

Illegal fishing bycatch overshadows climate as a driver of albatross population decline

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Supplement 1: Additional information on data used in the albatross population dynamics model

1.1 Capture-mark-recapture models

Using the data collected from the colony at Cañon des Sourcils Noirs, estimation of adult demographic parameters (number of breeding pairs, adult survival, breeding success, return rates, and survival from age one to five) for the period 1979-2013 was achieved using multi-event capture-mark-recapture models taking into account imperfect detection of individuals (Pradel 2005). These models incorporate uncertainty in the state (e.g. successful or failed breeder) of an individual at a given time (Pradel 2005). As the relationship between states and events is probabilistic, these models are within the Hidden Markov model family (Pradel 2005). The model structure of the multi-event capture-mark-recapture model was similar to Barbraud et al. (2013) for wandering albatrosses.

Juvenile survival until age five was estimated using a multistate capture-mark-recapture model following Lebreton & Pradel (2002) and Nevoux et al. (2010) for the period 1967-2002. Juvenile demographic data for the years 2003-2013 were excluded since recruitment of individuals from these cohorts was not terminated (Nevoux et al., 2010).

In the initial model for adults, survival, breeding probability, success probability, capture probability, and state assignment probability were state and time dependent. From this model, we first tested for temporal trends in detection probability and state assignment probability by fitting models where these probabilities varied according to a quadratic (or linear) trend on a logit scale as follows:

$$\log\left(\frac{\theta}{1-\theta_t}\right) = \text{logit}(\theta_t) = a + b * T_t + c * T_t^2$$

where θ is the parameter of interest, a is the intercept, b and c are the slopes of the linear and quadratic terms, respectively, on the logit scale. We then tested for state dependence on the demographic parameters.

Model selection was performed using the AIC and maximum likelihood estimates for demographic parameters were obtained from the program E-SURGE 1.9.0 (Choquet et al. 2009).

1.2 Monthly at-sea distributions by albatross category

Table S1.1 Summary of the distinct distribution at-sea patterns allocated each month to each category of albatross: currently breeding adults, adults failed breeding in the current season, non-breeding adults who failed the previous season, non-breeding adults who were successful the previous season, juveniles (fledged the current year through the following year), and immature birds (age 2 to the year prior to the first breeding attempt. Within a given category of albatross (e.g. breeding adult), temporal changes in the spatial distribution are noted by ‘Month’ (e.g. incubating vs non-breeding) ^a indicates males and females are modelled separately for the specified category. No juveniles are present at-sea until they fledge and migrate from the colony. Note that the model year begins in October, the beginning of the breeding season for black-browed albatross at the focal colony at Cañon des Sourcils Noirs, Kerguelen Island.

Month	Adult, breeding	Adult, failed breeding ^a	Adult, non-breeding: previously failed	Adult, non-breeding: previously successful	Juvenile	Immature
Oct	incubating	resident	resident	resident	independent	independent
Nov	incubating	resident	resident	resident	independent	independent
Dec	incubating	resident	resident	resident	independent	independent
Jan	rearing	resident	resident	resident	independent	independent
Feb	rearing	resident	resident	resident	independent	independent
Mar	rearing	migrating	migrating	migrating	independent	independent
April	rearing	migrating	migrating	migrating	migrating	independent
May	non-breeding	non-breeding	non-breeding	non-breeding	non-breeding	independent
June	non-breeding	non-breeding	non-breeding	non-breeding	non-breeding	independent
July	non-breeding	non-breeding	non-breeding	non-breeding	non-breeding	independent
Aug	non-breeding	non-breeding	non-breeding	non-breeding	non-breeding	independent
Sept	non-breeding	non-breeding	non-breeding	non-breeding	non-breeding	independent

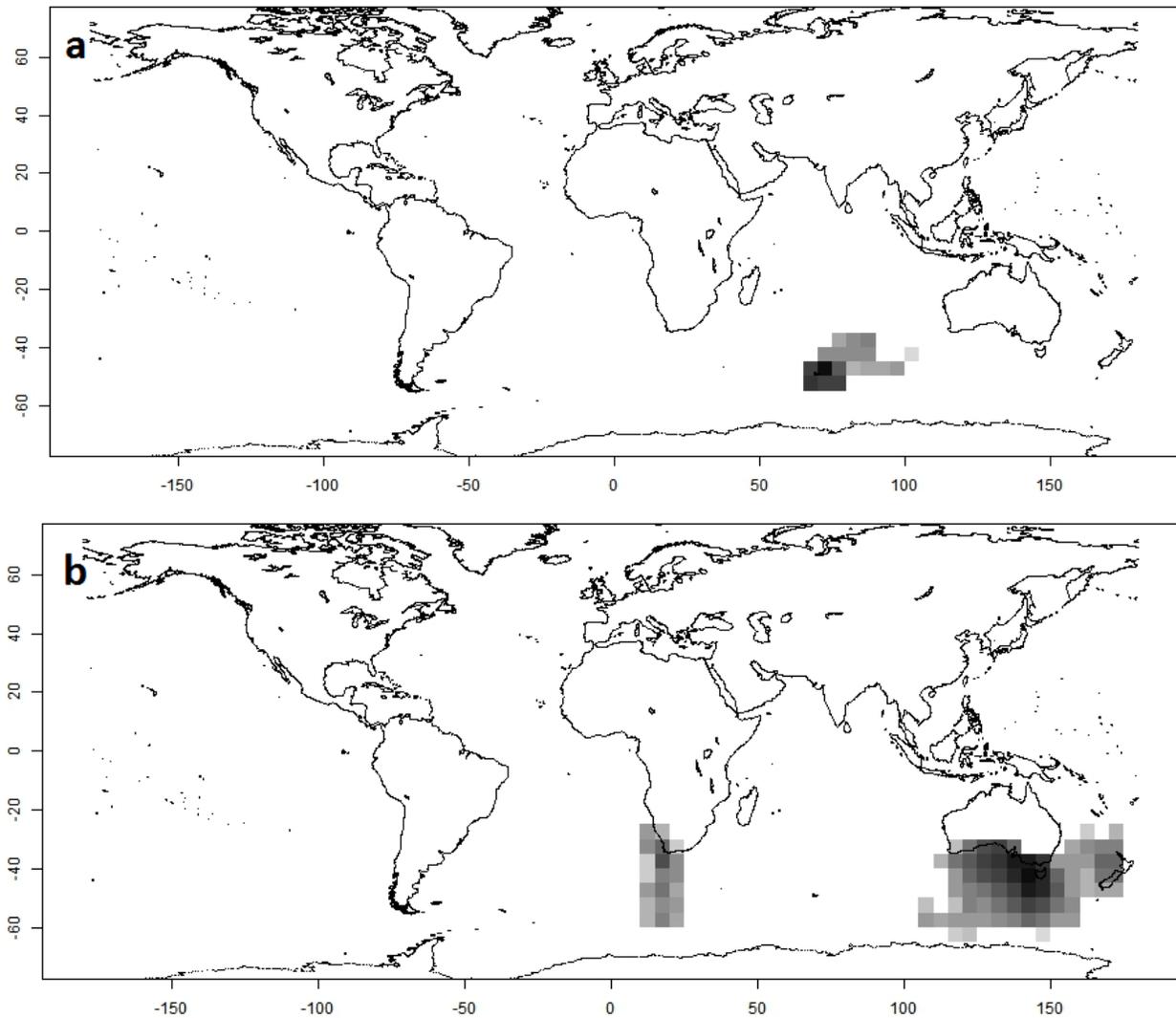


Figure S1.1 Relative at-sea distribution of breeding black-browed albatross during the (a) rearing and (b) winter or non-breeding periods. Distributions are shown as time spent per cell (Louzao et al. 2011, Delord et al. 2016) and from (Delord et al. 2013). Darker shading indicates greater use. Data are plotted at the scale modelled (5° latitude by 5° longitude).

1.3 Description of the refinements to the effort data for IOTC longline fleets

Context

Longline fisheries supply the majority of high value, sashimi-grade tuna representing a significant proportion of total tuna catch value (Hamilton et al. 2011). However, the magnitude, distribution, and the fleets allocating effort in this fishery have fluctuated over time. Commercial distant-water pelagic fishing vessels, often targeting tunas and tuna-like species, began in the 1950s, starting with the Japanese fleet (Moreno & Herrera 2013). The number of commercial longline fleets and the magnitude of effort rapidly increased over the next few decades. In the

1970s to mid-1980s, increasing fuel prices, changes in market demand, technological developments, and declarations of Exclusive Economic Zones altered the general trend of increasing and expanding effort for some fleets (Caton & Ward 1996). Increasing concern over the distribution and management of tuna catches as well as illegal, unreported, and unregulated (IUU) fishing resulted in the development of multi-nation Regional Fisheries Management Organizations (RFMOs), which play an important role in the governance of international fisheries. The magnitude and distribution of effort by various fleets has also changed in response to a reduction in the catch limits of some species (Tuck et al. 2003, Chen 2012). Additionally, previous and current efforts by multiple RFMOs to limit fishing capacity (Joseph et al. 2010, Aranda et al. 2012, Moreno & Herrera 2013) have likely altered the distribution of effort (Tuck et al. 2003, Michael et al. 2015).

Fishing effort in the Indian Ocean has region-specific dynamics. Firstly, the Indian Ocean as a whole has a much greater semi-industrial component than the Atlantic or Pacific; a component which is poorly understood, as many Indian Ocean Tuna Commission (IOTC) resolutions do not include vessels in this category (Moreno & Herrera 2013). Furthermore, piracy from Somalia impacted the tuna fishery in recent years (2009-2011), where multiple fleets shifted effort to other areas in the Indian Ocean or to other oceans (Moreno & Herrera 2013).

The southern (south of 20° S) Indian Ocean is likely less impacted by the semi-industrial fleet and piracy than more northern regions. The magnitude of longline effort is higher than the southern Atlantic, with the Taiwanese fleet expending greater effort than the Japanese (Michael et al. 2015). As more fleets provide effort data, additional insights into the dynamic nature of effort into this region are gained, including potential interactions with bycatch species (Barbraud et al. 2013, Tuck et al. 2015). However, as more information is obtained, the estimates of catch and effort based on these data can change slightly over time, with the most recent estimates based on more information.

The purpose of this section is to provide the methods used to obtain the updated estimates of the distribution and magnitude of longline effort in the southern Indian Ocean used in the current study. The fleets estimated include: deep-freezing pelagic longline effort for Taiwan, Korea, Seychelles, Spain, Reunion, China, and Taiwanese fresh longline. Japanese effort was also evaluated, although the effort estimates are not altered from those provided. Although there are possible inaccuracies in the reported species catch and/or effort location in the Japanese fleet (Polacheck & Davies 2008), it was beyond the scope of this study to account for this issue, and, to our knowledge, data accounting for this correction do not exist.

Methods

Nominal (yearly aggregate catch and effort) and logbook (monthly catch and effort by fishing cell) data were retrieved from the IOTC website: <http://www.iotc.org/data/datasets> on 2013 April 3. It is often the case that the annual catch data is not equal, generally larger, to the sum of the monthly logbook catch data. To obtain a more accurate estimate of effort, the number of hooks in the monthly logbook data were raised by the ratio of reported yearly catch to the annual sum of monthly logbook catch (Campbell 2003).

When both nominal and logbook data were present and fish weight was provided in logbook data, effort (number of hooks) data were regionally raised based on the ratio of the nominal to logbook catch for each year. This ratio is called the ‘raising factor’. The species used in this calculation were yellowfin tuna, bigeye tuna, albacore tuna, swordfish, and southern

bluefin tuna. When nominal data were provided but logbook data were provided without weights, the number of unraised hooks was estimated. This was done by multiplying the number of nominal hooks in the nearest following year with catch logbook catch weight by the ratio of catch weight of the five species mentioned above in the year in question to that of the nearest year.

To calculate the raised effort when logbook data were not provided or provided without species weights, the regional annually weighted raising factor (RAWRF) was used to estimate the number of hooks. The RAWRF is calculated as follows:

$$R_{ri} = (8/15) * R_{ri+1} + (4/15) * R_{ri+2} + (2/15) * R_{ri+3} + (1/15) * R_{ri+4}$$

where R is the raising factor in a given region r (usually east or west), in a given year i .

