1   Electronic supplementary material for:

2

6

7   **Supplementary Methods and Results**

8

9   *Data availability*

10

11   All data used in this supplementary material are publically available [1].

12

13   *Tag information and tagging procedures*

14

15   We used Sirtrak Kiwisat K2G-172A ARGOS telemetry tags for this study. The tags have
16   dimensions of 60 x 27 x 17mm, weigh 32g, and are depth rated to 250m. The tags were pre-
17   programmed by the manufacturer to attempt location estimation daily between 12:00 and
18   18:00 UTC. As programmed, expected life of the battery was 6 months.

19   Tag weight represented <1.07% of all fledgling weights, adhering to recommendations
20   for birds that transmitter weights be less than 3-5% of body weight [2]. Additionally, the tags
21   were equipped with an 18mm, flexible external antenna, mounted at a 45° angle. The tag was
22   oriented on the animal so that the antenna pointed caudally for all deployments, consistent
23   with best-practice advice for reducing drag on swimming penguins [3].

24   Tags were mounted directly to the back plumage in a caudal position [4] with
25   cyanoacrylate glue. Two small (2.5x150mm) black plastic cable ties were threaded through
26   underlying contour feathers and closed over the top of the tag as an additional fastener. Small
27   beads of glue were traced along the cable ties on top of the transmitter to help secure the
28   attachment.

29

30   *Fledgling mass*

31

32   Fledglings were weighed during standardized periods at Cape Shirreff and in Admiralty
33   Bay when Adélie and chinstrap penguins move from their nesting sites to seaside beaches just
34   prior to departure. Chicks were caught on the beaches at that time and weighed with spring
35   scales. Gentoo penguin chicks do not depart en masse, so we used a standard age of 85 days
36   (measured from the median egg lay date in the colony) to estimate their fledgling weight. We
37   used the mean weights from all years of data collection which comprises 5833 Adélie fledglings
38   from Admiralty Bay colonies over 34 years between 1982 and 2019, 4942 chinstrap fledglings

39 from Cape Shirreff over 23 years between 1997 and 2019 and 3427 gentoo fledglings from Cape
40 Shirreff over 21 years between 1998 and 2019.
41
42 **Figure S1**. Distribution of historical fledgling weights for Adélie (Admiralty Bay), gentoo, and
43 chinstrap penguins (Cape Shirreff). Vertical dashed lines represent mean mass of fledglings
44 tracked with satellite transmitters.
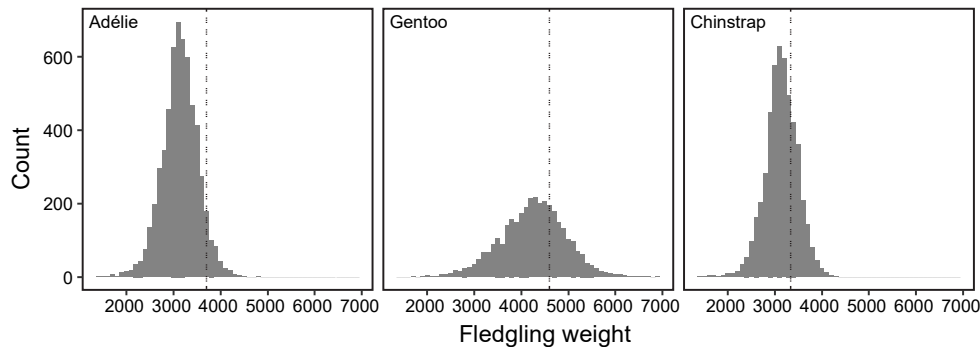

