarsveld (1994), Oliveira (1999) and Dabin et al. (2004) for each age class (Table 2). The number of individuals in each age class was calculated from the number of specimens found in each STDL interval. The sampling effort was calculated by time period and per unit of distance (km of beach covered by month). The density was calculated taking into account the number of individuals collected in 100 km, according to Oliveira (1999). It is important to mention that all model analyses were performed using the number of strandings as the response variable and effort as an offset. Density was only used for visualization purposes in the month and year graphs. This approach was adopted because the absolute number of strandings could be biased by monitoring effort variation. The months without beach monitoring were not included in the analyses.

Table 2 Age class defined by total length intervals (cm) of male and female sub-Antarctic fur seal, *Arctocephalus tropicalis*, recorded on the coast of Rio Grande do Sul between 1992 and 2013. Age class delineation followed Bester and Jaarsveld (1994), Oliveira (1999) and Dabin et al. (2004)

Age classes	Total Length (cm)	
	Males	Females
Yearling	≤92	≤ 80
Juvenile	>92.1 – 127	>80.1 – 90
Subadult	>127.1 – 147	>90.1–104
Adult	>147.1	> 104.1

Climatic indexes

To test the hypotheses of possible association between patterns of climate variation and the occurrences of SAFS in southern Brazilian coast, monthly time series of the climatic indices were used. On the Fig. 2 it is indicated the ocean basins locations from where climate index data were obtained.

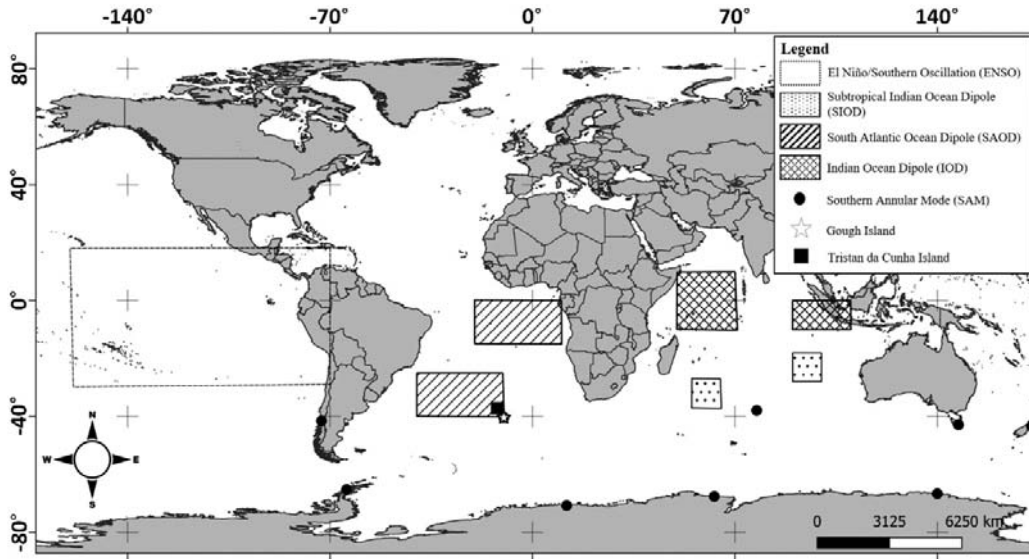


Fig. 2 Ocean basins localizations used in calculation of the climate index. The sub-Antarctic fur seal, *Arctocephalus tropicalis*, breeding colonies of Gough Island (black square) and Tristan da Cunha Island (white star) are also indicated

For ENSO, we used the time series data of the Multivariate ENSO Index second version (MEIv2) obtained from the National Center Atmospheric Research (NOAA) (<https://climatedataguide.ucar.edu/climate-data/multivariate-enso-index>). It considers five variables operating in the equatorial Pacific in the area between 30°S and 30°N, 100°E and 70°W: SST, sea level pressure (SLP), surface zonal winds (U), surface meridional winds (V), and outgoing longwave radiation (OLR). The positive values of this index represent the months of occurrence of El Niño, and the negative values are the months of La Niña (NCAR 2019). The monthly SAM data series was obtained from the National Center Atmospheric Research (<https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based>). The SAOD representative index data was extracted from the East Asian Climate (<http://ljp.gcess.cn/dct/page/65592>). SIOD and IOD data were obtained from the Japan Agency for Marine-Earth Science and Technology (http://www.jamstec.go.jp/virtualearth/data/SINTEX/SINTEX_SIOD.csv) and Global Climate Observing System (https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.Date), respectively.

Monthly recorded anomalies in chlorophyte concentration and sea surface temperature

The monthly recorded anomalies in the chlorophyte concentration (aChlor) and in SST (aSST) over the region of Gough and Tristan da Cunha Islands (Fig. 1) were obtained for 1998 to 2013, with due incorporation of the assumed 4 and 5 month time lags between the fur seals presumed departure from the islands and their arrival on the southern Brazilian coast. The procedure allowed evaluation of the possible association between the arrivals of SAFS on the coast of Rio Grande do Sul and the respective anomalies at their islands of departure.

The monthly data on the concentration of chlorophytes from the AQUA/MODIS satellite were obtained through the Giovanni geophysical parameters platform of the NASA GESDISC channel (https://giovanni.gsfc.nasa.gov/giovanni/#service=TmAvMp&starttime=&endtime=&data=NOBM_DAY

_R2017_dia&variable=dataFieldMeasurement%3APhytoplankton%3B). The various concentrations of chlorophytes were extracted from an image in GeoTIFF format with a resolution of 0.67 x 1.25 degrees for a grid that covered the region of the Tristan da Cunha Islands (breeding colonies of SAFS) (Fig. 1). In total, data from 210 extraction points were obtained for the study period.

The monthly SST data from the AQUA/MODIS satellite were obtained from 1,701 extraction points through Nasa Earth Observations - NEO (<https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MYD28M>). Each extraction was represented by a GeoTIFF image with 0.25 x 0.25 degrees resolution. This second grid was smaller due to the lack of continuous SST data for the studied time series and region in NEO platform.

The time series of anomalies were calculated using the ArcGIS program and the pixel values of the GeoTIFF image were obtained to generate the chlorophyte and SST values. Each pixel corresponded to an area of 112 km x 85 km for the concentration of chlorophytes, and 25 km x 25 km for SST, with the centroid of that pixel selected and its value extracted. aChlor and aSST were calculated from the difference between the monthly average of the month of the record of SAFS in relation to the mean in the sampled period.

Statistical analyses

To evaluate the predominance of one sex over the other in the occurrences of the species on the coast of Rio Grande do Sul, the sex ratio between males and females of SAFS recorded was tested using the chi-square test. We used a Generalized Linear Mixed Model (GLMM) with Negative Binomial error distribution (Zuur et al. 2009) to assess the relationship between the number of occurrences of SAFS in southern Brazil and month the climatic indexes (ENSO, SAM, SAOD, SIOD, IOD), aChlor and aSST recorded to Gough and Tristan da Cunha Islands, using year as a random factor. As the data used in this study consist of counts of deceased animals, we initially employed a GLMM with a Poisson distribution. However, this model exhibited overdispersion. According to Zuur et al. (2009), to address this issue, one of the options is to apply a negative binomial distribution.