If the raising factor for any of the four following years was not available, the raising factor for the year directly following was used. For years with nominal data before logbook data were provided, raised effort was calculated as follows:

$$\text{Raised effort}_{ri} = R_{ri} * (\text{Nominal catch weight}_{rij} / \text{Nominal catch weight}_{ri}) * \text{number of unraised hooks}_{rij}$$

where r is a given region, i is a given year, and ij is the most recent adjacent year.

The spatial distribution of effort for years with nominal but without logbook data was assigned by averaging the percent effort per $5^\circ \times 5^\circ$ cell from the following and (when available) preceding year. Spatial distribution for years preceding logbook data was assigned for the Chinese Deep-freezing longline fleet from 1995-1998 and Taiwanese Fresh longline fleet, for 2001-2006. The distribution of effort (percent of annual effort) was assumed as the average of 1999 and 2000 for China and from 2007 for the Taiwanese fresh longline fleet. For the Taiwanese fresh longline fleet, only 2007 was used as a precaution relating to decreasing reliability of data from relatively recent years (e.g. 2008), as information on these years may still be coming available to the IOTC.

As Japanese Nominal and logbook data describe catch in different units (weight and number of fish, respectively), and the average weight of tunas are likely to vary in space and time, we were unable to estimate effort for this fleet. Of the fleets evaluated, the data for the Korean fleet presented the most challenges to estimating effort and inspired the development of many of the above methods. Effort data are updated frequently and past estimates of effort can change as more information becomes available. Therefore, performing the above methods on the currently available data from the IOTC website is likely to yield slightly different estimates of total effort from those below.

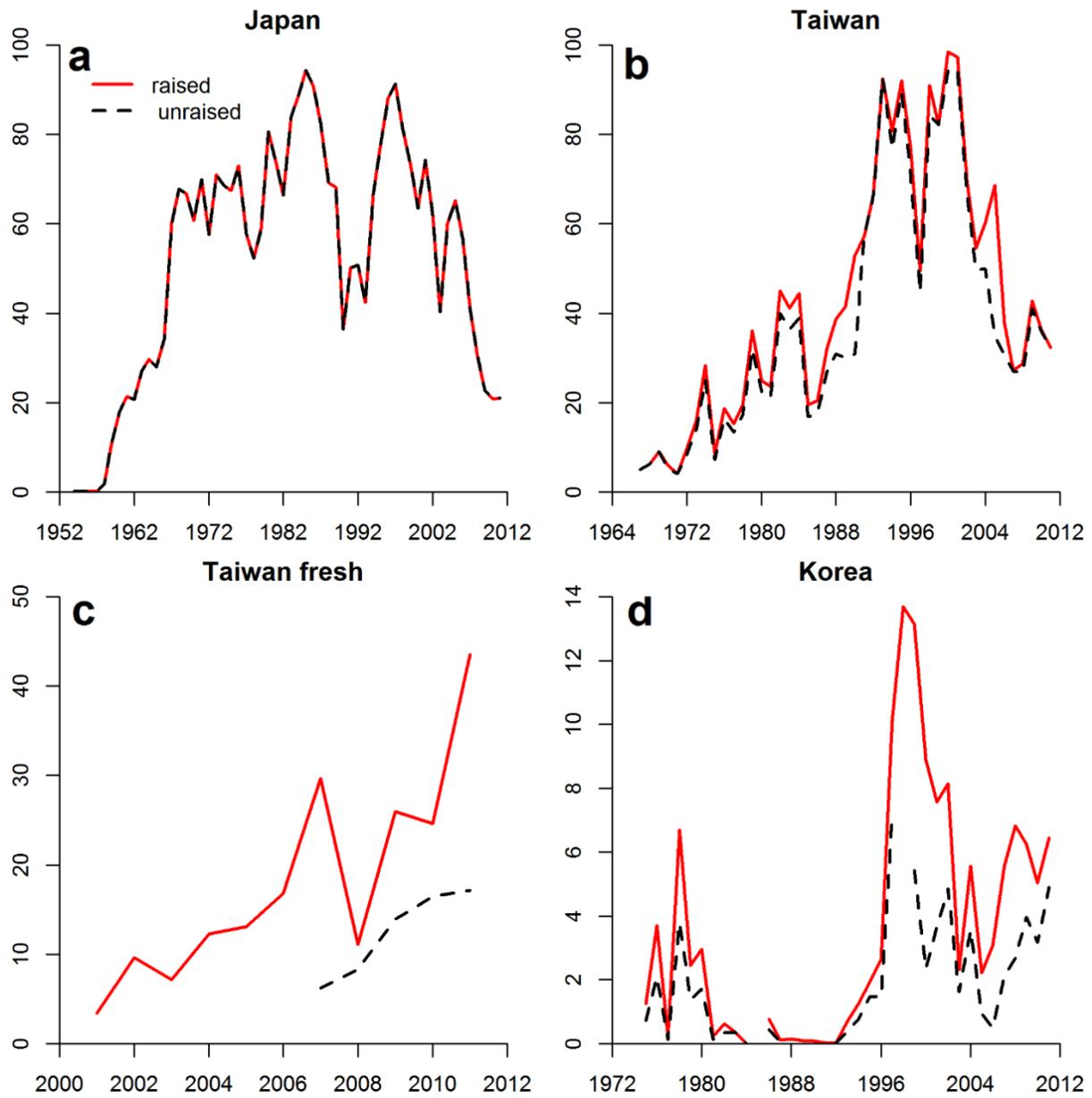


Figure S1.2 Annual sum of effort (million hooks) for the (a) Japanese, (b) Taiwanese, (c) Taiwanese fresh, and (d) Korean distant water longline fleets south of 20° S in the Indian Ocean from (black dashed) unraised and (red solid) raised data, downloaded from the IOTC website on 2013 April 3. No data were removed. Taiwanese effort (b) before 1967 are not shown because of a discrepancy between logbook (1967-2011) and nominal (1954-2011) data ranges.

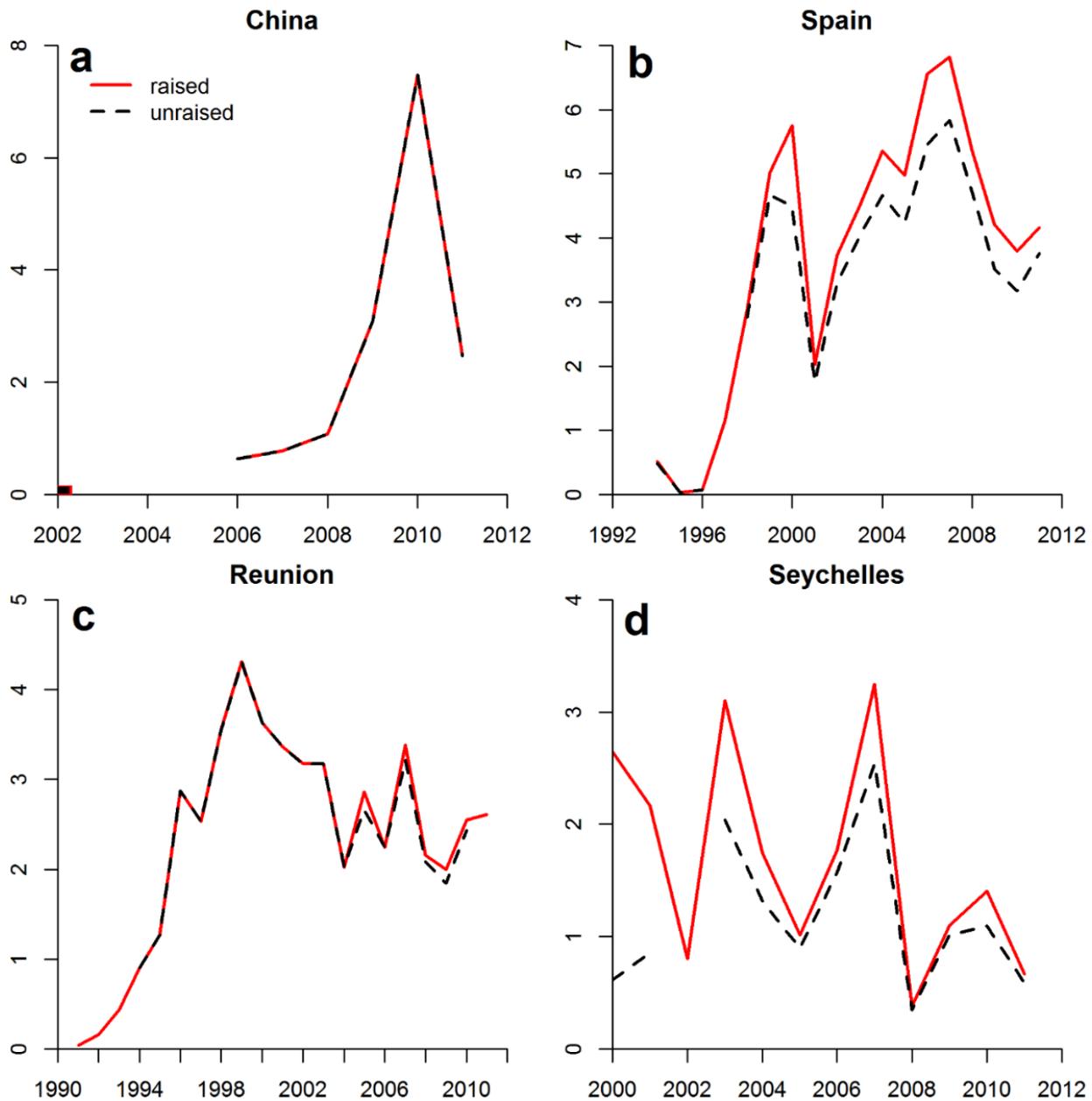


Figure S1.3 Annual sum of effort (million hooks) for the (a) Chinese, (b), Spanish, (c) Reunionese, and (d) Seychellois distant water longline fleets south of 20° S in the Indian Ocean from (black dashed) unraised and (red solid) raised data, downloaded from the IOTC website on 2013 April 3. The Seychellois effort data (d) do not start before 2000.

1.4 Summary of fleets used in model

Monthly reported effort data in 5° x 5° spatial cells were acquired from the Indian Ocean Tuna Commission, the Secretariat of the Pacific Community, the International Commission for the Conservation of Atlantic Tunas, Commission for the Conservation of Antarctic Marine Living Resources, the French Museum of Natural History (French and Ukrainian trawl fleets

within the Kerguelen French Exclusive Economic Zone; EEZ), and the national fishing agencies of South Africa, New Zealand and Australia. Effort data provided in Tuck et al. (2015) are available at: DRYAD entry: doi: 10.5061/dryad.7f63m). Data from Namibia and South American countries were obtained from Tuck et al. (2015), as were illegal, unreported and unregulated demersal longline (IUU) data. The IUU demersal longline data were allocated based on the distribution of the regulated Patagonian toothfish fishery, product landing reports, and IUU vessel sightings. For details, see Tuck et al. (2003) and Tuck et al. (2004).

Details on addressing IUU demersal longline effort near Kerguelen

To cooperatively develop both surveillance and scientific research near territorial islands in the southern Indian Ocean, the Government of Australia and the Government of the French Republic signed the Treaty on Cooperation in the Maritime Areas Adjacent to the French Southern and Antarctic Territories, Heard Island and McDonald Island in 2003. This Treaty, which entered into force in 2005, established a framework for cooperative information exchange and surveillance regarding IUU fishing in the vicinity of multiple islands, including Kerguelen (Duhamel & Williams 2011). Regional surveillance by vessels, a satellite surveillance system, and intermittent patrols have been successful at curbing IUU fishing activities, although derelict gear of suspected IUU origin was retrieved in late 2014, suggesting the fleet may still be active within the region (SC-CAMLR 2015). Surveillance within the French and Southern Territory EEZs is likely to continue, with the commissioning of two French vessels and a planned extension of satellite coverage providing imagery used to improve estimates of IUU fishing vessel presence (SC-CAMLR 2015). The estimated IUU effort in the model reflect the assumption that 2005 was the last year of IUU demersal longline activity within the French EEZ around Kerguelen (Duhamel & Williams 2011), while some IUU effort is allocated in adjacent areas, namely south of Kerguelen (Fig. S2.1), outside of the EEZ, resulting in some estimated albatross bycatch in 2006 and 2007 (Fig. 4). The spatial distribution and relative magnitude of IUU effort is shown in Fig. S1.4.

