



OPEN Population changes in a Southern Ocean krill predator point towards regional Antarctic sea ice declines

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While foraging, marine predators integrate information about the environment often across wide-ranging oceanic foraging grounds and reflect these in population parameters. One such species, the southern right whale (*Eubalaena australis*; SRW) has shown alterations to foraging behaviour, declines in body condition, and reduced reproductive rates after 2009 in the South African population. As capital breeders, these changes suggest decreased availability of their main prey at high-latitudes, Antarctic krill (*Euphausia superba*). This study analysed environmental factors affecting prey availability for this population over the past 40 years, finding a notable southward contraction in sea ice, a 15–30% decline in sea ice concentration, and a more than two-fold increase in primary production metrics after 2008. These environmental conditions are less supportive of Antarctic krill recruitment in known SRW foraging grounds. Additionally, marginal ice zone, sea ice concentration and two primary production metrics were determined to be either regionally significant or marginally significant predictors of calving interval length when analysed using a linear model. Findings highlight the vulnerability of recovering baleen whale populations to climate change and show how capital breeders serve as sentinels of ecosystem changes in regions that are difficult or costly to study.

Climate change has strong effects on marine ecosystems and its impacts have ramifications throughout the food web^{1–3}. In the Southern Ocean (SO), responses to climate change vary regionally and are often masked due to high levels of natural variability^{3–5}. The use of sentinel species in improving our understanding of environmental change is quickly gaining recognition, particularly in data-sparse and highly variable regions such as the SO^{6,7}. Baleen whales are especially useful in this regard due to their life histories as migratory capital breeders, which entails a period of intensive feeding that must fulfill the immense energetic requirements associated with reproduction^{8–10}.

One such baleen whale, the southern right whale (*Eubalaena australis*; hereafter SRW), has been monitored extensively since 1979 in the South African calving ground to assess its continued recovery from extensive whaling^{11–13}. Although the population is still growing steadily, results of this long time series reveal a decline in reproductive rates after 2009, with an increased probability of a female needing two consecutive resting years between calving¹⁴. Over the same period a decline in maternal body condition¹⁵, and a northward shift in foraging distribution were also observed^{16,17}. Due to the temporal scale, these databases provide an opportunity to explore potential environmental drivers behind the observed changes.

Based on historical whaling and telemetry data, South African SRWs are known to make use of high-latitude foraging grounds^{18,19}, with Antarctic krill (*Euphausia superba*) playing a significant role in meeting the energy requirements essential for reproduction^{20,21}. This dependence on krill stems from analyses of the stomach contents of 249 SRW caught during the illegal soviet whaling activities, with 99% of the stomachs of whales caught south of 50°S containing Euphausiids (although it is not specified whether all were Antarctic krill)¹⁸. Additionally, there are anecdotal reports of SRW feeding on Antarctic krill^{22,23}.

The observed reduction in reproductive rates and maternal body condition in South African SRW are therefore believed to be strongly linked to reduced availability of Antarctic krill^{15,20,21,24}. In turn, Antarctic krill have an intimate relationship with sea ice, using it primarily as a foraging habitat that offers protection from predation, particularly during early developmental stages^{25,26}. This association with sea ice and the role of environmental parameters in modulating the primary production necessary to support high densities of Antarctic krill results in vulnerability to environmental change^{27,28}. In fact, it has been proposed that large-scale recruitment failure of Antarctic krill due to unfavourable environmental conditions in a given year can lead to a 3- to 4 fold variation in Antarctic krill biomass and take several years of good conditions to regain initial densities²⁹.

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A wealth of krill data has been collected over the last century, particularly along the Antarctic Peninsula and south-west Atlantic³⁴. However, due to a shortage of repeat surveys, the patchy nature of Antarctic krill swarms and inconsistencies in sampling methods in the region of interest, assessing changes in prey distribution and biomass over the period of observed population level changes is not possible²⁸. Therefore, proxies for foraging habitat quality are necessary in evaluating changes in environmental conditions which are known to alter prey availability (Fig. 1).

Here, we use an approach guided by our knowledge of South African SRW population demographics, as well as migratory and foraging behaviour to assess environmental changes that may have rendered high-latitude foraging grounds less favourable for Antarctic krill recruitment. We investigate temporal patterns in four variables which characterize Antarctic krill availability across the known foraging domain of South African SRW's. In doing this, we evaluate the threat that future climate change imposes on krill-predators including still-recovering baleen whales, as well as the utility of baleen whale populations in monitoring the impacts of climate change on ecosystem functioning in the SO.

Methods

All statistical analysis and plots were performed using the R language environment³⁰, with the exception of the spatial plots in Fig. 6 which were created with QGIS version 3.26.1.

Calving interval

Annual aerial surveys of the South African SRW calving ground have been conducted since 1979 between Nature's Valley and Muizenberg, providing an extensive time-series of population demographic data. During these surveys, photographs of individuals, with a focus on mothers with calves, are taken to allow for individual identification through distinct callosity patterns and variations in dorsal pigmentation³¹. This process allows for matches between years to be made, and from this, to calculate the calving interval as described in Best et al. (2001). Three-year calving intervals are considered normal for SRW, including one year of gestation, one year of lactation and one year of recovery^{13,32}. Four-year intervals are regarded as either coming from a failure to conceive (and thus an extra year of recovery) or an early abortion, whereas 5-year intervals are regarded as stemming from late-term abortions³². Both 4- and 5-year intervals are thus regarded as reproductive failure. In this study, only details of 3-, 4- and 5-year intervals are provided, because longer calving intervals are difficult to interpret as they may include missed observations.

