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Supplementary Materials for

Hemispheric asymmetry in ocean change and the productivity of ecosystem sentinels

W. J. Sydeman*, D. S. Schoeman, S. A. Thompson, B. A. Hoover, M. García-Reyes, F. Daunt, P. Agnew, T. Anker-Nilssen, C. Barbraud, R. Barrett, P. H. Becker, E. Bell, P. D. Boersma, S. Bouwhuis, B. Cannell, R. J. M. Crawford, P. Dann, K. Delord, G. Elliott, K. E. Erikstad, E. Flint, R. W. Furness, M. P. Harris, S. Hatch, K. Hilwig, J. T. Hinke, J. Jahncke, J. A. Mills, T. K. Reiertsen, H. Renner, R. B. Sherley, C. Surman, G. Taylor, J. A. Thayer, P. N. Trathan, E. Velarde, K. Walker, S. Wanless, P. Warzybok, Y. Watanuki

*Corresponding author. Email: wsydeman@faralloninstitute.org

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Materials and Methods

Seabird breeding productivity

We requested annual mean data on seabird breeding productivity from various researchers across the globe who manage long-term monitoring programs. All potential data contributors responded by contributing data for this study (Table S1), with the greatest number of time series coming from two species, common murre and black-legged kittiwake in the northern hemisphere. Breeding productivity is measured similarly by seabird ecologists globally (see Materials and Methods from (*17*) for many examples), and it is herein defined as the average number of young produced (fledged) per nesting female per year at each study site. We requested data time series of at least a 20–year period, ending no sooner than the 2014 boreal breeding season (approximately Sept. 2014). Some data contributors submitted data in bulk for their location, sometimes including time series of shorter duration or time series that ended before the 2014 cutoff date. This prompted a re-evaluation of what data we should use based on the overall data contributed. Time series information by hemisphere is shown in Fig. S1.

Time series of less than 20 years in duration. Five time series were shorter than 20 years duration and we omitted one, least auklets from St. George Island, Alaska (10 years in length), from analysis. We decided to include four other time series that did not extend over a 20-year period, however, because they did extend over a decade and were provided at locations where multiple species studied resulted in time series that met inclusion criteria. These time series were: 1) pelagic cormorants from Middleton Island, Alaska (16 years), 2) red-faced cormorants from St. George Island, Alaska (18 years), 3) double-crested cormorants from Aiktak Island, Alaska (19 years), and wandering albatross from Kerguelen Islands, Indian Ocean (19 years) (Table S1).

Time series ending prior to 2014. Seven time series did not fit the initial criterion of continuing until 2014 (Table S1): 1) black-footed and Laysan albatross at Tern Island, Hawaii (ended in 2008), 2) wedge-tailed shearwater from Varanus Island, Western Australia (ended in 2013), 3) macaroni and gentoo penguins at Bird Island (ended in 2013), and 4) Adélie and gentoo penguins at Admiralty Bay, King George Island (ended in 2012). We included these time series because they met the criterion for longevity; we felt that they contributed valuable data from under-represented regions and were likely to provide conservative estimates because they did not extend into the strong El Niño period of 2015–2016 when other time series did.

Variation in trends between species

Trophic level and foraging depth. Prior to any analyses on species-specific variation in productivity trends, we assigned a simple trophic-level descriptor to each species based on published literature (e.g., see *38*) and consultation with data contributors who had direct knowledge of species diets at the locations used for this study (e.g., JT Hinke, PN Trathan for pygoscelid penguins). For each species, we asked: do parents primarily feed themselves and their offspring zooplankton, fish, or a combination of zooplankton, fish, and/or squids during the breeding season? We defined breeding seasons broadly as the period spanning the pre-breeding egg-formation period to the time immediately post-fledging. For each species, we characterized trophic level (TL) based upon diet composition over long (decadal) temporal scales. Since some species were studied at multiple locations (Table S2), we characterized TL based on the dominant trend in diet composition across the range of study sites. We defined primary TL by the diet that composed 80% or more of the food used on decadal time scales. Planktivorous species were defined as those species that fed primarily on mesozooplankton (e.g., large calanoid copepods or euphausiid crustaceans) or meroplankton (i.e., larval fish). Piscivorous species were defined as those that fed primarily upon age-0 piscivorous fish or age-0 and older age classes of coastal pelagic species (e.g., anchovy, sandeels). Omnivorous species were defined as those feeding upon a combination of plankton, fish, and/or squids within each breeding season.

Many seabird species feed primarily on mesozooplankton in the pre-breeding period, but switch to fish and squid for chick provisioning; species that always switched prey use during their breeding season were assigned to the omnivore TL class (Table S2). Some species may also prey switch at the end of each breeding season, but this kind of change could typically result in minor diet items (i.e., those comprising < 20% of the diet at decadal resolution) altering the TL assignment. For example, some pygoscelid penguins (e.g., Adélie) may consume fish towards the latter half of each breeding season (e.g., *39*), but are well known to be krill-dependent predators for successful reproduction (e.g., *40*). In particular, Adélie and chinstrap penguins, due to diets dominated by Antarctic krill and the potential for competition with krill fisheries, are key indicator species for ecosystem-based fisheries management efforts in the Southern Ocean (*41*). These species are therefore considered to be planktivores in this study. In contrast, gentoo penguins consume krill and fish throughout the breeding season (e.g., *42*); fish regularly comprise > 20% of their diet across decadal scales, so this species was considered to be omnivorous in this study.

To assign foraging modes, we determined the primary depth(s) of foraging for each species, and confirmed these specifications using available literature, when needed. We defined surface foragers as those species that primarily forage within the top 10 m of the water column. Sub-surface foragers were defined as those species that frequently forage at depths below 10 m. We selected 10 m as our cut-off because many species (e.g., shearwaters, terns, and gulls) are capable of limited surface diving, but rarely, if ever, forage to the thermocline. Species regularly foraging > 10 m included wing and foot-propelled divers that are also capable of foraging below the thermocline to depths of up to 100 m and sometimes deeper. This group included penguins, puffins, murres, cormorants and other diving species.

<u>Hemispheric differences in warming</u>

Hemispheric rates of sea surface temperature (SST) change (rate of ocean warming; °C per decade) and velocity of ocean warming (climate velocity; km per decade) were calculated using monthly 1° × 1° data from the Met Office Hadley Center reconstruction dataset HadISST1 (*43*, available at: https://www.metoffice.gov.uk/hadobs/hadisst/). Rate of ocean warming was estimated by the slope of the simple linear regression of SST on year for the 50-year period 1968–2017, during which most of the seabird data were collected. The corresponding spatial gradient in SST was calculated by averaging SST at each pixel over the 50-year period and then computing the vector sum of the latitudinal and longitudinal pairwise differences of the mean temperature at each focal cell using a 3 × 3 neighborhood window (°C per km). We followed Loarie *et al*. (*4*) in dividing rate of ocean warming by the spatial gradient to estimate velocity of ocean warming (for details in ocean settings, see *2, 44*). Both the rate of ocean warming and velocity of ocean warming were computed using the *VoCC R* package (*45*) in R 4.0 (*46*).