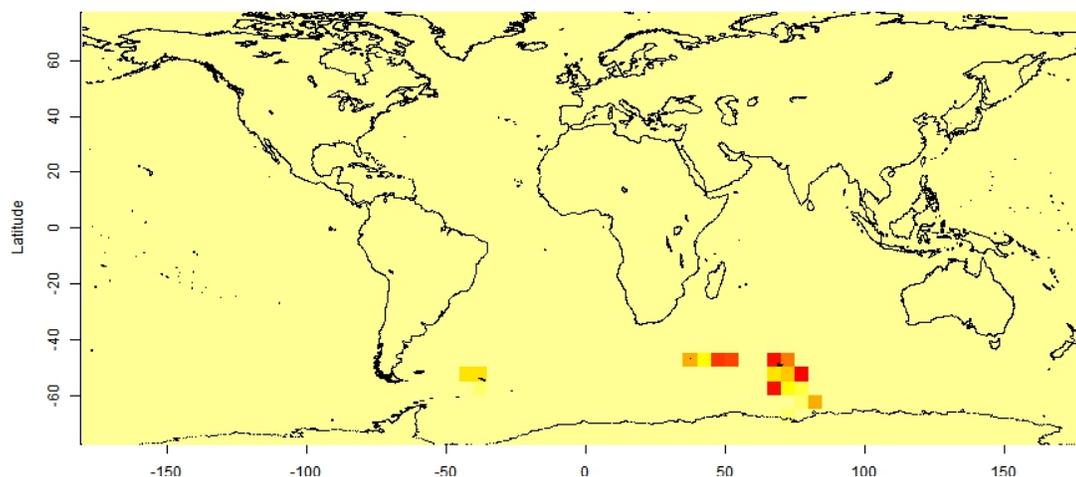


Figure S1.4: Spatial distribution and relative magnitude of IUU demersal longline effort. Red (yellow) indicates high (low) total magnitude of effort. The background is faint yellow to differentiate the map from those of albatross at-sea distributions.

Table S1.2 Summary of the fleets included in the model, the associated super-fleet, temporal range of data, and the average magnitude and standard error (SE) of effort in an average fished 5° x 5° cell across this temporal range. Effort is number of hooks (longline; “LL”) or hours trawling (trawl). Super-fleets include: Japanese pelagic longline south of 30° S (“Jap Pel LL”), other pelagic longline fleets (“Pel LL”), legal demersal longline (“Dem LL”), illegal, unreported, and unregulated (IUU) demersal longline in Committee for the Conservation of Antarctic Living Marine Resources waters (“IUU Dem LL”), and “Trawl”. IOTC = Indian Ocean Tuna Commission, ICCAT = International Commission for the Conservation of Atlantic Tunas, SPC = Secretariat of the Pacific Community, ETBF = eastern tuna and billfish, WA = Western Australia., combined, names following a coma (,) indicate target species, SWO = swordfish targeting, nonSWO = non-swordfish targeting. ^a indicates fleets whose effort is assumed to be 0 after the last year of data.

Fleet	Super-fleet	1st year	last year	Avg. mag. of effort	SE effort
Argentina; Hake, Ling	Dem LL	1992	2007	120,083	8,313
Argentina; Toothfish	Dem LL	1992	2007	60,053	2,686
Australia	Dem LL	1997	2006	121,660	6,658
CCAMLR legal	Dem LL	1985	2006	316,136	29,784
Chile; Hake, Ling ^a	Dem LL	1982	2006	5,568,666	326,556
Chile; Toothfish	Dem LL	1991	2005	1859293	81,108
Falkland within EEZ	Dem LL	1992	2008	12,504	64
Falkland outside of EEZ	Dem LL	1997	2008	12,085	124
Namibia	Dem LL	1997	2006	17312	42
New Zealand	Dem LL	1991	2006	42789	1,053
South Africa; Hake	Dem LL	1994	2004	55,331	1,491
South Africa; Kingklip ^a	Dem LL	1983	1990	226,548	10,587
CCAMLR IUU ^a	IUU Dem LL	1989	2007	86944	2,700
ICCAT Japan south of 30° S	Jap Pel LL	1961	2007	111,180	5,044
IOTC Japan south of 30° S	Jap Pel LL	1952	2011	81,574	924
SPC Japan south of 30° S	Jap Pel LL	1952	2006	184,329	5,690
Australia ETBF; SWO	Pel LL	1987	2008	988	2
Australia WA; nonSWO	Pel LL	1986	2007	1,158	4
Australia WA; SWO	Pel LL	1989	2007	1,140	2
Chile; SWO	Pel LL	1989	2007	72,107	2,671
ICCAT Brazil; nonSWO	Pel LL	1958	2006	68,386	1,591
ICCAT Brazil; SWO	Pel LL	1961	2007	8,918	225
ICCAT China	Pel LL	1993	2006	174,183	7,128
ICCAT Cuba	Pel LL	1959	2006	94,590	2,383

Fleet	Super-fleet	1st year	last year	Avg. mag. of effort	SE effort
ICCAT Cyprus	Pel LL	1975	2006	96744	6,415
ICCAT Greece	Pel LL	1981	2006	983,895	87,516
ICCAT Japan north of 30° S	Pel LL	1956	2007	97,633	1,083
ICCAT Korea	Pel LL	1964	2007	115,151	2,321
ICCAT Mexico	Pel LL	1981	2006	31,794	1,758
ICCAT Namibia	Pel LL	1997	2006	54,758	2,955
ICCAT others fleets	Pel LL	1959	2007	23,027	196
ICCAT Panama	Pel LL	1972	2006	105,365	10,808
ICCAT South Africa;	Pel LL	1963	2006	16,873	1,184
ICCAT South Africa; SWO	Pel LL	1998	2006	14,143	985
ICCAT Spain	Pel LL	1950	2006	178,336	3,284
ICCAT Taiwan	Pel LL	1962	2007	168,528	1,778
ICCAT Uruguay	Pel LL	1981	2007	45,991	5,623
ICCAT USA	Pel LL	1952	2006	21,887	476
ICCAT Vanuatu-Belize	Pel LL	2004	2006	109,373	8,683
ICCAT Venezuela	Pel LL	1957	2006	67,547	1,839
IOTC China	Pel LL	1995	2011	206,612	6,732
IOTC Japan north of 30° S	Pel LL	1959	2011	184,571	3,419
IOTC Korea	Pel LL	1975	2011	129,443	2,300
IOTC Mauritius; nonSWO	Pel LL	1978	2006	3,607	176
IOTC Mauritius; SWO	Pel LL	2001	2006	6,178	317
IOTC Reunion	Pel LL	1991	2011	39,167	1,509
IOTC South Africa; nonSWO	Pel LL	1998	2006	10,882	896
IOTC South Africa; SWO	Pel LL	1998	2006	10,253	830
IOTC South Africa; Shark	Pel LL	2004	2006	13,222	1,402
IOTC Seychelles	Pel LL	1983	2011	42,847	1,175
IOTC Spain	Pel LL	1993	2011	61,834	3,566
IOTC Taiwan Fresh	Pel LL	2001	2011	146,208	3,871
IOTC Taiwan	Pel LL	1967	2011	244,181	2,631
Southeast Pacific Spain	Pel LL	1990	2006	84,013	5,907
SPC Australia; nonSWO	Pel LL	1985	2007	64,111	2,721
SPC Japan north of 30° S	Pel LL	1950	2006	126,563	663
SPC Korea	Pel LL	1962	2007	148,976	1,674
SPC New Zealand	Pel LL	1990	2007	141,780	6,728
SPC other fleets	Pel LL	1981	2007	88,136	1,080

Fleet	Super-fleet	1st year	last year	Avg. mag. of effort	SE effort
SPC Taiwan	Pel LL	1958	2007	198,236	3,742
Argentina	Trawl	1958	2007	790	18
Australia	Trawl	1974	2008	2,998	63
Falkland	Trawl	1987	2007	1,072	32
France, Kerguelen EEZ ^a	Trawl	1979	1996	45	11
Namibia	Trawl	1964	2007	7,052	190
New Zealand; Hoki	Trawl	1997	2006	994	52
New Zealand; Squid	Trawl	1998	2006	4	n.a.
South Africa Offshore	Trawl	1930	2006	127	3
Ukraine, Kerguelen EEZ ^a	Trawl	1979	1995	269	40
Uruguay	Trawl	1950	2007	648	26

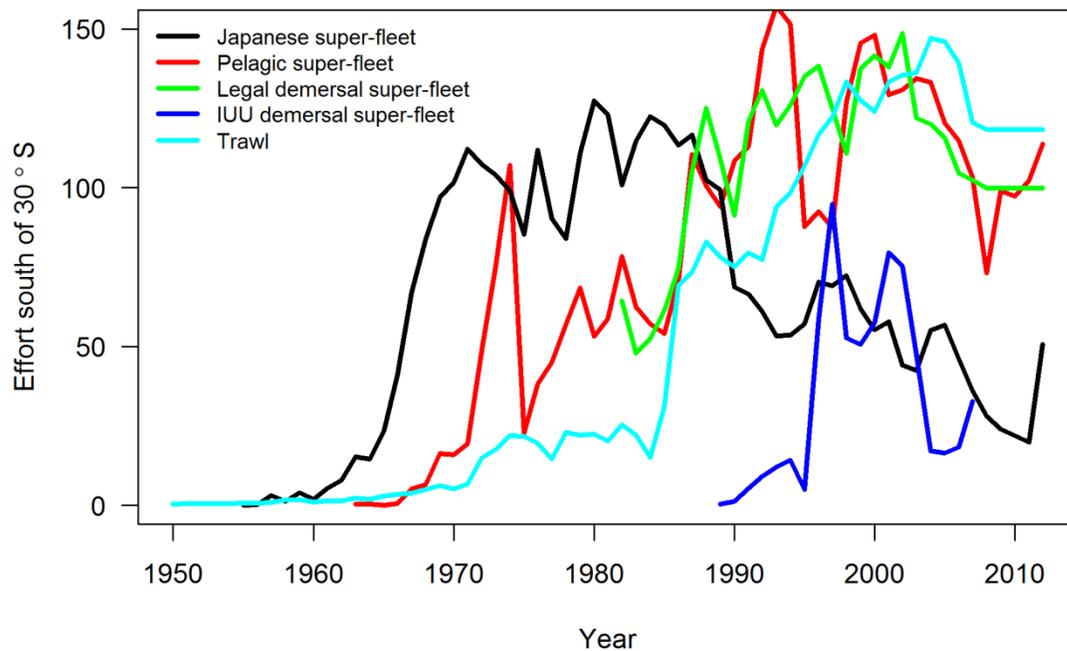


Figure S1.5 Annual estimated magnitude of effort (million hooks or thousand trawl hours) south of 30°S by super-fleet. Effort estimates include the last year of available data repeated until 2011, excluding fleets assumed to be inactive (see Table S1.2).

1.5 Summary of observed black-browed albatross bycatch rates and population multiplier estimates

Table S1.3 Summary of black-browed albatross bycatch rates obtained from published and unpublished sources. Super-fleet abbreviations are as in Table S1.2. Date ranges are described from the first month (Month 1) and year (Year 1) to last month (Month 2) and year (Year 2) and the area of bycatch is bounded by the four corners (Latitude South, Latitude North, Longitude West and Longitude East) of the overlapping $5^\circ \times 5^\circ$ cells, given as the center point of each cell. Bycatch rates are the number of birds / 1,000 hooks (longline) or / 1,000 hours trawled (trawl). The single IUU bycatch rate was estimated from the legal demersal longline fishery before the use of mitigation (Anonymous 2006). The population multiplier (Supplement Text S2.7) indicates the proportion of black-browed albatross likely to be a part of the focal population (Cañon des Sourcils Noirs, Kerguelen Island) where smaller values indicate a lower proportion.

