

Supplementary materials

Fisheries bycatch mitigation measures as an efficient tool for the conservation of seabird populations

Anaïs Dasnon^{1,2}, Karine Delord¹, Adrien Chaigne², Christophe Barbraud¹

¹ Centre d'Etudes Biologiques de Chizé, CNRS UMR7372, 79360 Villiers en Bois, France

² Réserve Naturelle Nationale des Terres Australes Françaises, TAAF, rue Gabriel Dejean, 97458 Saint-Pierre, France

Corresponding author: Anaïs Dasnon. E-mail: anais.dasnon@taaf.re

Appendix S1: Species' ecology and study area

White chinned petrel

The white-chinned petrel is a large Procellariidae (wingspan 51-58 cm, weight 1.1-1.5 kg) distributed throughout the southern hemisphere from sub-tropical areas during the non-breeding season (Péron et al., 2010) to subantarctic areas where it breeds in burrows on remote islands from September to early-May (Brooke, 2004). The white-chinned petrel has a slow demographic strategy with low fertility, late age at first breeding and high site and mate fidelity (de L. Brooke, 2004). Individuals do not breed systematically every year and can skip breeding. Breeding pairs meet regularly after arrival on breeding sites in mid-September, just before the pre-laying exodus that will last a month. Burrows are large, built on well drained soils and often have a small pool of water at the entrance. Eggs are laid in November and chicks hatch in January. Males and females alternate their foraging trips at sea and feed on fish, krill, squid as well as on baits and fishery wastes (Catard et al., 2000; Delord et al., 2010; Ridoux, 1994). During incubation, adults search for food at sea several hundred or thousands of kilometres from the nest and stay at sea from seven to 11 days in average (Catard et al., 2000). After hatching breeding adults have dual foraging tactics. They can make short trips close to breeding sites, less than 400 kilometres in less than three days, and alternate with long trips to the Antarctic icefront where they mainly feed on Antarctic krill (*Euphausia superba*) (Bestley et al., 2018; Péron et al., 2010; Delord et al., 2010), staying at sea sometimes more than 12 days and might cover up to 7800 kilometres (Catard et al., 2000). Fishing wastes and baits have been regularly found in adults and chicks stomachs (Catard et al., 2000; Delord et al., 2010), indicating that they encounter and interact with fishing vessels. Chick rearing ends in April when chicks fledge. Juvenile departure from Crozet breeding sites is followed by a two months North or North-East trip before they join their foraging habitat in the Eastern coast of South Africa (De Grissac et al., 2016). Little is known about juveniles because they do not come back to breeding sites until sexual maturity, reached at 4 years of age (Barbraud et al., 2008). Adults migrate in subtropical upwelling areas such as the Benguela current in the South-West of Africa in May where they spend the non-breeding season (Péron et al., 2010). The white-chinned petrel is classified as vulnerable by the International Union for Conservation of Nature (IUCN 2019) due to the fast decrease of its populations since the 1980's (Barbraud et al., 2008; Berrow et al., 2000).

Crozet archipelago, South Indian Ocean

Crozet Islands (46° S ; 51° E) is a subantarctic archipelago situated in the southern Indian Ocean. It is part of the French Southern Territories (Terres Australes et Antarctiques Françaises - TAAF). In 2006, the Réserve Naturelle Nationale des Terres Australes Françaises was created (<https://reserve->

australes.taaf.fr/en/page-daccueil/), reinforcing its conservation status. Possession Island (150 km²) is one of the five islands of the archipelago. The climate is cold and humid with a strong marine influence. The annual mean temperature from 2005 to 2015 was 5°C, varying from 3°C to 8°C. Total annual precipitation was 2233.2 mm, and atmospheric pressure varied from 939.9 hPa to 1097.6 hPa (www.infoclimat.fr).

Appendix S2: Details about surveys

Capture-mark-recapture survey

At Possession Island, capture mark recapture (CMR) surveys occurred every year from the 1985/1986 breeding season to the 2017/2018 breeding season on the colony situated at Station de Pompage. Five visits were made on 200 monitored burrows during each breeding season, from November to April. Three visits were made in December just after egg laying in order to identify the birds present in burrows and their breeding status (breeder if an egg was laid, non-breeder (NB) otherwise). The first visit in early December was made early in the breeding season of the white-chinned petrel (peak laying of white-chinned petrels at Possession Island is around 22 of November and laying is fairly synchronised) with the aim of discriminate individuals that attempted to breed but failed just after laying from those that were actually non-breeder individuals. Egg shell presence was also checked for during burrows visits to help ascertain breeding status. Adult individuals captured for the first time were marked with a unique stainless ring allowing their identification. At the end of January, a fourth visit was made to assess whether hatching occurred or not. Finally, in late March, before the first date of fledging recorded at Possession Island (early April), the last visit determined if chicks fledged or not, and fledglings were marked with a unique ring. If chicks fledged, the adults associated with the burrow were considered successful breeders (SB), and failed breeders (FB) otherwise.

Line-transect distance sampling survey

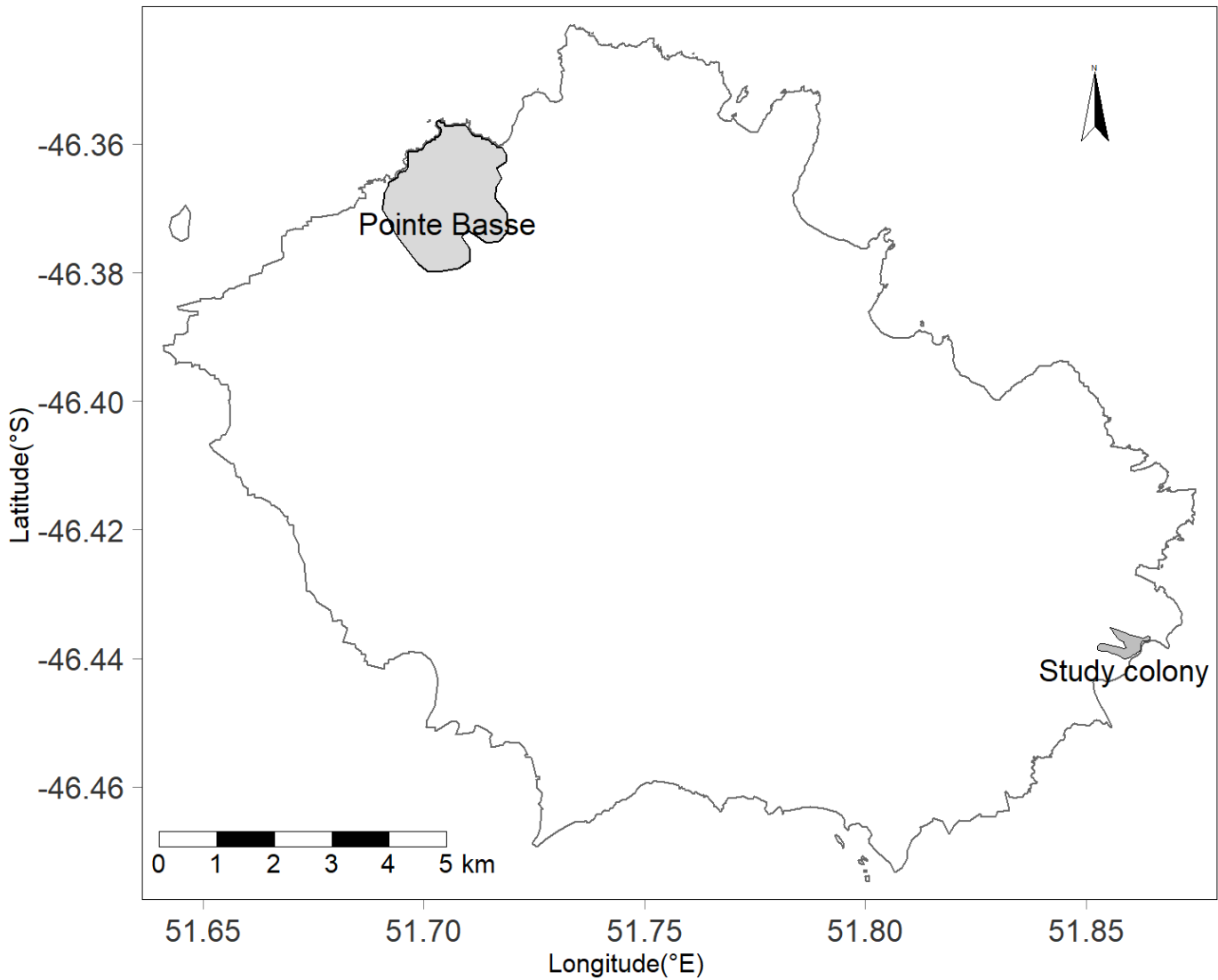
Line-transect surveys were conducted at Pointe Basse, Possession Island (Figure S2), during the 2011/2012 (hereafter 2011) and the 2017/2018 (hereafter 2017) breeding seasons to continue the monitoring of the population trend reported in Barbraud et al., (2008). Line transects surveys in 2011 and 2017 were both conducted during incubation in early-December. The start of the first line-transect was randomly chosen and others arranged in parallel at 200 meters distance from each other, covering the same area of favourable vegetation for white-chinned petrel breeding both years. The position of the observer along the lines was recorded every 0.01 km such as the position of each detected burrow using a hand-held GPS. For each detection of a burrow from the line, the perpendicular distance between the transect and the burrow was measured using a measuring tape or a telemeter.

Beforehand, in 1983 and then in 2004, exhausting counts were conducted in several areas of Possession Island, including the Pointe Basse area, following the same favourable vegetation patches and allowing comparison between the 1983 and the 2004 surveys (Marteau, 2008).

Burrow occupancy was determined using acoustic playback and the observation of frequentation indices: presence of a bird in the burrow, feces, egg shell, chick or adult feathers, dead chick, scraped ground or

vegetation, or footprints. A burrow was considered as occupied if there was at least one frequentation index, response to play-back and/or a white-chinned petrel observation.

Figure S2: Areas of the colony surveyed by distance sampling at Pointe Basse and the study colony surveyed by capture-mark-recapture method (grey polygons), Possession Island, Crozet archipelago, Southern Indian Ocean.



Appendix S3: Modelling breeding population density

Our aim was to compare densities of occupied burrows estimated from line transect distance sampling conducted in 2011 and 2017 with those reported in Barbraud et al., (2008) in the same area for 1983 and 2004, and make inference on the trend in breeding densities of white-chinned petrels over time. We modelled burrow detection probability and breeding population density using conventional distance sampling method (Buckland et al., 2001) with the software Distance v7.3 (Thomas et al., 2010). The occupancy rate was calculated as the proportion of burrows that presented frequentation indices and/or response to playback and was included with its standard error as a multiplier in the selected model to estimate the density of active burrows (Barbraud et al., 2009).

Using the conventional distance sampling method requires several assumptions to be fulfilled: (1) Objects identified must be motionless. By definition, that was the case for white-chinned petrel burrows. (2) Detection probability at distance zero meters (i.e. on the line transect) must be one. This condition was verified using two observers walking one behind the other and by checking that the first observer did not miss burrows situated less than one meter from the line. (3) The distance between the observer and the object must be measured precisely. The measuring tape and telemeter had 0.1 meter and one-meter precision, respectively. (4) Detections must be independent events. This point may be a cause of bias because white-chinned petrels concentrate their burrows in dense vegetation patches which were visible from along and may attract the attention of the observer. Thus, additional burrows detected while walking from the line transect to the burrow initially detected from the line, but not detected from the line, were not included in the analysis. Observers also walked at the same speed along all the lines. During each survey the burrows detected and burrow occupancy were noted using the observation of frequentation indices (feathers, dropping, scratches at the burrow entrance, fresh vegetation at the entrance) and acoustic play-back (Berrow, 2000; Barbraud et al., 2009).

Datasets were truncated at a distance of 20 meters from the line transect, distance at which burrows detection was close to zero (Barbraud et al., 2009). Detection distances were then classified in four to nine equal distance classes and probability of detection were modelled with a half-normal, hazard-rate or uniform function and adjustment functions (cosinus, Hermite polygone and polynomial). Model selection was based on the lowest Akaike Information Criterion (AIC) between models in a same class of distance (with a tolerance for a difference of two points of AIC, (Burnham & Anderson, 2002)), then on the goodness of fit of the model (p-value), and finally on the lowest density and detection probability coefficients of variation (Buckland et al., 2001). Detection probability from the selected models are shown on Figure 1 S3 and Figure 2 S3.

Figure 1 S3: Probability of detection of white chinned petrel burrows at Pointe Basse in 2011 modelled with a uniform function and a cosine adjustment (selected model). The dataset was binned in four classes of distance. GOF of the model: $P = 0.771$, effective strip width = 9.40 m. Detection probability = 0.47 ± 0.04 .