Study area: feeding grounds and Antarctic krill data

The core feeding regions for South African SRWs were inferred from American (1780–1920) and Soviet whaling (1951–1971) data as well as from a telemetry study conducted in 2001^{18,19,33}. Due to the potential spatial bias of whaling data, the study area was not limited to those areas with catches alone. Instead, a grid (divided by 5° latitude × 25° longitude cells) was used to connect areas of whaling catches and regions frequented by individuals tagged by Mate et al. (2011), creating a total of 16 regions (Fig. 2).

Antarctic krill density and distribution data were obtained from KRILLBASE³⁴. Densities from individual net hauls collected during surveys between 1926 and 2016 were averaged over a 2° × 2° grid.

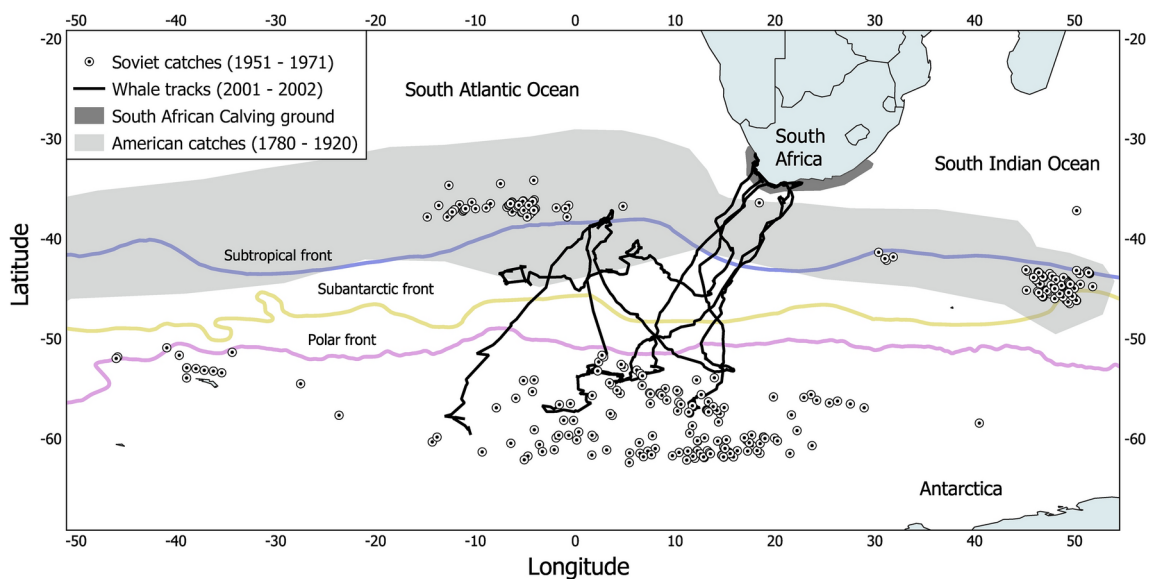


Fig. 1. Southern right whale offshore foraging habitat. American and Soviet southern right whale (*Eubalaena australis*) catches and satellite tracks of five individual southern right whales tagged in 2001^{18,19,34}, to summarize knowledge of offshore foraging habitat.

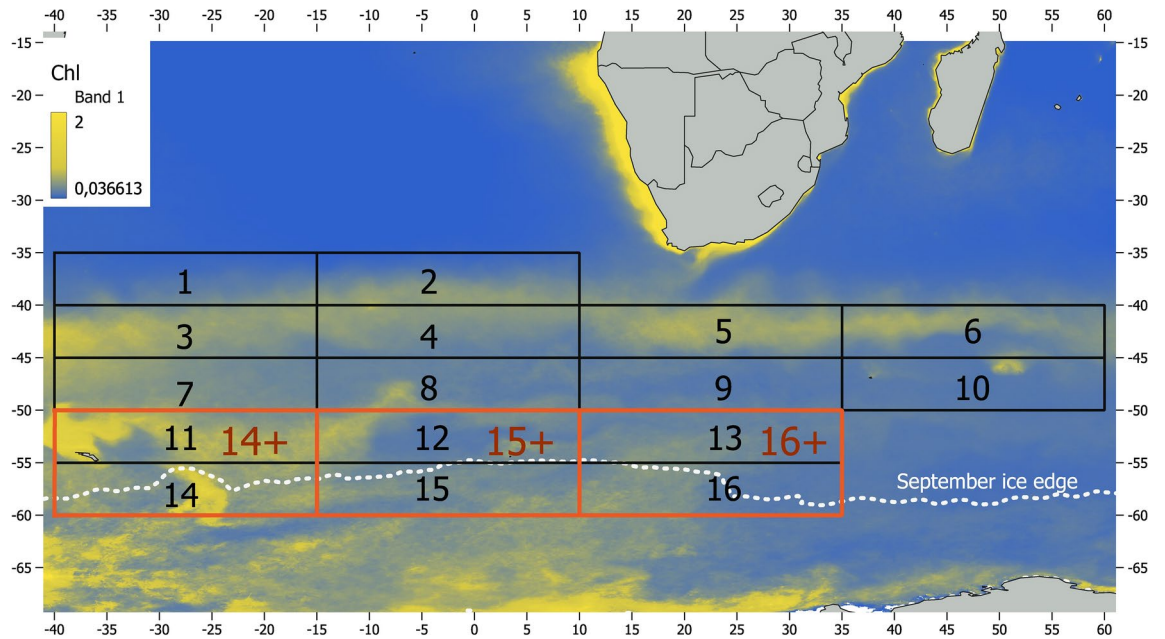


Fig. 2. Selected regions (Regions 1–16) representing South African southern right whale (*Eubalaena australis*) foraging grounds. Orange boxes combine regions where sea ice was analysed and referred to as 14+ (combination of Regions 11 and 14), 15+ (combination of Regions 12 and 15), and 16+ (combination of Regions 13 and 16) in the text. Colours represent the mean summer (January, February, and March) chlorophyll concentrations (2000–2020) from <https://oceancolor.gsfc.nasa.gov> using Terra-MODIS data, and the dashed line represents the mean position of the September 60% sea ice concentration contour (1988–2020) from Climate Data Records (CDR) from NOAA/NSIDC.