Super-fleet	Month 1	Year 1	Month 2	Year 2	Latitude South	Latitude North	Longitude West	Longitude East	Bycatch	Population Multiplier	Reference
Jap Pel LL	5	1988	6	1988	-42.5	-42.5	142.5	142.5	1.29E-01	4.14E-03	Brothers 1991
Jap Pel LL	4	1992	3	1993	-32.5	-47.5	112.5	152.5	2.71E-02	4.19E-03	Klaer & Polacheck 1997
Jap Pel LL	4	1993	3	1994	-32.5	-47.5	112.5	152.5	6.62E-02	4.19E-03	Klaer & Polacheck 1997
Jap Pel LL	4	1994	3	1995	-32.5	-47.5	112.5	152.5	4.21E-02	4.19E-03	Klaer & Polacheck 1997
Jap Pel LL	1	1998	12	2005	-37.5	-32.5	17.5	27.5	2.00E-02	2.51E-05	Petersen et al. 2009
Pel LL	10	2003	9	2004	-52.5	-27.5	162.5	187.5	6.83E-04	1.88E-04	Abraham & Thompson 2009
Pel LL	10	2005	9	2006	-52.5	-27.5	162.5	187.5	4.71E-03	1.88E-04	Abraham & Thompson 2009
Pel LL	10	2006	9	2007	-52.5	-27.5	162.5	187.5	1.05E-03	1.88E-04	Abraham & Thompson 2009
Pel LL	1	2007	12	2007	-42.5	-32.5	7.5	32.5	2.12E-02	2.20E-05	Ryan et al. 2009a, b
Pel LL	1	2008	12	2008	-42.5	-32.5	7.5	32.5	1.58E-03	2.20E-05	Ryan et al. 2009a, b
Dem LL	11	1994	4	1995	-47.5	-47.5	67.5	67.5	3.40E-02	4.33E-03	Weimerskirch et al. 2000
Dem LL	11	1995	4	1996	-47.5	-47.5	67.5	67.5	7.70E-02	4.33E-03	Weimerskirch et al. 2000
Dem LL	3	1996	7	1996	-57.5	-52.5	317.5	327.5	8.15E-02	3.48E-03	Anonymous 1996
Dem LL	11	1996	4	1997	-47.5	-47.5	67.5	67.5	2.00E-03	4.33E-03	Weimerskirch et al. 2000
Dem LL	3	1997	4	1997	-57.5	-52.5	317.5	327.5	3.48E-01	3.48E-03	Anonymous 1997
Dem LL	5	1997	8	1997	-57.5	-52.5	317.5	327.5	3.32E-03	3.48E-03	Anonymous 1997
Dem LL	4	1998	4	1998	-57.5	-52.5	317.5	327.5	3.84E-03	3.48E-03	Anonymous 1998
Dem LL	5	1999	7	1999	-57.5	-52.5	317.5	327.5	1.05E-02	3.48E-03	Anonymous 1999
Dem LL	9	2001	4	2002	-47.5	-47.5	62.5	72.5	1.90E-06	4.33E-03	Delord et al. 2005
Dem LL	9	2002	4	2003	-47.5	-47.5	62.5	72.5	2.71E-06	4.33E-03	Delord et al. 2005
IUU Dem LL	9	1995	4	1996	-57.5	-52.5	317.5	327.5	3.47E-01	8.71E-04	Anonymous 2006
Trawl	4	2004	9	2004	-37.5	-32.5	17.5	27.5	9.04E+01	2.51E-05	Watkins & Ryan 2008

Super-fleet	Month 1	Year 1	Month 2	Year 2	Latitude South	Latitude North	Longitude West	Longitude East	Bycatch	Population Multiplier	Reference
Trawl	10	2004	3	2005	-37.5	-32.5	17.5	27.5	2.57E+01	2.51E-05	Watkins & Ryan 2008
Trawl	4	2005	9	2005	-37.5	-32.5	17.5	27.5	9.04E+01	2.51E-05	Watkins & Ryan 2008
Trawl	10	2005	12	2005	-37.5	-32.5	17.5	27.5	2.57E+01	2.51E-05	Watkins & Ryan 2008
Trawl	1	2006	12	2006	-37.5	-32.5	17.5	27.5	8.68E-06	2.51E-05	Maree et al. 2014
Trawl	1	2007	12	2007	-37.5	-32.5	17.5	27.5	8.68E-06	2.51E-05	Maree et al. 2014
Trawl	1	2008	12	2008	-37.5	-32.5	17.5	27.5	8.68E-06	2.51E-05	Maree et al. 2014
Trawl	1	2009	12	2009	-37.5	-32.5	17.5	27.5	8.68E-06	2.51E-05	Maree et al. 2014
Trawl	1	2010	12	2010	-37.5	-32.5	17.5	27.5	8.68E-06	2.51E-05	Maree et al. 2014
Trawl	1	2011	12	2011	-37.5	-32.5	17.5	27.5	8.68E-06	2.51E-05	Maree et al. 2014

1.6 Summary of the proportion of birds having bred at a given age

Table S1.4 Proportion of birds having bred at a given age calculated from observed age at first breeding data. '1' indicates all birds of that age have bred at least once.

age	proportion
1	0.00
2	0.00
3	0.00
4	0.00
5	0.01
6	0.08
7	0.23
8	0.47
9	0.63
10	0.78
11	0.86
12	0.91
13	0.94
14	0.98
15	0.99
16	1.00

1.7 Return rates for black-browed albatross

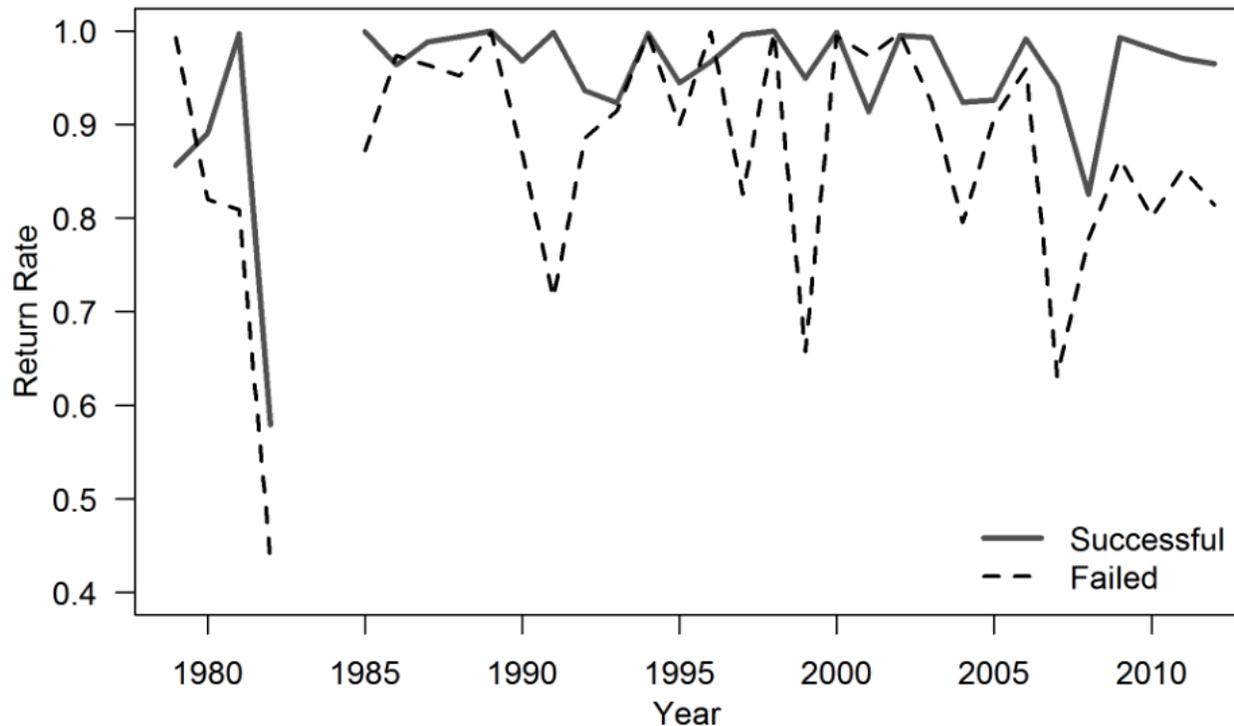


Figure S1.6 Return rates for black-browed albatross which were successful (grey solid) or failed (black-dashed) breeders the previous year from the capture-mark-recapture model (Supplement Text S1.1).

Supplement 2: Technical description of albatross population model

To apply this model to the Kerguelen BBA population through 2011, a range of new data were required. Fishing effort for major Indian Ocean pelagic longline fleets were updated (see Supplement Text S1.3), appropriate environmental covariates were developed, as well as colony, species-specific bycatch rates and weighting of bycatch estimates, and popmulti estimates. The categories for birds within the population differ slightly, as do return rates for previously successful and failed breeders, with the addition of non-breeding individuals who previously failed breeding, non-breeding individuals who previously successfully breed (fledged a chick), and distinct spatial distributions for juvenile and immature birds. These alterations result in slight differences in the equations presented in Supplement Text S2 in Tuck et al. (2015) and Supplement Text S3 in Thomson et al. (2015).

Briefly, distribution at-sea data are combined with fishing effort data to calculate the degree of overlap and the vulnerability to fisheries bycatch and an estimated bycatch catchability parameter for each fleet. The model also considers the probability that a given bycatch report involved a bird from the focal population (e.g. population multiplier; Supplement Text S2.7). As successfully fledging a chick typically requires provisioning from both parents (Tickell 1968),

we assume that the death of either partner would result in the death of a chick, i.e. breeding failure. Therefore, in a given model year, a breeding bird can become a failed breeder due to the loss of a partner through natural or bycatch related mortality, or the death of their chick through natural chick mortality. This change is reflected in the number of failed breeders in the following month. This is also true of age-specific mortality rates, which are density-dependent for chicks and juveniles / immatures (Supplement Text S2.3-S2.4) and all but chicks (from egg to pre-fledging) are directly susceptible to bycatch. At the start of each model year, birds are re-allocated to breeding or non-breeding status, as appropriate, and one year is added to each bird's age. The change in a given bird's age might be reflected in a change of category (e.g. juvenile to immature, immature to adult) when appropriate. Note that chicks move to the juvenile category less than a full year after hatching, at the end of the breeding season when they fledge and become vulnerable to bycatch as juveniles.

2.1 Within year dynamics

As successfully fledging a chick often requires provisioning from both parents (Tickell 1968, Warham 1990), we assume that the death of either partner (p) would result in the death of a chick, therefore breeding failure.

The model year begins on 1 October (model month $m = 1$) when breeding commences. The number of birds hatched at the beginning of model year y (designated as 'chicks') is given by N_y^0 . Once chicks leave the colony (fledge) in April, they become 'juveniles, J ' until the end of that model year. From the start of their second year of life birds are termed immatures until they first recruit to the breeding colony (given by an ogive; Table S1.4, starting at age five).

The population is divided into chicks, and an additional six categories (breeding bx , failed breeders bf , non-breeding individuals who failed breeding the previous season $ns-f$, non-breeding individuals who successfully breed the previous season $ns-s$, juveniles J and immatures I), so that the number of birds of sex g , and age a and in any category c during year y and month m is given by $N_{g,a,y,m}^c$,

$$N_{g,a,y,m}^c = \left[N_{g,a,y,m}^{bx}, N_{g,a,y,m}^{bf}, N_{g,a,y,m}^{ns-f}, N_{g,a,y,m}^{ns-s}, N_{g,a,y,m}^J, N_{g,a,y,m}^I \right]$$

Sex-specific at-sea distributions are used failed breeders. The model 'year' begins when birds arrive at their breeding colony (assumed to be the same day, for all birds of a given population) and ends at the end of April the following calendar year. On arrival, birds are assigned to the 'breeding' category $N_{g,a,y,m}^{bx}$ and, unless their breeding attempt fails during any month, they remain in this category until the end of the breeding season (at the end of month Q). Each month m , some surviving birds fail in their breeding attempt because their mate dies of natural causes (at instantaneous monthly rate $M/12$) or is caught by a fishery (at instantaneous monthly rate $F_{g,y,m}^{bx}$ for adult birds in category $c = bx$ or their chick dies (at instantaneous annual rate $M_y^0/12$). The number of surviving birds remaining in the breeding category at the start of month m is given by

$$N_{g,a,y,m}^{bx} = N_{g,a,y,m-1}^{bx} e^{-(M/12+F_{g',y,m-1}^{bx}+M_y^0/12)} e^{-(M/12+F_{g,y,m-1}^{bx})} \quad m = 2 \dots Q$$

where g' is the sex of the mate of a bird of sex g .