To explore global variability in temporal trends in features of marine heatwaves, we followed Smale *et al*. (*47*) in using the package *heatwaveR* (*48*) to compute statistics on marine heatwaves using the National Oceanic and Atmospheric Administration's ¼° daily optimum interpolation SST dataset (*49*, *50*). Here, a marine heatwave is considered to be a discrete event lasting five or more days during which the SST remained warmer than the 90th percentile relative to the SST during a 30-year historical baseline period (*51*), which we took to be the period 1983–2012. We first aggregated data to 0.5° (by mean), then computed the number of days within marine heatwaves, as well as the cumulative intensity of marine heatwaves (°C.days, the sum of the daily exceedance of the SST relative to its baseline 90th percentile) for the period 1982–2017. This period was selected because 1982 is the first full year for which these daily data are available, and 2017 is the last year we used in computing rate and velocity of ocean warming. We then computed temporal trends (per decade) in both statistics using median-based linear models using the Theil-Sen single-median method in package *mblm* (*52*). We elected to use median-based models because they are more robust to breakpoints in time series than are simple linear regressions.

Finally, we downloaded data on cumulative human impacts presented by Halpern *et al*. (*3*) from https://knb.ecoinformatics.org/view/doi:10.5063/F12B8WBS. These data were re-projected (nearest-neighbor) from their native Mollweide projection to WGS84 and then aggregated (by taking the mean) to 0.5° × 0.5°. From these data, we elected to follow Halpern *et al*. (*3*) in presenting estimates of the cumulative human impact in 2003 (the closest available year to the median year of all data in our dataset, 2001), and in the rate of change (linear regression) in this impact between 2003 and 2013.

Finally, to avoid potential latitudinal bias associated with varying grid-cell size in simple gridded data (WGS84), we re-gridded (nearest-neighbor) all metrics of hemispheric asymmetry to equal-area hexagonal bins of 3098 km^2 (~0.5° at the equator) for computation and visual representation.

Statistical model

We used generalized mixed-effects models to explore spatial and temporal variation in two response variables using the following models:

$$
\begin{aligned}
\mu_{i,j} = \alpha + \ & \beta_1 \times Year_{i,j} + \beta_2 \times Hemisphere_{i,j} \\
& + \beta_3 \times TrophicLevel_{i,j} + \beta_4 \times Depth_{i,j} \\
& + \beta_5 \times Year_{i,j} \times Hemisphere_{i,j} \\
& + \beta_6 \times Year_{i,j} \times TrophicLevel_{i,j} \\
& + \beta_7 \times Year_{i,j} \times Depth_{i,j} \\
& + \beta_8 \times Hemisphere_{i,j} \times TrophicLevel_{i,j} \\
& + \beta_9 \times Hemisphere_{i,j} \times Depth_{i,j} \\
& + \beta_{10} \times TrophicLevel_{i,j} \times Depth_{i,j} \\
& + \beta_{11} \times Year_{i,j} \times Hemisphere_{i,j} \times TrophicLevel_{i,j} \\
& + \beta_{12} \times Year_{i,j} \times Hemisphere_{i,j} \times Depth_{i,j} \\
& + \beta_{13} \times Year_{i,j} \times TrophicLevel_{i,j} \times Depth_{i,j} \\
& + a_i \\
& + b_i \\
& + \varepsilon_{i,j} \qquad \text{[Model 1]}
\end{aligned}
$$

and

$$
\begin{aligned}
\mathrm{logit}(\pi_{i,j}) = \alpha + \ & \beta_1 \times Year_{i,j} + \beta_2 \times Hemisphere_{i,j} \\
& + \beta_3 \times TrophicLevel_{i,j} + \beta_4 \times Depth_{i,j} \\
& + \beta_5 \times Year_{i,j} \times Hemisphere_{i,j} \\
& + \beta_6 \times Year_{i,j} \times TrophicLevel_{i,j} \\
& + \beta_7 \times Year_{i,j} \times Depth_{i,j} \\
& + \beta_8 \times Hemisphere_{i,j} \times TrophicLevel_{i,j} \\
& + \beta_9 \times Hemisphere_{i,j} \times Depth_{i,j} \\
& + \beta_{10} \times TrophicLevel_{i,j} \times Depth_{i,j} \\
& + \beta_{11} \times Year_{i,j} \times Hemisphere_{i,j} \\
& \times TrophicLevel_{i,j} \\
& + \beta_{12} \times Year_{i,j} \times Hemisphere_{i,j} \times Depth_{i,j} \\
& + \beta_{13} \times Year_{i,j} \times TrophicLevel_{i,j} \times Depth_{i,j} \\
& + a_i \\
& + b_i \\
& + \varepsilon_{i,j} \qquad \text{[Model 2]}
\end{aligned}
$$

where

$$
\begin{gathered}
Y_{i,j} \sim \mathrm{Bin}(1, \pi_{i,j}) \\
a_i \sim N(0, \sigma_{0i}^2) \\
b_i \sim N(0, \sigma_{1i}^2) \\
\varepsilon_{i,j} \sim N(0, \sigma^2)
\end{gathered}
$$

Here, $\mu_{i,j}$ is the mean standardized breeding success (raw metrics of breeding productivity scaled to a mean of zero and standard deviation of one per time series) of observation j in time series i. $Y_{i,j}$ is the probability of breeding failure, defined as 1 if breeding success of observation $j \leq 10\%$ of the mean of breeding success for time series i and 0, otherwise. $Year_{i,j}$ is a continuous variable representing the year of observation j in time series i, relative to the earliest year across all time series. $Hemisphere_{i,j}$ is a categorical variable representing the hemisphere in which time series i is located (North or South). $TrophicLevel_{i,j}$ is a categorical variable representing the trophic level of the species associated with time series i (Planktivore, Omnivore or Piscivore). $Depth_{i,j}$ is a categorical variable representing the general depth of feeding of the species associated with time series i (Shallow if the species forages primarily within the top 10 m of the water column, Deep, otherwise). a_i and b_i are random adjustments to the intercepts and slopes of relationships with $Year$ for time series i, allowing the analysis to account for effects specific to each time series.

In each case, we omitted four-way interactions because there were too few observations in some combinations of multiple discrete predictors to allow robust parameter estimation. Moreover, we introduced an auto-regressive model of order 1 to the error structure to account for the likelihood that residuals for consecutive years in each time series are likely to be more correlated than residuals separated by longer intervals (*53*). For this, we used function *corCAR1* in the R package *nlme* because it allows for unequally spaced observations in time. This was essential because approximately half of our time series included a few missing years of data (Table S1).

For standardized breeding success (Model 1), the generalized mixed-effects models were fit using maximum likelihood and a Gaussian error structure via the function *lme* in the R package *nlme* (*54*). For the probability of breeding failure (Model 2), we used penalized quasi-likelihood (PQL) and a binomial error structure via the *glmmPQL* function in the R package *MASS* (*55*). Having fit the full models as specified above, we proceeded to eliminate model terms on the basis of log-likelihood ratio tests and Wald t-tests, respectively. We prioritized non-significant terms for removal on the basis of AIC (in the case of Model 1) and did not remove terms or interactions that contributed to more complex interactions retained in the model. Note that *PQL* does not yield log-likelihood or information-theoretic statistics with which to perform standard model-simplification procedures.

On arriving at the simplest supported model for standardized breeding success, we estimated coefficients based on a restricted maximum likelihood fit. For probability of breeding failure, we proceeded with coefficients from the *PQL* fit. In each case, to mitigate the risk of over-interpreting final model coefficients, we relied instead on interpreting plots constructed from these model outputs (Fig. 2).