Measures of foraging habitat quality

Four measures of potential foraging habitat quality were analysed over the period. Satellite-derived chlorophyll was used to develop two indicators of general foraging conditions for SRW's, and two variables of sea ice were used as measures of Antarctic krill habitat suitability.

Chlorophyll

Daily 4 km resolution Terra-MODIS chlorophyll (mg/m^3) ocean colour data were obtained from <https://oceancolor.gsfc.nasa.gov> as a proxy for potential food availability through primary production. From these data, a monthly chlorophyll index was calculated for each of the 16 regions by computing the pixel-wise monthly cumulative sum from daily chlorophyll data and calculating the spatial average for each region in every month (2000–2020). Only months with more than 90% of measurement days were included. The monthly standard deviation of mean monthly chlorophyll was calculated and averaged for each region as a measure of food variability over the same period (2000–2020). The anomalies were calculated by subtracting the monthly means from the mean climatology of the seasonal cycle over the whole period (2000–2020). Three-year moving means were calculated for the Monthly Chlorophyll Index and chlorophyll standard deviation using the Zoo package in R³⁵.

Sea ice

All sea ice data was derived from 25 km resolution sea ice concentration data from the sea ice Climate Data Records (CDR) from NOAA/NSIDC to make sea ice metrics comparable^{36,37}. Regions influenced by sea ice (Regions 11–16) were pooled into longitudinal bands and were named based on the three most southerly regions (Region 14+ combines Regions 11 and 14; Region 15+ combines Region 12 and 15; Region 16+ combines Region 13 and 16; see Fig. 2). The mean monthly sea ice concentration (SIC) was calculated for each region. The marginal ice zone (MIZ) variability indicator proposed by Vichi (2022) was used³⁸, which is defined as the standard deviation of daily SIC anomalies from the monthly mean. The mean monthly MIZ extent (for the period 1988–2020) was calculated by filtering out pixels with low chances of encountering MIZ conditions³⁸, and calculating the area by summing the number of pixels and multiplying by the pixel area. Monthly MIZ extent and SIC anomalies were calculated by subtracting the climatological monthly cycle computed over the 1988–2020 period. Five-year moving means were calculated for SIC and MIZ extents using the Zoo package in R³⁵. Additionally, spatial anomaly plots of the MIZ variability indicator and SIC for October and November are also presented to highlight changes over selected periods before and after 2009, being the onset of the observed changes in SRW reproductive rates. These diagnostics were created by computing 5-year means and subtracting them from the 1988–2020 mean.

Linear models

Linear models were developed to quantitatively assess the temporal relationship between MIZ, SIC, Monthly Chlorophyll Index, chlorophyll standard deviation and calving interval. To test this, a linear model was fitted to the annual rolling mean of each predictor, with the calving interval as the response variable. Only the years 2000–2020 were assessed since this is the time range with data from all four variables. The predictor variables were MIZ extent, SIC, Chlorophyll Index, and chlorophyll standard deviation at 1- and 2-year lags. This is under the hypothesis that, at the individual level, and assuming a 3-year calving interval, foraging conditions within the 2 years leading up to a mother giving birth are the most influential determinant of reproductive success⁹. All predictor variables were normally distributed. However, the calving interval was lognormally distributed, so the natural logarithm of the calving interval was used in the model. Collinearity between continuous predictors was assessed using a cross-correlation matrix. A high threshold of collinearity ($r > 0.9$) was chosen since the focus of this exercise was to assess the role of all variables investigated and collinearity between highly related variables is inevitable. Predictors were considered significant at the $p < 0.05$ level, and marginally significant between $0.05 < p < 0.10$. Three linear models were developed for each of the three sea ice regions (Regions 14+, 15+, and 16+).

Results

Calving interval

The period between 1983 and 2009 was characterized by a high proportion of 3-year calving intervals, with a mean proportion \pm standard deviation of 0.86 ± 0.05 (Fig. 3). Between 2010 and 2015, the proportion of 3-year calving intervals declined rapidly, and 4- and 5-year calving intervals became more prevalent. The mean proportion \pm standard deviation of 3-year calving intervals between 2010 and 2020 was 0.46 ± 0.15 . Following this period, 2016–2020 saw a cessation to this rapid decline in 3-year calving intervals, with variable proportions in 3-, 4- and 5-year intervals (Fig. 3).

Regional changes in monthly chlorophyll index

Monthly chlorophyll index displayed considerable regional and temporal variability. Generally, regions north of 45°S revealed no noteworthy changes over the period (Fig. 4a, b). An exception to this was Region 6 which experienced an increase in chlorophyll production biomass after 2015 (Supplementary Fig. S1d). More southerly regions, particularly south of 50°S exhibited substantial increases in monthly chlorophyll index after 2009 in December–March (Fig. 4c, d, Supplementary Fig. S2d, S3). This signal was strongest in Regions 11 and 12 (Supplementary Fig. S2 and Fig. 3d respectively).