Chick mortality M_y^0 and adult mortality M are independent of sex and adult category, but fishing mortality $F_{g,y,m}^c$, because it depends on spatial overlap with fishing fleets differs between sexes g , and between adult (categories bx , bf , $ns-f$, and $ns-s$), and pre-breeding birds (categories J and I) and changes monthly as at-sea distributions for fishing fleets vary. Any breeding bird that fails in its breeding attempt during month $m-1$ is moved into the failed breeders category at the start of the following month $N_{g,a,y,m}^{bf}$. The number of birds in the failed breeder category at the start of month m is given by those that remain from the previous month (that survive both natural and fishing mortality), plus those (surviving) breeders whose breeding attempt failed during the previous month $m-1$,

$$N_{g,a,y,m}^{bf} = N_{g,a,y,m-1}^{bf} e^{-(M/12+F_{g,y,m-1}^{bx})} + N_{g,a,y,m-1}^{bx} \left[1 - e^{-(M/12+F_{g',y,m-1}^{bx}+M_y^0/12)} \right] e^{-(M/12+F_{g,y,m-1}^c)} \quad m = 2 \dots Q$$

After the breeding season ends, all surviving breeding or failed birds move into the non-breeding category alongside surviving birds that did not attempt to breed during year y , relative to their success or failure breeding the year prior,

$$\begin{aligned} N_{g,a,y,Q+1}^{ns-f} &= N_{g,a,y,Q}^{ns-f} e^{-(M/12+F_{g,y,Q}^{ns-f})} + N_{g,a,y,Q}^{bx} e^{-(M/12+F_{g,y,Q}^{bx})} + N_{g,a,y,Q}^{bf} e^{-(M/12+F_{g,y,Q}^{bf})} \\ N_{g,a,y,Q+1}^{ns-s} &= N_{g,a,y,Q}^{ns-s} e^{-(M/12+F_{g,y,Q}^{ns-s})} + N_{g,a,y,Q}^{bx} e^{-(M/12+F_{g,y,Q}^{bx})} + N_{g,a,y,Q}^{bf} e^{-(M/12+F_{g,y,Q}^{bf})} \\ N_{g,a,y,Q+1}^{bx} &= N_{g,a,y,Q+1}^{bf} = 0 \end{aligned} \quad (2.1)$$

Adult birds that did not attempt to breed during year y remain in the non-breeding category for the duration of the year, and suffer natural M and fishing mortality ($F_{g,y,m}^{ns-f}$ or $F_{g,y,m}^{ns-s}$) during each month (the number of non-breeding birds at the start of month $m=Q+1$ is given by equation 2.1), relative to their success or failure breeding the prior year

$$\begin{aligned} N_{g,a,y,m}^{ns-f} &= N_{g,a,y,m-1}^{ns-f} e^{-(M/12+F_{g,y,m-1}^{ns-f})} & m = 2K(Q-1), (Q+1) \dots 12 \\ N_{g,a,y,m}^{ns-s} &= N_{g,a,y,m-1}^{ns-s} e^{-(M/12+F_{g,y,m-1}^{ns-s})} & m = 2K(Q-1), (Q+1) \dots 12 \end{aligned}$$

Similarly, juvenile and immature birds remain in their respective categories throughout the month and suffer both natural and fishing mortality.

Juveniles and immatures share their own age and density-dependent natural mortality rate $M_{a,y}^{J,I}$ (see section 2.3) but have slightly different fishing mortality rates as they have different at-sea distributions (see section 2.1 for details and Supplement Text S1.2, Table S1.1 for a summary of these categories).

$$\begin{aligned} N_{g,a,y,m}^J &= N_{g,a,y,m-1}^J e^{-(M_{a,y}^{J,I}/12 + F_{g,y,m-1}^J)} & m = 2K \dots 12 \\ N_{g,a,y,m}^I &= N_{g,a,y,m-1}^I e^{-(M_{a,y}^{J,I}/12 + F_{g,y,m-1}^I)} & m = 2K \dots 12 \end{aligned} \quad (2.2)$$

Any chicks that survive to fledge at the end of the breeding season, are added to the juvenile category, age 0, at the beginning of month $Q+1$. For clarity of presentation, this is not shown in equation 2.2.

All eggs are assumed to be laid on the first day of the breeding season. The number of chicks (including eggs) present in the colony during the breeding season at the start of month m is given by those that survive from the previous month. Death occurs due to natural causes (e.g. environmental, or physiological) M_y^0 or through the natural M or fishing related $F_{g,y,m}^{bx}$ death of either parent,

$$N_{g,y,m}^0 = N_{g,y,m-1}^0 e^{-M_y^0/12 - \sum_{g'=1}^2 (M/12 + F_{g',y,m-1}^{bx})} \quad m = 2K \dots Q$$

At the end of the breeding season all chicks move into the juvenile category and become vulnerable to incidental catch by fisheries (equation 2.2).

2.2 Between year dynamics

At the end of each year (i.e. start of the next year), all birds move to the next age class, a proportion of each immature age class recruits into the breeding adult category (Table S1.1), and some adult birds move from the non-breeding categories to the breeding category.

The number of breeding birds of sex g and age $a+1$ at the start of year $y+1$ (month 1) $N_{g,a+1,y+1,1}^{bx}$ is given by the sum of the number of returning failed breeders and non-breeders (at rate ϕ_y^{ns-f}), the returning successful non-breeders (also at rate ϕ_y^{ns-s}), and the maturing juveniles (at age-specific rate λ_a),

$$N_{g,a+1,y+1,1}^{bx} = \phi_y^{ns-f} (N_{g,a,y,13}^{bf} + N_{g,a,y,13}^{ns-f}) + \phi_y^{ns-s} (N_{g,a,y,13}^{ns-s}) + \lambda_a N_{g,a,y,13}^J \quad a = 1 \dots A-2$$

where A is the maximum age and is a (a plus group) so that,

$$N_{g,A,y+1,1}^{bx} = N_{g,A,y,13}^{bx} + N_{g,A-1,y,13}^{bx} + \phi_y (N_{g,A-1,y,13}^{bf} + N_{g,A-1,y,13}^{ns-f} + N_{g,A-1,y,13}^{ns-s}) + \lambda_{A-1} N_{g,A-1,y,13}^J$$

Note that ‘13’ indicates the number of birds present at the very end of month 12 of year y (i.e. the start of ‘month 13’) and is used for clarity of presentation so that mortality that occurred during the last month of the year need not be shown.

No birds are assigned to the failed breeder category at the start of the year,

$$N_{g,a+1,y+1,1}^{bf} = 0 \quad g = 1,2; a = 2 \dots A-1$$

Some adult birds take a year’s sabbatical (at rate $1 - \phi_y$),

$$N_{g,a+1,y+1,1}^{ns-f} = (1 - \phi_y^{ns-f}) N_{g,a,y,13}^{ns-f} \quad g = 1,2; a = 2 \dots A-1$$

$$N_{g,a+1,y+1,1}^{ns-s} = (1 - \phi_y^{ns-s}) N_{g,a,y,13}^{ns-s} \quad g = 1,2; a = 2 \dots A-1$$

See Table S1.4 for return rates.

Juvenile birds leave to join the adult breeding category at age-specific rate λ_a (note that surviving chicks from the previous year y became juveniles of age zero $N_{0,y,Q+1}^J$ during that year, at the end of the breeding season), but do not become immatures until the start of year $y+2$,

$$N_{g,a+1,y+1,1}^J = (1 - \lambda_a) N_{g,a,y,13}^J \quad a = 0 \dots A-1$$

The number of breeding pairs $B_{y,m}$ present in the colony during the first month of the breeding season is given by the smaller of the number of breeding males and breeding females. As albatross only lay a single egg per breeding attempt, the number of breeding pairs is also the number of chicks (or eggs) $N_{y,1}^0$ at the start of the breeding season ($m=1$). Assuming a 1:1 sex ratio at birth

$$N_{g,y,1}^0 = 0.5 B_{y,1} = \min \left(\sum_{a=1}^A N_{1,a,y,1}^{bx}, \sum_{a=1}^A N_{2,a,y,1}^{bx} \right) \quad (2.3)$$

2.3 Density-dependence on juvenile and immature mortality

Density-dependence for juveniles and immatures is modelled by, initially, making two key assumptions; first that the lowest mortality rate for juveniles and immatures (achieved at population size zero) is equal to that of adults M ; and second, that juvenile and immature mortality increases linearly with increasing population size, to its maximum rate $M_0^{J,I}$ when the population is at its unfished equilibrium size N_0^{1+} . The $1+$ population size is given by the total number of birds aged $a=1$ or more, in all categories c in the population at the start of year y (month $m=1$), N_y^{1+} ,

$$N_y^{1+} = \sum_c \sum_{g=1}^2 \sum_{a=1}^A N_{g,a,y,1}^c$$

By simple linear regression (linear, that is, if $\gamma=1$), for any population size N_y^{1+} the corresponding density-dependent juvenile and immature mortality rate $M_y^{J,I}$ is,

$$M_y^{J,I} = M + (M - M_0^{J,I}) \left(\frac{N_y^{1+}}{N_0^{1+}} \right)^\gamma$$

Juvenile and immature birds assume natural mortality rate $M_y^{J,I}$ to the age of five, thereafter taking the adult natural mortality rate M . The shape of this function is governed by the parameter γ , which is estimated.

2.4 Density-dependence on chick mortality

Density-dependence is modelled for the chick mortality term as a function of the number of breeding pairs in the population B_y . Chick mortality (before accounting for environmental effects \bar{M}_y^0) is assumed to be at its lowest rate at zero population size, when it is assumed to be equal to that of adults M . At maximum population size chick mortality is M_0^0

$$\bar{M}_y^0 = M \exp\left[\left(B_y/B_0\right)^\kappa \ln(M_0^0/M)\right] \quad (2.4)$$

where

$$M_0^0 = -2 M p^B - \ln(\tilde{S}_0) \quad (2.5)$$

The highest rate of chick mortality M_0^0 reflects the mortality of both parents during the portion of the year represented by the breeding season p^B , and the number of chicks fledged when the population is at unexploited equilibrium \tilde{S}_0 , which is an estimated model parameter. Given a 6 month breeding season (1 Oct to end March) $p^B=1/2$. The parameter κ controls the level of density-dependent compensation ($\kappa=0$ gives density independent chick mortality) and is also an estimated parameter.

Environmental variables further influence the realized chick mortality rate in year y M_y^0 , see section 2.5.

2.5 Environmental variables

Environmental variables cause the chick mortality rate M_y^0 in a given year y to deviate from the average level \bar{M}_y^0 given by equation 2.4)

$$M_y^0 = \bar{M}_y^0 \sum_{i \in I} f(x_i)$$

Where $f(x_i)$ is a functional relationship for environmental covariate x_i (of the set of covariates I used by the model). A flexible, exponential, functional form was used

$$f(x_i) = \exp(\theta_i x_i^b)$$

Here the parameters θ_i , termed “slope” parameters are estimated by the model whereas the b parameter is fixed at 1.

2.6 Modeling incidental catch

The instantaneous fishing mortality rate $F_{g,y,m}^c$ for birds in any category c of sex g during month m of year y is calculated from the number of birds caught during the month $C_{g,y,m}^c$ by assuming that all birds are caught in a pulse at the middle of each month, after half the month’s natural mortality has occurred,

$$F_{g,y,m}^c = -\log \left(1 - \frac{C_{g,y,m}^c}{\sum_{a=1}^A N_{g,y,m}^c e^{-0.6M/12}} \right)$$

Note that fishing mortality rates depend on the at-sea distribution of each category (Table S1.1). The relative susceptibility of different classes of black-browed albatross to bycatch has not been explored in this study and is assumed to be proportional to the overlap with a given fleet / super-fleet.