Supplemental Text

<u>Sensitivity tests for models including hemisphere as a fixed effect</u>

Given the strong hemispheric pattern in rate of ocean warming and velocity of ocean warming (Fig. 1), we assumed that the models we present account for effects of climate change on standardized breeding success and probability of breeding failure by including hemisphere as a fixed effect. To test this assumption, we refit the model for standardized breeding success without the effect of hemisphere, and then proceeded to simplify using the same approach as for the main model. We then extracted the random effects for slope, which quantify the degree to which slopes of each time-series deviate from the population-level slope, and modelled these as a function of rate of ocean warming and velocity of ocean warming, respectively, using a simple linear model. We estimated rate of ocean warming and velocity of ocean warming by extracting mean values within a radius of 300 km from the location of each time series from the data layers used to prepare Fig. 1. To account for the fact that we had greater confidence in estimates from better-observed time series, we weighted random slopes by the number of observations in their respective time series.

Across the 46 sample locations, rate of ocean warming and velocity of ocean warming were strongly positively correlated ($r = 0.78$, $t = 8.2583$, $df = 44$, $p = 1.722\times10^{-10}$), and both models yielded significant negative slopes: rate of ocean warming ($F = 5.867$, $df = 1, 120$, $p = 0.017$); velocity of ocean warming ($F = 5.208$, $df = 1, 120$, $p = 0.024$). This confirms that time series-level trends of standardized breeding success (adjusted for trophic level) are lower than the overall average for that trophic level where rates or velocities of warming are higher and vice versa (i.e., standardized breeding success is declining faster than estimated where ocean temperatures are warming fastest).

Additional data collection and funding acknowledgements

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Fig. S1. Histogram of time series duration (years). (A) data for the northern (top) and southern (bottom) hemispheres. (B) comparison of cumulative annual sample size in the northern and southern hemisphere through time, showing remarkable similarly in the growth of relative numbers of long-term seabird studies in both hemispheres, despite fewer time series in the south.

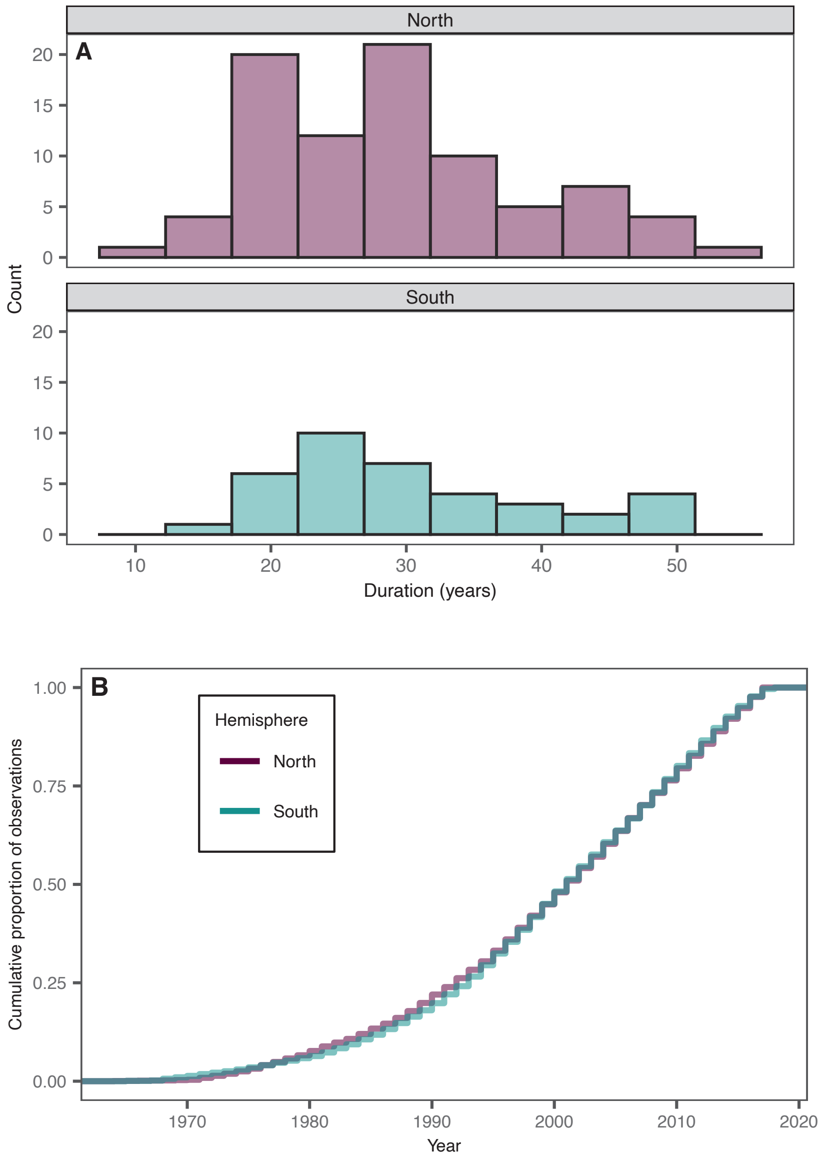

Fig. S2. Raw annual breeding productivity values with species-specific time series trend lines through time (~1970 to ~2017) by site in the (A) northern hemisphere and (B) southern hemisphere. Sites where more than six species were studied were broken into two panels (i.e., SE Farallon and SE Farallon2, Buldir and Buldir2). Different line colors indicate trends for different species at the same site, but have no other meaning.