45
46
47 *Critical weights and recruitment*
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49 　　　We used data from fledgling Adélie penguins that were banded and weighed in
50 Admiralty Bay between 1981 and 2010. Methods of banding have been previously described
51 [5]. In total, 3909 banded and weighed Adélie fledglings were released. The first observation of
52 a banded bird within its natal colony in a subsequent year indicated a successful recruitment
53 event. In total, 11.4% (446) of released birds recruited.
54 　　　We fitted binomial generalized linear models with linear and quadratic terms to
55 estimate the relationship between weight at fledging and eventual recruitment to the natal
56 colony. We used AIC for model selection, which indicated a quadratic model provided the best
57 fit to the data (figure S2).
58 　　　With the best fitting model, we estimated critical masses (respectively M_{crit50} and M_{crit10})
59 at which the probability of recruitment was expected to be 50% and 10% of its maximum level
60 (0.12, figure S2). We estimated critical masses only for the left tail of the quadratic curve
61 because, regardless of initial mass, fledglings would only be expected to lose weight if
62 maintenance rations were not consumed. M_{crit50} was estimated to be 2125 g, and M_{crit10} was
63 estimated to be 1575 g. Note that the smallest fledgling ever observed to subsequently recruit
64 to the breeding population weighed 2100g.

65 **Figure S2.** Best-fitting quadratic relationship between fledging weight and recruitment for
66 Adélie penguins in Admiralty Bay. Critical fledgling masses with probabilities of recruiting at
67 10% (1575 g) and 50% (2125 g) of the maximum recruitment probability are highlighted with
68 red dots. The upper and lower hash marks identify, respectively, the weights of recruited and
69 non-recruited fledglings.

70
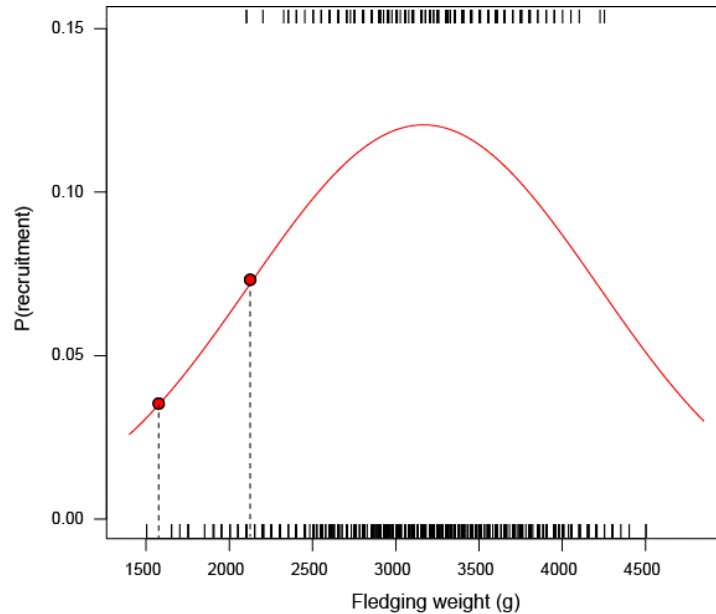
71

72 *At-sea observations of dead penguins and the timing of fledging*

73

74   Nine years (2003 – 2011) of at-sea surveys, consisting of two legs that each repeated the
75 same survey grid [6], were conducted throughout January and again in February/March.
76 Observers recorded the locations and numbers of penguin carcasses floating on the sea surface
77 during normal marine mammal and seabird observation periods using methods previously
78 described [7]. Here, we illustrate the distribution of dates when carcasses were observed
79 (figure S3).
80   The carcass observations correspond to the main fledging periods of Adélie and
81 chinstrap penguins. At independence, Adélie and chinstrap fledglings depart their natal colonies
82 en masse over the course of a few days. The dates for this departure period were recorded at
83 all Admiralty Bay and Cape Shirreff colonies from the time the first fledgling birds are observed
84 on beaches (i.e., no longer associated with their parents or nesting sites) until no more
85 fledglings are found in the colony (i.e., all departed to sea). The timing of this departure period
86 can vary by species, colony location, and year. In our study colonies, these periods typically
87 occur from mid-January to mid-February for Adélie penguins and from late February into March
88 for chinstrap penguins (figure S3). Note that there is no corresponding fledging period for
89 gentoo penguins, since this species does not exhibit mass departures from natal colonies [8].