Environmental changes to the seasonal sea ice zone

The three sea ice regions displayed high-levels of month-to-month variability. Two distinct periods of reduced sea ice were observed over the time series. The first period occurred between 1996 and 2002 and was centred over Region 16+, with declines in both SIC and MIZ extent in this region, but only in SIC in Regions 14+ and 15+ (Fig. 5a, b and Supplementary Fig. S4 and S5). The second period occurred between 2008 and 2014 and

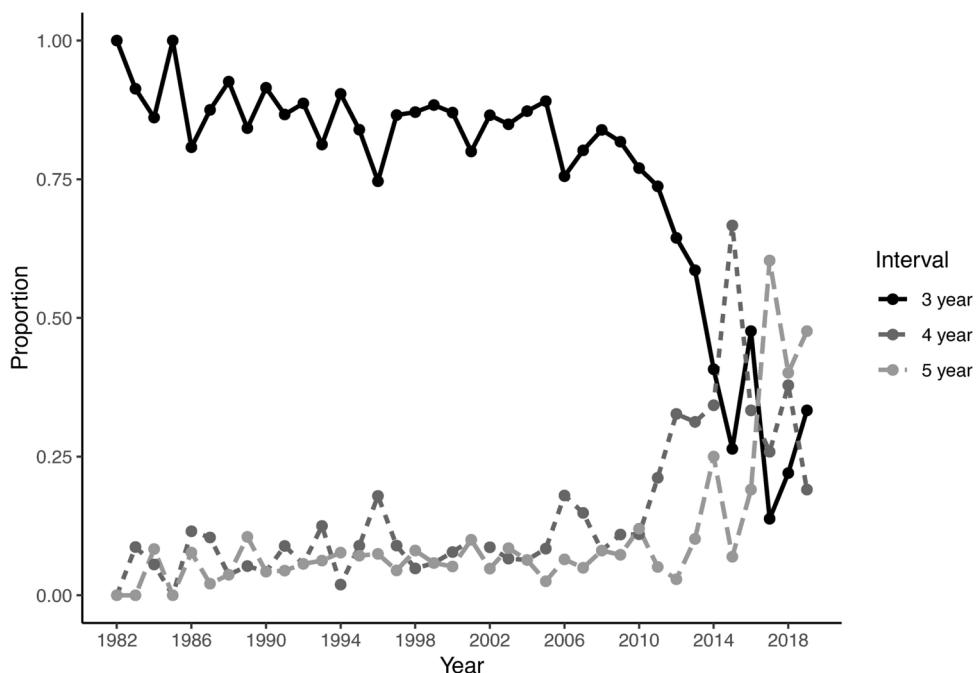


Fig. 3. Annual proportion of 3-, 4- and 5-year calving intervals for the South African population of southern right whales (*Eubalaena australis*).