All the predictor variables were standardized and centralized, with a mean of 0 and a standard deviation of 1, adjusted for the assumed lags of 4 and 5 months and tested for their collinearities using the “*vif*” (variance inflation factor) function of the HH package (Heiberger 2020) in RStudio software (R Core Team 2021). One by one, variables with a “*vif*” higher than three (highly collinear relationship to the other variables) were removed, and the analysis was performed again without the variable with the highest index. In the end, variables with indexes between zero and three were included in the model (Zuur et al. 2009).

The interaction between independent variables increases the complexity of the model and may indicate that interaction effects occur when the value of one independent variable depends on the effects of another variable (Hastie and Pregibon 2017). Therefore, to verify which lags period (4 or 5 months) best represented the conditions for the departure of SAFS specimens from their reproductive colonies, two models of climatic variability (ENSO, SAM, SAOD, SIOD, IOD) and months were built. Both models included interactive effects between variables, since the exploratory data analysis indicated a significance for the interactive and individual variables and had the following structure:

$$\text{Occurrences} = \text{Cosine} + \text{Sine} + \text{SAOD}*\text{SAM} + \text{SAOD}*\text{ENSO} + \text{SAOD}*\text{SIOD} + \text{SAOD}*\text{IOD} + \text{SAM}*\text{ENSO} + \text{SAM}*\text{SIOD} + \text{SAM}*\text{IOD} + \text{SIOD}*\text{ENSO} + \text{IOD}*\text{SIOD} + \text{ENSO}*\text{IOD} + \text{Offset}(\text{Effort}) + (1|\text{Year})$$

where (*) represents interactions between variables. It is worth noting that, the statistical information of each variable in the model is summarized in the RStudio software (using the summary function), presented both interactively and additively (effect of the variable alone). The months variables were transformed into sine and cosine, and later into quantitative variables. The sine and cosine signals represent the four seasons of the year, in addition to adding cyclicity to seasonality analyses. For the sine, the peaks (positive and negative) occurred at the equinoxes and the null value at the solstices. For cosine, the analysis was inverted, null at the equinoxes and peaks at the solstices. This process consisted of dividing 360° by 12 months, thus finding the angle for each month. Subsequently, the sine and cosine values for the corresponding angle were calculated. The difference in the number of occurrences of SAFS between the years was analysed from the standard deviation of the random effect and the specimen number of occurrences graph (see results, Fig. 4a), since the software of statistical packages does not provide values of degrees of freedom and p for random effects.

The best model was chosen according to the lowest value of the Akaike information criterion (*AIC*) and following the Backward Stepwise Regression method (Hocking 1976; Mazerolle 2006). This is a stepwise regression approach that starts with a complete (saturated) model and at each step gradually eliminates the model variables to find a reduced model that best explains the data. Also known as backward elimination regression, the stepwise approach is useful because it reduces the number of predictors, reducing the multicollinearity problem and is one of the ways to solve overfitting (Hocking 1976). The selection of variables by the Backward Stepwise Regression method was stopped when the model reached its lowest *AIC* value.

To analyse the possible link between the occurrences of SAFS and the aChlor and aSST, two models were also generated (again one considering a 4-months lag and the other a 5-months lag), both including the interactive effects between the variables. The structure of both full models was as follow:

$$\text{Occurrences} = \text{aChlor}*\text{aSST} + \text{Offset}(\text{Effort}) + (1|\text{Year})$$

where (*) represents interactions between variables. For this model, it was not necessary to perform the Backward Stepwise Regression process, as the model showed only aChlor and aSST interacting.

It is worth noting that the reason we separated the data into two models, one from 1992 to 2013 (sine, cosine, and climate modes) and 1998 to 2013 (aChlor and aSST), was that the local environmental variable, chlorophytes, only had data available from 1998 onwards, with no data available for the earlier period. Data on climate modes and SST were available from 1992 to 2013. Since the characteristics of climate modes are specific to their oceanic basins, we chose to keep them separate. Along with the data from 1992 to 2013, we included a temporal analysis of seasonality (sine and cosine) to determine if there were months with a higher occurrence of the species in the study area (Hypothesis II of our study). Although we had SST data for the period from 1992 to 2013, we did not include them in the analysis because they

were collinear with the sine variable ($vif > 3$), and therefore, we could not include them together in the analysis.

Effort was included in all models as an offset, i.e. as a way of compensating the bias that could be caused given the uneven sampling collection throughout the years. It is worth noting that, concerning the models, the climatic and environmental variables are exactly the same, but one has a 4-month lag, and the other has a 5-month lag. All analyzes were performed using R version 4.1.2 (R Core Team 2021).

RESULTS

Age and sex ratio patterns of SAFS occurrences in Southern Brazil

From 1992 to 2013, a total of 254 carcasses of SAFS were recorded throughout the study area. Of this total, 147 were males, 52 were females, and 55 of undetermined sex. The sex ratio was statistically different from the 1:1, with 2.82 males registered for each female ($X_1 = 45.35$, $p < 0.0001$). The standard nose-tail length could be measured in the majority of the records ($n = 179$, $n = 132$ males, $n = 47$ females), with most specimens being adult males ($n = 71$, 40%), adult females ($n = 35$, 20%) and subadult males ($n = 27$, 15%). Juveniles and yearlings of both males ($n = 18$, 10%; $n = 16$, 9%, respectively) and females ($n = 3$, 2%; $n = 9$, 5%, respectively) were also recorded (Fig. 3). This result suggests that adult and subadult males are the predominant age category and sex of the individuals arriving in southern Brazil.

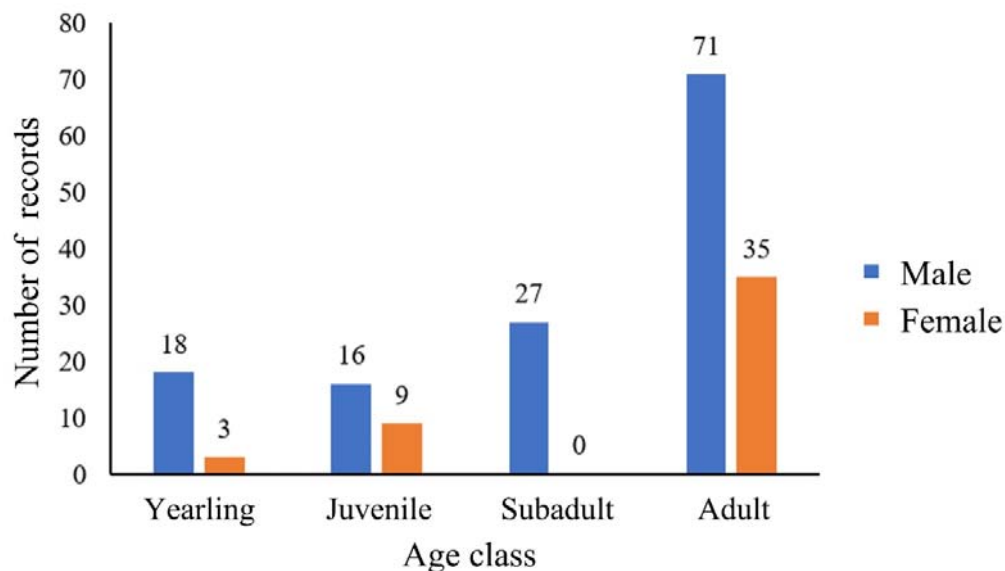


Fig. 3 Age class distribution per sex of sub-Antarctic fur seal, *Arctocephalus tropicalis*, found between 1992 and 2013 on the coast of Rio Grande do Sul, southern Brazil