90   However, tracked fledgling gentoo penguins generally initiated dispersal by late February or
91   early March [8].

92

93   **Figure S3**. Histogram of the timing of penguin carcass observations from U.S. AMLR cruises,
94   2003-2011. Overlaid are the historical ranges of fledging dates for Adélie penguins and
95   chinstrap penguins from the Admiralty Bay and Cape Shirreff colonies, as indicated by
96   horizontal lines with end caps. The final dates of location estimates from satellite telemetry for
97   all deployments are indicated with colored dots.

98
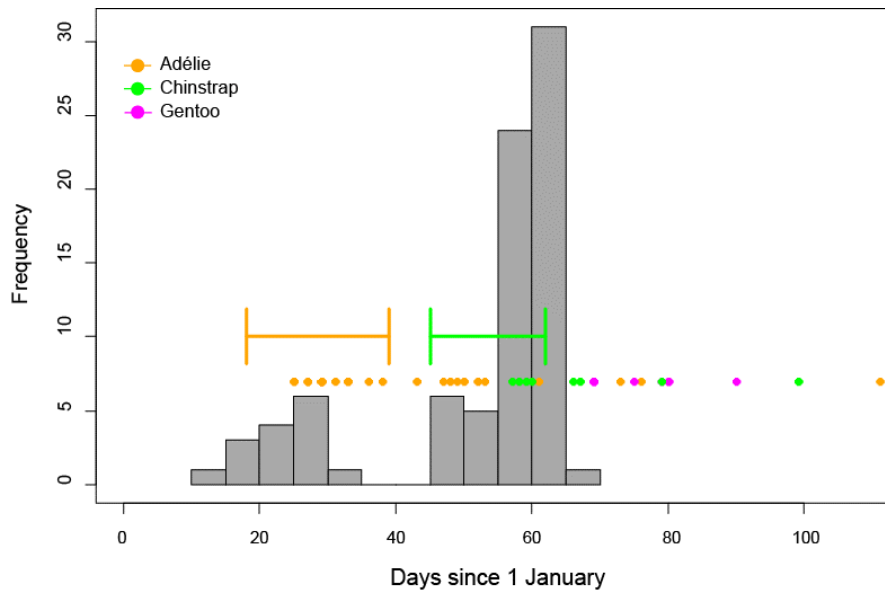
99

100   *Recruitment indices*

101

102   Recruitment indices, calculated as the proportion of flipper-banded birds that return to
103   natal colonies and adjusted for likely band-loss rates, have been described previously [5]. We
104   update them here for Adélie, chinstrap, and gentoo penguins from Admiralty Bay and Cape
105   Shirreff colonies. Across species and sites, recruitment rates were variable but averaged 0.20 ±
106   0.02 for cohorts fledged from 1981 through 2016. This corresponds to an average loss of 80% of
107   banded individuals from a given cohort over the first few years of life.