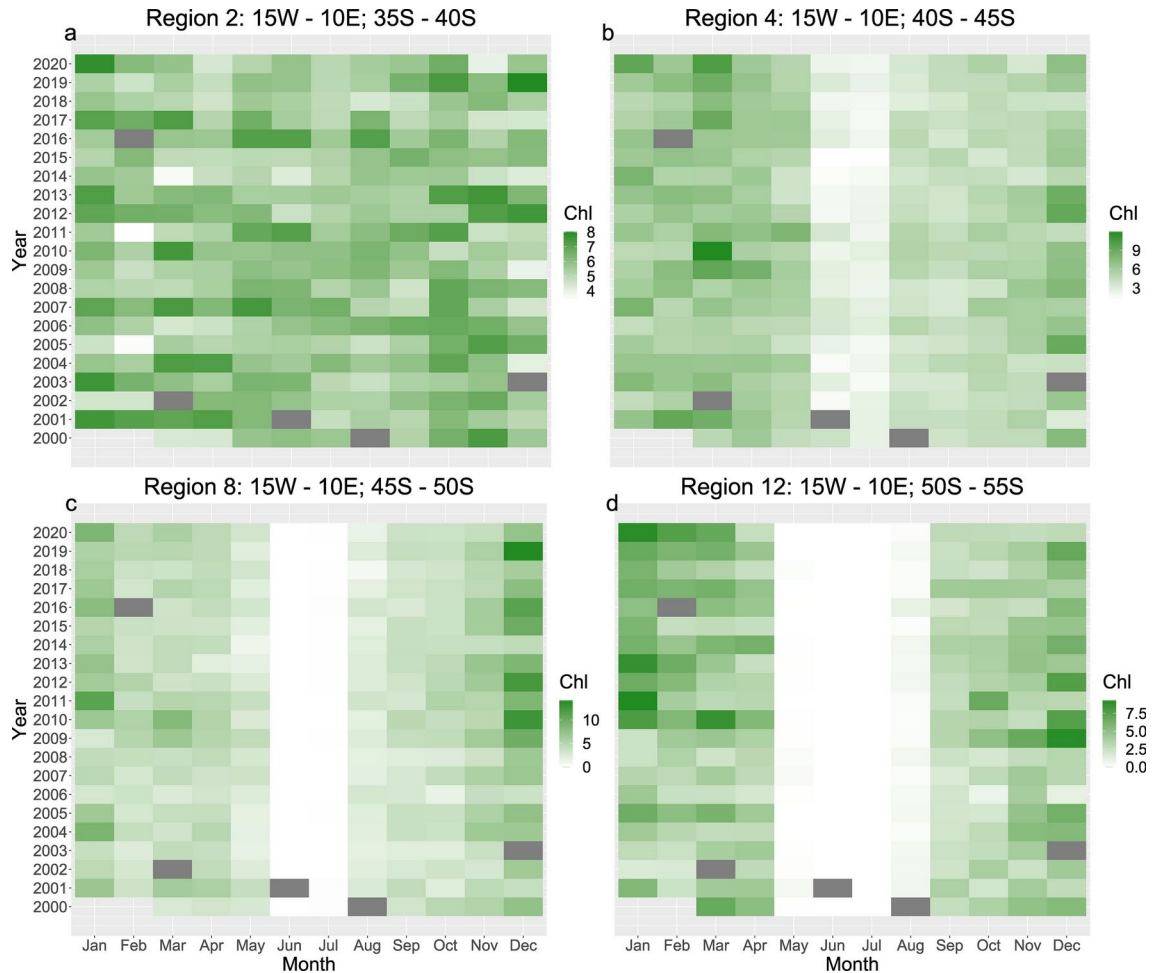


Fig. 4. Heat maps of monthly chlorophyll index for selected regions (2000–2020). Monthly mean chlorophyll index heat maps for (a) Region 2, (b) Region 4, (c) Region 8 and (d) Region 12 over the time series (2000–2020). Grey blocks indicate months which had insufficient observations to compute the monthly chlorophyll index (see Sect “Methods”). Refer to Supplementary for regions not depicted here.

was most intense in Regions 14+ and 15+ with substantial declines in both MIZ extent and SIC (Fig. 5a, b and Supplementary Figs. S4 and S5). Patterns in primary production metrics mirrored these observed changes in sea ice, with elevated Monthly Chlorophyll Index and chlorophyll standard deviation during periods of reduced SIC and MIZ extent, and increased MIZ variability (Fig. 5c, d and Supplementary Figs. S4 and S5). A notable and abrupt increase in both Monthly Chlorophyll Index and chlorophyll standard deviation was observed after 2009 in Regions 14+ and 15+ (Fig. 5c, d and Supplementary Fig. S4). Region 16+ also experienced an increase in primary production metrics after 2009, however, highest positive anomalies occurred between 2011 and 2016.

Spatial data shown in Fig. 6 provides some context to the regional and temporal variability in sea ice signals shown in Fig. 5. Sea ice anomalies of 5-year periods help to elucidate large-scale changes to the sea ice environment, focussing on the two distinct periods of negative SIC anomalies observed over the time-series (Fig. 6). The period between 2008 and 2012 reveals an expansive area of negative SIC anomalies, and southward contraction in the MIZ along the Antarctic Peninsula and South Atlantic, encompassing the region where most of the global Antarctic krill stock resides (Fig. 6). This configuration of anomalies was unique to the timeframe examined (see Supplementary Figs. S6 and S7). On the contrary, the period of reduced sea ice between 1998 and 2002 revealed no clear pattern in the spatial distribution of anomalies, particularly over important regions for Antarctic krill (Fig. 6).

Effect of environmental variables on calving interval

All variables analysed were found to influence calving intervals but in different regions and with variable significance (see Table 1). In Region 14+, Monthly Chlorophyll index and chlorophyll standard deviation at 1-year lags were the only variables significantly impacting calving intervals ($p=0.035$ and 0.029 respectively). In Region 15+, MIZ extent at a 2-year lag ($p=0.003$) and SIC at a 2-year lag ($p=0.023$ and 0.04 respectively) were found to impact calving intervals significantly. Additionally, MIZ extent ($p=0.056$), chlorophyll index ($p=0.058$) and chlorophyll standard deviation ($p=0.09$) were found to be marginally significant predictors. No environmental predictors in Region 16+ were found to significantly influence calving intervals.