Temporal patterns, and association with climate variability modes

Model 1 best explained the association between climatic indexes and the number of occurrences of SAFS, explaining 80% of all variability in the response variable (Table 3). Regarding the temporal patterns, the records of SAFS in the coast of Rio Grande do Sul occurred only between May and November of each year, with 1 until 92 individuals observed per year [$\bar{x} = 11.5 \pm 18.9$ individuals ($n = 254$) and SD of the random effect $\pm 1.12e^{-05}$]. The year of 2002 has the highest number of occurrences of the species (n

= 92), followed by 2003 ($n = 21$). The years 1993 and 2005 had only one individual recorded. The Fig. 4a, shows the observed annual density of the species. The months with the highest number of records of SAFS in the study area were mainly August and September, suggesting a pattern of occurrences of the species related to late winter (Fig. 4b), with a significant difference according to sine and cosine values (Table 4). Based on the climatic variables (Table 4), significant interactions were observed between the climatic modes SAOD and SAM, in addition to the weather mode IOD without interaction. All Akaike Information Criterion (*AIC*) results from the models tested during the Backward Stepwise Regression method were included in the Online resource 3. It is important to mention that Model 2 presented results very close behind, explaining 78% of variability. This proximity may indicate that the lag interval between 4 and 5 months could be explaining the temporal patterns and association between climatic indexes and the number of occurrences of SAFS.

Table 3 Concurrent models (M) for the temporal pattern in the occurrences of sub-Antarctic fur seal, *Arctocephalus tropicalis* on the coast of Rio Grande do Sul between 1992 and 2013, and the potential influence of the climatic variability patterns. The following acronyms represent the values of the Akaike Information Criterion (*AICc*), Weight (*AICcWt*), *Delta_AICc*, number of parameters for each model (*K*), and coefficient of determination (R^2) of the selected model

Models (M)	<i>AICc</i>	<i>AICcWt</i>	<i>Delta_AICc</i>	<i>K</i>	R^2
M1: 4 months interaction	340.86	1	0.00	20	0.80
M2: 5 months interaction	352.89	0.00	12.03	20	0.78

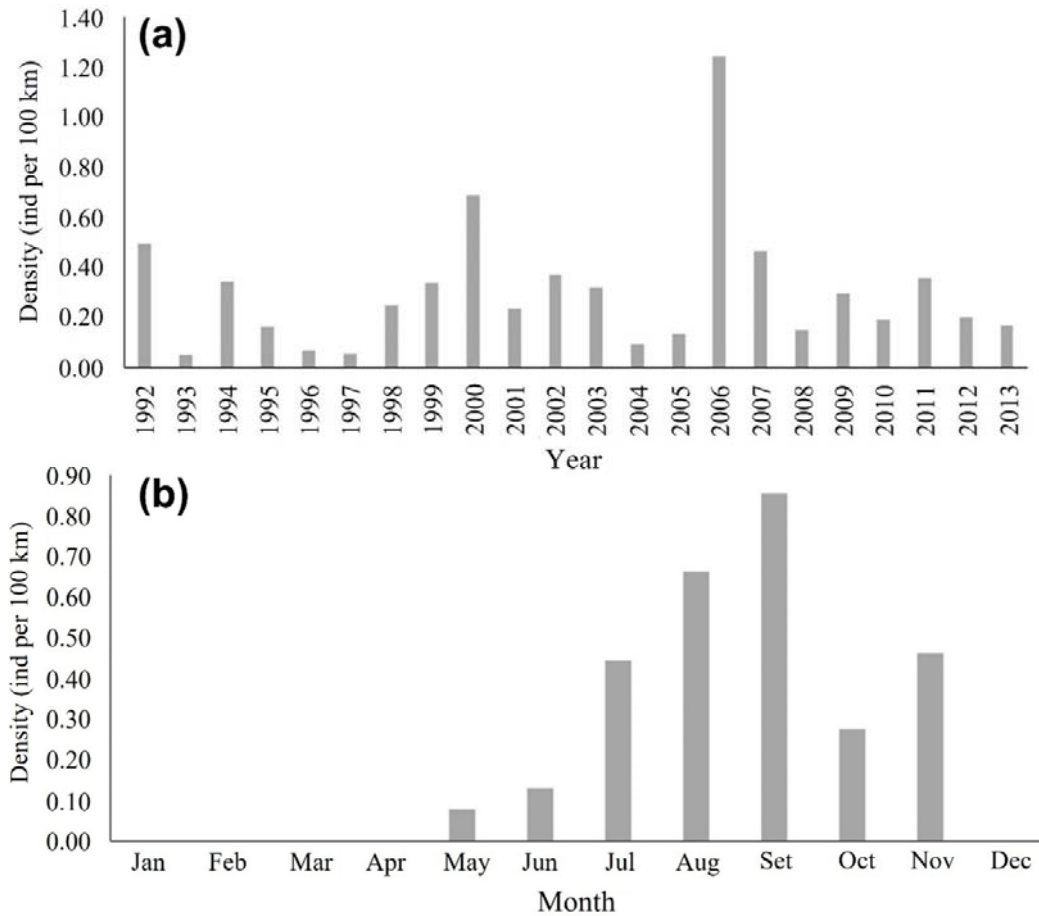


Fig. 4 Density of the sub-Antarctic fur seal, *Arctocephalus tropicalis*, in relation to year (a) and month (b) of records between 1992 and 2013 on the coast of Rio Grande do Sul, southern Brazil

Table 4 Estimated effects of model predictors for the number of occurrences of the sub-Antarctic fur seal, *Arctocephalus tropicalis*, in southern Brazil, based on Model 1, after the selection of variables by the Backward Stepwise Regression method. South Atlantic Ocean Dipole (SAOD), Indian Ocean Dipole (IOD), El Niño Southern Oscillation (ENSO) and Southern Annular Mode (SAM). In bold, significant association ($p < 0.01$) (*) interaction of variables

Variables	Estimated (a)	Z value	P
SINE	1.31607	6.037	< 0.0001
COSINE	-1.12532	-5.247	< 0.0001
SAOD*SAM	0.40293	2.795	0.0052
IOD	0.54479	3.002	0.0027
ENSO*IOD	-0.26311	-1.497	0.1344

A positive association was found between both the interactive effect of SAM and SAOD and IOD and the occurrence of SAFS in southern Brazil, with larger numbers of the species recorded during positive SAM events in interaction with neutral to positive SAOD phases (Fig. 5) and during positive phases of the IOD (Fig. 6). These results suggest that the temporal pattern of variation in the occurrence of SAFS in

southern Brazil is influenced by patterns of climate variability, but this influence was not related to ENSO or LNSO as proposed by Oliveira (1999).