108   **Figure S4**. Updated indices of recruitment for Adélie, chinstrap, and gentoo penguins for
109   cohorts fledged from 1981 through 2016. The average recruitment across all species and sites
110   (20%) is indicated as the dashed horizontal line.
111
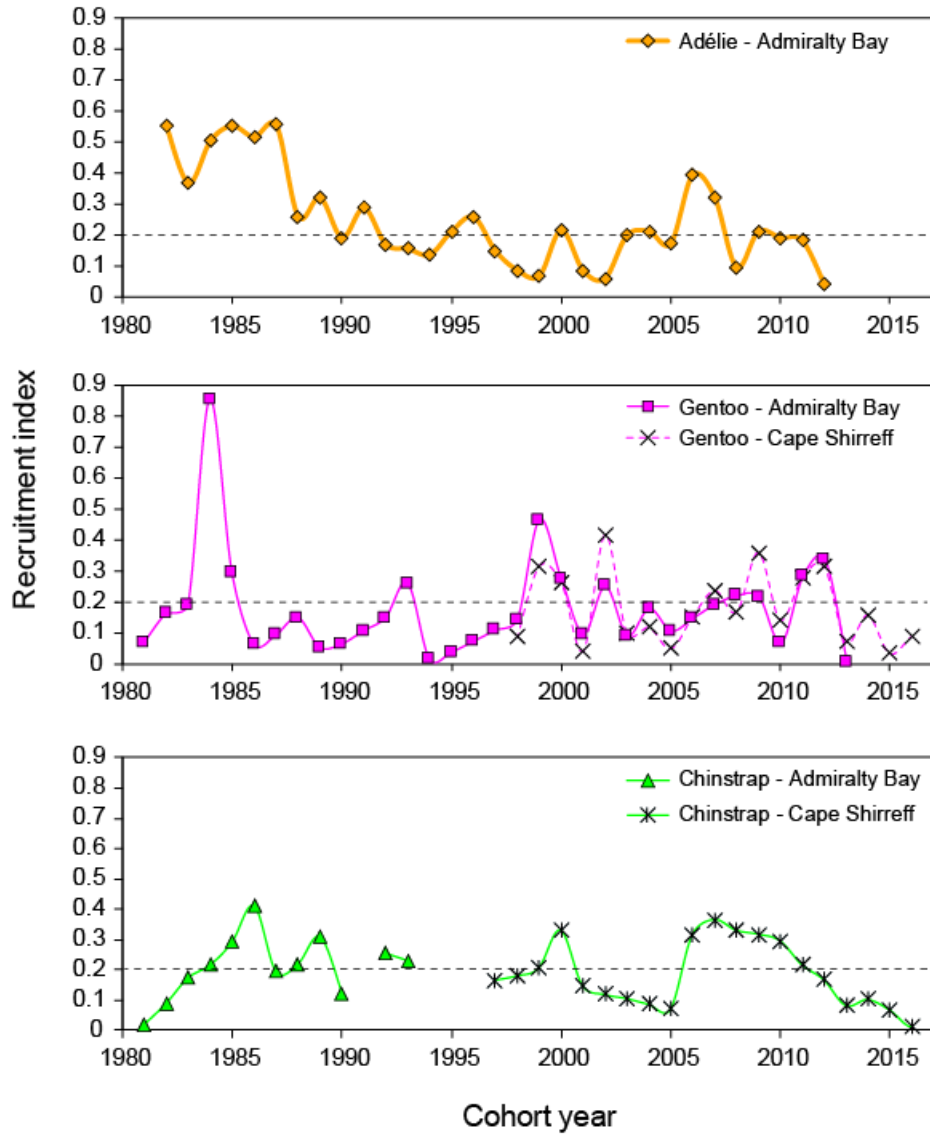
112   *Carcass counts at Cape Shirreff*

113

114   A count of beach-cast fledgling carcasses is conducted annually at Cape Shirreff. One
115   week after the fledging period for chinstrap penguins ends all accessible beaches are searched
116   for freshly depredated chick carcasses. The data represent a crude and conservative index of
117   local predation, noting that 1) leopard seals, fur seals, and giant petrels are present in the
118   colonies at this time and 2) depredation at sea does not guarantee a carcass will wash ashore.
119   The carcass counts exhibit marked inter-annual variation, with counts exceeding 5% of local
120   chick production in some years.