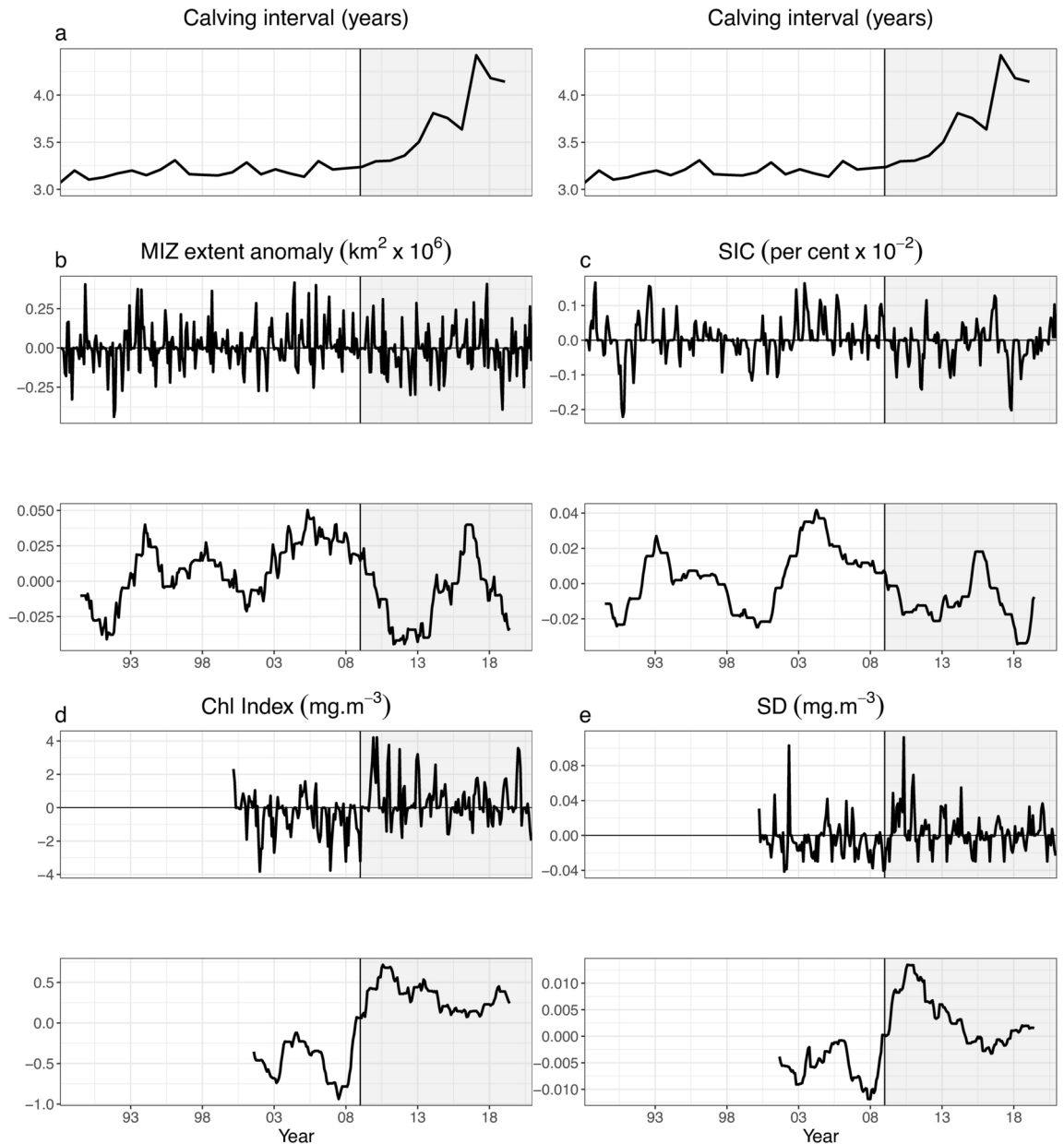


Fig. 5. Indicators for Region 15+. Monthly anomalies (top panel) and rolling mean of the anomaly (bottom panel) for (a) mean monthly marginal ice zone (MIZ) extent anomaly compared to the 1988–2020 mean, (b) mean monthly sea ice concentration anomaly (SIC) compared to the 1988–2020 mean, (c) monthly chlorophyll index anomaly compared to the 2000–2020 mean and (d) Monthly chlorophyll standard deviation anomaly compared to the 2000–2020. The grey-shaded region highlights the period of reduced southern right whale reproductive success after 2009 (refer to Fig. 3). Refer to Supplementary for regions not depicted here.

Discussion

This study reveals large-scale environmental changes in the seasonal sea ice zone in important foraging grounds for South African SRWs, which likely drove a decline in the population's reproductive success^{14–16}. A southward contraction in sea ice marked by a decrease in MIZ extent and a decline in SIC of up to 15–30% over 5 years affected the region where most of the Antarctic krill stock is known to reside between 2008 and 2012. These reductions occurred in conjunction with a more than two-fold increase in primary producers' biomass in regions that experienced the greatest declines in sea ice. Furthermore, all variables assessed were either found to be significant or marginally significant predictors of calving interval length when fitted with a linear model. Due to the intimate relationship between sea ice and Antarctic krill, these changes are likely to be an indication of reduced prey availability for SRWs at high-latitudes. On the other hand, mid-latitude foraging grounds (regions north of 50°S) experienced regional increases in chlorophyll metrics but no indication of changes that would have ramifications for prey abundance at large spatial scales.