To model the total catch $C_{g,y,m}^c$ of birds from category c of sex g taken during month m of year y , the catch of birds of each age a in each $5^\circ \times 5^\circ$ cell b by each fishery f is summed. The catch in a particular cell h is a function of the number of birds in the population at the middle of the month $\bar{N}_{g,a,y,m}^c$, present in cell h at that time. Presence in cell b is given by $P_{y,m,b}^c$ the proportion of the birds from category c that have been observed to occupy cell h (i.e. the at-sea distribution), multiplied by $P_{g,m}^S$ the number of birds that are likely to be at sea. This is, in turn, multiplied by the effective number of hooks (longline) deployed or hours (trawled) fished in that cell at that time, which is given by the product of the total recorded number of

hooks $E_{y,m,b}^f$ deployed by each fishery f multiplied by the model estimated ‘catchability’ of hooks for fishery f , q^f , inflated by the greater catchability of the proportion of the population that belongs to the more susceptible type. The total effective number of hooks is calculated by summing across all fisheries f . The total catch during month m of year y is given by summing over all sexes g , ages a and $5^\circ \times 5^\circ$ cells h ,

$$C_{y,m}^c = \sum_{g,a,h} \left(\bar{N}_{g,a,y,m}^c P_{y,m,h}^c P_{g,m}^S \sum_f q^f (1 + p_{y,m}^B q^B) E_{y,m,h}^f \right) \quad (2.6)$$

The number of birds in the middle of the month $\bar{N}_{g,a,y,m}^c$ is given by the product of the numbers at the start of the month $N_{g,a,y,m}^c$ and half the natural mortality for birds of age a in category c .

2.7 Matching observed bycatch rate

For each of the observed bycatch rates by super-fleet collected from the literature, the model estimates a bycatch rate for the study area (matched as closely as possible by one or more $5^\circ \times 5^\circ$ cell) over the years and months during which the data were collected (Table S1.3). To estimate the probability that a given BBA bycatch observation involved an individual from the focal population we calculated a ‘population multiplier’. This value is calculated from the proportion of BBA from the focal population versus all populations and is used to scale the reported bycatch rate to a focal-population specific bycatch rate estimate. This involved first dividing the number of individuals from a given population k in particular strata in space and time u by the sum of individuals across all strata, as follows:

$$X_{u,k} = \frac{D_{u,k}}{\sum_U D_{U,k}} W_k$$

where $D_{u,k}$ is the observed number of observed individuals of a given population in a given area and time, U is an index for all strata and W_k is the population size of population k as defined by ACAP (2012).

For the Kerguelen population, $D_{u,k}$ (for all u) were based on tagging data. Given differences in access to information on the at-sea distribution of BBA from colonies other than Kerguelen, the number of individuals of a given population in a given area and time, $D_{u,k}$ was estimated in different ways for the different populations. We focused on BBA populations in the Seabird Tracking Database (www.seabirdtracking.org) that overlapped with the distribution of our focal population (Bird Island, South Georgia and Islas Diego Ramírez), as well as Macquarie Island (Terauds et al., 2006), as they also overlap. The proportion of BBA originating from Bird Island was calculated from individual tracks shared through the Seabird Tracking Database

(BirdLife International, 2004; R. Phillips, datasets; 457, 492, 493). Locations of BBA from Diego Ramirez were estimated visually using the Seabird Tracking Database as the proportion of locations that occurred within a bycatch area. Lastly, the proportion of BBA from Macquarie Island in each bycatch area was approximated by distribution at-sea maps (Terauds et al., 2006). The temporal and spatial location of bycatch is described in Section 2.4, Table 2.3. If a reported BBA bycatch occurred during breeding and non-breeding periods, the total number of birds occurring in the area across seasons was used.

The probability that a BBA caught in a given bycatch area originated from a given population $P_{u,k}$, was calculated by dividing the number of individuals from a given population $X_{u,k}$, by the sum of individuals from all populations K , in a given strata as follows:

$$P_{u,k} = \frac{X_{u,k}}{\sum_K X_{u,K}}$$

For the current study, $k = \text{Kerguelen population}$.

2.8 Initial conditions

We assume the population is at an unfished equilibrium at the beginning of the modeling period (1950). We calculate the juvenile and immature natural mortality rate ($\overline{M}_0^{J,I}$) that will maintain the population at this unfished equilibrium, given the resource dynamics equations shown above, the assumed adult natural mortality rate M and the pristine chick natural mortality rate M^0 (from equation 2.5 and model parameter \tilde{S}). Initial values for estimated parameters were based on observed demographic data (population size; 1,310) productivity (0.673; Barbraud et al. 2011), juvenile / immature mortality (0.72; Nevoux et al. 2010, does not consider density-dependence).

2.9 Fitting procedure

The demographic response variables (i.e. for which data time series exist) are the numbers of breeding pairs at the start of each year $B_{y,1}$, the numbers of chicks fledged at the end of the breeding season $N_{0,Q+1}^J$, the annual adult survival rate S_y^A , and juvenile survival to age five S_y^J .

The number of breeding pairs in the population at the time of census $B_{y,1}$ is given by equation 2.3. The number of chicks fledged \tilde{S}_y in year y is given by the number of chicks fledged at the end of the breeding season $N_{0,Q+1}^J$ (they are allocated to the juvenile category at the

start of the first month after the breeding season ends, $Q+1$) divided by the number of pairs that made a breeding attempt,

$$\tilde{S}_y = N_{0,Q+1}^J / B_{y,1}$$

Adult survival S_y^A (a percentage) is given by,

$$S_y^A = 100 N_{y+1}^A / N_y^A$$

where A is the maximum age group in the model (a plus group).

The juvenile and immature survival rate to age five (a percentage) is

$$S_y^{J,I} = 100 e^{-Z_y^{J,I}}$$

where $Z_y^{J,I}$ is the total mortality rate over the previous 4 years for immatures that are age five at the start of year y ,

$$Z_y^{J,I} = \sum_{y'=y-3}^y \left[\sum_{a=1}^4 M_{a,y'}^{J,I} + \sum_{m=1}^{12} F_{y',m}^{J,I} \right]$$

Note that the survival through the juvenile and immature stages until age five $S_y^{J,I}$ cannot easily be expressed in terms of a ratio of the numbers of immatures present in various years because birds leave a category through maturation, not just through mortality.

Note that the annual breeding success is given by the number of chicks fledged divided by the number of breeding pairs. Therefore one can choose to condition the model on any two of the three quantities: number of breeding pairs, number of chicks fledged, or breeding success. We have conditioned the model on the number of breeding pairs and the number of chicks fledged.

Finally, a response variable was calculated to match the observed bycatch rate, representing numbers of birds per thousand trawl hours, observed in a specified set of 5° cells over a span of months by super-fleet. This was given by the estimated catch in number of birds C_i divided by the effort in thousands of trawl hours E_i over that region and time, for the single bycatch observation i ,

$$R_i = p_i^G C_i / E_i$$

The number of birds caught C_i is estimated in the same way as $C_{y,m}^c$ in equation 2.6, with appropriate summation over $5^\circ \times 5^\circ$ cells and time periods and over all categories c .

2.10 Likelihood

Maximum likelihood was used to estimate the model parameters. Normal distributions are assumed for the residuals for the expected $B_{y,1}$ and observed $B_{y,1}^{obs}$ number of breeding pairs,

$$B_{y,1} \sim N(B_{y,1}^{obs}, \sigma_B)$$

for all years y for which observations exist. Similarly, a normal distribution is assumed for the residuals of the expected \tilde{S}_y and observed \tilde{S}_y^{obs} numbers fledged for all years y for which observations exist,

$$\tilde{S}_y \sim N(\tilde{S}_y^{obs}, \sigma_{\tilde{S}})$$

A binomial distribution was assumed for the adult survival rate, along with an assumed effective sample size of 100 animals, which seemed to achieve a good balance with the other data sources. The binomial probability was given by the observed survival rates $p = S_{y,1}^{A,obs}$, and the number of observations was the integer part of $(100 S_y^A)$ out of 100 trials.

$$100 S_y^A \sim Binom(100, S_{y,1}^{A,obs})$$

Similarly, for juvenile and immature survival,

$$100 S_y^{J,I} \sim Binom(100, S_{y,1}^{J,I,obs})$$

As the objective function maximizes the log likelihood by minimizing the negative log likelihood, it is necessary to weight each series of data. This was done using inverse variance weighting of each data source. Given the broad range of data sources and values for the estimated bycatch estimates within and across fleets (Table S1.3), bycatch for all super-fleets was placed at $2.2659e^{-3}$; the greatest observed variability in bycatches across super-fleets. Although somewhat arbitrary, this allowed bycatch observations to be equally weighted across fleets.

2.11 Estimated parameters

The estimated parameters of the model are the number of chicks fledged at unexploited equilibrium \tilde{S}_0 , the number of breeding pairs B , the adult natural mortality rate M , the parameters governing density-dependence for juvenile and immature birds γ , and for chicks κ , the catchability parameters for the Japanese pelagic longline south of 30° S q^j , other pelagic longline q^p , demersal longline q^d trawl q^t , and illegal demersal longline q^{iuru} super-fleets; and the three environmental parameters θ_i .

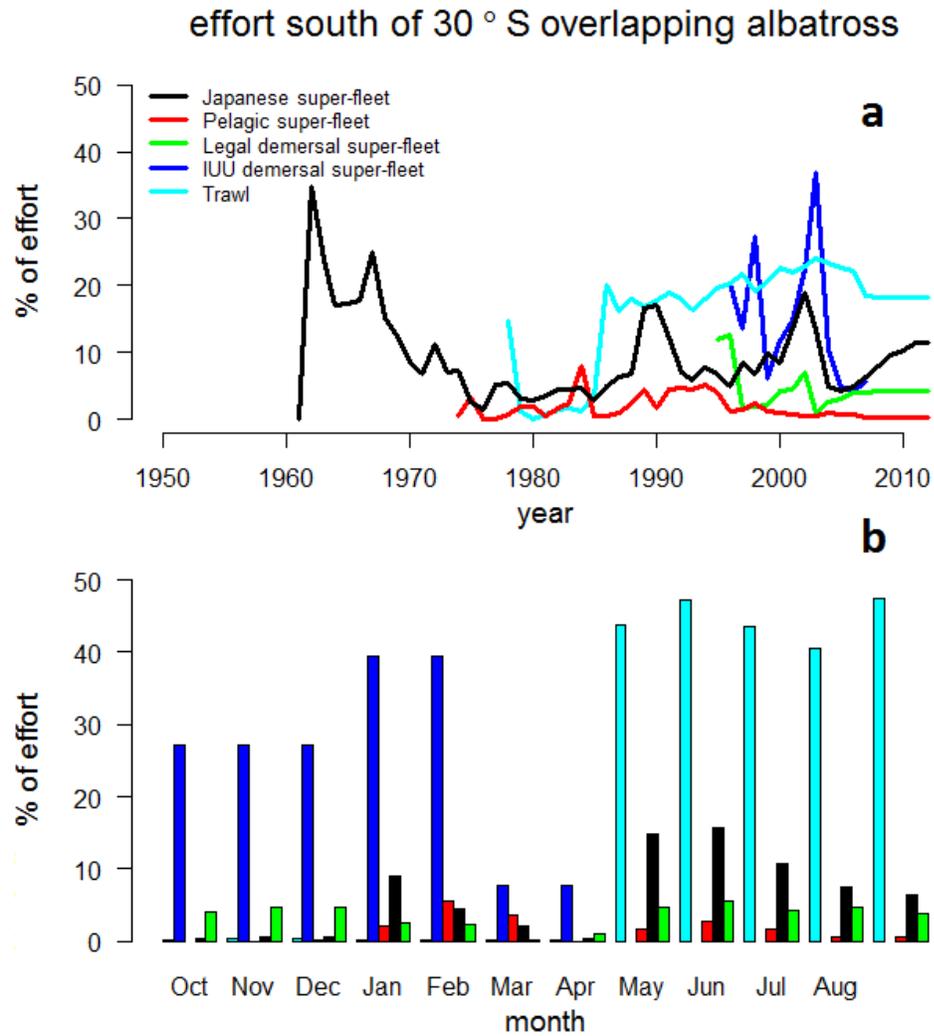


Figure S2.1 The percent (hooks or trawl hours) of effort south of 30°S overlapping BBA at-sea distribution by super-fleet summed across (a) year and (b) month. The BBA at-sea distribution includes cells with the presence of albatross in all of the temporally applicable albatross categories (Table S1.1). Overlap was defined as a 5° x 5° longitude by latitude, monthly cell with the presence of both effort and albatross.