121

122   **Figure S5**. Annual counts of depredated chinstrap penguin chicks from Cape Shirreff, given as a
123   proportion of annual chinstrap chick production in the colony.
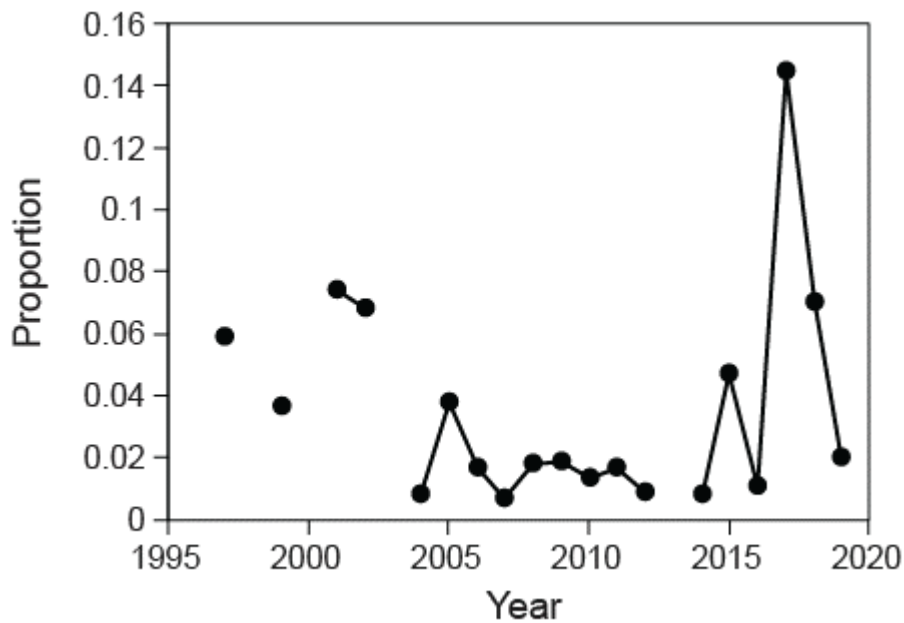
124   *Bootstrapping*

125

126   We developed a bootstrapping procedure to simulate alternative scenarios of tag failure

127   that may affect the timing of a survival bottleneck and magnitude of mortality estimated within

128   the bottleneck. Specifically, we evaluate how the timing of the bottleneck and the magnitude of

129   loss due to animal death varies as increasingly larger proportions of tags are assumed to have

130   been lost for reasons other than animal death.

131   The bootstrapping algorithm assumes that faulty tags, weak tag attachments, and tags

132   that fail prematurely for other reasons are more likely to fail early, causing transmission of

133   location information to cease. The simulated failed deployments are therefore removed from

134   the bootstrap analysis, leaving only samples that failed due to death.

135   To simulate such failures, we weighted sampling of the pooled data based on the

136   inverse of deployment duration to reject short-duration deployments preferentially. We sample

137   from the data without replacement to reinforce preferential removal of short-duration

138   deployments. The resulting sample of data represents the tags whose losses are attributable to

139   death, but with mortality estimates that account for the proportion of tags lost due to other

140   reasons.

141   Note that we tested alternatives to the above, namely by bootstrapping with

142   replacement and by weighting sampling to preferentially reject long-duration deployments.

143   Ultimately, we believe that the methods described above (and in the main paper) provide a

144   conservative approach to quantifying plausible ranges of mortality inside the bottleneck. For

145   example, a weighting that preferentially rejected long-duration deployments effectively

146   increased the magnitude of mortality within the bottleneck but did not affect the timing of the

147   bottleneck.

148   We rely on a published report [9] that suggests 50% failure rates are common in most

149   tracking studies to establish a plausible lower bound on our estimates of mortality within the

150   bottleneck, though we present results for simulated failure rates from 2% to 80%.

151   The bootstrapping results for a range of plausible data-rejection rates are provided in

152   figure 2b and figure S6. As more data are rejected due to premature tag failure, the proportion

153   of tags potentially lost to animal death is reduced, but the breakpoint is consistently around 16

154   days.