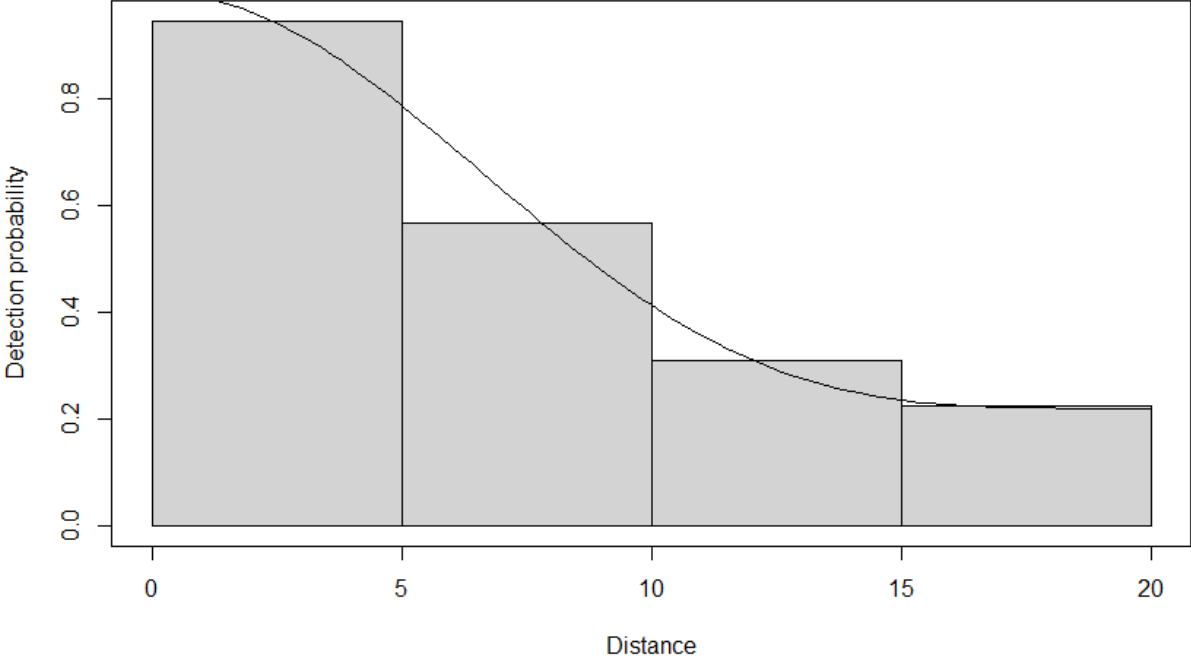


Figure 2 S3: Probability of detection of white chinned petrel burrows at Pointe Basse in 2017 modelled with a uniform function and a cosine adjustment (selected model). The dataset was binned in four classes of distance. GOF of the model: $P = 0.350$, effective strip width = 11.0 m. Detection probability = 0.55 ± 0.03 .

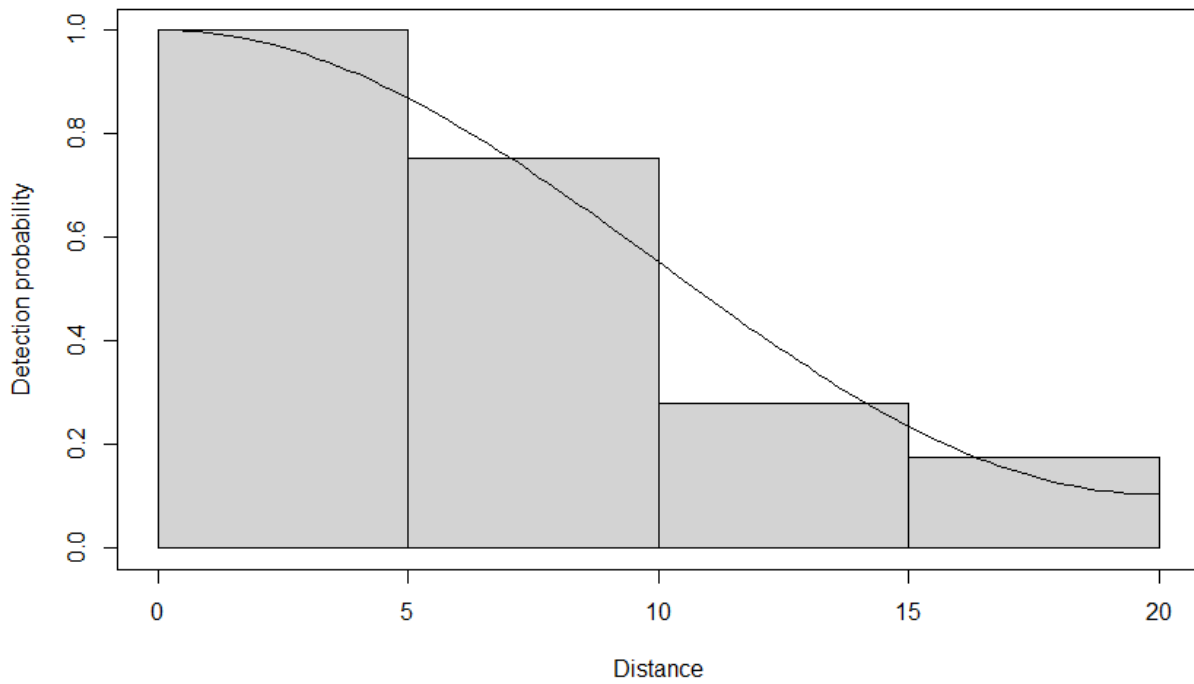


Table 1 S3: Modelling white-chinned petrels burrow detection probability (P) and density (D) with 95% lower and upper confidence intervals (CI- and CI+) at Pointe Basse, Possession Island. N: number of detected burrows, ΔAIC : difference in Akaike Information Criterion between the selected model and the model with the lowest AIC, ESW: effective strip width, GOF: goodness of fit of the model, CV: coefficient of variation (in %).

Year	N	ΔAIC	AIC	ESW	D	CI-	CI+	CV(D)	GOF	P	CV(P)
2011	119	0.05	285.80	9.40	5.65	4.09	7.81	15.82	0.77	0.47	9.37
2017	126	0.25	303.85	11.04	5.68	3.76	8.58	18.85	0.35	0.55	5.06

Appendix S4: Modelling demographic parameters and model selection

Adult demographic parameters

We considered observations of individuals during the period 1986-2017 to build encounter histories. We discarded the capture-recapture data from the 1985-1986 survey because it was the first year of implementation of the protocol. This resulted in capture histories of 842 adult individuals. The sex of individuals was unknown (the species is not dimorphic). To estimate demographic parameters while taking account of imperfect detectability of marked individuals and uncertainty in breeding status (some individuals were observed as breeders but with a not confirmed breeding status), we used multi-event capture-mark-recapture (MECMR) models (Pradel, 2005). We started with a general model with all parameters varying freely with time independently for every breeding state. However, this model was not full rank (i.e. it was not possible to estimate all the parameters in this model (Hunter & Caswell, 2009)). This was likely due to the very few observations of non-breeder individuals that usually do not return at the colony. A common source of rank-deficiency in multi-event CMR models is the estimation of survival probability between the last two capture events. We thus constrained the state assignment probability, the capture probability for NB individuals and the survival probability for NB individuals to be constant, and constrained the survival probability estimates to be equal for the two last time steps. All other parameters were modelled varying freely with time and state. This constrained model was full rank.

Pattern matrix used in E-SURGE:

Survival-transition matrix:

$$\phi = \begin{pmatrix} \text{NB} & \text{FB} & \text{SB} & \text{Dead} \\ \begin{pmatrix} s_{NB}(1 - \beta_{NB}) & s_{NB}\beta_{NB}(1 - \gamma_{NB}) & s_{NB}\beta_{NB}\gamma_{NB} & 1 - s_{NB} \\ s_{FB}(1 - \beta_{FB}) & s_{FB}\beta_{FB}(1 - \gamma_{FB}) & s_{FB}\beta_{FB}\gamma_{FB} & 1 - s_{FB} \\ s_{SB}(1 - \beta_{SB}) & s_{SB}\beta_{SB}(1 - \gamma_{SB}) & s_{SB}\beta_{SB}\gamma_{SB} & 1 - s_{SB} \\ 0 & 0 & 0 & 1 \end{pmatrix} & \begin{matrix} \text{NB} \\ \text{FB} \\ \text{SB} \\ \text{Dead} \end{matrix} \end{pmatrix},$$

Event matrix:

$$B = \begin{pmatrix} \text{Not seen} & \text{NB} & \text{FB} & \text{SB} & \text{B} \\ \begin{pmatrix} 1 - p_{NB} & p_{NB} & 0 & 0 & 0 \\ 1 - p_{FB} & 0 & p_{FB}\delta_{FB} & 0 & p_{FB}(1 - \delta_{FB}) \\ 1 - p_{SB} & 0 & 0 & p_{SB}\delta_{SB} & p_{SB}(1 - \delta_{SB}) \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix} & \begin{matrix} \text{NB} \\ \text{FB} \\ \text{SB} \\ \text{Dead} \end{matrix} \end{pmatrix},$$

Table 1 S4: Definition of parameters used in the multievent mark-recapture model

Parameter	Definition
s	Probability that an individual in state S at time t survives to time $t + 1$ and does not permanently emigrate from the study area
β	Probability that an individual in state S at time t breeds at time $t + 1$ given that it survives to $t + 1$
γ	Probability that an individual in state S at time t breeds successfully at time $t + 1$ given that it survives to and breeds at time $t + 1$
p	Probability that an individual in state S at time t is encountered at time t
δ	Probability that the state of an individual is observed given that it is in state S at time t and encountered at time t

Constraint phrases used in E-SURGE (GEMACO) for the MECMR general model:

s : f(1)+f(2,3).t(1_29,30:31)

β : f.to.t

γ : f.to.t

p : firste+nexte.[to(2) + to(3, 4).t]

δ : to

Recruitment and juvenile survival probabilities

Capture histories were coded considering three events corresponding to field observation: 0 = not observed, 1 = captured and marked as a chick, 2 = seen as a breeder at least once during the study. The dead state was not observable. We used multi-state capture-mark-recapture (MSCMR) model (Lebreton et al., 2009; Pradel, 1996). In this model all parameters were age dependent. Individuals seen on an egg during one breeding season were considered as recruited for breeding for the following seasons. Juveniles generally do not return to their birth colony until their first reproduction, i.e., until they recruit. In our study, youngest recruited birds had five years old, so remained in an unobservable state before this age. Thus, survival probability was estimated by constraining to one the survival probability from ages 2 to 4 included, allowing us to estimate the survival probabilities from fledgling to five years old. We constrained recapture probability to be the same for all age classes since age dependence caused rank deficiency. We then tested different models according to maximum age of recruitment, from six to twelve years old. Beyond five years old, survival probability was modelled as a factor of age from six to twelve years old in order to estimate the age at which survival stabilizes. We finally tested the effect of time on the probability of juvenile survival from one to five years old.

Pattern matrix used in E-SURGE:

Survival-transition matrix:

$$\phi = \begin{matrix} & \begin{matrix} 1 & 2 & \text{Dead} \end{matrix} \\ \begin{pmatrix} s_{j1}(1-r) & s_{j1}r & 1-s_{j1} \\ 0 & s_{j2} & 1-s_{j2} \\ 0 & 0 & 1 \end{pmatrix} & \begin{matrix} 1 \\ 2 \\ \text{Dead} \end{matrix} \end{matrix},$$

Event matrix:

$$B = \begin{matrix} & \begin{matrix} \text{Not} & 1 & 2 \\ \text{seen} \end{matrix} \\ \begin{pmatrix} 1 & 0 & 0 \\ 1-p_j & 0 & p_j \\ 1 & 0 & 0 \end{pmatrix} & \begin{matrix} 1 \\ 2 \\ \text{Dead} \end{matrix} \end{matrix},$$

Constraint phrases used in E-SURGE (GEMACO) for the MSCMR general model:

s_j : from(1 2).t(1:27).[a(1)+a(2:4)+a(5:6)]+from(1 2).a(7:13)

r : from.to.a(1:4,5_7)

p : firste+nexte.[to(3).a(1:4,5:13)+to(2)]

Table 2 S4: Modelling early-life survival and recruitment (i.e. first return at the colony as breeder) probabilities of white chinned petrels at Possession Island, 1986-2017. K: number of estimated parameters, QAIC: quasi-Akaike Information Criterion. n+: age class of n years old and older, n_m: the parameter was modelled as varying from n years old to m years old, n:m: the parameter was modelled from n to m years old as a single age class. In bold: selected model following lowest QAICc. Recapture probability was modelled as constant.