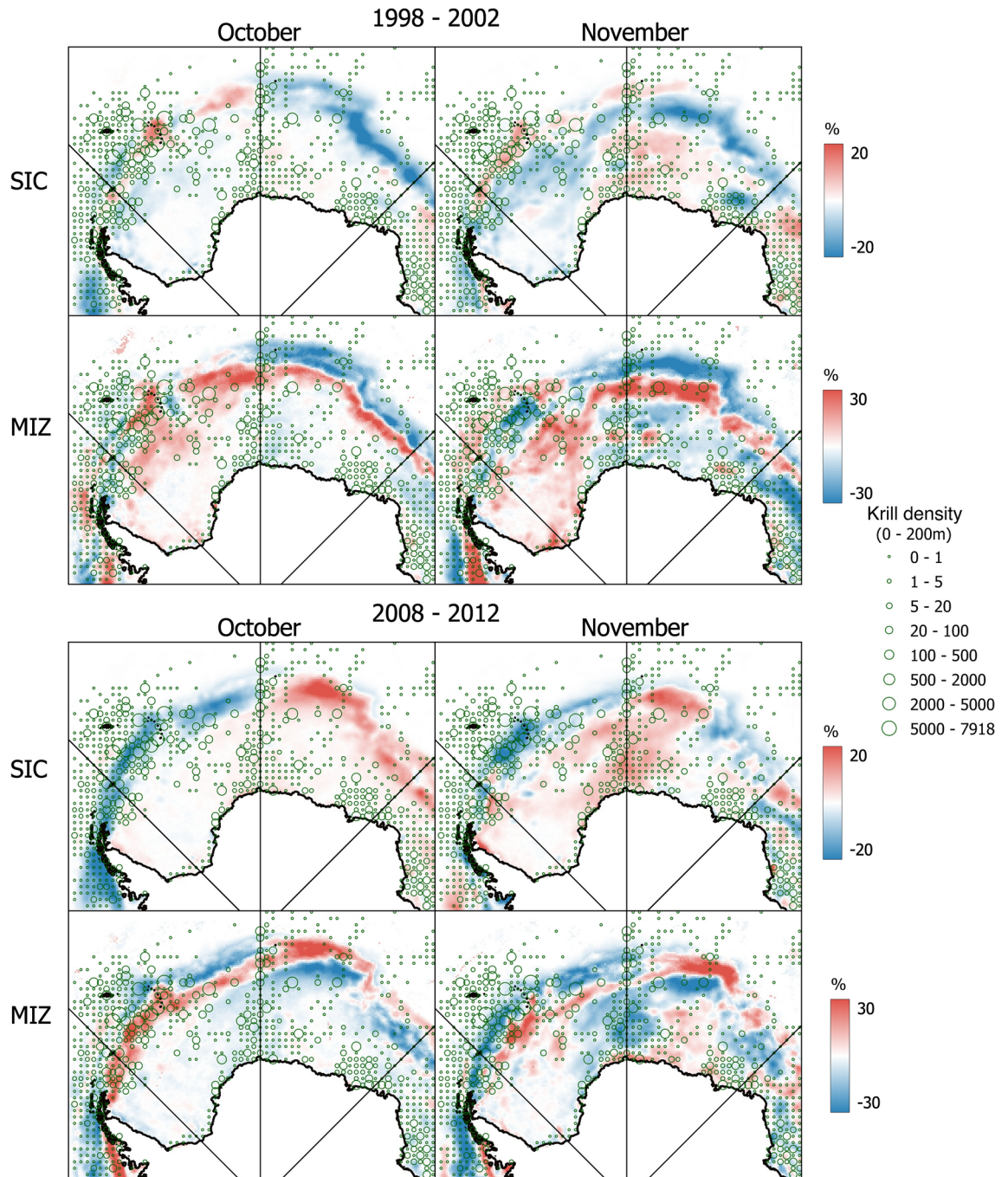


Fig. 6. Sea ice concentration (SIC) and marginal ice zone (MIZ) indicator anomalies. The two periods of reduced sea ice (1998–2002 and 2008–2012) are presented here to compare the spatial configuration in anomalies. The anomalies represent 5-year means compared to the 1988–2020 mean. Antarctic krill densities from surveys between 1926 and 2016 are also presented³³. Refer to Supplementary figures for regions not depicted here.

The influence of food availability on calving success is well documented in baleen whales due to the elevated energetic costs associated with reproduction^{39–41}. Specifically in SRW, sea ice has been shown to influence population demographics due to its crucial role in the recruitment success of Antarctic krill^{20,21,24–26,28,42}. Considerable uncertainty exists about the true nature of the relationship between sea ice and Antarctic krill abundance and biomass. Despite these uncertainties, the role of sea ice in providing sheltered foraging habitat is well established²⁸. Antarctic krill have relatively long and complex life histories and may be dependent on repeated years of favourable ice conditions^{43,44}. Additionally, the presence of sea ice is a strong mediator of ecosystem state and plays a pivotal role in shaping community assemblages. Low ice years, for example, have been found to result in the dominance of gelatinous zooplankton such as salps (*Salpa thompsoni*)^{43,45}. Sea ice

Predictors	Region 14+			
	Estimate	SE	t	P
MIZ (1 year lag)	0.125	0.100	1.196	0.266
MIZ (2-year lag)	0.000	0.090	0.001	0.999
SIC (1 year lag)	-0.683	0.590	-1.157	0.281
SIC (2-year lag)	-0.609	0.516	-1.181	0.272
Chl (1 year lag)	0.007	0.003	2.539	0.035*
Chl (2-year lag)	0.002	0.003	0.456	0.661
Chl SD (1 year lag)	-0.383	0.145	-2.650	0.029*
Chl SD (2-year lag)	0.203	0.283	0.718	0.493
Model	SE	DF	Adj-R ²	P
	0.005	8.000	0.635	0.024*
Predictors	Region 15+			
	Estimate	SE	t	P
MIZ (1 year lag)	0.110	0.052	2.23	0.056
MIZ (2-year lag)	-0.190	0.044	-4.29	0.003**
SIC (1 year lag)	-0.550	0.200	-2.80	0.023*
SIC (2-year lag)	0.570	0.230	2.45	0.040*
Chl (1 year lag)	0.010	0.004	2.21	0.058
Chl (2-year lag)	0.001	0.005	0.21	0.840
Chl SD (1 year lag)	-0.550	0.290	-1.92	0.090
Chl SD (2-year lag)	0.200	0.280	0.72	0.490
Model	SE	DF	Adj-R ²	P
	0.004	8.000	0.779	0.004**
Predictors	Region 16+			
	Estimate	SE	t	P
MIZ (1 year lag)	0.090	0.198	0.456	0.661
MIZ (2-year lag)	0.021	0.102	0.203	0.844
SIC (1 year lag)	-0.541	0.620	-0.871	0.409
SIC (2-year lag)	-0.390	1.300	-0.300	0.770
Chl (1 year lag)	0.011	0.012	0.969	0.361
Chl (2-year lag)	-0.001	0.009	-0.060	0.950
Chl SD (1 year lag)	-0.690	0.790	-0.870	0.410
Chl SD (2-year lag)	0.240	0.510	0.480	0.650
Model	SE	DF	Adj-R ²	P
	0.007	8.000	0.302	0.199

Table 1. Linear model results of the effects of 1- and 2-year lagged variables in Region 14+, 15+ and 16+ on the calving interval. Significance levels are indicated with asterisks: * $p < 0.05$ and ** $p < 0.01$. *MIZ* marginal ice zone, *SIC* sea ice concentration, *Chl* monthly chlorophyll index, *Chl SD* chlorophyll standard deviation.

has been impacted by climate change through ocean and atmospheric warming⁴⁶ and increased poleward wind stress associated with a more positive Southern Annular Mode which prevents sea ice expansion^{47,48}. Therefore, there is considerable concern within the scientific community on the fate of Antarctic krill in the face of rapid climate change²⁸.