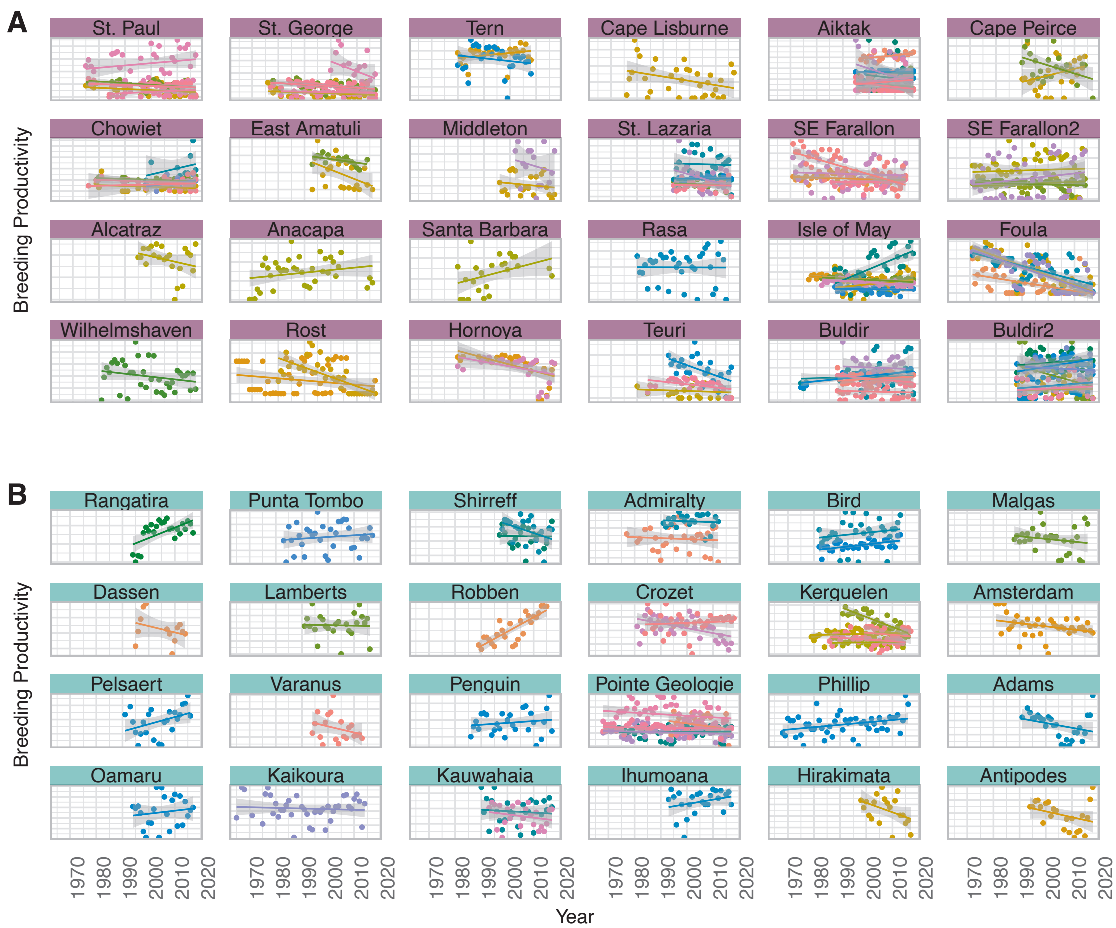

Fig. S3. Standard diagnostic plots for the final model from Table S5 confirm that model assumptions are not violated.

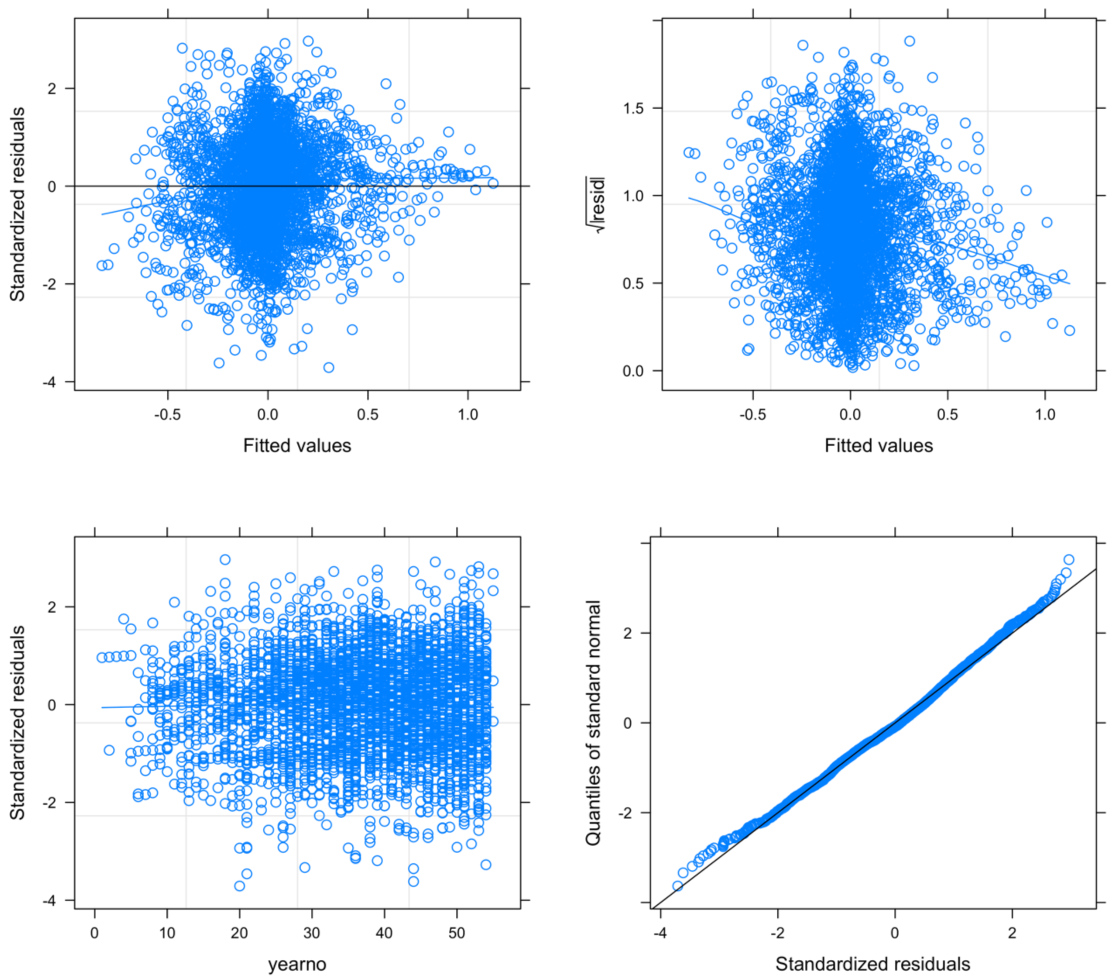

Table S1. Time series characteristics. Shown are time series number, site, species, duration, number of years of observations across the study period (i.e., omitting years with no data), linear trend of breeding success (slope: chicks fledged female^{-1} year^{-1}), and data contributor for each time series of seabird species at each site. Trends and significance are from generalized least-squares fits for each time series, adjusted for temporal autocorrelation at a lag of one year. Nominal significance for trends are indicated *significant at $p < 0.05$, **significant at $p < 0.01$, and ***significant at $p < 0.001$.

Time series number	Site	Species	Duration	N Years Data	Linear trend slope	Data contributor
1	Rost	Atlantic puffin	1964-2017	54	-0.0056	Norwegian Institute for Nature Research; Tycho Anker-Nilssen
2	Rost	black-legged kittiwake	1980-2017	36	-0.0193*	Norwegian Institute for Nature Research; Tycho Anker-Nilssen
3	Teuri	black-tailed gull	1980-2016	21	-0.0051	Yutaka Watanuki
4	Teuri	Japanese cormorant	1992-2016	24	-0.0415	Yutaka Watanuki
5	Teuri	rhinoceros auklet	1984-2016	28	-0.0096	Yutaka Watanuki
6	Robben	African penguin	1989-2015	26	0.0326***	Department of Environment, Forestry and Fisheries, South Africa; Richard B. Sherley
7	Foula	great skua	1971-2017	47	-0.0208**	Robert W. Furness
8	Foula	parasitic jaeger	1971-2017	47	-0.0265**	Robert W. Furness
9	Foula	arctic tern	1971-2017	47	-0.0129**	Robert W. Furness
10	Foula	black-legged kittiwake	1971-2017	47	-0.0272***	Robert W. Furness
11	Lamberts	Cape gannet	1991-2016	24	-0.0012	Department of Environment, Forestry and Fisheries, South Africa; Robert Crawford
12	Malgas	Cape gannet	1988-2016	29	-0.0027	Department of Environment, Forestry and Fisheries, South Africa; Robert Crawford
13	Isle of May	common murre	1982-2017	36	-0.0037	UK Centre for Ecology & Hydrology; Francis Daunt
14	Isle of May	razorbill	1982-2017	36	-0.0047**	UK Centre for Ecology & Hydrology; Francis Daunt
15	Isle of May	Atlantic puffin	1977-2017	41	-0.0045*	UK Centre for Ecology & Hydrology; Francis Daunt
16	Isle of May	European shag	1987-2017	31	0.0366*	UK Centre for Ecology & Hydrology; Francis Daunt
17	Isle of May	black-legged kittiwake	1987-2017	31	0.0080	UK Centre for Ecology & Hydrology; Francis Daunt
18	Isle of May	northern fulmar	1987-2017	31	-0.0014	UK Centre for Ecology & Hydrology; Francis Daunt
19	Tern	black-footed albatross	1980-2008	29	0.0031	Hawaiian Islands National Wildlife Refuge; Elizabeth Flint
20	Tern	Laysan albatross	1980-2008	29	-0.0040	Hawaiian Islands National Wildlife Refuge; Elizabeth Flint
21	Aiktak	common murre	1995-2017	23	-0.0125	Alaska Maritime National Wildlife Refuge; Heather Renner
22	Aiktak	fork-tailed storm-petrel	1995-2017	18	-0.0020	Alaska Maritime National Wildlife Refuge; Heather Renner
23	Aiktak	Leach's storm-petrel	1995-2017	18	0.0011	Alaska Maritime National Wildlife Refuge; Heather Renner
24	Aiktak	horned puffin	1996-2017	18	0.0146	Alaska Maritime National Wildlife Refuge; Heather Renner
25	Aiktak	thick-billed murre	1995-2017	22	-0.0134	Alaska Maritime National Wildlife Refuge; Heather Renner
26	Aiktak	tufted puffin	1995-2017	22	0.0073	Alaska Maritime National Wildlife Refuge; Heather Renner
27	Aiktak	double-crested cormorant	1999-2017	18	-0.0140	Alaska Maritime National Wildlife Refuge; Heather Renner
28	Aiktak	red-faced cormorant	1995-2017	21	0.0098	Alaska Maritime National Wildlife Refuge; Heather Renner