Survival	Recruitment	K	QAICc	Δ QAICc	Deviance
	5_12	12	453.4	10.3	1107.1
	5_11	11	451.6	8.5	1107.7
	5_10	10	449.6	6.5	1107.9
Three age classes: 1:4, 5:12 and 13+ years old	5_9	9	448.1	5.0	1109.4
	5_8	8	446.2	3.1	1109.6
	5_7	7	444.2	1.1	1109.7
	5_6	6	443.1	0.0	1112.1
1:4, 5_12, 13+		14	455.2	27.6	1101.3
1:4, 5_11, 12+		13	452.7	25.1	1100.2
1:4, 5_10, 11+		12	448.2	20.6	1093.8
1:4, 5_9, 10+		11	444.1	16.4	1088.3
1:4, 5_8, 9+	5_7	10	438.6	10.9	1079.3
1:4, 5_7, 8+		9	433.1	5.4	1070.5
1:4, 5_6, 7+		8	429.7	2.0	1067.0
1:4, 5, 6+		7	428.5	0.8	1069.3
1:4, 5:6, 7+		7	427.7	0.0	1067.1
1:4 not depending of time, 5:6, 7+,		7	427.7	0.0	1067.1
1:4 depending of time, 5:6, 7+,	5_7	33	467.0	39.3	1029.7

Table 3 S4: Testing for linear trends on population parameters according to breeding state at $t - 1$. s : survival probability, β : breeding probability and γ : success probability. SB: successful breeder, FB: failed breeder, NB: non-breeder. K: number of estimated parameters, F: Fisher and Snedecor F-test value, R^2 : Coefficient of determination.

Parameter	Breeding state at $t - 1$	Model	K	Deviance	F	P-value	R^2
		Varying with time	314	13105.4			
s	SB	Linear trend	286	13147.1	0.19	0.660	<0.01
		Constant	285	13147.4			
	FB	Linear trend	286	13162.9	0.09	0.770	<0.01
		Constant	285	13163.1			
β	SB	Linear trend	285	13161.8	0.41	0.529	0.02
		Constant	284	13161.8			
	FB	Linear trend	285	13145.8	5.25	0.030	0.19
		Constant	284	13155.1			
	NB	Linear trend	285	13206.4	0.03	0.860	<0.01
		Constant	284	13206.5			
γ	SB	Linear trend	285	13183.6	6.79	0.015	0.24
		Constant	284	13208.7			
	FB	Linear trend	285	13158.9	4.62	0.040	0.17
		Constant	284	13169.5			
	NB	Linear trend	285	13138.8	2.47	0.130	0.09
		Constant	284	13142.0			

Goodness of fit tests and model selection

We ran the test on the JollyMoVe (Brownie et al., 1993) umbrella model for multistate data (Tables 4 S4 & 5 S4). There was a lack of fit due to transient and to trap-dependance in the MSCMR model, after transforming it into a one-stage model for testing. We considered that transient issues were fixed with the introduction of two states in the capture histories (juveniles and adults) and we calculated the overdispersion coefficient to account for remaining GOF issues in order to take it into account in the model selection.

We performed model selection using the software E-SURGE 2.1.4 (Choquet et al., 2009). Model selection was done using the AIC corrected for small samples size (AICc) (Burnham & Anderson, 2002). The best model was the lowest AICc model, and we considered that two models *i* and *j* were different when the $\Delta AICc$ was greater than 2, where $\Delta AICc = AICc_i - AICc_j$ (Anderson & Burnham, 2002). Following (Anderson & Burnham, 2002; Arnold, 2010), we report all models and discuss support of alternative models depending on the level of reduction in deviance. If an alternative model was within 2 AICc units from the best model and with larger value of the deviance we considered the best model as supported (Burnham & Anderson, 2002). We first modelled the recapture probability and then the demographic parameters one by one.

Table 4 S4: GOF test of multi-event capture-mark-recapture model on white-chinned petrel adult capture-histories dataset from Possession Island (Crozet Archipelago, 1986-2017). WBWA: test for memory, 3G.SR: test for transience, 3G.Sm: complementary test, M.ITEC: test for trap-dependence, M.LTEC: complementary test, df: degrees of freedom, χ^2 : Pearson chi-square statistics.

Test	χ^2	df	p value
WBWA	91.43	68	0.03
3G.SR	74.44	76	0.53
3G.Sm	249.54	265	0.74
M.ITEC	13.79	5	0.02
M.LTEC	3.49	3	0.32
Sum of tests	432.70	417	0.29

Table 5 S4: GOF test of multi-state capture-mark-recapture model on white-chinned petrel sub-adults capture-histories dataset from Possession Island (Crozet Archipelago, 1986-2017). 3.SR: test for transients, 3.SM: complementary test, 2.CT: test for trap-dependence, 2.CL: complementary test, df: degrees of freedom, χ^2 : Pearson chi-square statistics.

Test	χ^2	df	P value
3.SR	446.41	21	<0.001
3.SM	33.33	12	<0.001
2.CT	72.36	21	<0.001
2.CL	51.48	28	<0.001
Sum of tests	603.59	82	<0.001

Appendix S5: Matrix population model

Recruitment occurred from five to seven years old. We used estimations of demographic parameters from the MSCMR and MECMR model selection for recruitment and adult parameters respectively (Table 1 S5). Since true juvenile survival was underestimated due to natal dispersal outside the monitored burrows, we fixed survival from fledgling to one year old at 0.7 following (Barbraud et al., 2008). Survival from seven years old to adult breeding states was constrained to be equal to survival of adults in the successful breeder state. Then, survival of age classes between one to seven years old was modelled following a logarithmic function.

Since we were not able to estimate time and age-dependent juvenile survival and recruitment due to limitation of the chick CMR dataset, we could not estimate process variance and these parameters were assumed constant. A total of 100 steps and 1000 trajectories using Monte Carlo simulations were run for each model. All models were performed using the software ULM 6.0. (Legendre & Clobert, 1995).

Table 1 S5: Scenarios used to model population growth rate. No additive mortality: survival estimate from the intercept of the negative linear relationship between number of hooks in demersal longline fisheries and survival of breeding individuals. Demographic parameters: survival s , breeding β , success γ .

Scenarios for population matrix model										
	Rat	Trawl	Longline	Mitigation	(1) Trawl ¹ No rat control ³	(2) Longline ² No rat control	(3) Longline Rat control ⁴	(4) Longline mitigation ⁵ No rat control	(5) Longline mitigation Rat control	(6) No additive mortality Rat control
A					s, β, γ	γ		γ		
B						s, β	s, β, γ			
C								s, β	s, β, γ	β, γ

¹ trawl fishery, ² demersal longline fishery, ³ no control of rat population, ⁴ control of rat population, ⁵ mitigation measures applied to reduce demersal longline fishery bycatch

Appendix S6: Assessing covariates effect on demographic parameters

Fishing effort data

We used fishing effort data, in number of hooks, obtained from the Indian Ocean Tuna Commission (IOTC, <https://iotc.org>), the Commission for the Conservation of Southern Bluefin Tuna (CCSBT, www.ccsbt.org), the International Commission for the Conservation of Atlantic Tunas (ICCAT, <https://iccat.int>) and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR, www.ccamlr.org). We selected data depending on the type of fisheries (longlines only), the quality of the data (we selected aggregated data with a 5x5 degrees cell precision or more accurate), the area (longitude/ latitude) and the month of the year corresponding the spatio-temporal distribution of white-chinned petrels throughout the year (Figure 1 S6). To test for the effect of fishing effort in the wintering area of the white-chinned petrel (defined according to Péron (2011)), we used ICCAT and CCSBT data (ICCAT_w and CCSBT_w). We used CCAMLR data in the CCAMLR area 58.6 during the reproduction period (CCAMLR_r) and CCAMLR areas 58.6, 58.4.4 and 58.4.2 during the chick rearing (CCAMLR_cr) according to the foraging distribution based on Catard et al. (2000). Illegal, unreported and unregulated (IUU) fishing effort data came from CCAMLR fishery reports (Agnew & Kirkwood, 2005; CCAMLR, 2018), and hake fishing effort (in kilo tons) data in the Namibian EEZ came from Sea Around Us database <http://www.seaaroundus.org>. We focused on fishery effects on adult survival probability and probability of success because of their hypothesized sensitivity to accidental bycatch.

Climate data

Sea surface temperature anomalies (SSTa) and sea ice concentration (SIC) data were downloaded from <http://iridl.ldeo.columbia.edu>. Sea surface temperature (SST) and chlorophyll a concentration (Chla) were downloaded from <https://earthdata.nasa.gov>. We tested the effect of SSTa, SST and Chla in the white-chinned petrel wintering area (SSTa_w, SST_w, Chla_w) from June to August at time t on the survival, breeding and success at time t+1. Chla dataset were available only from 2002 to 2017. We tested the effect of SSTa and SST in the foraging area during reproduction (pre-laying, laying, incubation; SSTa_r, SST_r), and of SSTa, SST and SIC in foraging areas during chick rearing (SSTa_cr, SST_cr, SIC_cr) at time t on breeding success at time t. Southern oscillation index (SOI) data, download from <https://crudata.uea.ac.uk> and southern annular mode (SAM) data from <https://legacy.bas.ac.uk>, were tested on survival, breeding and success. An annual mean of SAM was tested without time lag. We tested for a multivariate cross-correlation between SOI and SSTa in the white-chinned petrel breeding area in order to know if there was a lag between variations in SOI and its consequences on climate around Crozet (Guinet et al., 1998). We found that SSTa was influenced by SOI with a one-year lag. We thus tested annual mean from year t-1 of SOI on white-chinned petrel demographic parameters at year t (Figure 2 S6).

Figure 1 S6: Distribution areas (dotted lines) of white chinned petrels breeding on Possession Island: 1: wintering area from June to August, 2: breeding area from October to January and 3: chicks rearing area from February to April.

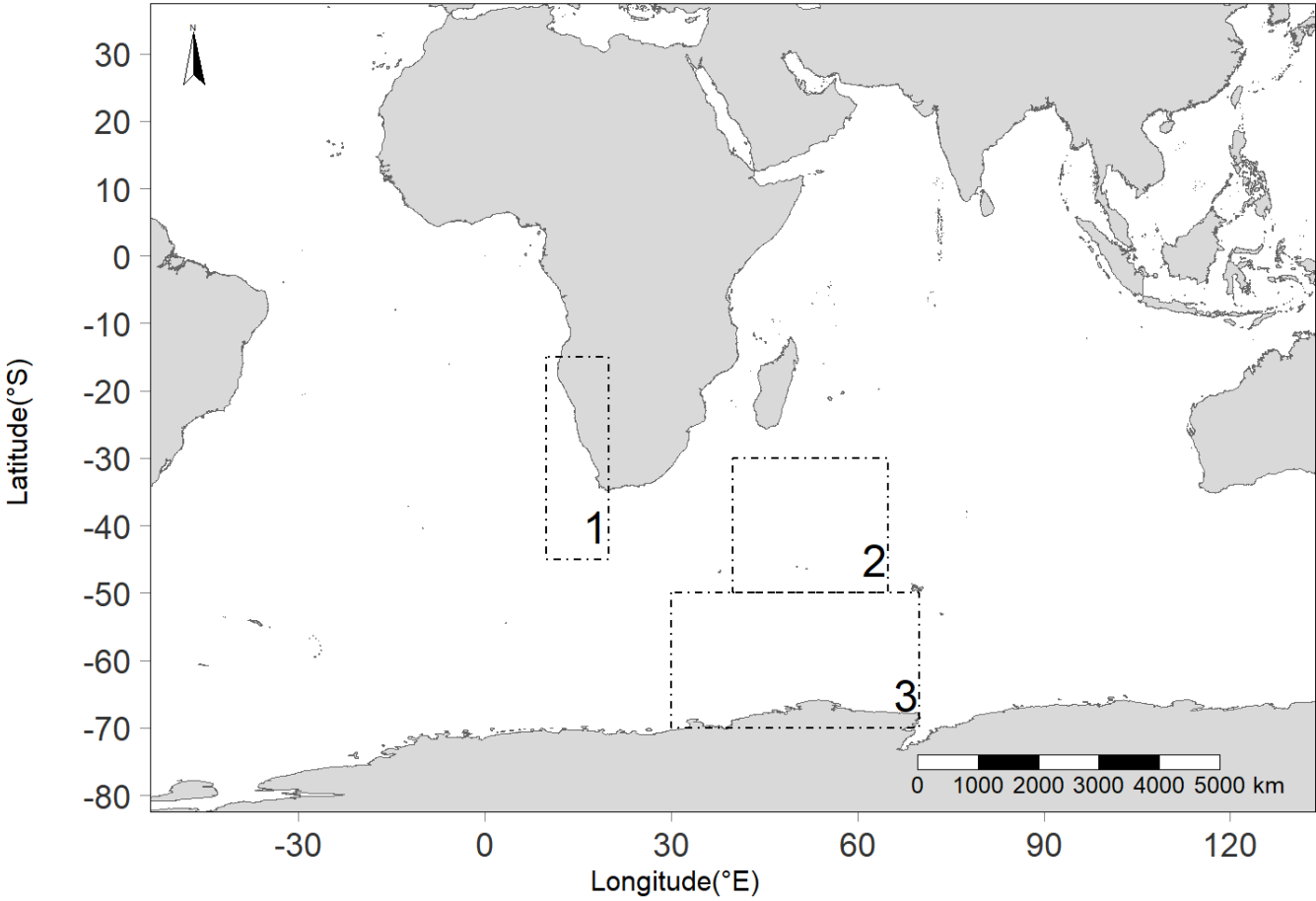


Figure 2 S6: Lagged cross-correlation between the SSTa from white-chinned petrel breeding area around Crozet Island from 1987 to 2017 and the southern oscillation index. Dashed lines indicate statistical significance of the coefficient correlation at the threshold $p = 0.05$.