155   **Figure S6**. Bootstrap simulation results for seven alternative data exclusion rates. Individual
156   bootstrapped samples are plotted in light blue. For visual reference, an overall segmented
157   model fitted to the pooled bootstrap data is in black. The dashed vertical line denotes its
158   breakpoint.
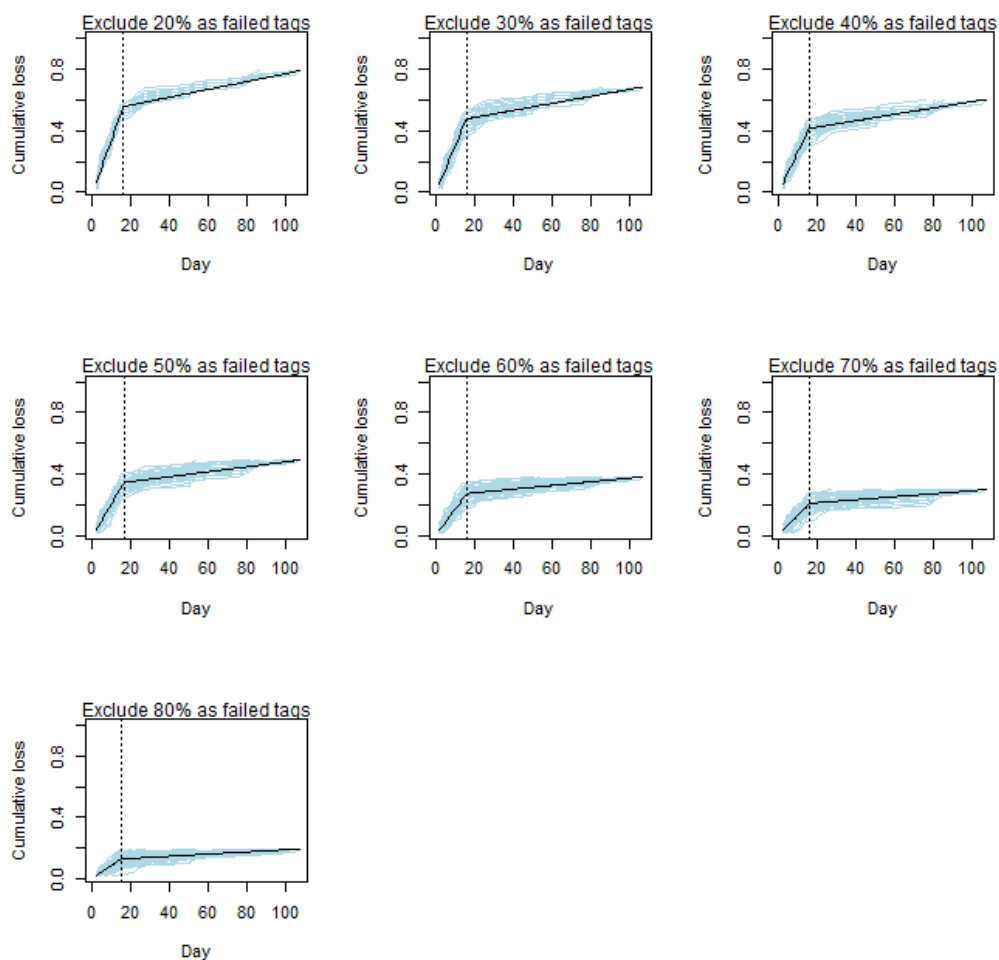
159
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161

162   We used ANOVA to assess parsimony of segmented versus non-segmented linear
163   models because the non-segmented linear model is nested within the segmented linear model.
164   We plotted histograms of the p-values from these tests (figure S7). Except for bootstrap
165   samples with the highest rejection rate, segmented models fitted the data better than non-
166   segmented models in all cases. At the highest rejection rate we tested, segmented models
167   fitted the data better than non-segmented models 89% of the time. Note that an 80% rejection
168   rate selects only nine tags for subsequent analysis.