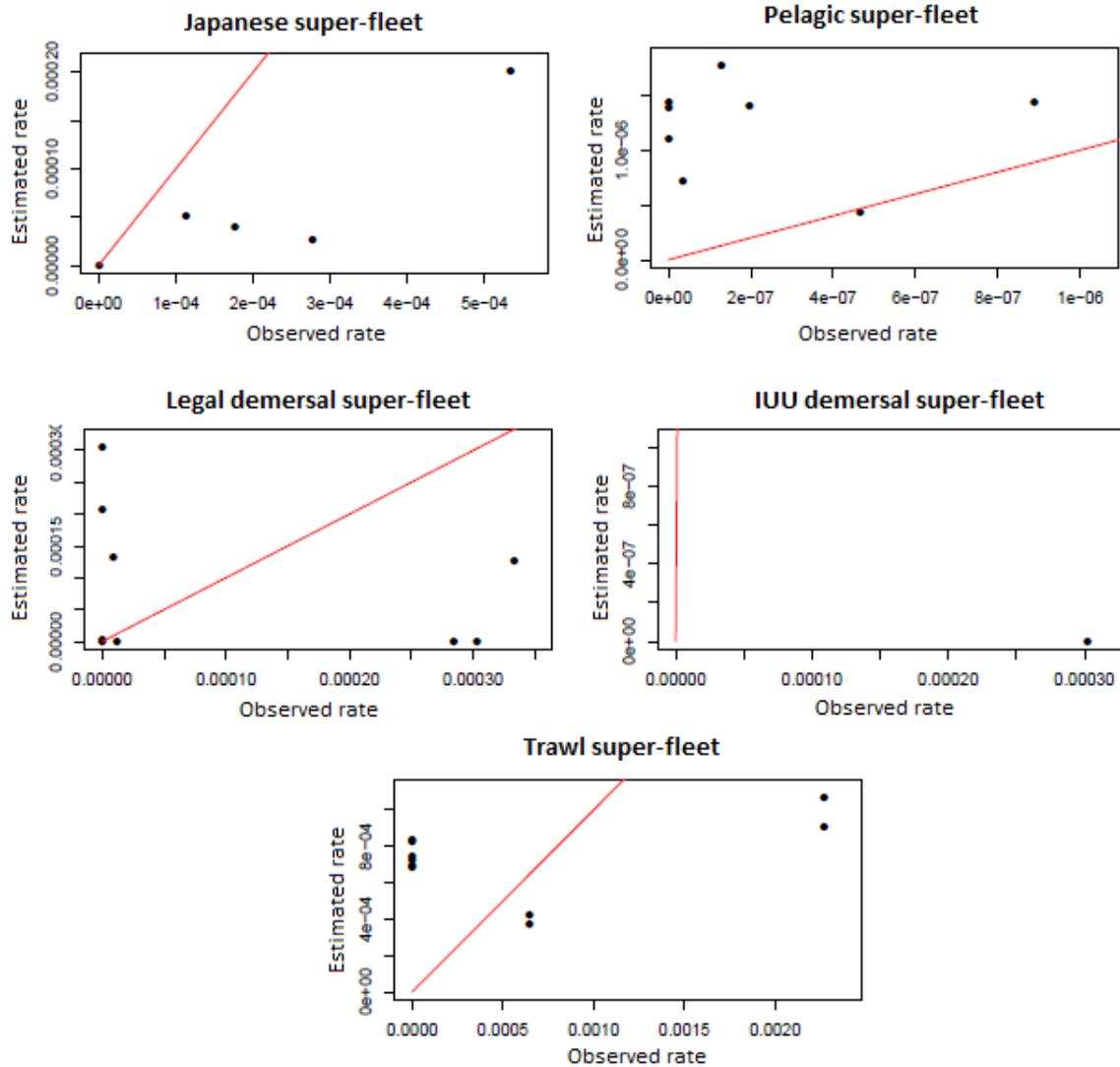


Figure S2.2 The (x-axis) observed and (y-axis) estimated bycatch rates by super-fleet for the final 'Ix' model. Red line indicates a 1:1 relationship between observed and predicted bycatch. Bycatch rates are calculated as: reported bycatch multiplied by the probability that the caught black-browed albatross originated from the focal colony (population multiplier). When the right-side of this line exits the plot above (below) the upper-right corner, this indicates an average tendency to underestimate (overestimate) the observed bycatch rate. Note that the single IUU bycatch rate was estimated from the legal demersal longline fishery before the use of mitigation (Agnew & Kirkwood 2005, Anonymous 2006). The estimated rate for the IUU super-fleet was four orders of magnitude smaller than the observed including the population multiplier (estimated (Table 3) 1.57E-8, observed (Table S1.3) $3.47E-01 * 3.02E-04 = 1.05E-04$).

Supplement 3: Sensitivity of model estimated parameter values to the estimated IUU demersal longline data and unobserved bycatch

The sensitivity of the model to the estimated IUU data was assessed by comparing the parameter estimates from a null model (with no environmental variables) assuming

- (i) the estimated IUU effort and bycatch rate and the same bycatch rate for the Japanese as other pelagic longline fleets

to alternative models with the following assumptions;

- (ii) no IUU effort,
- (iii) no IUU effort, and Japanese bycatch rate allowed to differ from other pelagic longline fleets,
- (iv) twice the estimated magnitude of IUU effort,
- (v) half the estimated magnitude of IUU effort,
- (vi) no fitting to the observed IUU bycatch rate, and
- (vii) the largest estimated bycatch population multiplier in the model (4.33×10^{-3}), is applied to the IUU observation instead of the original value (8.71×10^{-4}). See Supplement Text S2.7 for details on the calculation of these population multipliers.

We also assess the impact of the estimated magnitude of IUU effort on the:

- (viii) 'Ix' model, which allows the sea-surface temperature (SST) near Kerguelen during the incubation period to influence chick mortality,

with a model that differed from the Ix model in that it had:

- (ix) no IUU effort.

To assess the potential impact of unobserved bycatch within the 'Ix' model, we assumed:

- (x) total bycatch rates are two and 8.66 times greater than the reported observed rates for all pelagic longline super-fleets and the trawl fleet, respectively (Brothers et al. 2010, Richard & Abraham 2013).

Table S3.1 Final parameter estimates for the models (i – ix) assessing the sensitivity of the albatross population model to estimated IUU demersal longline fleet data. Model names correspond to i - x and are briefly described for ease of interpretation. ‘Japan sep.’ = Japanese pelagic longline fleet south of 30° S bycatch rate can be estimated, ‘unobs. bycatch’ = unobserved bycatch. ‘negLnL’ = negative loglikelihood, ‘popmulti’ = population multiplier. alpha = juvenile and immature mortality rate including density-dependence (which is the same value), NBop = number of breeding pairs, qJpel = Japanese pelagic longline super-fleet bycatch south of 30° S rate, qpel = other pelagic longline super-fleet bycatch catchability, qdem = demersal longline super-fleet bycatch catchability, qill = illegal, unreported and unregulated super-fleet bycatch catchability, qtrawl = trawl super-fleet bycatch catchability, MCpar= chick mortality rate including density-dependence, prod = productivity of the albatross population, inc = slope of the relationship between the average SST near Kerguelen during the incubation period and chick mortality. ‘Fledge’ = chicks fledged, ‘Sjuv’ = juvenile survival, ‘Sadult’ = adult survival, ‘Sum’ = sum of likelihood components excluding ‘Bycatch’. ‘^a’ indicates that the catchability was not estimated separately from other pelagic longline fleets. Madult = adult mortality. See Supplement 2). ‘^{db}’ indicates models whose negative log likelihood values cannot be compared with those of any other model presented here due to differences in the data used. All log likelihood values without a superscript can be compared with one another. Table continued on next page.

parameter	model									
	(i) null	(ii) no IUU effort, Japan sep.	(iii) no IUU effort	(iv) 2x IUU effort	(v) half IUU effort	(vi) IUU, no observed bycatch	(vii) IUU, larger popmulti	(viii) Ix	(ix) Ix, no IUU	(x) unobs. bycatch
negLnL	285.76	290.46	290.28 ^b	285.76	285.76	285.76 ^b	285.76 ^c	281.54	289.10 ^b	328.26
alpha	6.25	2.88	4.03	6.25	6.25	6.25	6.25	8.80	8.28	12.2
NBop	1111	1064	1051	1111	1111	1111	1111	1107	1049	1106
qJpel ^a	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10
qpel	3.58E-10	1.79E-09	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10	3.58E-10
qdem	5.92E-10	3.39E-09	3.21E-09	5.92E-10	5.92E-10	5.92E-10	5.92E-10	5.92E-10	3.31E-09	6.64E-10
qill	1.54E-08	-	-	7.69E-09	3.08E-08	1.54E-08	1.54E-08	1.57E-08	-	6.85E-09
qtrawl	7.67E-08	1.04E-07	1.01E-07	7.67E-08	7.67E-08	7.67E-08	7.67	7.55E-08	1.03E-07	5.85E-07
MCpar	0.626	0.792	1.01	0.626	0.626	0.626	0.626	0.551	1.08	0.421
prod	0.586	0.562	0.584	0.586	0.586	0.586	0.586	0.589	0.585	0.582
inc	-	-	-	-	-	-	-	-0.552	-0.100	-0.537
Nbp	166.32	167.04	166.88	166.32	166.32	166.32	166.23	166.39	166.88	165.86
Fledge	166.52	168.39	167.86	166.52	166.52	166.52	166.52	163.39	167.00	163.71
Sjuv	53.18	54.33	54.93	53.18	53.18	53.18	53.18	52.04	54.55	51.58
Sadult	23.14	23.51	23.52	23.14	23.14	23.14	23.14	23.11	23.51	23.25
Sum	409.16	413.27	413.19	409.16	409.16	409.16	409.07	404.93	411.94	404.40
Bycatch	-123.40	-122.81	-122.89	-123.4	-123.40	-123.40	-123.40	-123.403	-122.85	-76.14

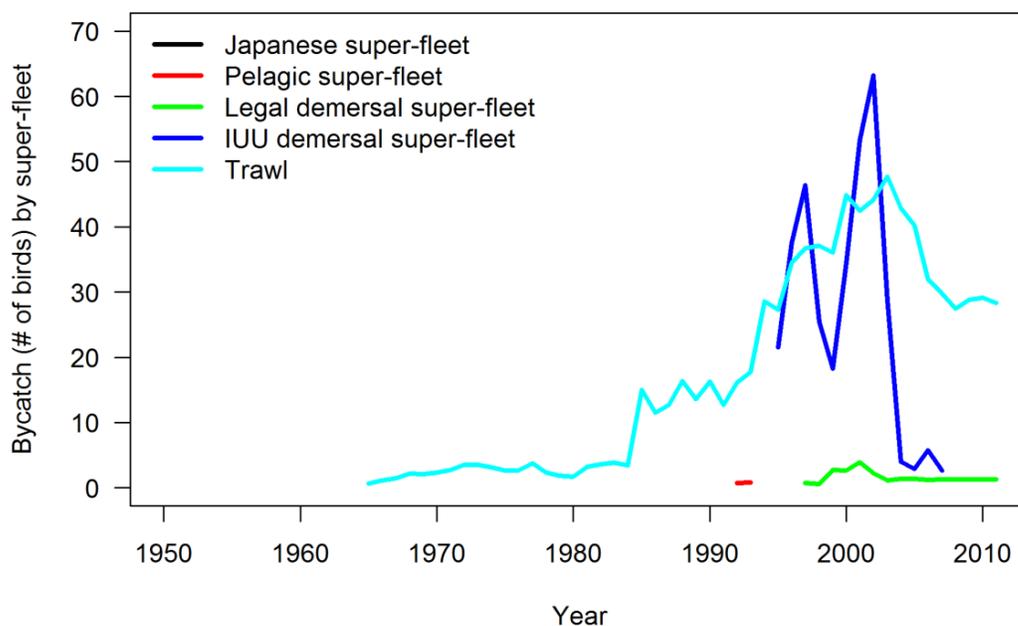


Fig. S3.1 The estimated annual number of birds caught as bycatch by each super-fleet incorporating unobserved bycatch: model 'x' (Table 3.1). Model 'x' allows the SST near Kerguelen during the incubation period to influence chick mortality and assumes that total bycatch rates are two and 8.66 times greater than the reported observed rates for all pelagic longline super-fleets and the trawl fleet, respectively, for the 'Ix' model (Brothers et al. 2010, Richard & Abraham 2013). As estimated bycatch can be a fraction of a bird, values > 0.5 are not shown and assumed to be 0.