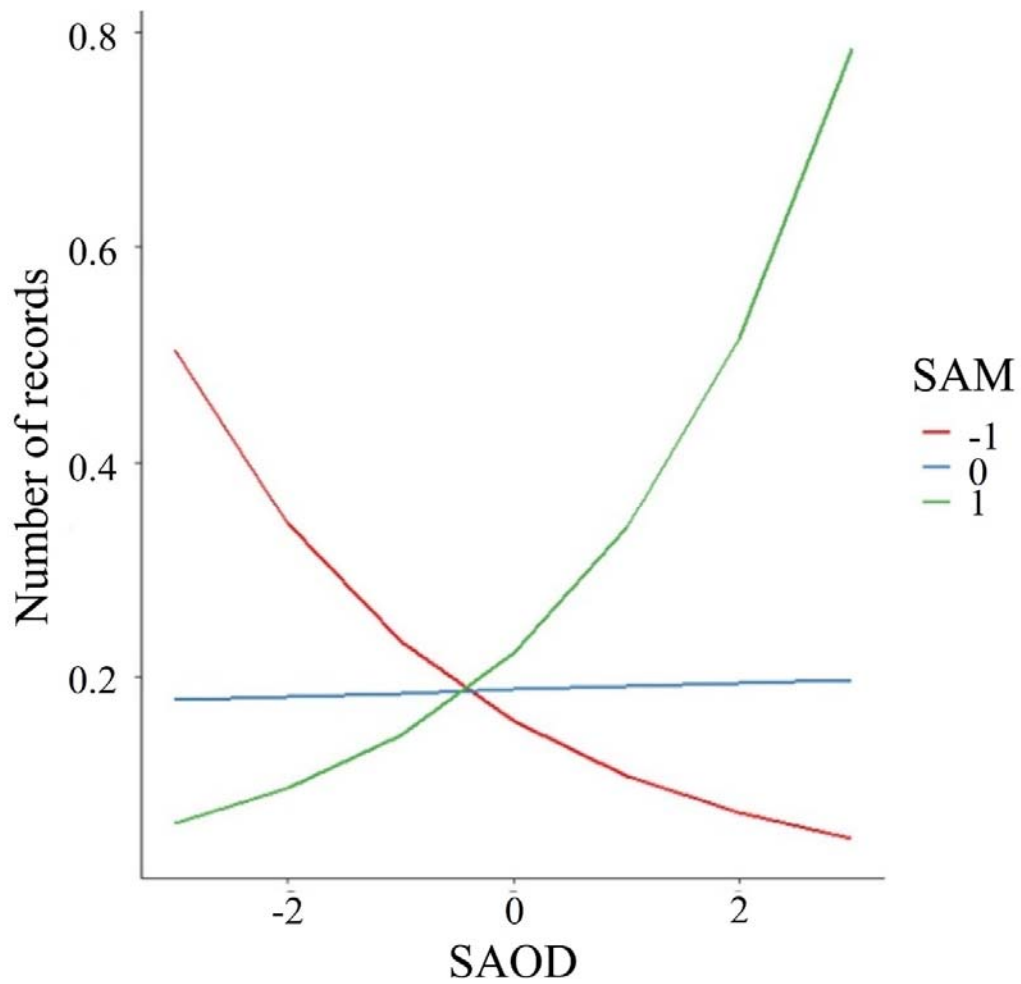


Fig. 5 Number of records of sub-Antarctic fur seal, *Arctocephalus tropicalis*, collected between 1992 and 2013 off the coast of Rio Grande do Sul, Southern Brazil, in relation to the interaction of the pattern of climate variability of the Southern Annular Mode (SAM) and South Atlantic Ocean Dipole (SAOD), considering a 4-months lag. The red, blue, and green lines correspond to South Annular Mode (SAM) in the positive, neutral, and negative phases, respectively