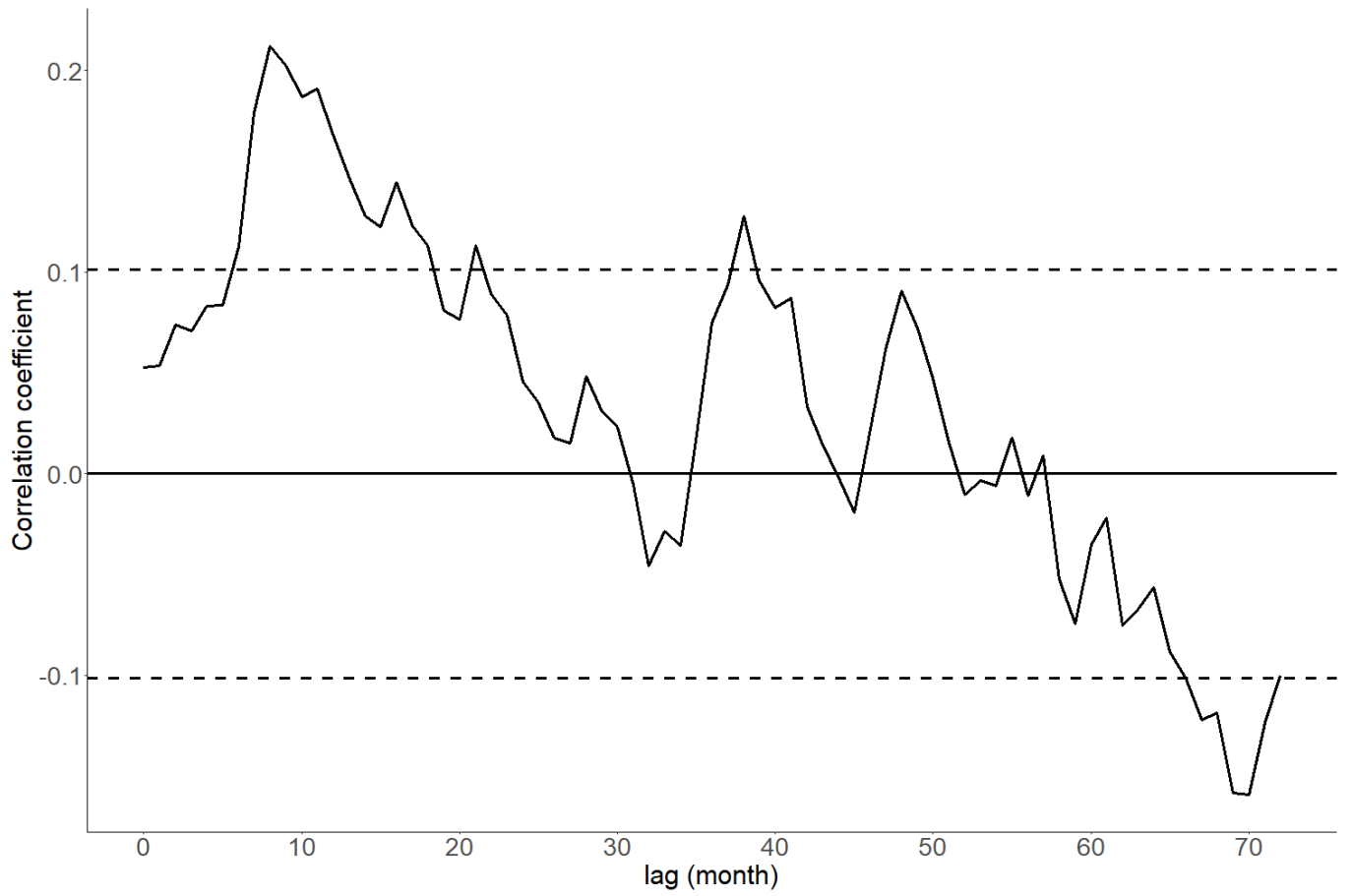


Table 1 S6: Climate covariates used in ANODEV tests on demographic parameters: s , β and γ are respectively the survival, breeding and breeding success probabilities. SIC: sea ice concentration, SAM: southern annular mode, SOI: southern oscillation index, SSTa: sea surface temperature anomalies. The suffix $_p$ indicates the white chinned petrel distribution area used to covariate selection: $_{cr}$: chick rearing, $_{w}$: wintering, $_{r}$: breeding.

Covariate	Ecological hypothesis	Area	Period	Unity	Parameters
SIC $_{cr}$	Positive effect on breeding success due to higher krill abundance when SIC increases (Loeb et al., 1997)	3	Feb-Apr	IU	γ
SAM	Positive values of SAM could impact food availability, survival and breeding success (Sallée et al., 2010)	global	Annual	hPa	γ, β, s
SOI	Negative values of SOI could impact survival and breeding success (Guinet et al., 1998; Narayanasetti et al., 2016)	global	Annual	IU	γ, β, s
SST $_w$ and SSTa $_w$	Negative effect on breeding success through reduced food availability during breeding (Quillfeldt & Masello, 2013)	1	June-Aug	$^{\circ}\text{C}$	γ, β, s
SST $_r$ and SSTa $_r$		2	Oct-Jan	$^{\circ}\text{C}$	γ
SST $_{cr}$ and SSTa $_{cr}$		3	Feb-Apr	$^{\circ}\text{C}$	γ
Chla $_w$	Used as an index of food availability	1	June-Aug	mg m^{-3}	γ, β, s

Table 2 S6: Fisheries covariates used in ANODEV tests on demographic parameters: s , β and γ are respectively the survival, breeding and breeding success probabilities. Trawl: Trawl fishing tonnage, IUU: illegal, unregulated and unreported fisheries. The suffix $_p$ indicates the white chinned petrel distribution area used to covariate selection: $_{cr}$: chick rearing, $_{w}$: wintering, $_{r}$: breeding.

Covariate	Ecological hypothesis	Area	Period	Unity	Parameters
Trawl	Negative effect on survival due to additive mortality (Croxall, 2008)	Namibian EEZ	Annual	Kilo tons	s
IUU		CCAMLR 58.6 area	Annual	Kilo tons	γ, s
CCAMLR $_{r}$		CCAMLR 58.6 area	Oct-Jan	Nb of hooks	γ, s
CCAMLR $_{cr}$	Negative effect on survival due to additive mortality (Barbraud et al., 2008) and on success due to widowing (Mills & Ryan, 2005)	CCAMLR 58.6, 58.4.4 and 58.4.2 areas	Feb-Apr	Nb of hooks	γ, s
IOTC $_{r}$		2	Oct-Jan	Nb of hooks	γ, s
ICCAT $_{w}$		1	June-Aug	Nb of hooks	s
CCSBT $_{w}$		1	June-Aug	Nb of hooks	s

Figure 3 S6: Variations in summed pelagic longline fishing effort (solid line: data from the CCSBT, dashed line: data from the ICCAT, dotted line: data from the IOTC), summed demersal longline fishing effort (solid line: data from the 58.6 CCAMLR area, dashed line: data from the 58.4.4 and 58.4.2 CCAMLR areas), IUU: illegal, unregulated and unreported data from the 58.6 CCAMLR area and hakes trawling fishing effort from Namibian EEZ.

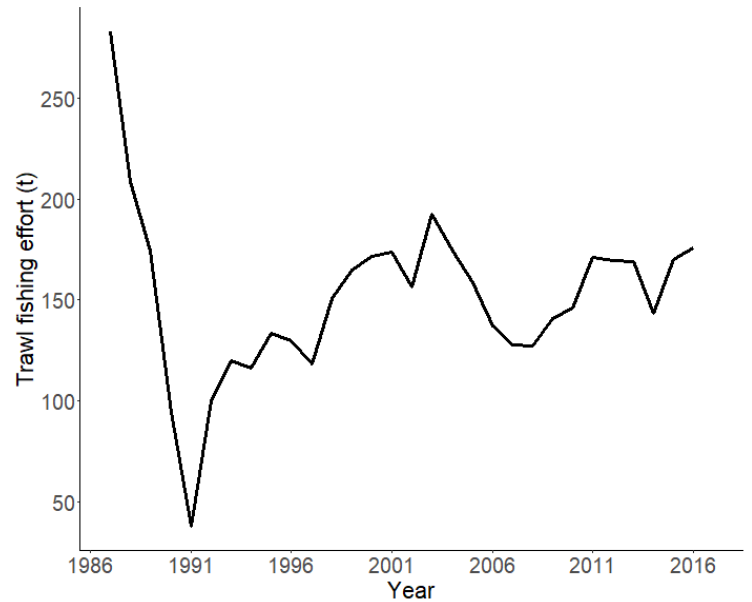
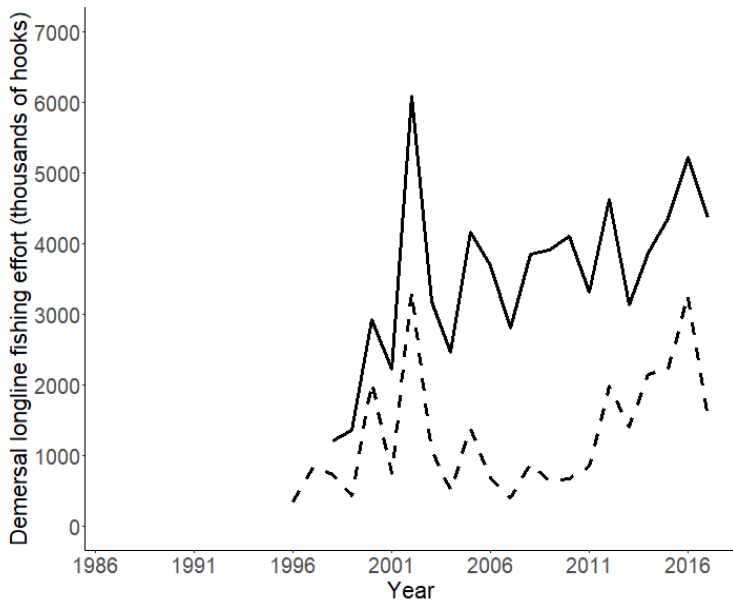
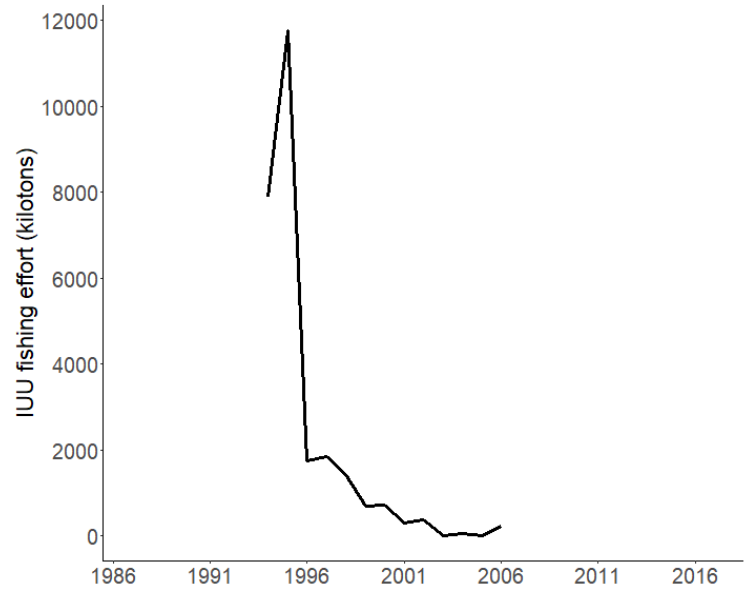
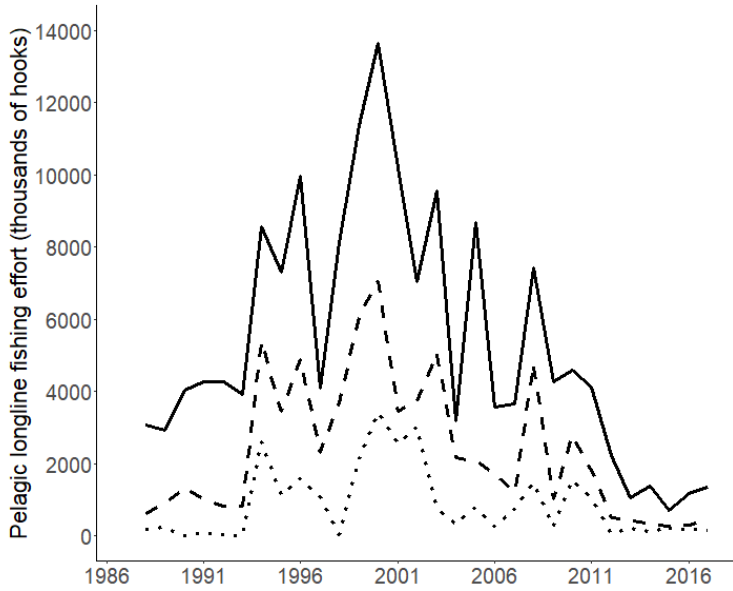


Figure 4 S6: Sum of sea ice concentrations in white-chinned petrel foraging areas during chick rearing, variations in annual mean of concentration in chlorophyll a in white-chinned petrel wintering area, annual mean of southern annular mode and annual mean of southern oscillation index.