29	Aiktak	pelagic cormorant	1995-2017	20	-0.0395	Alaska Maritime National Wildlife Refuge; Heather Renner
30	Aiktak	ancient murrelet	1997-2017	21	0.0124*	Alaska Maritime National Wildlife Refuge; Heather Renner
31	Buldir	black-legged kittiwake	1988-2017	30	0.0008	Alaska Maritime National Wildlife Refuge; Heather Renner
32	Buldir	common murre	1989-2017	27	-0.0129	Alaska Maritime National Wildlife Refuge; Heather Renner
33	Buldir	crested auklet	1988-2017	29	0.0042	Alaska Maritime National Wildlife Refuge; Heather Renner
34	Buldir	horned puffin	1988-2017	30	0.0036	Alaska Maritime National Wildlife Refuge; Heather Renner
35	Buldir	least auklet	1988-2017	29	0.0067	Alaska Maritime National Wildlife Refuge; Heather Renner
36	Buldir	parakeet auklet	1991-2017	26	-0.0021	Alaska Maritime National Wildlife Refuge; Heather Renner
37	Buldir	red-legged kittiwake	1988-2017	30	0.0022	Alaska Maritime National Wildlife Refuge; Heather Renner
38	Buldir	thick-billed murre	1988-2017	30	-0.0077**	Alaska Maritime National Wildlife Refuge; Heather Renner
39	Buldir	tufted puffin	1988-2017	30	-0.0017	Alaska Maritime National Wildlife Refuge; Heather Renner
40	Buldir	fork-tailed storm-petrel	1974-2017	31	0.0019	Alaska Maritime National Wildlife Refuge; Heather Renner
41	Buldir	Leach's storm-petrel	1974-2017	31	0.0087**	Alaska Maritime National Wildlife Refuge; Heather Renner
42	Buldir	whiskered auklet	1988-2017	29	0.0036	Alaska Maritime National Wildlife Refuge; Heather Renner
43	Buldir	pelagic cormorant	1990-2014	24	-0.0109	Alaska Maritime National Wildlife Refuge; Heather Renner
44	Buldir	glaucous-winged gull	1997-2017	18	0.0081	Alaska Maritime National Wildlife Refuge; Heather Renner
45	Chowiet	black-legged kittiwake	1979-2017	22	-0.0034	Alaska Maritime National Wildlife Refuge; Heather Renner
46	Chowiet	common murre	1979-2017	22	-0.0037	Alaska Maritime National Wildlife Refuge; Heather Renner
47	Chowiet	thick-billed murre	1979-2017	22	-0.0046	Alaska Maritime National Wildlife Refuge; Heather Renner
48	St. George	black-legged kittiwake	1976-2017	40	-0.0035	Alaska Maritime National Wildlife Refuge; Heather Renner
49	St. George	common murre	1978-2017	34	-0.0062*	Alaska Maritime National Wildlife Refuge; Heather Renner
50	St. George	red-legged kittiwake	1981-2017	34	-0.0017	Alaska Maritime National Wildlife Refuge; Heather Renner
51	St. George	thick-billed murre	1977-2017	37	-0.0058	Alaska Maritime National Wildlife Refuge; Heather Renner
52	St. Paul	black-legged kittiwake	1975-2017	35	-0.0047	Alaska Maritime National Wildlife Refuge; Heather Renner
53	St. Paul	common murre	1976-2017	31	-0.0070*	Alaska Maritime National Wildlife Refuge; Heather Renner
54	St. Paul	red-legged kittiwake	1984-2017	28	0.0047	Alaska Maritime National Wildlife Refuge; Heather Renner
55	St. Paul	thick-billed murre	1976-2017	33	-0.0048	Alaska Maritime National Wildlife Refuge; Heather Renner
56	St. Paul	red-faced cormorant	1975-2017	33	0.0118	Alaska Maritime National Wildlife Refuge; Heather Renner
57	St. Lazaria	common murre	1994-2016	23	-0.0039	Alaska Maritime National Wildlife Refuge; Heather Renner
58	St. Lazaria	fork-tailed storm-petrel	1995-2016	22	0.0037	Alaska Maritime National Wildlife Refuge; Heather Renner
59	St. Lazaria	Leach's storm-petrel	1995-2016	22	0.0010	Alaska Maritime National Wildlife Refuge; Heather Renner
60	St. Lazaria	thick-billed murre	1994-2016	23	-0.0009	Alaska Maritime National Wildlife Refuge; Heather Renner
61	St. Lazaria	glaucous-winged gull	1994-2016	23	-0.0029	Alaska Maritime National Wildlife Refuge; Heather Renner
62	St. Lazaria	pelagic cormorant	1994-2016	21	-0.0295	Alaska Maritime National Wildlife Refuge; Heather Renner
63	Cape Lisburne	black-legged kittiwake	1976-2017	34	-0.0094	Alaska Maritime National Wildlife Refuge; Heather Renner
64	Cape Peirce	black-legged kittiwake	1990-2014	25	0.0077	Togiak National Wildlife Refuge; Kara Hilwig
65	Cape Peirce	common murre	1990-2017	23	-0.0100*	Togiak National Wildlife Refuge; Kara Hilwig