There was relatively little change in the estimated parameter values across models (Table 3.1). Note that models iv and v do not alter the model at all, they merely change the “unit” of effort for the bycatch fleet, thereby alter the unit of the estimated catchability parameter. Halving the effort simply doubles the catchability estimate and vice versa for doubling it. As expected, the parameters estimated in models i, iv, v, and vi produce virtually identical modelled, as evidenced by the likelihood components. This clearly demonstrates that the allocation of the majority of bycatch to the IUU fleet was not due to the assumed magnitude of effort. Similarly, altering the bycatch assumptions regarding the observed bycatch value by not fitting to this value (model vi), or increasing it (model vii; through increasing the population multiplier) had little effect on estimated parameter values, including the catchability for the IUU fleet. Models that exclude the IUU super-fleet (models ii, iii, and ix) attributed the IUU bycatch to the legal demersal and trawl super-fleets. However, these models also show overall poorer agreement with the observations, compared with the models that include the IUU super-fleet (see individual likelihood components, Table 3.1). Incorporating unobserved bycatch (x) increased the trawl

bycatch rate and decreased the legal and illegal demersal bycatch, resulting in reduced IUU and increased trawl super-fleet bycatch (Table 3.1, Fig. 3.1). However, the IUU bycatch rate was still greater than other longline super-fleets, as was the magnitude of IUU bycatch versus all other super-fleets. This model (x) produced the poorest agreement with the assumed bycatch rates of any model evaluated (bycatch likelihood components, Table 3.1).

References

- Abraham ER, Thompson FN (2009) Capture of protected species in New Zealand trawl and longline fisheries, 1998-99 to 2006-07. Technical report. New Zealand Aquatic Environment and Biodiversity. Report No. 32
- ACAP (2012) ACAP Species Assessment: Black-browed Albatross *Thalassarche melanophrys*. Available at: <http://www.acap.aq/acap-species/download-document/1183-black-browed-albatross>
- Agnew DJ, Kirkwood GP (2005) A statistical method for estimating the level of IUU fishing: application to CCAMLR Subarea 48.3. *CCAMLR Science* 12:119-141
- Anonymous (1996) Report of the working group on fish stock assessment: Annex 5. Technical report. CCAMLR, Hobart, Australia
- Anonymous (1997) Report of the working group on fish stock assessment: Annex 5. Technical report. CCAMLR, Hobart, Tasmania
- Anonymous (1998) Report of the working group on fish stock assessment: Annex 5. Technical report. CCAMLR, Hobart, Tasmania
- Anonymous (1999) Report of the working group on fish stock assessment: Annex 5. Technical report. CCAMLR, Hobart, Tasmania
- Anonymous (2006) Report of the working group on fish stock assessment: Annex 5. Technical report. CCAMLR, Hobart, Tasmania
- Aranda M, Murua H, de Bruyn P (2012) Managing fishing capacity in tuna regional fisheries management organisations (RFMOs): Development and state of the art. *Mar Pol* 36:985-992
- Barbraud C, Rivalan P, Inchausti P, Nevoux M, Rolland V, Weimerskirch H (2011) Contrasted demographic responses facing future climate change in Southern Ocean seabirds. *Journal of Animal Ecology* 80:89-100
- Barbraud C, Tuck GN, Thomson R, Delord K, Weimerskirch H (2013) Fisheries Bycatch as an Inadvertent Human-Induced Evolutionary Mechanism. *PLoS ONE* 8
- BirdLife International (2004) Tracking ocean wanderers: the global distribution of albatrosses and petrels. Proc Results from the Global Procellariiform Tracking Workshop. Cambridge, UK: BirdLife
- Brothers N (1991) Albatross mortality and associated bait loss in the Japanese longline fishery in the Southern Ocean. *Biological Conservation* 55:255-268

- Brothers N, Duckworth AR, Safina C, Gilman EL (2010) Seabird bycatch in pelagic longline fisheries is grossly underestimated when using only haul data. *PLoS ONE* 5:e12491
- Delord K, Barbraud C, Bost CA, Cherel Y, Guinet C, Weimerskirch H (2013) Atlas of top predators from French Southern Territories in the Southern Indian Ocean. *CNRS*:252
- Delord K, Gasco N, Weimerskirch H, Barbraud C, Micol T (2005) Seabird mortality in the Patagonian toothfish longline fishery around Crozet and Kerguelen Islands. *CCAMLR Science* 12:53-80
- Delord K, Pinet P, Pinaud D, Barbraud C, De Grissac S, Lewden A, Cherel Y, Weimerskirch H (2016) Species-specific foraging strategies and segregation mechanisms of sympatric Antarctic fulmarine petrels throughout the annual cycle. *Ibis* 158:569-586
- Campbell RA Overview of Longlining in the Indian Ocean. In: Long KJ, Schroeder BA (eds). *Proc International Technical Expert Workshop on Marine Turtle Bycatch in Longline Fisheries*
- Caton AE, Ward PJ (1996) Access arrangements for Japanese longliners in eastern Australian waters. In: Ward PJ (ed) *Japanese Longlining in Eastern Australian Waters 1962-1990*. Bureau of Resource Sciences, Canberra, Australia
- Chen CL (2012) Taiwan's response to international fisheries management after 2005 as influenced by ICCAT and fishers' perception. *Mar Pol* 36:350-357
- Choquet R, Lebreton J-D, Gimenez O, Reboulet A-M, Pradel R (2009) U-CARE: Utilities for performing goodness of fit tests and manipulating CAPture-REcapture data. *Ecography* 32:1071-1074
- Duhamel G, Williams R (2011) History of whaling, sealing, fishery and aquaculture trials in the area of the Kerguelen Plateau. In: Duhamel G, Welsford DC (eds) *The Kerguelen Plateau: Marine Ecosystem and Fisheries*. Société française d'ichtyologie, Paris
- Hamilton A, Lewis A, McCoy MA, Havice E, Campling L (2011) Market and industry dynamics in the global tuna supply chain. *Pacific Islands Forum Fisheries Agency (FFA)*
- Joseph J, Squires D, Bayliff W, Groves T (2010) Addressing the problem of excess fishing capacity in tuna fisheries. In: Allen R, Joseph J, Squires D (eds) *Conservation and Management of Transitional Tuna Fisheries*. Wiley-Blackwell, Iowa, USA
- Klaer N, Polacheck T (1997) By-catch of albatrosses and other seabirds by Japanese longline fishing vessels in the Australian Fishing Zone from April 1992 to March 1995. *Emu* 96:150-167
- Lebreton J-D, Pradel R (2002) Multistate recapture models: modelling incomplete individual histories. *Journal of Applied Statistics* 29:353-369
- Louzao M, Pinaud D, Péron C, Delord K, Wiegand T, Weimerskirch H (2011) Conserving pelagic habitats: seascape modelling of an oceanic top predator. *Journal of Applied Ecology* 48:121-132 doi: 110.1111/j.1365-2664.2010.01910.x

- Maree BA, Wanless RM, Fairweather TP, Sullivan BJ, Yates O (2014) Significant reductions in mortality of threatened seabirds in a South African trawl fishery. *Animal Conservation* 17:520-529
- Michael PE, Tuck GN, Strutton P, Hobday A (2015) Environmental associations with broad-scale Japanese and Taiwanese pelagic longline effort in the southern Indian and Atlantic Oceans. *Fisheries Oceanography* 24:478-493
- Moreno G, Herrera M Estimation of fishing capacity by tuna fishing fleets in the Indian Ocean. Proc Report at the 16th Session of the Scientific Committee of the Indian Ocean Tuna Commission
- Nevoux M, Weimerskirch H, Barbraud C (2010) Long- and short-term influence of environment on recruitment in a species with highly delayed maturity. *Oecologia* 162:383-392
- Petersen SL, Honig MB, Ryan PG, Underhill LG (2009) Seabird bycatch in the pelagic longline fishery off southern Africa. *African Journal of Marine Science* 31:191-204
- Pradel R (2005) Multievent: An Extension of Multistate Capture–Recapture Models to Uncertain States. *Biometrics* 61:442-447
- Richard Y, Abraham ER (2013) Risk of commercial fisheries to New Zealand seabird populations. *New Zealand Aquatic Environment and Biodiversity Report No 109*
- Ryan PG, Goren M, Petersen SL, Smith C (2009a) Seabird bycatch in pelagic longlines in the IOTC area off South Africa in 2007 and 2008: the effect of individual vessel limits on bycatch rates. Technical report. Percy FitzPatrick Institute, University of Cape Town, South Africa
- Ryan PG, Goren M, Petersen SL, Smith C (2009b) Seabird bycatch on pelagic longlines in the ICCAT area off South Africa in 2007 and 2008: the effect of individual vessel limits on bycatch rates. Technical report. Percy FitzPatrick Institute, University of Cape Town, South Africa
- SC-CAMLR (2015) Information on IUU fishing in the French EEZs around Kerguelen and Crozet and in the CCAMLR Statistical Area 58. CCAMLR-XXIV/23
- Terauds A, Gales R, Barry Baker G, Alderman R (2006) Foraging areas of black-browed and grey-headed albatrosses breeding on Macquarie Island in relation to marine protected areas. *Aquatic Conservation: Marine and Freshwater Ecosystems* 16:133-146
- Thomson RB, Alderman RL, Tuck GN, Hobday AJ (2015) Effects of Climate Change and Fisheries Bycatch on Shy Albatross (*Thalassarche cauta*) in Southern Australia. *PLoS ONE* 10:e0127006
- Tickell WLN (1968) The Biology of the Great Albatrosses, *Diomedea Exulans* and *Diomedea Epomophora*. Antarctic Bird Studies. American Geophysical Union
- Tuck GN, Polacheck T, Bulman C (2004) Chapter 1: Spatio-temporal trends of longline fishing effort in the southern ocean and implications for seabird bycatch. In: Tuck GN, Polacheck T, Croxall JP, Weimerskirch H, Ryan P, Nel D, Wayte S, Bulman CM (eds) A comprehensive study of the ecological impacts of the worldwide pelagic longline industry: Southern Hemisphere studies. CSIRO, Hobart

- Tuck GN, Polacheck T, Bulman CM (2003) Spatio-temporal trends of longline fishing effort in the Southern Ocean and implications for seabird bycatch. *Biological Conservation* 114:1-27
- Tuck GN, Thomson RB, Barbraud C, Delord K, Louzao M, Herrera M, Weimerskirch H (2015) An integrated assessment model of seabird population dynamics: can individual heterogeneity in susceptibility to fishing explain abundance trends in Crozet wandering albatross? *Journal of Applied Ecology* 52:950-959
- Warham J (1990) *The petrels: their ecology and breeding systems*. Academic Press, New York
- Watkins BP, Petersen, S. L., Ryan PG (2008) Interactions between seabirds and deep-water hake trawl gear: an assessment of impacts in South African waters. *Animal Conservation* 11:247-254
- Weimerskirch H, Capdeville D, Duhamel G (2000) Factors affecting the number and mortality of seabirds attending trawlers and long-liners in the Kerguelen area. *Polar Biology* 23:236-249