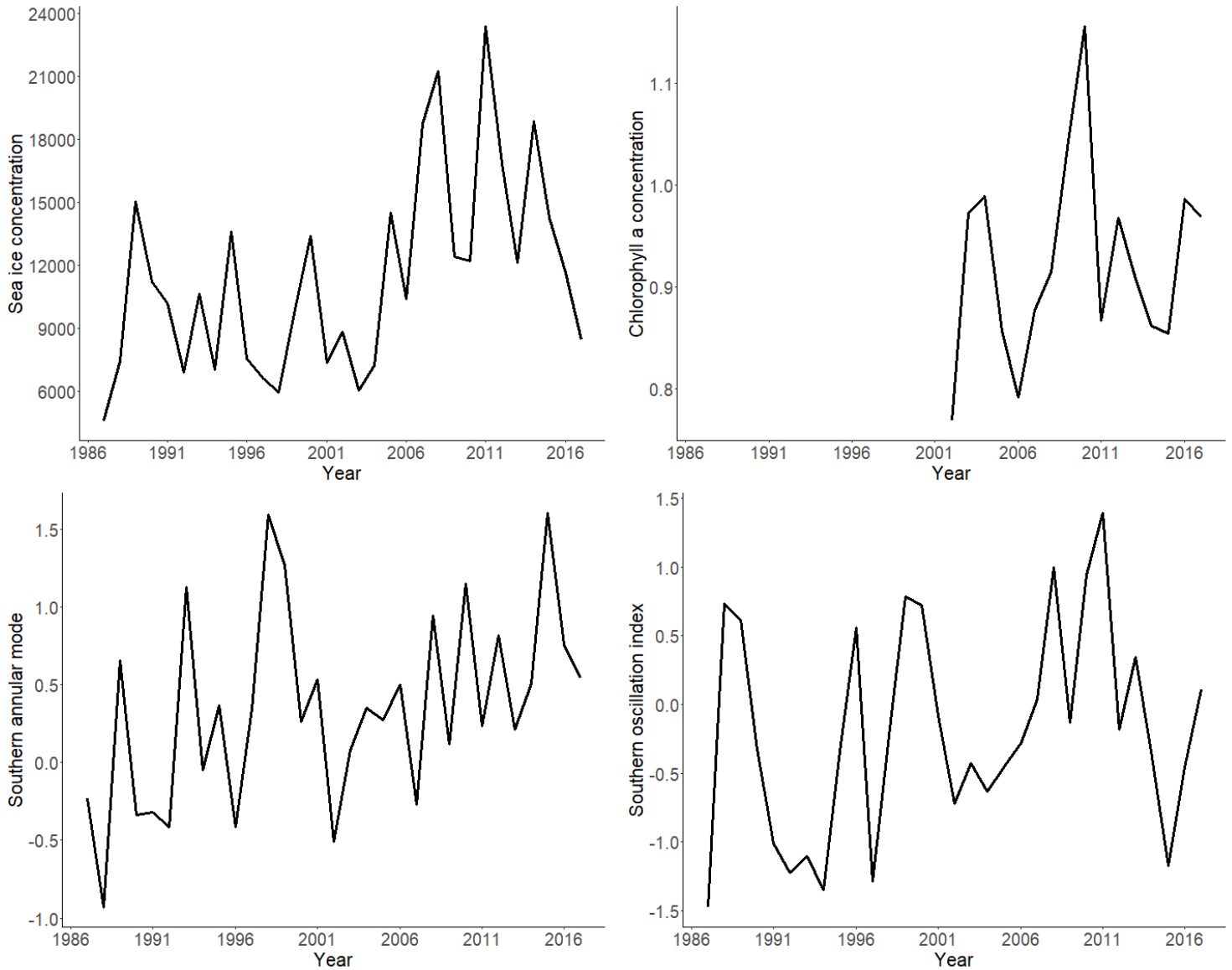


Figure 5 S6: Variations in annual mean of sea surface temperature anomalies in (a) white-chinned petrel breeding area, (b) wintering area and (c) foraging area during chick rearing, and variations in annual sea surface temperature in (d) white-chinned petrel breeding area, (e) wintering area and (f) foraging area during chick rearing.

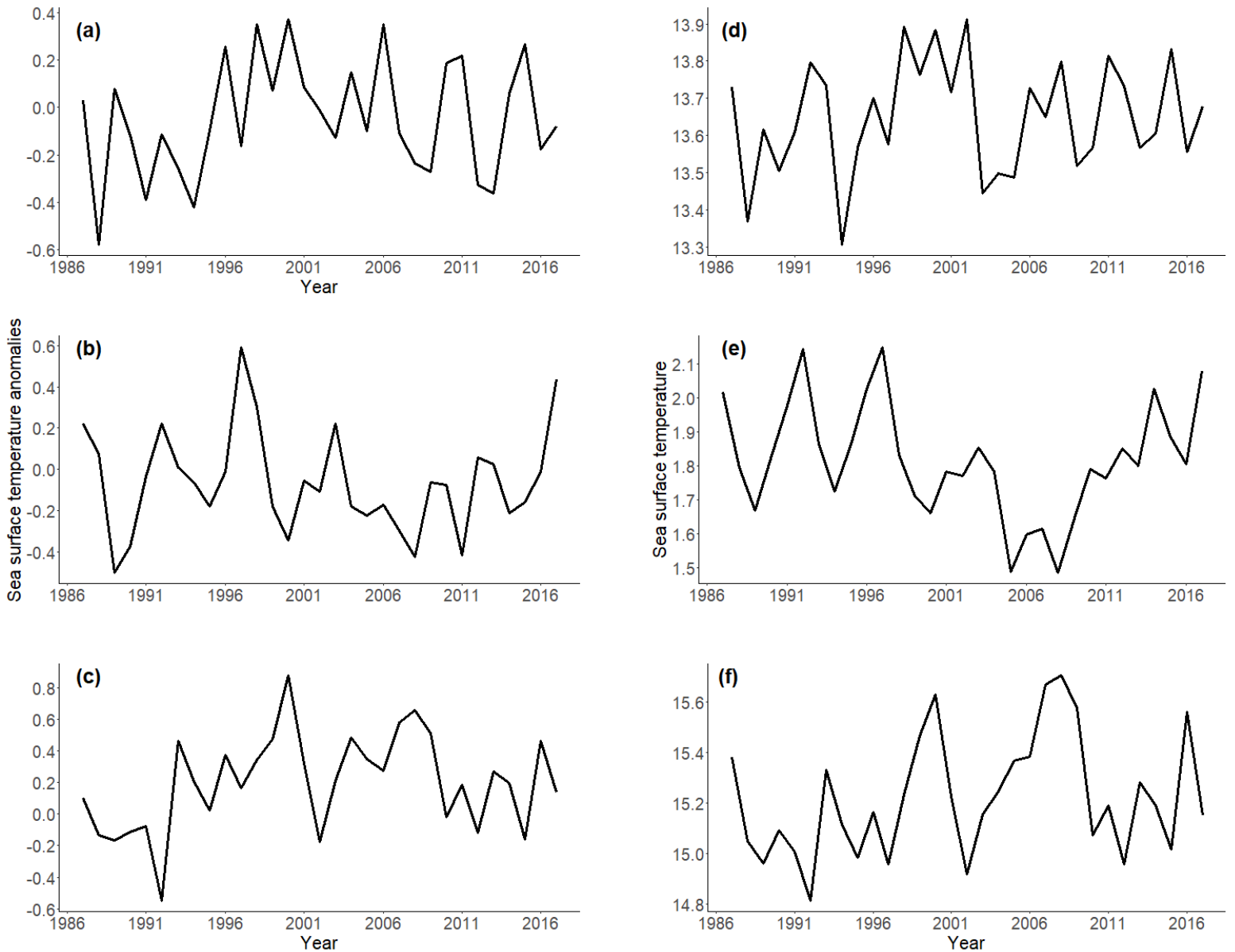


Table 3 S6: Effect of covariates on demographic parameters of white-chinned petrels at Possession Island, 1987-2017. s : survival, β : breeding, γ : success, SB: successful breeder, FB: failed breeder. -: negative linear effect, +: positive linear effect, +/-: positive effect of B1 and negative effect of B2 in the quadratic relationship ($\text{Logit}(s, \gamma) = \text{Intercept} + B1 * \text{covariate} + B2 * \text{covariate}^2$), 0: no effect detected, NT: not tested. IUU: illegal, unregulated and unreported fisheries, SAM: southern annular mode, SOI and SOI_{-1} : southern oscillation index without or with a one-year lag respectively, SSTa: sea surface temperature anomalies, SIC and $\text{SIC}_{\text{detrend}}$: sea ice concentration and detrended sea ice concentration respectively.

Covariate	Phenological period	Effect on tested parameter					
		s , SB	s , FB	β , SB	β , FB	γ , SB	γ , FB
Fisheries							
Demersal longline fishing effort	Breeding	-	0	NT	NT	0	0
	Chick rearing	0	0	NT	NT	0	0
Pelagic longline fishing effort	Breeding	0	0	NT	NT	0	0
	Wintering	0	0	NT	NT	NT	NT
Trawl fishing tonnage	Wintering	0	0	NT	NT	NT	NT
IUU fishing effort	Breeding	0	0	NT	NT	0	0
Climate							
SAM	All year	0	0	0	0	0	0
SOI	All year	0	0	0	0	0	0
SOI_{-1}	Previous year	0	0	0	0	0	0
SSTa	Breeding	NT	NT	NT	NT	+	0
	Chick rearing	NT	NT	NT	NT	-	0
	Wintering	0	0	0	0	0	+
SIC	Chick rearing	NT	NT	NT	NT	+ ; +/-	0
$\text{SIC}_{\text{detrend}}$	Chick rearing	NT	NT	NT	NT	0	NT
	Breeding	NT	NT	NT	NT	0	0
SST	Chick rearing	NT	NT	NT	NT	-	0
	Wintering	0	0	0	0	0	0
Chla	Wintering	0	0	0	0	0	0

Table 4 S6: Linear regression of covariates as a function of time from 1986 to 2017. df: number of degrees of freedom, F-statistic: Fisher and Snedecor F-test value, R²: coefficient of determination. SIC: sea ice concentration, SAM: southern annular mode, SOI: southern oscillation index, SSTa: sea surface temperature anomalies, Hakes: trawl fishing tonnage, IUU: illegal, unregulated and unreported fisheries. The suffix _p indicates the white chinned petrel distribution area used to covariate selection: _cr: chick rearing, _w: wintering, _r: breeding.

Covariate	df	F-statistic	P-value	R ²	slope	intercept
Fisheries						
CCAMLR_r	20	4.407	0.049	0.18	57506	-114112866
CCAMLR_cr	18	5.028	0.038	0.22	64557	-127394902
Trawl	28	0.232	0.634	0.01	0.4312	-711.8328
IOTC_r	28	0.317	0.578	0.01	-11933	24770446
IUU	11	11.450	0.006	0.51	-656.600	1315267.300
ICCAT	29	1.542	0.224	0.05	-31879	65249104
CCSBT	29	5.750	0.023	0.17	-78186	159509421
Climate						
SAM	29	6.589	0.016	0.19	0.030	-58.81332
SIC	29	8.976	0.006	0.24	253.550	-496148.650
SOI	29	1.948	0.173	0.06	0.02141	-43.062
SSTa_r	29	0.766	0.389	0.03	0.004	-8.720
SSTa_cr	29	0.107	0.747	<0.01	-0.002	3.280
SSTa_w	29	2.245	0.145	0.07	0.009	-17.670

Appendix S7: Analysis of deviance (ANODEV) tests

We used likelihood ratio tests and analyses of deviance (ANODEV) (Grosbois et al., 2008) to test for temporal trends on demographic parameters and to assess the effects of covariates. Each test needs the calculation of the deviance of three MECMR models: first, a constant model, noted *cst*, where the demographic parameter of interest is not a factor of time. Second, a time-dependent model, noted *t*, where the demographic parameter of interest is a factor of time. Third, a covariate model, noted *co*, where the demographic parameter of interest is a function of the covariate.

The F statistic was calculated as:

$$F_{test_{cst/co/t}} = \frac{\left(\frac{Dev(F_{cst}) - Dev(F_{co})}{J-1}\right)}{\hat{\epsilon}} \quad (1)$$

$$\text{where } \hat{\epsilon} = \frac{Dev(F_{cst}) - Dev(F_t)}{n-J} \quad (2)$$

and *n* is the number of parameters estimated in the time dependent model, *J* is the number of parameters used in the model constrained by the covariate. $Dev(F_{cst})$, $Dev(F_t)$ and $Dev(F_{co})$ are deviances of constant model, time and covariate (or trend) dependent models respectively. This F statistic was compared to the value from the Fisher and Snedecor table with $\alpha = 0.05$, $df = J - 1$ and $n - J$. When a linear trend were detected on both the demographic parameter and the environmental variable (Table 2 S6), the ANODEV test were applied with detrended variables (Grosbois et al., 2008). All covariates were standardized. As the number of climate covariate was relatively high, we controlled for the false discovery rate of ANODEV by comparing raw P values with Benjamini-Hochberg adjusted P values (Benjamini & Hochberg, 1995).