66	East Amatuli	black-legged kittiwake	1993-2016	22	-0.0224	Alaska Maritime National Wildlife Refuge; Heather Renner
67	SE Farallon	Brandt's cormorant	1971-2014	44	0.0043	Point Blue Conservation Science; Pete Warzybok
68	SE Farallon	Cassin's auklet	1971-2014	44	0.0052	Point Blue Conservation Science; Pete Warzybok
69	SE Farallon	common murre	1972-2014	43	-0.0032	Point Blue Conservation Science; Pete Warzybok
70	SE Farallon	pelagic cormorant	1971-2014	44	0.0142	Point Blue Conservation Science; Pete Warzybok
71	SE Farallon	pigeon guillemot	1971-2014	44	-0.0023	Point Blue Conservation Science; Pete Warzybok
72	SE Farallon	rhinoceros auklet	1986-2014	29	0.0000	Point Blue Conservation Science; Pete Warzybok
73	SE Farallon	western gull	1971-2014	44	-0.0249***	Point Blue Conservation Science; Pete Warzybok
74	SE Farallon	ashy storm-petrel	1971-2014	44	-0.0023	Point Blue Conservation Science; Pete Warzybok
75	Anacapa	brown pelican	1969-2016	38	0.0051	California Institute for Environmental Studies
76	Santa Barbara	brown pelican	1980-2016	24	0.0160	California Institute for Environmental Studies
77	Alcatraz	Brandt's cormorant	1995-2017	23	-0.0164	Farallon Institute; Julie Thayer
78	Rasa	Heermann's gull	1980-2014	35	-0.0011	Enriqueta Velarde
79	Hornoya	Atlantic puffin	1980-2017	30	-0.0126*	Rob Barrett, Kjell Einar Erikstad, and Tone Kristin Reiertsen
80	Hornoya	razorbill	1980-2017	25	-0.0072	Rob Barrett, Kjell Einar Erikstad, and Tone Kristin Reiertsen
81	Kaikoura	red-billed gull	1965-2014	42	-0.0008	James A. Mills
82	Penguin	little penguin	1986-2017	28	0.0045	Belinda Cannell
83	Varanus	wedge-tailed shearwater	1994-2013	20	-0.0103	Halfmoon Biosciences; Chris Surman
84	Pelsaert	lesser noddy	1991-2016	24	0.0056	Halfmoon Biosciences; Chris Surman
85	Bird	macaroni penguin	1982-2013	32	0.0093***	British Antarctic Survey; Phil N. Trathan
86	Bird	gentoo penguin	1982-2013	32	0.0086	British Antarctic Survey; Phil N. Trathan
87	Middleton	black-legged kittiwake	1996-2017	22	-0.0100	Institute for Seabird Research and Conservation; Scott Hatch
88	Admiralty	Adélie penguin	1977-2012	31	-0.0026	National Marine Fisheries Service; Jefferson T. Hinke
89	Admiralty	gentoo penguin	1991-2012	22	-0.0025	National Marine Fisheries Service; Jefferson T. Hinke
90	Cape Shirreff	chinstrap penguin	1997-2017	21	-0.0006	National Marine Fisheries Service; Jefferson T. Hinke
91	Cape Shirreff	gentoo penguin	1998-2017	20	-0.0231	National Marine Fisheries Service; Jefferson T. Hinke
92	Dassen	African penguin	1995-2014	13	0.0084	Department of Environment, Forestry and Fisheries, South Africa; Richard B. Sherley
93	Chowiet	glaucous-winged gull	1998-2017	10	0.0213	Alaska Maritime National Wildlife Refuge; Heather Renner
94	Chowiet	parakeet auklet	1998-2017	14	0.0139	Alaska Maritime National Wildlife Refuge; Heather Renner
95	Chowiet	tufted puffin	1976-2017	13	0.0028	Alaska Maritime National Wildlife Refuge; Heather Renner
96	St. George	red-faced cormorant	2000-2017	18	-0.0356	Alaska Maritime National Wildlife Refuge; Heather Renner
97	East Amatuli	common murre	1993-2014	17	-0.0066	Alaska Maritime National Wildlife Refuge; Heather Renner
98	Middleton	pelagic cormorant	2002-2017	15	-0.0219	Institute for Seabird Research and Conservation; Scott Hatch
99	Phillip	little penguin	1968-2016	49	0.0105*	Phillip Island Nature Parks; Peter Dann
100	Oamaru	little penguin	1994-2017	24	0.0072	Oamaru Blue Penguin Colony; Philippa Agnew
101	Adams	Gibson's wandering albatross	1991-2018	27	0.0115	New Zealand Department of Conservation; Kath Walker and Graeme Elliott
102	Antipodes	Antipodean wandering albatross	1994-2018	23	0.0016	New Zealand Department of Conservation; Kath Walker and Graeme Elliott

103	Kauwahaia	sooty shearwater	1993-2017	24	-0.0043	New Zealand Department of Conservation; Graeme Taylor
104	Kauwahaia	flesh-footed shearwater	1990-2017	27	-0.0019	New Zealand Department of Conservation; Graeme Taylor
105	Ihumoana	grey-faced petrel	1993-2017	25	0.0032	New Zealand Department of Conservation; Graeme Taylor
106	Rangatira	Chatham petrel	1994-2017	24	0.0107	New Zealand Department of Conservation; Graeme Taylor
107	Hirakimata	Takoketai (black petrel)	1998-2017	20	-0.4141	Wildlife Management International Ltd., Elizabeth A. Bell
108	Punta Tombo	Magellanic penguin	1983-2017	34	0.0029	P. Dee Boersma
109	Wilhelmshaven	common tern	1981-2017	37	-0.0122	Institute of Avian Research; Peter H. Becker and Sandra Bouwhuis
110	Pointe Geologie	snow petrel	1968-2017	50	-0.0025	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
111	Pointe Geologie	southern fulmar	1968-2017	49	-0.0013	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
112	Pointe Geologie	emperor penguin	1974-2017	44	0.0006	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
113	Pointe Geologie	Adélie penguin	1993-2017	25	-0.0133	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
114	Pointe Geologie	south polar skua	1968-2017	50	-0.0059	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
115	Kerguelen	black-browed albatross	1979-2016	37	0.0024	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
116	Kerguelen	brown skua	1991-2016	26	-0.0308***	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
117	Kerguelen	wandering albatross	1999-2017	19	-0.0038	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
118	Crozet	wandering albatross	1984-2018	35	0.0016	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
119	Crozet	sooty albatross	1981-2017	37	-0.0073*	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
120	Amsterdam	Amsterdam albatross	1981-2018	38	-0.0047	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
121	Kerguelen	blue petrel	1987-2015	29	0.0010	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord
122	Kerguelen	thin-billed prion	1986-2015	30	-0.0034	French Polar Insitute (IPEV); Christophe Barbraud and Karine Delord

Table S2. Species characteristics. Given are foraging depth, trophic level, number of time series, and number of bird-years of breeding success data for each species. Species are listed in phylogenetic order.