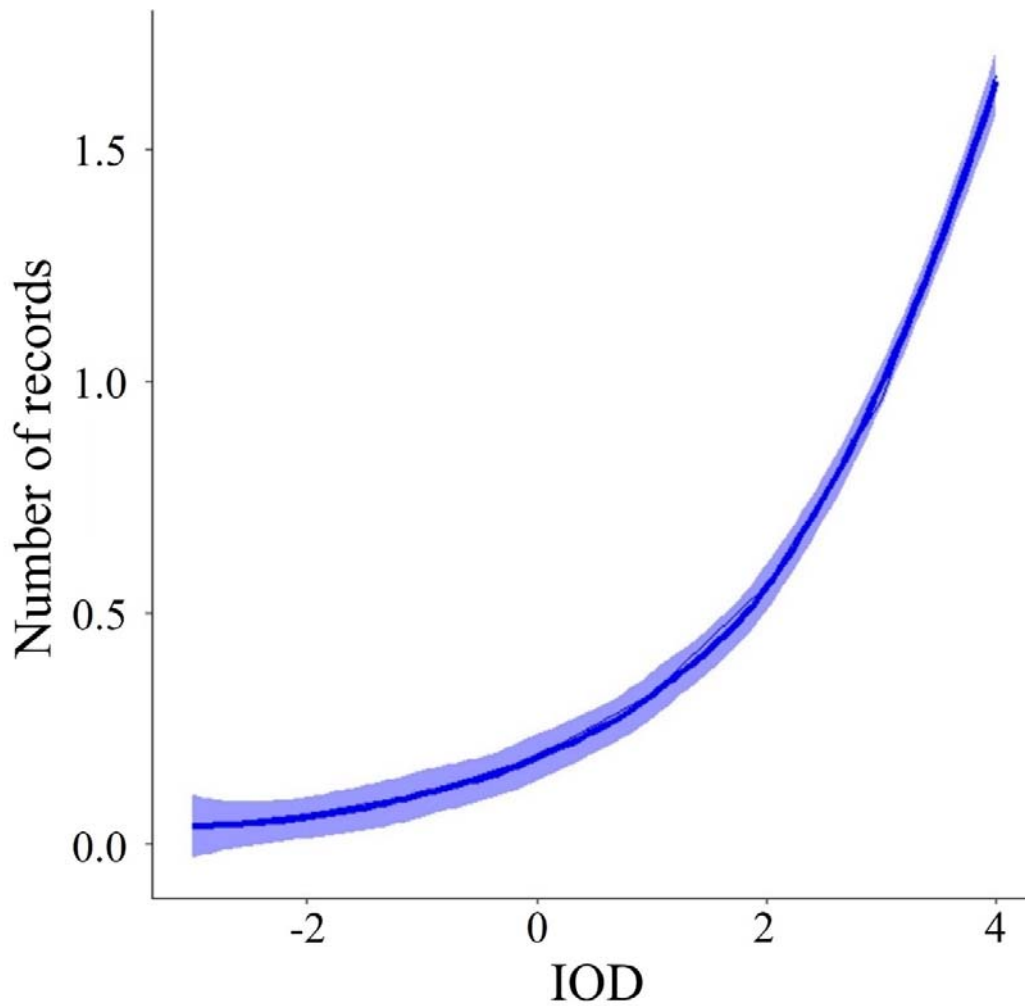


Fig. 6 Number of records of sub-Antarctic fur seal, *Arctocephalus tropicalis*, collected between 1992 and 2013 off the coast of Rio Grande do Sul, southern Brazil, in relation to the Indian Ocean Dipole (IOD), considering a 4-months lag

Association with monthly anomalies of chlorophyte concentration and sea surface temperature

Model 4 best explained the association between the number of occurrences of SAFS on the coast of Rio Grande do Sul and the aChlor and aSST in the period from 1998 to 2013. This model explained 71% of the variability in the occurrences of SAFS (Table 5). The best fit for Model 4 included aChlor and the interaction between aChlor and aSST as explanatory variables (Table 6).

Table 5 Candidate models for the association of anomalies in the concentration of chlorophytes (aChlor) and sea surface temperature (aSST) in the vicinities of Gough and Tristan da Cunha Islands with the occurrences of sub-Antarctic fur seal, *Arctocephalus tropicalis*, on the coast of Rio Grande do Sul, between 1998 and 2013. Values of the Akaike information criterion (*AICc*), Weight (*AICcWt*), *Delta_AICc*, and number of parameters for each model (*K*), coefficient of determination (*R*²) of the best model. (*) represents interactions between variables

Models (M)	<i>AICc</i>	<i>AICcWt</i>	<i>Delta_AICc</i>	<i>K</i>	<i>R</i> ²
M4: 5 months_aChlor*aSST	257.75	1.00	0.00	6	0.71
M3: 4 months_aChlor*aSST	283.37	0.00	25.61	6	0.46

Table 6 Estimated effects of the predictor variables on the number of occurrences of the sub-Antarctic fur seal, *Arctocephalus tropicalis*, based on Model 4 chlorophyte concentration anomalies (aChlor), sea surface temperature anomalies (aSST) in Gough and Tristan da Cunha Islands. In bold, significant association ($p < 0.01$) (*) interaction of variables

Variables	<i>Estimated (α)</i>	<i>Z value</i>	<i>P</i>
aChlor	-1.2311	-3.467	0.0005
aChlor*aSST	0.8427	3.145	0.0017
aSST	0.4843	2.049	0.0404

There was a negative relationship between aChlor at Gough and Tristan da Cunha Islands and the occurrences of SAFS in the coast of Rio Grande do Sul, with the largest number of records of this species in southern Brazilian coast occurring 5 months after their departure from their breeding colonies of SAFS. When this potential departure of SAFS occurred, the concentrations of chlorophyte are low (Table). Figure 7 shows the levels of chlorophyte extracted from the breeding colonies of Gough and Tristan da Cunha Islands 5 months before their arrival to the Brazilian coast, this is probably the departure time of SAFS. Most of the period investigated has negative concentration levels of chlorophytes, suggesting that these low concentration levels of chlorophytes can be one of the triggers for the dispersal of the SAFS towards the southern Brazilian coast. Regarding the interaction between aChlor and aSST, the highest numbers of individuals of SAFS observed on the coast of Rio Grande do Sul occurred during negative anomalies of both environmental variables (Fig. 8). All these results support that the temporal pattern of variation in the occurrences of SAFS in southern Brazil is influenced by environmental parameters, such as chlorophyte concentration and SST in the breeding colonies of the species.

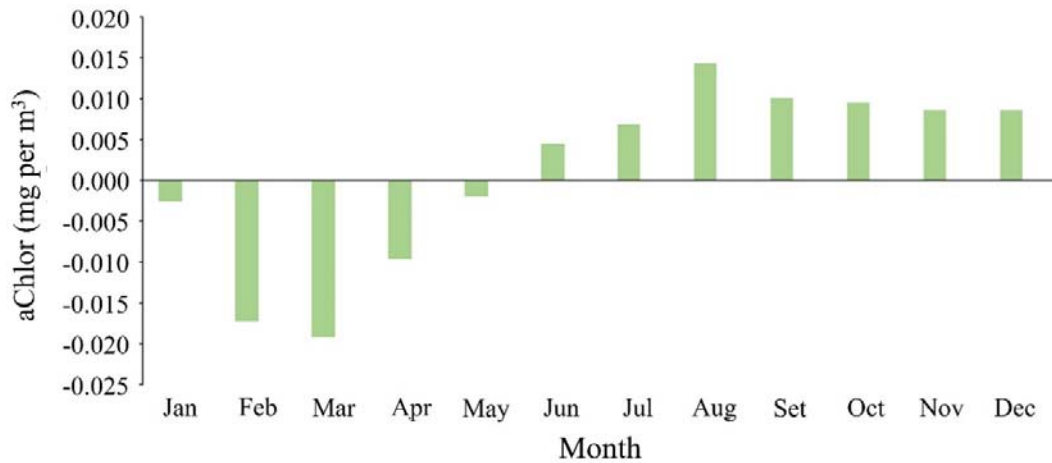


Fig. 7 Anomalies of chlorophytes [aChlor (mg per m³)] for Tristan da Cunha Islands with a 5-months lag in relation to occurrences of the sub-Antarctic fur seal, *Arctocephalus tropicalis* on the coast of Rio Grande do Sul, southern Brazilian coast, between 1998 and 2013