The proportion of deviance explained by covariates was estimated following (Skalski, 1996):

$$R^2 = \frac{Dev(F_{cst}) - Dev(F_{co})}{Dev(F_{cst}) - Dev(F_t)} \quad (3)$$

and represented the part of the deviance that was explained by the covariate.

Table 1 S7: Testing for the **linear** effects of climate covariates on s (survival), β (breeding) and γ (success) probabilities according to success state at $t - 1$. FB: failed breeder, SB: successful breeder, K: number of estimated parameters, F: Fisher and Snedecor F-test value, R^2 : Coefficient of determination. SIC: sea ice concentration, SAM: southern annular mode, SOI: southern oscillation index, SSTa: sea surface temperature anomalies, SST: sea surface temperature, Chla: chlorophyll a concentration. Corrected P-value: Benjamini-Hochberg corrected P-value.

Covariate	Area	Parameter	Breeding state at $t - 1$	K	AICc	Deviance	F	P-value	Corrected P-value	R^2
SAM	Global	s	SB	286	13717.7	13145.7	1.18	0.286	0.810	0.04
			FB	286	13732.8	13160.8	1.11	0.301	0.546	0.04
		β	SB	285	13730.1	13160.1	1.27	0.269	0.515	0.04
			FB	285	13723.4	13153.4	0.95	0.338	0.492	0.03
		γ	SB	285	13773.7	13203.7	1.4	0.246	0.338	0.05
			FB	285	13739.4	13169.4	0.02	0.891	0.891	< 0.01
SOI	Global	s	SB	286	13716.0	13144.0	0.08	0.776	0.810	0.08
			FB	286	13734.8	13162.8	0.10	0.752	0.902	<0.01
		β	SB	285	13731.1	13161.1	0.03	0.872	0.872	0.03
			FB	285	13724.2	13154.2	0.49	0.488	0.492	0.02
		γ	SB	285	13771.4	13201.4	2.05	0.163	0.256	0.07
			FB	285	13738.9	13168.9	0.28	0.599	0.659	0.01
SOL ₁	Global	s	SB	286	13718.7	13146.7	0.46	0.501	0.810	0.02
			FB	286	13735.0	13163.0	0.01	0.910	0.910	<0.01
		β	SB	285	13731.0	13161.0	0.81	0.375	0.515	0.03
			FB	285	13723.7	13153.7	0.82	0.374	0.492	0.03
		γ	SB	285	13777.4	13207.4	0.35	0.557	0.605	0.01
			FB	285	13735.8	13165.8	1.68	0.206	0.378	0.06
SIC	Chick rearing	γ	SB	285	13757.4	13187.4	5.97	0.021	0.086	0.21
			FB	285	13735.7	13165.7	1.74	0.198	0.378	0.06
SIC _{detrended}	Chick rearing	γ	SB	286	13754.3	13182.3	0.49	0.490		0.02

Table 1 S7 (continued):

SSTa	Wintering	s	SB	286	13719.0	13147.0	0.26	0.610	0.810	0.01
			FB	286	13732.3	13160.3	1.36	0.253	0.546	0.05
		β	SB	285	13729.2	13159.2	1.73	0.199	0.515	0.06
			FB	285	13723.8	13153.8	0.76	0.391	0.492	0.03
	γ	SB	285	13776.4	13206.4	0.63	0.435	0.532	0.02	
		FB	285	13720.3	13150.3	8.67	0.006	0.066	0.3	
	Breeding	γ	SB	285	13761.5	13191.5	4.81	0.037	0.086	0.17
			FB	285	13738.0	13168.0	0.65	0.425	0.584	0.02
	Chick rearing	γ	SB	285	13762.1	13192.1	4.65	0.039	0.086	0.16
			FB	285	13735.5	13165.5	1.81	0.189	0.378	0.06
SST	Wintering	s	SB	286	13715.0	13143.0	2.97	0.096	0.576	0.11
			FB	286	13733.3	13161.3	0.85	0.364	0.546	0.03
		β	SB	285	13731.3	13161.3	0.64	0.429	0.515	0.02
			FB	285	13724.2	13154.2	0.48	0.492	0.492	0.02
	γ	SB	285	13752.9	13182.9	7.23	0.012	0.086	0.25	
		FB	285	13732.6	13162.6	3.10	0.089	0.326	0.11	
	Breeding	γ	SB	285	13764.2	13194.2	4.07	0.053	0.097	0.14
			FB	285	13738.6	13168.6	0.40	0.533	0.651	0.01
	Chick rearing	γ	SB	285	13760.4	13190.4	5.14	0.031	0.086	0.18
			FB	285	13730.4	13160.4	4.09	0.052	0.286	0.14
Chla	s	SB	301	13734.0	13132.0	0.06	0.810	0.810	<0.01	
		FB	301	13745.9	13143.9	2.32	0.138	0.546	0.15	
	Wintering	β	SB	300	13727.1	13127.1	1.54	0.235	0.515	0.11
			FB	300	13720.3	13120.3	1.75	0.207	0.492	0.13
	γ	SB	300	13761.0	13161.0	0.28	0.605	0.605	0.02	
		FB	300	13735.9	13135.9	0.79	0.389	0.584	0.06	

Table 2 S7: Testing for the **linear** effects of fisheries covariates on s (survival), β (breeding) and γ (success) probabilities according to success state at $t - 1$. FB: failed breeder, SB: successful breeder, K: number of estimated parameters, F: Fisher and Snedecor F-test value, R^2 : Coefficient of determination. (RFMO): indicate from which RFMO the data came from.

Covariate	Area	Parameter	Breeding state at $t - 1$	K	AICc	Deviance	F	P-value	R^2
Demersal longline fishing effort	Breeding	s	SB	295	13715.4	13125.4	5.85	0.026	0.31
			FB	295	13740.8	13150.8	0.10	0.750	<0.01
		γ	SB	294	13756.2	13168.2	0.06	0.814	<0.01
			FB	294	13731.7	13143.7	0.96	0.339	0.05
	chick rearing	s	SB	297	13724.4	13130.4	2.77	0.115	0.16
			FB	297	13741.6	13147.6	1.09	0.311	0.06
		γ	SB	296	13755.9	13163.9	0.07	0.788	<0.01
			FB	296	13733.4	13141.4	0.09	0.770	0.01
Pelagic longline fishing effort	Breeding (IOTC)	s	SB	286	13718.5	13146.5	0.65	0.430	0.02
			FB	286	13734.8	13162.8	0.14	0.710	<0.01
		γ	SB	285	13773.2	13201.2	2.06	0.163	0.07
			FB	285	13740.5	13168.5	0.47	0.497	0.02
	Wintering (CCSBT)	s	SB	286	13719.1	13147.1	0.25	0.618	0.01
			FB	286	13734.8	13162.8	0.10	0.750	<0.01
		Wintering (ICCAT)	SB	286	13718.0	13146.0	0.94	0.340	0.03
			FB	286	13735.0	13163.0	0.01	0.917	<0.01
Trawl fishing effort	Wintering	s	SB	286	13719.3	13147.3	0.08	0.775	<0.01
		FB	286	13728.5	13156.5	3.16	0.086	0.11	
IUU fishing effort	Breeding	s	SB	303	13726.5	13120.5	0.91	0.338	0.09
			FB	303	13731.5	13125.5	0.57	0.447	0.06
		γ	SB	302	13154.2	13148.2	0.32	0.586	0.03
			FB	302	13741.2	13135.2	0.59	0.460	0.05

Table 3 S7: Testing for the **quadratic** effects of climate covariates on s (survival), β (breeding) and γ (success) probabilities according to success state at $t - 1$. FB: failed breeder, SB: successful breeder, K: number of estimated parameters, F: Fisher and Snedecor F-test value, R^2 : Coefficient of determination. SIC: sea ice concentration, SAM: southern annular mode, SOI: southern oscillation index, SSTa: sea surface temperature anomalies, SST: sea surface temperature, Chla: chlorophyll a concentration. Corrected P-value: Benjamini-Hochberg corrected P-value.

Covariate	Area	Parameter	Breeding state at $t - 1$	K	AICc	Deviance	F	P-value	Corrected P-value	R^2
SAM	Global	s	SB	287	13735.8	13161.8	0.30	0.741	0.890	0.02
			FB	297	13720.5	13126.5	1.52	0.237	0.711	0.27
		β	SB	286	13732.5	13160.5	0.51	0.607	0.856	0.04
			FB	286	13726.5	13154.5	0.15	0.861	0.904	0.01
		γ	SB	286	13779.6	13207.6	0.15	0.863	0.863	0.01
			FB	286	13737.3	13165.3	0.93	0.408	0.641	0.07
SOI	Global	s	SB	287	13717.5	13143.5	1.25	0.301	0.860	0.23
			FB	287	13725.8	13151.8	2.63	0.090	0.540	0.19
		β	SB	286	13731.8	13159.8	0.70	0.507	0.856	0.05
			FB	286	13725.8	13153.8	0.35	0.707	0.904	0.03
		γ	SB	286	13756.0	13184.0	3.34	0.050	0.137	0.24
			FB	286	13730.6	13158.6	2.37	0.112	0.457	0.17
SOL ₁	Global	s	SB	287	13716.8	13142.8	6.53	0.005	0.030	0.11
			FB	287	13735.9	13161.9	0.27	0.766	0.828	0.02
		β	SB	286	13734.0	13162.0	0.16	0.856	0.856	0.01
			FB	286	13726.6	13154.6	0.14	0.866	0.904	0.01
		γ	SB	286	13779.2	13207.2	0.20	0.818	0.863	0.42
			FB	286	13736.9	13164.9	1.00	0.382	0.641	0.07
SIC	Chick rearing	γ	SB	286	13754.6	13182.6	3.53	0.043	0.137	0.25
			FB	286	13735.4	13163.4	1.33	0.281	0.618	0.10

Table 3 S7 (continued):

SSTa	Wintering	s	SB	287	13720.2	13146.2	0.38	0.686	0.890	0.03	
			FB	287	13736.2	13162.2	0.19	0.828	0.828	0.01	
		β	SB	286	13722.5	13150.5	2.96	0.068	0.408	0.21	
			FB	286	13725.3	13153.3	0.50	0.612	0.904	0.04	
		γ	SB	286	13777.4	13205.4	0.44	0.650	0.794	0.03	
			FB	286	13722.0	13150.0	4.26	0.024	0.264	0.30	
	Breeding	γ	SB	286	13762.6	13190.6	2.45	0.104	0.143	0.18	
			FB	286	13741.4	13169.4	0.02	0.982	0.982	<0.01	
	Chick rearing	γ	SB	286	13762.1	13190.1	2.51	0.099	0.143	0.18	
			FB	286	13738.5	13166.5	0.65	0.527	0.725	0.05	
	SST	Wintering	s	SB	287	13718.7	13144.7	0.87	0.430	0.860	0.06
				FB	287	13735.1	13161.1	0.45	0.643	0.828	0.03
β			SB	286	13733.3	13161.3	0.32	0.730	0.856	0.02	
			FB	286	13726.7	13154.7	0.10	0.904	0.904	0.01	
γ			SB	286	13753.4	13181.4	3.69	0.038	0.137	0.26	
			FB	286	13732.7	13160.7	1.92	0.166	0.457	0.14	
Breeding		γ	SB	286	13762.5	13190.5	2.47	0.103	0.143	0.18	
			FB	286	13739.9	13167.9	0.34	0.713	0.871	0.02	
Chick rearing		γ	SB	286	13760.4	13190.4	2.48	0.102	0.143	0.18	
			FB	286	13730.4	13160.4	1.98	0.157	0.457	0.14	
Chla		Wintering	s	SB	302	13735.8	13131.8	0.08	0.924	0.924	0.01
				FB	302	13744.9	13140.9	0.62	0.543	0.828	0.10
	β		SB	301	13729.4	13127.4	0.64	0.544	0.856	0.10	
			FB	301	13720.5	13118.5	1.48	0.263	0.904	0.23	
	γ	SB	301	13763.5	13161.5	0.07	0.010	0.110	0.01		
		FB	301	13739.1	13137.1	0.14	0.873	0.960	0.02		

Table 4 S7: Testing for the effects of the interaction between longline fisheries effort and climate covariates on s : survival probability, according to success state at $t - 1$. FB: failed breeder, SB: successful breeder, K: number of estimated parameters, F: Fisher and Snedecor F-test value, R^2 : Coefficient of determination. SIC: sea ice concentration, SAM: southern annular mode, SOI: southern oscillation index, SSTa: sea surface temperature anomalies, SST: sea surface temperature, Chla: chlorophyll a concentration.