Family	Species common name	Scientific name	Foraging depth	Trophic level	Chick provisioning	Number time series	Number bird-years
Alcidae	razorbill	*Alca torda*	Sub-surface	Omnivore	Piscivore	2	61
Alcidae	rhinoceros auklet	*Cerorhinca monocerata*	Sub-surface	Omnivore	Omnivore	2	57
Alcidae	common murre	*Uria aalge*	Sub-surface	Omnivore	Piscivore	10	279
Alcidae	thick-billed murre	*Uria lomvia*	Sub-surface	Omnivore	Piscivore	6	167
Alcidae	pigeon guillemot	*Cepphus columba*	Sub-surface	Piscivore	Piscivore	1	44
Alcidae	Atlantic puffin	*Fratercula arctica*	Sub-surface	Piscivore	Piscivore	3	125
Alcidae	tufted puffin	*Fratercula cirrhata*	Sub-surface	Piscivore	Omnivore	3	65
Alcidae	horned puffin	*Fratercula corniculata*	Sub-surface	Piscivore	Omnivore	2	48
Alcidae	crested auklet	*Aethia cristatella*	Sub-surface	Planktivore	Planktivore	1	29
Alcidae	parakeet auklet	*Aethia psittacula*	Sub-surface	Planktivore	Planktivore	2	40
Alcidae	least auklet	*Aethia pusilla*	Sub-surface	Planktivore	Planktivore	1	29
Alcidae	whiskered auklet	*Aethia pygmaea*	Sub-surface	Planktivore	Planktivore	1	29
Alcidae	Cassin's auklet	*Ptychoramphus aleuticus*	Sub-surface	Planktivore	Planktivore	1	44
Alcidae	ancient murrelet	*Synthliboramphus antiquus*	Sub-surface	Planktivore	Planktivore	1	21
Stercorariidae	brown skua	*Stercorarius antarcticus*	Surface	Omnivore	Omnivore	1	26
Stercorariidae	south polar skua	*Stercorarius maccormicki*	Surface	Omnivore	Omnivore	1	50
Stercorariidae	parasitic jaeger	*Stercorarius parasiticus*	Surface	Omnivore	Omnivore	1	47
Stercorariidae	great skua	*Stercorarius skua*	Surface	Omnivore	Omnivore	1	47
Laridae	black-tailed gull	*Larus crassirostris*	Surface	Omnivore	Piscivore	1	21
Laridae	glaucous-winged gull	*Larus glaucescens*	Surface	Omnivore	Omnivore	3	51
Laridae	western gull	*Larus occidentalis*	Surface	Omnivore	Omnivore	1	44
Laridae	lesser noddy	*Anous tenuirostris*	Surface	Piscivore	Piscivore	1	24
Laridae	Heermann's gull	*Larus heermanni*	Surface	Piscivore	Piscivore	1	35
Laridae	red-legged kittiwake	*Rissa brevirostris*	Surface	Piscivore	Piscivore	3	92
Laridae	black-legged kittiwake	*Rissa tridactyla*	Surface	Piscivore	Piscivore	11	344
Laridae	common tern	*Sterna hirundo*	Surface	Piscivore	Piscivore	1	37
Laridae	arctic tern	*Sterna paradisaea*	Surface	Piscivore	Piscivore	1	47
Laridae	red-billed gull	*Chroicocephalus novaehollandiae scopulinus*	Surface	Planktivore	Planktivore	1	42
Diomedeidae	Amsterdam albatross	*Diomedea amsterdamensis*	Surface	Omnivore	Omnivore	1	38
Diomedeidae	Antipodean wandering albatross	*Diomedea antipodensis antipodensis*	Surface	Omnivore	Omnivore	1	23
Diomedeidae	Gibson's wandering albatross	*Diomedea antipodensis gibsoni*	Surface	Omnivore	Omnivore	1	27

Diomedeidae	wandering albatross	*Diomedea exulans*	Surface	Omnivore	Omnivore	2	54
Diomedeidae	Laysan albatross	*Phoebastria immutabilis*	Surface	Omnivore	Omnivore	1	29
Diomedeidae	black-footed albatross	*Phoebastria nigripes*	Surface	Omnivore	Omnivore	1	29
Diomedeidae	sooty albatross	*Phoebetria fusca*	Surface	Omnivore	Omnivore	1	37
Diomedeidae	black-browed albatross	*Thalassarche melanophris*	Surface	Omnivore	Omnivore	1	37
Procellariidae	sooty shearwater	*Ardenna grisea*	Sub-surface	Omnivore	Omnivore	1	24
Procellariidae	wedge-tailed shearwater	*Ardenna pacifica*	Sub-surface	Omnivore	Omnivore	1	20
Procellariidae	northern fulmar	*Fulmarus glacialis*	Surface	Omnivore	Omnivore	1	31
Procellariidae	southern fulmar	*Fulmarus glacialoides*	Surface	Omnivore	Piscivore	1	49
Procellariidae	grey-faced petrel	*Pterodroma gouldi*	Surface	Omnivore	Omnivore	1	25
Procellariidae	flesh-footed shearwater	*Ardenna carneipes*	Surface	Piscivore	Piscivore	1	27
Procellariidae	blue petrel	*Halobaena caerulea*	Surface	Planktivore	Planktivore	1	29
Procellariidae	thin-billed prion	*Pachyptila belcheri*	Surface	Planktivore	Planktivore	1	30
Procellariidae	snow petrel	*Pagodroma nivea*	Surface	Planktivore	Piscivore	1	50
Procellariidae	black petrel	*Procellaria parkinsoni*	Surface	Planktivore	Planktivore	1	20
Procellariidae	Chatham petrel	*Pterodroma axillaris*	Surface	Planktivore	Planktivore	1	24
Hydrobatidae	fork-tailed storm-petrel	*Hydrobates furcatus*	Surface	Planktivore	Piscivore	3	71
Hydrobatidae	ashy storm-petrel	*Hydrobates homochroa*	Surface	Planktivore	Planktivore	1	44
Hydrobatidae	Leach's storm-petrel	*Oceanodroma leucorhoa*	Surface	Planktivore	Omnivore	3	71
Spheniscidae	macaroni penguin	*Eudyptes chrysolophus*	Sub-surface	Omnivore	Omnivore	1	32
Spheniscidae	gentoo penguin	*Pygoscelis papua*	Sub-surface	Omnivore	Omnivore	3	74
Spheniscidae	Magellanic penguin	*Spheniscus magellanicus*	Sub-surface	Omnivore	Piscivore	1	34
Spheniscidae	emperor penguin	*Aptenodytes forsteri*	Sub-surface	Piscivore	Piscivore	1	44
Spheniscidae	little penguin	*Eudyptula minor*	Sub-surface	Piscivore	Piscivore	3	101
Spheniscidae	African penguin	*Spheniscus demersus*	Sub-surface	Piscivore	Piscivore	2	39
Spheniscidae	Adélie penguin	*Pygoscelis adeliae*	Sub-surface	Planktivore	Planktivore	2	56
Spheniscidae	chinstrap penguin	*Pygoscelis antarcticus*	Sub-surface	Planktivore	Planktivore	1	21
Sulidae	Cape gannet	*Morus capensis*	Surface	Piscivore	Piscivore	2	53
Phalacrocoracidae	European shag	*Phalacrocorax aristotelis*	Sub-surface	Piscivore	Piscivore	1	31
Phalacrocoracidae	double-crested cormorant	*Phalacrocorax auritus*	Sub-surface	Piscivore	Piscivore	1	18
Phalacrocoracidae	Japanese cormorant	*Phalacrocorax capillatus*	Sub-surface	Piscivore	Piscivore	1	24
Phalacrocoracidae	pelagic cormorant	*Phalacrocorax pelagicus*	Sub-surface	Piscivore	Piscivore	5	124
Phalacrocoracidae	Brandt's cormorant	*Phalacrocorax penicillatus*	Sub-surface	Piscivore	Piscivore	2	67
Phalacrocoracidae	red-faced cormorant	*Phalacrocorax urile*	Sub-surface	Piscivore	Piscivore	3	72
Pelecanidae	brown pelican	*Pelecanus occidentalis*	Surface	Piscivore	Piscivore	2	62

Table S3. Site characteristics. Location information is shown for sites in the data set and the number of species with breeding success data at each site. We rejected latitude as a covariate in the analyses because of an unequal distribution of samples by latitude between hemispheres.