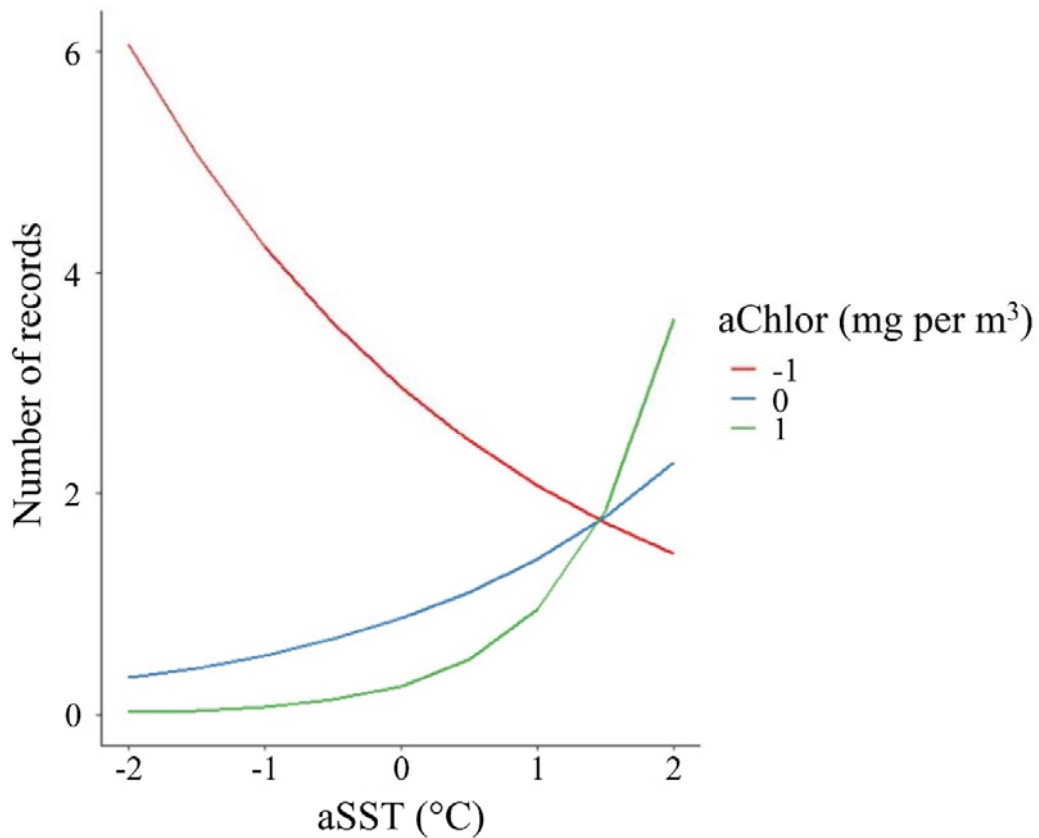


Fig. 8 Number of records of sub-Antarctic fur seal, *Arctocephalus tropicalis*, registered between 1998 and 2013 off the coast of Rio Grande do Sul, southern Brazil, in relation to the anomalies of concentration of chlorophytes [aChlor (mg per m³)] and sea surface temperature [aSST (°C)], considering a 5-months lag. Anomaly values refer to breeding colonies located at the Tristan da Cunha Islands with a 5-month lag period. Red line: negative concentration values of aChlor, blue line: concentration values close to zero and green line: positive concentration values of aChlor

DISCUSSION

The occurrences of SAFS on the southern coast of Brazil showed a predominantly adult and subadult males, which support the first hypothesis that says that males may disperse more and consequently they can use more frequently extra-limital areas. Regarding seasonality and the temporal pattern of occurrences on the coast of Rio Grande do Sul, the highest records of individuals were in the years 1992, 2000, and 2006, primarily in the months of July, August, and September, suggesting a pattern of occurrences of the species is related to late winter. Based on these results, we also accept the second hypothesis that suggests that there are years and months of greater occurrence of the species in the study region. The temporal pattern of SAFS on the Southern Brazilian coast was associated with climate variabilities as SAOD interacting with the SAM and the IOD. All these climatic variability indexes are then believed to influence the marine environment at the breeding colonies of the species at Gough and Tristan da Cunha Islands four months before the arrival of the fur seals in Southern Brazil. Apparently, the ENSO or the LNSO do not have an influence on the presence of the species in the study area, as suggested in our hypotheses and also by Oliveira (1999). Moreover, the highest number of SAFS recorded on the southern Brazil coast occurred five months subsequent to negative aChlor, with or without interactions with negative aSST, in the region of the breeding colonies at the Tristan da Cunha Islands. In this context, our results support our third hypotheses about the patterns of climate variability and environmental parameters that causes the SAFS occurrences on the southern coast of Brazil, with some caveats.

The same predominance of adult males (60%, $n = 6$) in the records of SAFS was detected by Oliveira (1999) on the northern coast of Rio Grande do Sul, between 1982 and 1998. Moura et al. (2007) also found a greater number of males than females (10 males and 2 females) on the coast of Rio de Janeiro, Brazil, between 1994 and 2006. Similarly, Shaughnessy and Ross (1980) recorded 22 wandering specimens on the coast of South Africa, of which 59% ($n = 13$) were males. Males also predominated amongst the vagrants (78%, $n = 41$) at the Juan Fernández Archipelago in Chile between 1982 and 1984 (Torres et al. 1984). The lower numbers of adult females amongst *A. tropicalis* of extralimital occurrence were probably due to their involvement in the long parental care with the offspring at the species' breeding colonies (a period of lactation from 10 to 11 months), which would make it impossible for lactating females travel far during this period (Bester 1981). Despite the majority of individuals being adults, the presence of yearlings in southern Brazilian coast suggests that recently weaned individuals, already moving away from their typical foraging around breeding colonies (Bester 1981). One stranding of this class has been made in Saldanha Bay, South Africa (32°S, 18°E) in September 1984, with the record occurring some 2,300 km distant from its believed place of birth at Marion Island, south Indian Ocean (Bester 1989). Similarly, yearlings from the Tristan da Cunha Islands could be carried towards the south coast of Brazil, aided or not by sea currents associated with oceanographic events linked to the modes of climatic variability (Oliveira 1999).

Pinedo (1990) first reported the species on the southern Brazilian coast, registering 23 specimens in August and September between 1980 and 1985. The existence of a temporal pattern of arrival of SAFS in this region was first mentioned by Oliveira (1999), based on the collection of carcasses of the species found on the north coast of Rio Grande do Sul between 1982 and 1998, the highest frequency recorded in August and September 1992, 1994, and 1998. Oliveira (1999) also described the same pattern for the

Atlantic coast of South America in specific years, but due to the varying sampling efforts across countries, no statistical analysis of the data could be produced. Prado et al. (2016) recorded the species on numerous occasions ($n = 219$) in the coastal region of Southern Brazil from 1976 to 2013. They found it to be the third most common Otariid species, and the second most recorded fur seal species on this coast. Our results corroborate findings from Prado et al. (2016), with July, August, and September as the months with the highest occurrence of the species in the years 1984, 1992, 1998, 2000, and 2002. Moura et al. (2007) found SAFS ($n = 18$) off the coast of Rio de Janeiro, from May to October between 1994 and 2006, based on data from long-term monitoring and pictures provided by lifeguards, fishermen, bathers, and others. Shaughnessy and Ross (1980) recorded, for the west and east coasts of South Africa, 19 of 22 specimens between May and September in the year 1966, 1970 to 1979. Therefore, these previous studies corroborated our results on the occurrence of SAFS in extra-limit regions mainly at the end of autumn, winter, and spring months.