Covariate	* fishing Area	Parameter	Breeding state at $t - 1$	K	AICc	Deviance	F	P-value	R^2
SAM	Global	s	SB	297	13720.5	13126.5	1.52	0.232	0.27
			FB	297	13743.0	13149.0	0.25	0.864	0.04
SOI	Global	s	SB	297	13723.6	13129.6	0.91	0.448	0.16
			FB	297	13745.0	13151.0	<0.01	1.000	<0.01
SOL ₁	Global	s	SB	297	13720.2	13126.2	1.58	0.218	0.28
			FB	297	13742.7	13148.7	0.29	0.832	0.05
SSTa	Wintering	s	SB	297	13723.3	13129.3	0.97	0.422	0.17
			FB	297	13743.7	13149.7	0.16	0.923	0.03
SST	Wintering	s	SB	297	13722.7	13128.7	1.10	0.367	0.19
			FB	297	13743.3	13149.3	0.21	0.890	0.04
Chla	Wintering	s	SB	303	13731.0	13125.0	0.97	0.428	0.27
			FB	303	13749.8	13143.8	0.11	0.951	0.03

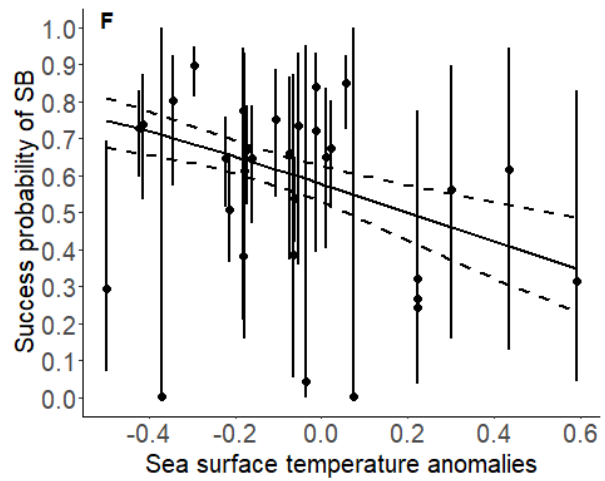
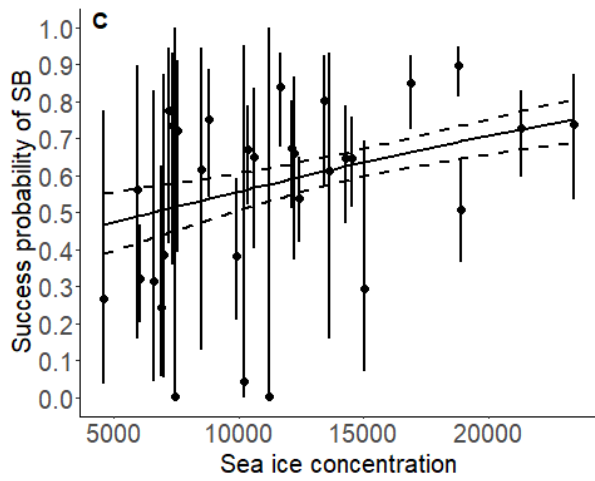
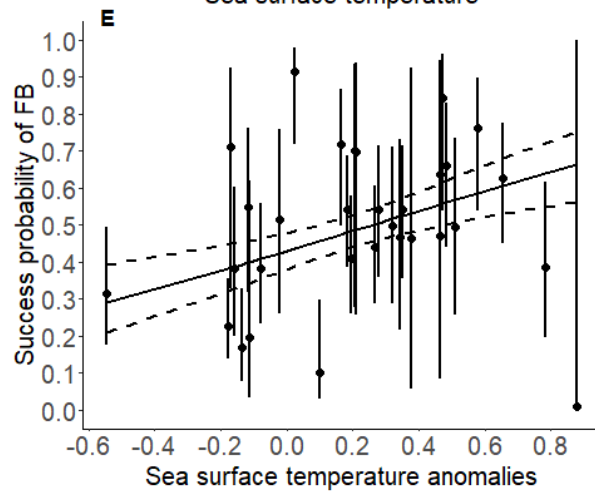
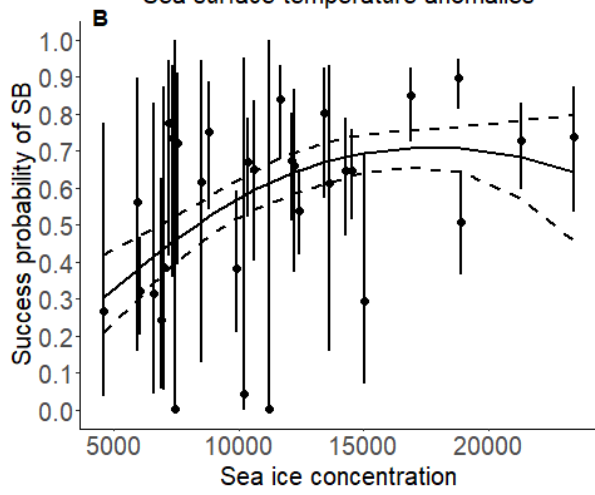
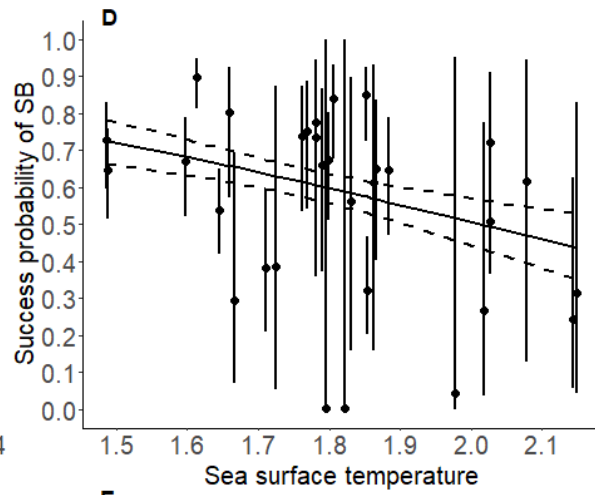
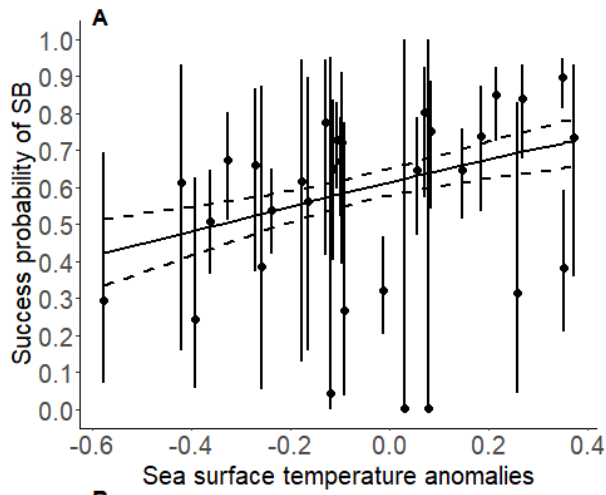
Appendix S8: Relationships between demographic parameters of white-chinned petrels and covariates

We did not find any significant effect of the interaction between longline fishing effort and climate covariates on survival probabilities. When a P-value was <0.05 while testing for the effect of the environmental covariate on a demographic parameter, we took account of this result only when the mathematical parameters (i.e. Intercept, B1 and B2 in the relationship: $\text{Logit}(s, \gamma) = \text{Intercept} + B1 * \text{covariate} + B2 * \text{covariate}^2$) did not include zero into their confidence intervals (Table S8).

Table S8: Estimated parameters of the significant (ANODEV tests, P-value < 0.05) relationships between white-chinned petrel survival (s) and success (γ) probabilities according to success state at $t - 1$, FB: failed breeder, SB: successful breeder, and environmental covariates: SIC: sea ice concentration, SOI: southern oscillation index, SSTa: sea surface temperature anomalies. Parameters correspond to the relationship $\text{Logit}(s, \gamma) = \text{Intercept} + B1 \cdot \text{covariate} + B2 \cdot \text{covariate}^2$. Intercept, B1 and B2 are presented on the logit scale with 95% confidence intervals in brackets.

Covariate tested	Parameter	Breeding state at $t - 1$	Intercept	B1	B2
Demersal longline fishing effort	s	SB	2.50 [2.16 ; 2.84]	-0.51 [-0.77 ; -0.25]	0
SOI-1 quadratic		SB	2.25 [1.99 ; 2.52]	-0.01 [-0.23 ; 0.22]	-0.28 [-0.53 ; -0.04]
SIC		SB	0.32 [0.14 ; 0.50]	0.31 [0.17 ; 0.45]	0
SIC quadratic		SB	0.28 [0.11 ; 0.45]	1.67 [0.69 ; 2.64]	-1.27 [-2.26 ; -0.27]
SOI quadratic		SB	0.34 [0.09 ; 0.60]	0.27 [0.08 ; 0.46]	1.08 [-0.08 ; 2.24]
SSTa_w		FB	-0.04 [-0.22 ; 0.13]	0.35 [0.17 ; 0.53]	0
SSTa_w quadratic	γ	FB	-0.14 [-0.31 ; 0.03]	0.46 [0.21 ; 0.71]	-0.20 [-0.46 ; 0.07]
SSTa_r		SB	0.40 [0.25 ; 0.55]	0.33 [0.17 ; 0.50]	0
SSTa_cr		SB	0.41 [0.22 ; 0.59]	-0.39 [-0.59 ; -0.20]	0
SSTa_cr quadratic		SB	0.39 [0.21 ; 0.57]	-0.35 [-0.56 ; -0.14]	-0.10 [-0.38 ; 0.18]
SST_cr		SB	0.37 [0.20 ; 0.54]	-0.31 [-0.46 ; -0.16]	0
SST_cr quadratic		SB	0.37 [0.19 ; 0.55]	1.69 [-3.95 ; 7.32]	-2.06 [-7.73 ; 3.62]

Figure S8: Relationships between breeding success probability of white-chinned petrel and (A) sea surface temperature anomalies in the foraging area during chick rearing, (B and C) sea ice concentration in the foraging and between annual adult survival probabilities, (D) sea surface temperature in the foraging area during chick rearing,, (E) sea surface temperature anomalies in the wintering area and (F) sea surface temperature anomalies in the foraging area during breeding. Error bars indicate 95% confidence intervals. The modelled relationship between the demographic parameter and the climate covariate is indicated by the black line. Dotted lines indicate 95% confidence intervals. SB: individuals that were successful breeders at time $t - 1$; FB: individuals that were failed breeder at time $t - 1$.



Appendix S9: Sensitivity analysis of demographic parameters to covariates

We considered the sensitivity of λ to demographic parameters and the sensitivity of demographic parameters to covariates (estimated from the partial derivative of the parameter with respect to each covariate):

$$\frac{d\lambda}{dc^T} = \frac{d\lambda}{d\theta^T} \frac{d\theta}{dc^T}$$

The first term on the right side describes the sensitivity of λ to demographic parameter θ and the second term the sensitivity of demographic parameter (θ) to covariate c . Interpretation of sensitivities can be complex, as environmental variables are measured in different units. Therefore, the sensitivity of λ to changes in a covariate X can be difficult to compare with sensitivities to the covariate Y . Elasticity analysis estimates the effect of a proportional change in covariates on population growth. Thus, we estimated elasticity of λ to environmental covariates by considering sensitivity of λ to environmental covariates and scaled covariates between 0 and 1.

In order to assess the relative importance of each covariate according to the different demographic parameters, we compared the effect sizes of the covariates and calculated the partial derivative of the parameter with respect to each covariate in a sensitivity analysis (Horswill et al., 2014). The sensitivity (S) of the demographic trait (θ) to the covariate X was :

$$S = \frac{\partial \theta}{\partial X} = \hat{\beta}_1(\hat{\theta} - \hat{\theta}^2)$$

where $\text{logit}(\hat{\theta}) = \beta_0 + \beta_1 X$.