The global Antarctic krill population is predominantly concentrated along the Antarctic Peninsula and the South Atlantic Ocean, with the former considered a vital source region for the latter^{25,45,49,50}. Based on sea ice conditions described here, the years between 1988 and 2003 appeared to be highly favourable for Antarctic krill recruitment, with extensive sea ice cover over the Antarctic Peninsula and South Atlantic region of the SO. Changes began occurring in the 2000s along the Antarctic Peninsula, with declines in SIC and reduced stability of the MIZ. The analysis performed by Ichii et al. (2023) also revealed a regime shift after the 2000s, characterised by significantly reduced probabilities of Antarctic krill transport from the Antarctic Peninsula to the South Atlantic region due to reduced sea ice cover⁵². Therefore, changes to transport processes because of declines in sea ice likely began to negatively impact prey abundance in regions reliant on source regions such as South Georgia and Bouvet Island after 2000^{50–52}.

Linear models only indicated a significant effect of sea ice, particularly MIZ extent, in region 15+. Region 14+ displayed high levels of month-to-month variability in MIZ extent and SIC, which likely prevented a significant effect of sea ice on calving intervals from emerging. Region 16+ also didn't reveal any sea ice effects, however this is likely due to the atmospheric circulation patterns that drive regional changes in sea ice extent. The

sea ice contraction that occurred in the late 2000s and early 2010s was driven by the presence of the Amundsen Sea Low, which acts to reduce ice along the Antarctic Peninsula, and expand ice over the South Indian Ocean⁵³.

In conjunction with changes in the sea ice environment post-2009, primary production substantially increased in almost all high-latitude feeding grounds. Additionally, primary production metrics were significant, and marginally significant predictors of calving interval in Regions 14+ and 15+ respectively. Towards the end of the timeseries (2016–2020), primary production and sea ice metrics return to conditions similar to those seen prior to the increase in calving cycles. At the same time, some recovery is evident in the calving interval, however 4- and 5-year intervals were still more prevalent than 3-year intervals.

The increasing trends in chlorophyll concentration are in line with other analyses of chlorophyll trends in the seasonal sea ice zone and are likely a reflection of changes in sea ice dynamics which drive changes in primary production and phytoplankton community structure^{54–57}. Reduced sea ice extends the growth season for pelagic phytoplankton due to increased periods of open-water conditions from an earlier retreat and later onset of sea ice growth, which allows for more solar radiation to penetrate the water column⁵⁷. At the same time, ice-dependent zooplankton experience a shorter duration of protection under the sea ice habitat, potentially affecting their life histories and rendering them more susceptible to predation^{58,59}. Furthermore, salps have been found to outcompete Antarctic krill under low ice regimes due to faster reproductive and clearance rates, with studies along the Antarctic Peninsula reporting increases in the ratio of salps to krill in recent years^{43,60,61}. Reduced grazing rates on phytoplankton during periods of low Antarctic krill stocks may have also contributed to the elevated primary production observed in the open ocean⁶². For example, Ryabov et al., (2017) reported the occurrence of stronger seasonal blooms and increased phytoplankton biomass during periods of reduced Antarctic krill biomass²⁷. Additional pressure on Antarctic krill stocks is likely being added by recovering baleen whale populations, particularly humpback (*Megaptera novaeangliae*) and fin (*Balaenoptera physalus*) whales, as well as the growing Antarctic krill fishery^{63–66}. Indeed, intraspecific competition for Antarctic krill is likely increasing as most species recover from commercial whaling^{67,68}. This will inevitably result in the emergence of density-dependent changes in foraging behaviour with implications for reproductive success. Unlike what is observed here, such changes would likely be gradual as species steadily recover, and would act as an additional pressure determining the carrying capacity of the system under different regimes of climate variability. How other krill-dependent species are impacted by the observed environmental changes is difficult to ascertain as time series data on demographic parameters of marine predators, particularly SO baleen whales, are scarce.

Additional data indicative of a South African SRWs response to changing climate conditions in their high latitude foraging grounds relates to changes in their foraging behaviour. This was inferred from shifts in stable isotope values over the same period as the observed declines in reproductive rates¹⁶, with a suggested reduction in the use of historically important high-latitude foraging grounds¹⁷. However, it is evident that these adaptive strategies through altering migratory behaviour are associated with energetic costs as revealed by Vermeulen et al. (2023). These energetic costs may arise due to reduced foraging efficiency in the high-latitudes, individuals having to undertake longer migrations, and/or ecological traps arising from site fidelity to foraging grounds^{16,69,70}. Ecological traps arise due to the continued usage of learned migratory routes despite environmental changes which have rendered regions unfavourable for foraging. Therefore, females may be taking longer to achieve the energy requirements necessary to produce a calf, thereby decreasing in body condition¹⁵, and lengthening their calving interval¹⁴.

The presented results highlight the sensitivity of SRWs to environmental variability in their foraging grounds and the risk that climate change poses to continued population recovery post-whaling. This sensitivity also reveals the potential of the species as climate change sentinels in a system of ever-increasing rates of change and the potential baleen whales hold in improving our knowledge of future impacts of climate change in the SO and other krill-dependent predators.

Data availability

All chlorophyll and sea ice concentration metrics were obtained from online sources (refer to Sect “Methods”). The marginal ice zone indicator and calving interval data sets are available from the corresponding author upon reasonable request.

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Author contributions

M.G. wrote the paper, performed the analysis and assisted with conceptualizing the idea. M.V. provided guidance, assisted with conceptualizing the idea and edited the manuscript. E.V. provided guidance, assisted with conceptualizing the idea and edited the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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