Historically, the occurrence of SAFS on the coast of southern Brazilian coast has been attributed to population growth at the source islands, mainly to explain the first records of this species in the 1980s on the Rio Grande do Sul coast and other areas outside its distribution limits (Pinedo 1990). Moreover, since the 1990-decade, beach surveys focus on monitoring marine mammals were systematically conducted in the region, which may affect the number of records of this species. The increasing number of scientific institutions conducting beach surveys in the southern Brazilian coast after 1990 represented an important change in the observer effort in the studied area. In this context, although there are evidences of some increase in abundance of some specific breeding sites at Gough Island over the study period (Bester et al. 2006, 2019), the increase in population sizes may not be the only explanation for fluctuations in the errant occurrence of specimens in southern Brazil (this study), and perhaps for other extra-limital sightings as well (Bester 2021b). The records of SAFS on the southern Brazilian coast were associated with low concentration of chlorophytes and positive events of SAM and SAOD influencing the ocean basin of the South Atlantic. These variables had been acting together from four to five months prior to, and during the fur seals journey, and arrival on the Brazilian coast, in the region of the main breeding colonies of the species at the Tristan da Cunha Islands, in the South Atlantic Ocean. Taking into account that concentrations of chlorophytes is a proxy of productivity, we can speculate that the occurrence of the SAFS in southern Brazilian coast during relatively low concentrations of chlorophytes at the breeding colonies, may suggest that they just explore extra-limital waters when the productivity is low.

In the present study, we suggested that environmental factors are a possible driver of dispersion of the specimens, triggering the departure of the *A. tropicalis* individuals from their breeding colonies closest to south Brazil. We considered the period of departure of the SAFS from their South Atlantic breeding colonies to be the final months of summer (March) and austral autumn (April and May), based on telemetry data (M.R.I. unpublished data). In this context, it was assumed that the period of displacement of *A. tropicalis* between the colonies of origin (most likely the Tristan da Cunha Islands, where most of the individuals originated from according to Ferreira et al. 2008) and the coast of Rio Grande do Sul would last approximately four and five months. This period coincides with the end of the moulting phase after a small second peak in numbers of adult males ashore during March at their breeding colonies (Bester 1990). April and May represent the months when almost all adult males abandon the breeding colonies, as do most of

the other age and sex classes of this fur seal (Bester 1981), except lactating females (Bester 1981, 1995) that need to return to suckle their pups in between at-sea foraging trips (Bester 1995). After the moulting period, the SAFS males, and non-lactating females will adjust their foraging movements to the spatial distribution of resources (Wege et al. 2019). It is therefore reasonable to assume that due to relatively low local productivity, as a result of the decrease in the concentration of chlorophytes in the surrounding waters of the breeding colonies, interacting with anomalies of cold sea surface temperatures as found in this study, the fur seals would travel further afield.

During the estimated four and five months of dispersion, individuals would be influenced by a different oceanographic front until arrival in Brazil. Top marine predator foraging may be associated with oceanographic fronts, where they can find favourable feeding conditions in different the oceanic system (Kinder et al. 1983; Haney 1986; Ainley et al. 2005). Female SAFS from Amsterdam Island and Prince Edward Islands forage mainly in the Subtropical front and follow the seasonal latitudinal variation of that front (George et al. 2000; Kirkman et al. 2016). Following this rationale, the breeding colonies of SAFS are believed to be affected by the influence of anomalies on the Antarctic and Subantarctic fronts, such as the displacement of both towards the south, under the influences of SAM, SAOD, and IOD, all in their positive phase. Extreme weather events associated with aSST also can affect the foraging behaviour and population dynamics of king penguins *Aptenodytes patagonicus* in the Crozet Archipelago (Bost et al. 2015). In this study it was described that positive subtropical dipole events in the Atlantic and Indian Oceans associated with positive aSST in 1997, shifted the polar front further south, leading the penguins to forage in more distant areas from the colony and at greater depths. These changes resulted in a 34% decrease in population size, which only recovered in 2002.

Zhang and Han (2021) found that positive IOD events influence the increase of SSTs in the tropical Atlantic Ocean, initiating the Atlantic Niño. This increase in SSTs can further intensify the SAOD in the positive phase and shift the fronts further south, withdrawing nutrient-rich waters from the Antarctic and Subantarctic fronts in the opposite direction to the Subtropical front, decreasing primary productivity and, consequently, leading to a decrease in of SAFS prey in the Gough and Tristan da Cunha Islands. This high productivity in the Antarctic and Subantarctic fronts can be transported to the southern Brazilian coast by the dynamics of cyclogenesis in the Southern Hemisphere influenced by the positive phase of the SAM (Aquino 2012; Aquino et al. 2013; Ayers and Strutton 2013; Sallée et al. 2008), which can have induced individuals to look for food on the South American coast.

Years of positive SAM events during the fall seem to be related to negative monthly air temperature anomalies in southern Brazil (Aquino 2012). In order to explain the mechanism of this correlation, the author analyzed the fields of pressure anomalies at sea level, zonal and meridional wind speed for the autumn seasons. The decrease in sea level pressure favours cyclogenesis, and the zonal and meridional components of the wind are related to displacement in the longitudinal and latitudinal directions, respectively. Positive pressure anomalies (high-pressure zones) were observed in southeastern and southern South America and a marked cyclonic activity (low-pressure zone) in the South Atlantic Ocean, in the region of 40°S. The meridional wind component was displaced from south to north, from the Weddell Sea towards the south of Brazil. The associated high-pressure zones are responsible for the displacement of more intense cold air masses, from the Weddell Sea towards the south of Brazil during SAM positive

(Aquino 2012; Aquino et al. 2013). For the zonal component of the wind, Aquino et al. (2013) observed a wind flow of further south from the Gough Island, moving from east to west, towards the South American coast. The synergy between these events could make the coast of the southern region of Brazil favourable for individuals of SAFS that seek suitable areas for foraging.

Another event that could influence the occurrences of SAFS identified in the study is the spillage of the Agulhas vortices. The South Atlantic Ocean is influenced by interoceanic exchanges of waters, such as the “leak” of the Agulhas (Lutjeharms 2006). In addition to warmer and saline waters, the Agulhas vortices can take nutrients and phytoplankton from the Agulhas Current in the Indian Ocean to the South Atlantic Ocean. The more southerly shifts of ocean fronts, particularly the Subtropical Front, may strengthen the spillage of Agulhas vortices in the Atlantic Ocean (Beal et al. 2011), as well as positive IOD events, especially associated with ENSO, may prevent the Agulhas vortices from entering the Atlantic (Schouten et al. 2002).