In the case of quadratic relationships between demographic parameters and covariates, the sensitivity was:

$$S = \frac{\partial \theta}{\partial X} = (2\hat{\beta}_2 X + \hat{\beta}_1)(\hat{\theta} - \hat{\theta}^2)$$

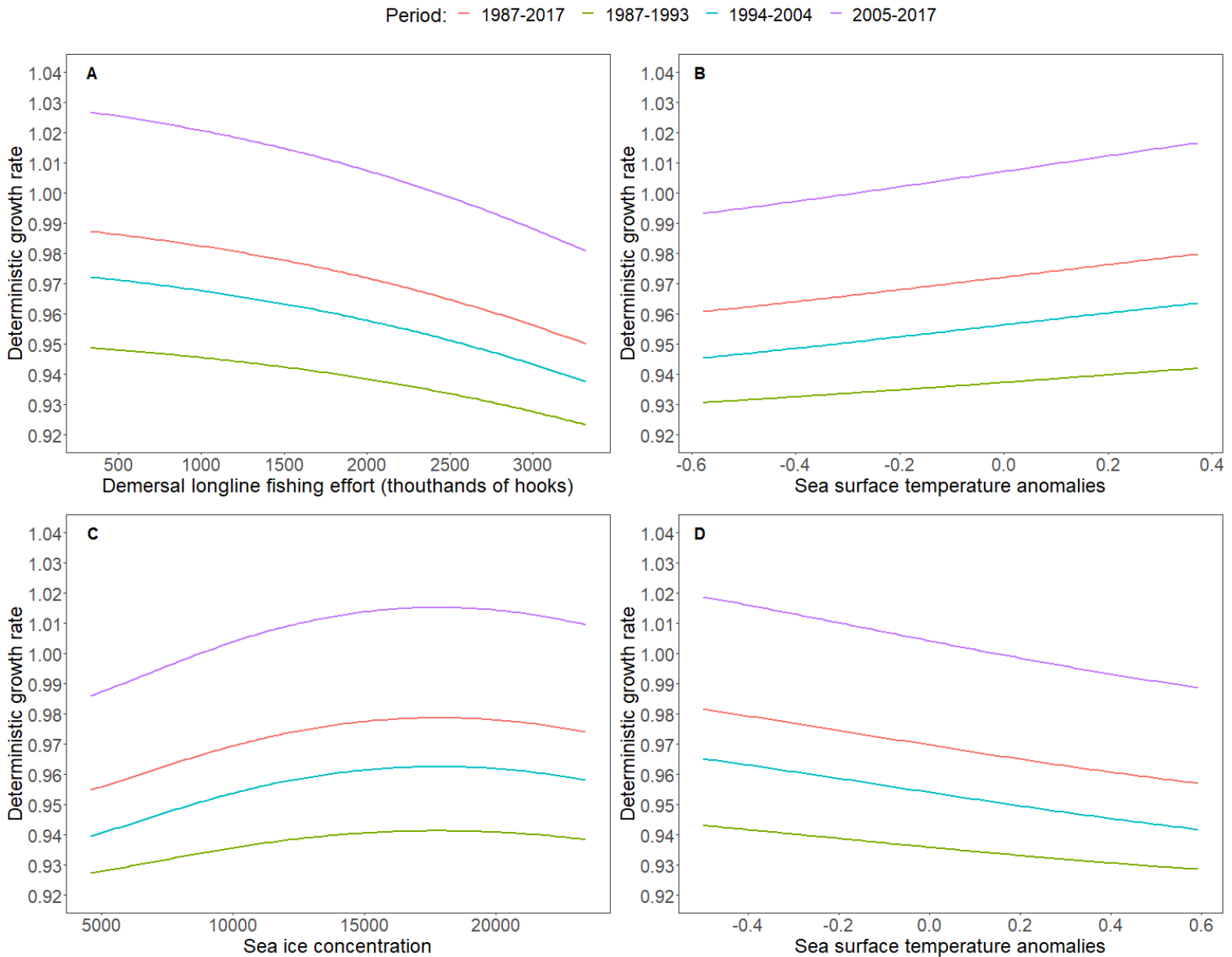
where $\text{logit}(\hat{\theta}) = \beta_0 + \beta_1 X + \beta_2 X^2$

Following (Pacoureau et al., 2019), in order to have comparable sensitivities for linear and quadratic regression models, sensitivities were calculated on the slope of the secant lines of the curve before and after the inflexion point (*i.e.* we broke the quadratic curve in two linear regressions). Sensitivity thus represented the linear sensitivity of a demographic trait to a given range of values of a covariate.

Table S9: Sensitivities and elasticities of white chinned petrel population growth rate to environmental covariates. CCAMLR: demersal longline fishing effort from the 58.6 CCAMLR area, SIC: sea ice concentration, SSTa: sea surface temperature anomalies, SOI-1: southern oscillation index at t-1, SST: sea surface temperature. The suffix indicates the white chinned petrel distribution area used during covariate selection: _cr: chick rearing, _w: wintering, _r: breeding.

Covariate	Sensitivity	Elasticity
CCAMLR_r	-0.0129	-0.0042
SIC	0.0043	0.0016
SIC ²	0.0083	0.0031
SSTa_r	0.0046	0.0027
SSTa_cr	-0.0055	-0.0023
SSTa_w	0.0041	0.0022
SST_cr	-0.0044	-0.0019

Figure S9: Deterministic growth rate of white-chinned petrels at Possession Island as a function of A: the effect of demersal longline fisheries effort in Crozet French EEZ on survival of successful breeders, B: the effect of mean sea surface temperature anomalies in the foraging area during breeding on breeding success of successful breeders, C: the effect of the sum of sea ice concentrations over the foraging area during chick rearing, and D: the effect of mean sea surface temperature anomalies in the foraging area during chick rearing on breeding success of successful breeders. Population growth rate was calculated using mean values of demographic parameters estimated for the entire study period and for the three periods corresponding to fisheries and rat predation management (see Methods).



References

- Agnew, D., & Kirkwood, G. (2005). A statistical method for estimating the level of IUU fishing: Application to CCAMLR Subarea 48.3. *Ccamlr Science*, *12*.
- Anderson, D. R., & Burnham, K. P. (2002). Avoiding pitfalls when using information-theoretic methods. *The Journal of Wildlife Management*, *912–918*.
- Arnold, T. W. (2010). Uninformative parameters and model selection using Akaike's Information Criterion. *The Journal of Wildlife Management*, *74(6)*, 1175–1178.
- Barbraud, C., Delord, K., Marteau, C., & Weimerskirch, H. (2009). Estimates of population size of white-chinned petrels and grey petrels at Kerguelen Islands and sensitivity to fisheries. *Animal Conservation*, *12(3)*, 258–265.
- Barbraud, C., Marteau, C., Ridoux, V., Delord, K., & Weimerskirch, H. (2008). Demographic response of a population of white-chinned petrels *Procellaria aequinoctialis* to climate and longline fishery bycatch. *Journal of Applied Ecology*, *45(5)*, 1460–1467.
- Barbraud, C., & Weimerskirch, H. (2012). Estimating survival and reproduction in a quasi-biennially breeding seabird with uncertain and unobservable states. *Journal of Ornithology*, *152(2)*, 605–615.
- Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57(1)*, 289–300.
- Berrow, S. D. (2000). The use of acoustics to monitor burrow-nesting white-chinned petrels *Procellaria aequinoctialis* at Bird Island, South Georgia. *Polar Biology*, *23(8)*, 575–579.
- Berrow, S. D., Croxall, J. P., & Grant, S. D. (2000). Status of white-chinned petrels *Procellaria aequinoctialis* Linnaeus 1758, at Bird island, South Georgia. *Antarct. Sci.*, *12(4)*, 399–405.
- Bestley, S., Raymond, B., Gales, N. J., Harcourt, R. G., Hindell, M. A., Jonsen, I. D., Nicol, S., Péron, C., Sumner, M. D., & Weimerskirch, H. (2018). Predicting krill swarm characteristics important for marine predators foraging off East Antarctica. *Ecography*, *41(6)*, 996–1012.

- Brooke, M. (2004). *Albatrosses and petrels across the world*. Oxford University Press.
- Brownie, C., Hines, J. E., Nichols, J. D., Pollock, K. H., & Hestbeck, J. B. (1993). Capture-recapture studies for multiple strata including non-Markovian transitions. *Biometrics*, 1173–1187.
- Buckland, S., Anderson, D., Burnham, K., Laake, J., Borchers, D., & Thomas, L. (2001). Introduction to Distance Sampling: Estimating Abundance of Biological Populations. In *Oxford University Press* (Vol. xv).
- Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach* (2nd ed). Springer.
- Catard, A., Weimerskirch, H., & Cherel, Y. (2000). Exploitation of distant Antarctic waters and close shelf-break waters by white-chinned petrels rearing chicks. *Marine Ecology Progress Series*, 194, 249–261.
- CCAMLR. (2018). *Fishery Report 2018: Dissostichus eleginoides Crozet Island French EEZ (Subarea 58.6)* / CCAMLR. <https://www.ccamlr.org/en/document/publications/fishery-report-2018-dissostichus-eleginoides-crozet-island-french-eez-subarea>
- Choquet, R., Rouan, L., & Pradel, R. (2009). Program E-SURGE: A software application for fitting multievent models. In *Modeling demographic processes in marked populations* (pp. 845–865). Springer.
- Croxall, J. P. (2008). Seabird mortality and trawl fisheries. *Animal Conservation*, 11(4), 255–256. <https://doi.org/10.1111/j.1469-1795.2008.00196.x>
- De Grissac, S., Börger, L., Guitteaud, A., & Weimerskirch, H. (2016). Contrasting movement strategies among juvenile albatrosses and petrels. *Scientific Reports*, 6, 26103.
- de L. Brooke, M. (2004). The food consumption of the world's seabirds. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 271(suppl_4), S246–S248.
- Delord, K., Cotté, C., Péron, C., Marteau, C., Pruvost, P., Gasco, N., Duhamel, G., Cherel, Y., & Weimerskirch, H. (2010). At-sea distribution and diet of an endangered top predator: Relationship

- between white-chinned petrels and commercial longline fisheries. *Endangered Species Research*, 13(1), 1–16.
- Grosbois, V., Gimenez, O., Gaillard, J.-M., Pradel, R., Barbraud, C., Clobert, J., Møller, A. P., & Weimerskirch, H. (2008). Assessing the impact of climate variation on survival in vertebrate populations. *Biological Reviews*, 83(3), 357–399.
- Guinet, C., Chastel, O., Koudil, M., Durbec, J. P., & Jouventin, P. (1998). Effects of warm sea–surface temperature anomalies on the blue petrel at the Kerguelen Islands. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 265(1400), 1001–1006.
- Horswill, C., Matthiopoulos, J., Green, J. A., Meredith, M. P., Forcada, J., Peat, H., Preston, M., Trathan, P. N., & Ratcliffe, N. (2014). Survival in macaroni penguins and the relative importance of different drivers: Individual traits, predation pressure and environmental variability. *Journal of Animal Ecology*, 83(5), 1057–1067. <https://doi.org/10.1111/1365-2656.12229>
- Hunter, C. M., & Caswell, H. (2009). Rank and redundancy of multistate mark-recapture models for seabird populations with unobservable states. In *Modeling demographic processes in marked populations* (pp. 797–825). Springer.
- Lebreton, J.-D., Nichols, J. D., Barker, R. J., Pradel, R., & Spendelov, J. A. (2009). Modeling individual animal histories with multistate capture–recapture models. *Advances in Ecological Research*, 41, 87–173.
- Legendre, S., & Clobert, J. (1995). ULM, a software for conservation and evolutionary biologists. *Journal of Applied Statistics*, 22(5–6), 817–834.
- Loeb, V., Siegel, V., Holm-Hansen, O., Hewitt, R., Fraser, W., Trivelpiece, W., & Trivelpiece, S. (1997). Effects of sea-ice extent and krill or salp dominance on the Antarctic food web. *Nature*, 387(6636), 897–900.
- Marteau, C. (2008). *Impact de la pêche à la légine austral sur les populations de petrels à menton blanc et petrel gris de Crozet et Kerguelen*. Ecole Pratique des Hautes Etudes, unpublished report.

- Mills, M. S., & Ryan, P. G. (2005). Modelling impacts of long-line fishing: What are the effects of pair-bond disruption and sex-biased mortality on albatross fecundity? *Animal Conservation*, 8(4), 359–367.
- Narayanasetti, S., Swapna, P., Ashok, K., Jadhav, J., & Krishnan, R. (2016). Changes in biological productivity associated with Ningaloo Niño/Niña events in the southern subtropical Indian Ocean in recent decades. *Scientific Reports*, 6(1), 27467.
- Pacoureau, N., Delord, K., Jenouvrier, S., & Barbraud, C. (2019). Demographic and population responses of an apex predator to climate and its prey: A long-term study of South Polar Skuas. *Ecological Monographs*, 89(4), e01388.
- Péron, C. (2011). *Impact des changements climatiques et distribution spatiale des oiseaux marins de l’Océan Austral* [PhD Thesis].
- Péron, C., Delord, K., Phillips, R. A., Charbonnier, Y., Marteau, C., Louzao, M., & Weimerskirch, H. (2010). Seasonal variation in oceanographic habitat and behaviour of white-chinned petrels *Procellaria aequinoctialis* from Kerguelen Island. *Marine Ecology Progress Series*, 416, 267–284.
- Pradel, R. (1996). Utilization of capture-mark-recapture for the study of recruitment and population growth rate. *Biometrics*, 703–709.
- Pradel, R. (2005). Multievent: An extension of multistate capture–recapture models to uncertain states. *Biometrics*, 61(2), 442–447.
- Quillfeldt, P., & Masello, J. F. (2013). Impacts of climate variation and potential effects of climate change on South American seabirds—a review. *Marine Biology Research*, 9(4), 337–357.
- Ridoux, V. (1994). The diets and dietary segregation of seabirds at the subantarctic Crozet Islands. *Oceanographic Literature Review*, 12(42), 1128.
- Sallée, J. B., Speer, K. G., & Rintoul, S. R. (2010). Zonally asymmetric response of the Southern Ocean mixed-layer depth to the Southern Annular Mode. *Nature Geoscience*, 3(4), 273–279.
- Skalski, J. R. (1996). Regression of abundance estimates from mark recapture surveys against environmental covariates. *Canadian Journal of Fisheries and Aquatic Sciences*, 53(1), 196–204.

Thomas, L., Buckland, S. T., Rexstad, E. A., Laake, J. L., Strindberg, S., Hedley, S. L., Bishop, J. R., Marques, T. A., & Burnham, K. P. (2010). Distance software: Design and analysis of distance sampling surveys for estimating population size. *Journal of Applied Ecology*, 47(1), 5–14.