Site	Location	Latitude	Longitude	Ocean domain	Number of species
Adams	New Zealand	-50.90	166.00	Southwest Pacific	1
Admiralty	Antarctica	-62.18	-58.44	Southern	2
Aiktak	USA	54.19	-164.84	North Pacific	10
Alcatraz	USA	37.83	-122.42	Northeast Pacific	1
Amsterdam	France	-37.82	77.53	South Indian	1
Anacapa	USA	34.00	-119.39	Northeast Pacific	1
Antipodes	New Zealand	-49.67	178.81	Southwest Pacific	1
Bird	South Georgia	-54.01	-38.05	Southwest Atlantic	2
Buldir	USA	52.36	175.92	North Pacific	14
Cape Lisburne	USA	68.88	-166.21	Arctic	1
Cape Peirce	USA	58.55	-161.77	North Pacific	2
Cape Shirreff	Antarctica	-62.46	-60.79	Southern	2
Chowiet	USA	56.03	-156.70	North Pacific	6
Crozet	France	-46.42	51.83	South Indian	2
Dassen	South Africa	-33.42	18.09	Southeast Atlantic	1
East Amatuli	USA	58.92	-151.99	North Pacific	2
Foula	United Kingdom	60.13	-2.07	Northeast Atlantic	4
Hirakimata	New Zealand	-36.19	175.41	Southwest Pacific	1
Hornoya	Norway	70.39	31.16	Arctic	2
Ihumoana	New Zealand	-36.89	174.44	Southwest Pacific	1
Isle of May	United Kingdom	56.19	-2.56	Northeast Atlantic	6
Kaikoura	New Zealand	-42.40	173.68	Southwest Pacific	1
Kauwahaia	New Zealand	-36.89	174.44	Southwest Pacific	2
Kerguelen	France	-48.40	68.37	South Indian	5
Lamberts	South Africa	-32.08	18.30	Southeast Atlantic	1
Malgas	South Africa	-33.05	17.93	Southeast Atlantic	1
Middleton	USA	59.44	-146.33	North Pacific	2
Oamaru	New Zealand	-45.11	170.98	Southwest Pacific	1
Pelsaert	Australia	-28.90	113.90	Southeast Indian	1
Penguin	Australia	-32.31	115.69	Southeast Indian	1
Phillip	Australia	-38.48	145.23	Southwest Pacific	1
Pointe Geologie	Antarctica	-66.67	140.02	Southern	5
Punta Tombo	Argentina	-44.05	-65.22	Southwest Atlantic	1
Rangatira	New Zealand	-44.35	-176.17	Southwest Pacific	1
Rasa	Mexico	28.82	-112.98	Northeast Pacific	1
Robben	South Africa	-33.80	18.37	Southeast Atlantic	1
Rost	Norway	67.47	11.98	Arctic	2
Santa Barbara	USA	33.48	-119.04	Northeast Pacific	1
SE Farallon	USA	37.72	-123.03	Northeast Pacific	8
St. George	USA	56.57	-169.61	North Pacific	5
St. Lazaria	USA	56.99	-135.70	North Pacific	6
St. Paul	USA	57.20	-170.28	North Pacific	5
Tern	USA	23.87	-166.28	Central Pacific	2
Teuri	Japan	44.42	141.30	Western Pacific	3
Varanus	Australia	-20.65	115.57	Southeast Indian	1

Wilhelmshaven	Germany	53.51	8.11	Northeast Atlantic	1

Table S4. Results of model-simplification for analysis of normalized breeding success (Model 1) fit by maximum likelihood. For each model-simplification step, we removed interactions or main effects that did not result in a significant deterioration in model fit as indicated by results of conventional log-likelihood ratio test ($\alpha = 0.05$). Term removals are indicated by "-". Significance of remaining terms is presented below the model-simplification results. The final model explained 3.4% of the total deviance, with an additional 2.7% explained by the random effects.

Fixed effects	**DF**	**AIC**	**Chi-sq**	**p-value**
Elimination of terms, in sequence:				
Full model		9823.6		
-Year×TrophicLevel×Depth	2	9794.6	1.244	0.537
-TrophicLevel×Depth	2	9791.3	0.786	0.675
-Year×Hemisphere×Depth	1	9790.4	1.047	0.306
- Hemisphere×Depth	1	9788.6	0.164	0.686
-Year×Depth	1	9788.2	1.621	0.203
- Depth	1	9788.5	2.289	0.130
Remaining model terms:				
Year	1		19.050	1.274×10^{-05}
Hemisphere	1		0.456	0.500
TrophicLevel	2		0.061	0.970
Year×Hemisphere	1		5.790	0.016
Year×TrophicLevel	2		22.962	1.033×10^{-05}
Hemisphere×TrophicLevel	2		0.100	0.951
Year×Hemisphere×TrophicLevel	2		11.610	0.003

Table S5. Results of model-simplification for analysis of probability of breeding failure (Model 2) fit by penalized quasi-likelihood. For each model-simplification step, we removed interactions or main effects for which none of the coefficients are significant on the basis of marginal Wald t-tests. Term removals are indicated by "-". Significance of remaining coefficients is presented below the model-simplification results.

Fixed effects	**Value**	**Std. Error**	**DF**	**t-value**	**p-value**
Elimination of terms, in sequence:					
-Year×Hemisphere[South] ×Depth[Deep]	-0.014	0.0479	3454	-0.2907	0.7713
- *Hemisphere[South] ×Depth[Deep]*	-0.3180	0.8267	112	- 0.3847	0.7012
Remaining model terms:					
Remaining coefficients:					
Intercept	-2.5352	2.3969	3455	-1.0577	0.2903
Year	-0.1101	0.0776	3455	-1.4192	0.1559
Hemisphere[South]	-2.8439	2.8498	113	-0.9979	0.3205
TrophicLevelL[Omnivore]	-8.1071	2.8229	113	-2.8719	0.0049
TrophicLevelL[Piscivore]	-0.5892	2.4388	113	-0.2416	0.8095
Depth[Deep]	-2.0438	2.737	113	-0.7467	0.4568
Year × Hemisphere[South]	0.0793	0.0675	3455	1.1758	0.2398
Year × TrophicLevel[Omnivore]	0.2884	0.084	3455	3.4335	0.0006
Year × TrophicLevel[Piscivore]	0.1505	0.0781	3455	1.9267	0.0541
Year × Depth[Deep]	0.126	0.0814	3455	1.5485	0.1216
Hemisphere[South] × TrophicLevel[Omnivore]	8.0706	3.3576	113	2.4037	0.0179
Hemisphere[South] × TrophicLevel[Piscivore]	1.0207	3.1156	113	0.3276	0.7438
TrophicLevel[Omnivore] × Depth[Deep]	5.0622	3.2046	113	1.5796	0.117
TrophicLevel[Piscivore] × Depth[Deep]	2.748	2.8099	113	0.978	0.3302
Year × Hemisphere[South] × TrophicLevel[Omnivore]	-0.2539	0.0807	3455	-3.1471	0.0017
Year × Hemisphere[South] × TrophicLevel[Piscivore]	-0.0784	0.0733	3455	-1.0695	0.2849
Year × TrophicLevel[Omnivore] × Depth[Deep]	-0.1915	0.0892	3455	-2.1466	0.0319
Year × TrophicLevel[Piscivore] × Depth[Deep]	-0.1547	0.0824	3455	-1.8775	0.0605

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