Dower and Lucas (1993) found that concentrations of chlorophyll-a were lower inside the vortex and higher at the edge, as did Ansoerge et al. (2010) for cyclonic vortices. Wege et al. (2019) investigated how the environmental characteristics of foraging areas differ between two colonies of sympatrically breeding SAFS and *A. gazella* during summer and winter (2009-2015) in the Indian Ocean. During the winter, females of both species from Marion Island foraged more in regions associated with cyclonic eddies, probably because these vortices could provide pockets of productivity during the southern winter within a habitat that otherwise lacks resources (Wege et al. 2019). Although the eddies are known to weaken as they advance from their origin, some of them are known to arrive in southern Brazil. Guerra et al. (2018) analysed 140 Agulhas vortices that escaped to the South Atlantic Ocean from 1993 to 2016. Of these, 74 vortices were considered long-lived and went west, with three of them reached the Current of Brazil. In addition to the interaction with the Current of Brazil, one of the vortices was accompanied by interacting with two cyclonic swirls, which increased the speed of the chain three-fold. Therefore, we suggest that the vortices of the Agulhas current in displacement into the South Atlantic Ocean could serve as pockets of productivity for some individuals of SAFS dispersing to other areas of the South Atlantic.

The low concentrations of chlorophytes interacting with cold sea surface waters in the proximity of the fur seal breeding colonies at Gough and Tristan da Cunha islands during the study period can also influence the dispersion of SAFS to areas distant from their colonies in search of suitable areas for foraging. Arthur et al. (2017) used habitat models to predict which environmental factors would be influencing the choice of foraging habitat of *A. gazella* females, which presented a clear choice, passing through areas of presumably low quality in search of habitats that probably had better productivity. Wind speed, bathymetry, and distance from the breeding colony, as well as the concentration of chlorophyll-a and SST, were the main variables in the choice of foraging habitats (Arthur et al. 2017).

The results obtained in the present analysis suggest a connection from the closest colonies of SAFS at the Gough and Tristan da Cunha Islands to the southern South America coast. For the northeast and probably southeast regions of the Brazilian coast, the possible routes of dispersion of the species are via the South Atlantic Anticyclonic System (Rodriguez et al. 1995; Oliveira 1999; Ferreira et al. 2008), based on studies with plastic drift cards (Stander et al. 1969; Shannon et al. 1973). It was proposed that the SAFS would be displaced from the Southern Ocean to the Benguela Current towards the north, and in the vicinity

of the Equator, and then be carried by the South-Equatorial Current towards the Brazilian coast (Rodriguez et al. 1995; Oliveira 1999; Bastida and Rodriguez 2003). However, Ferreira et al. (2008) detected a specimen off the coast of Rio Grande do Sul that originated from the Crozet Islands (45° 95'S; 50°33'E), located between the African and Australian continents, in the South Indian Ocean. The authors suggested that this individual would have travelled approximately 16,500 km clockwise westward, probably helped by the West Drift and around Antarctica before reaching the cold Malvinas Current, where it would be taken to the south of Brazil. On the other hand, Bester (2021a) proposed a totally different route to explain the arrival of a vagrant SAFS at Ascension Island, one of the mid-Atlantic ridge islands (Bester 2021b). After reaching the Brazilian coast, most likely from the Tristan da Cunha Islands (Ferreira et al. 2008; Bester 2021a) the vagrant probably moved north, influenced by the flow of the Malvinas Current, and later reached Ascension Island. However, this may seem unlikely as the fur seal would have been struggling against the Brazilian and Anticyclonic current systems, as the Malvinas Current usually does not flow that far north in the region.

The most direct and accurate method to determine the routes and/or movements of a species with great dispersion power would be satellite telemetry. The only information available for dispersion/dispersal of SAFS from breeding colonies in the western part of the South Atlantic Ocean, is the unpublished, incomplete tracking data for two females from Tristan da Cunha Island, that travelled between 1,500 km and 2,000 km in the direction of South America at latitude 45°S in 2 months, suggesting an almost direct path from their breeding colony (Mamaal Research Institute, University of Pretoria, unpublished data). Since there are records of SAFS from the northeast to the south coasts of Brazil, it seems feasible to consider that two routes can be used by the individuals. Records from further north on the Brazilian coast suggest that their displacement was influenced by the South Atlantic Anticyclonic System, in association with the Benguela, South-Equatorial, and Brazil currents. Records from the Rio Grande do Sul in southern Brazil, suggest a possible route almost in straight line between Gough and Tristan da Cunha islands and South America. This journey would be influenced by the dynamics of ocean fronts and the formation of cyclogenesis in the region southwest of the South Atlantic Ocean, related to SAM and SAOD and perhaps related to other standards, as SIOD, IOD, and ENSO. Moreover, we can speculate that the individuals could take advantage of the rings of Agulhas vortex to reach southern Brazilian coast.

The present study provides the first investigation of the link between individuals of SAFS stranded in southern Brazil and climatic variability and environmental variables. In general, studies that investigate the influence of climatic-oceanographic variables on seal dispersion are mainly carried out through satellite tracking of individuals (Ream et al. 2005; Campagna et al. 2006; Constable et al. 2014; Bost et al. 2015). However, the analysis of the circumstances around the presence of seal carcasses found on the beaches is also an important source of information, allowing the observation of temporal and biological patterns associated with such occurrence. This was recently corroborated by Sousa-Lima et al. (2022), that suggested that the extra-limital occurrences SAFS must be considered as sentinels of changes of patterns related to biological, physical and oceanographic conditions (including their anomalies), which may be under the influence of the polar regions of the southern hemisphere.

Our results indicated that climate variability is influencing the ecology SAFS, because it affects the environmental factors close to the breeding colonies, which act consequently as a driver of dispersion

of the species. Considering the current scenario of global climate change, we expect that SAFS will continue to disperse to areas beyond their regular distribution, not only towards the coasts of South America, Australia and Africa (for a review see Bester 2021b and Sousa-Lima et al. 2022), but also further south, since models of species distribution and statistical climate suggest a shift in the distribution of marine animals towards higher latitudes by 2100 (Cheung et al. 2013).

But how big and significant the expansion of SAFS extra-limital distribution will be? Should we expect potential establishment of new haulout areas of the species in southern oceans? These are the unanswered questions that are in the scientists' minds, mainly due to the global climate change scenario and because the species has the greatest dispersion among pinnipeds in the Western South Atlantic (Hofmeyr 2015). To predict potential colonization process of new breeding sites and understand the dynamics between habitats and species' niche will demand a multiple monitoring program on the species dispersal movements, population census, extra-limital records of the species, as well as environmental, climatic and oceanographic modelling. It seems a huge prediction challenge, but SAFS fits perfectly into it.

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COMPLIANCE WITH ETHICAL STANDARDS

All authors declare they had no conflict of interest whatsoever.

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Ethics approval

All records used for this research derived from animals stranded and naturally dead. No animal was intentionally caught or killed during the summarized research. All procedures conducted in the study were in accordance with the licenses for capture, collection, transport and exhibition of fauna and zoological material issued by the Ministry of the Environment, Government of Brazil, Brazilian Institute of the Environment and Renewable Natural Resources - IBAMA and System Brazilian Authorization and Information on Biodiversity - SISBIO, nº 015-04, nº 12022-1 and nº 16586-2. These licenses certify that the authors did not violate any ethical rules when collecting animal samples.