169   **Figure S7**. Histogram of p-values from ANOVA of the segmented and non-segmented linear
170   models for each iteration of the bootstrapping procedure for each exclusion rate. Bins are set at
171   a width of 0.01.
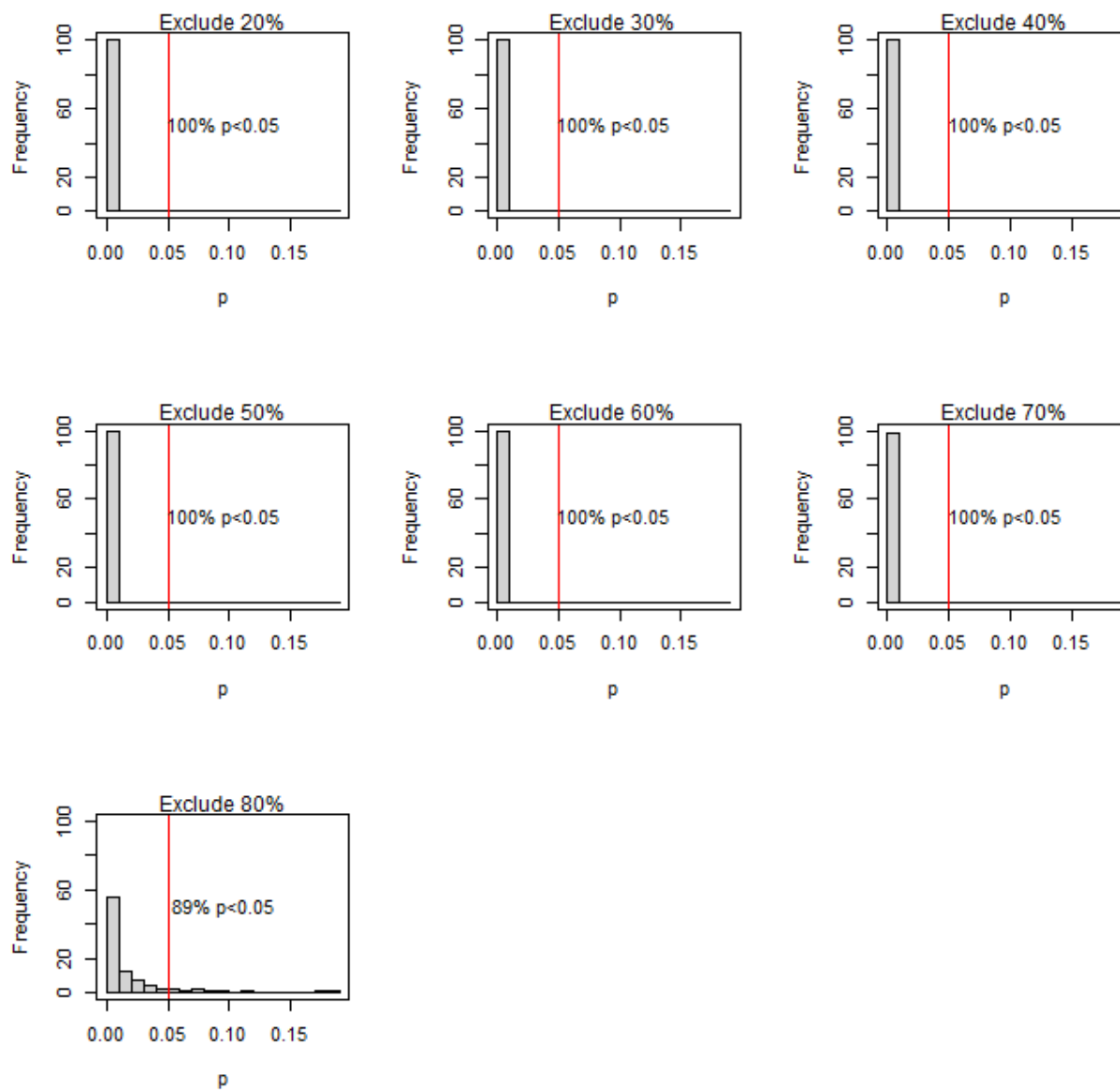
172   We also computed the ratio of estimated slopes before and after (Beta1 and Beta2

173   respectively) the estimated breakpoints in our bootstrap samples. In all cases, Beta1 is greater

174   than Beta2, often by an order-of-magnitude. This demonstrates that high loss rates

175   immediately after fledging are insensitive to the proportions of tags lost due to reasons other

176   than animal death.

177

178   **Figure S8**. Histograms of the logged ratio between slope parameters (Beta1 and Beta2) in the

179   segmented models. Values ≥1 indicate order-of-magnitude differences between slopes before

180   and after estimated breakpoints.
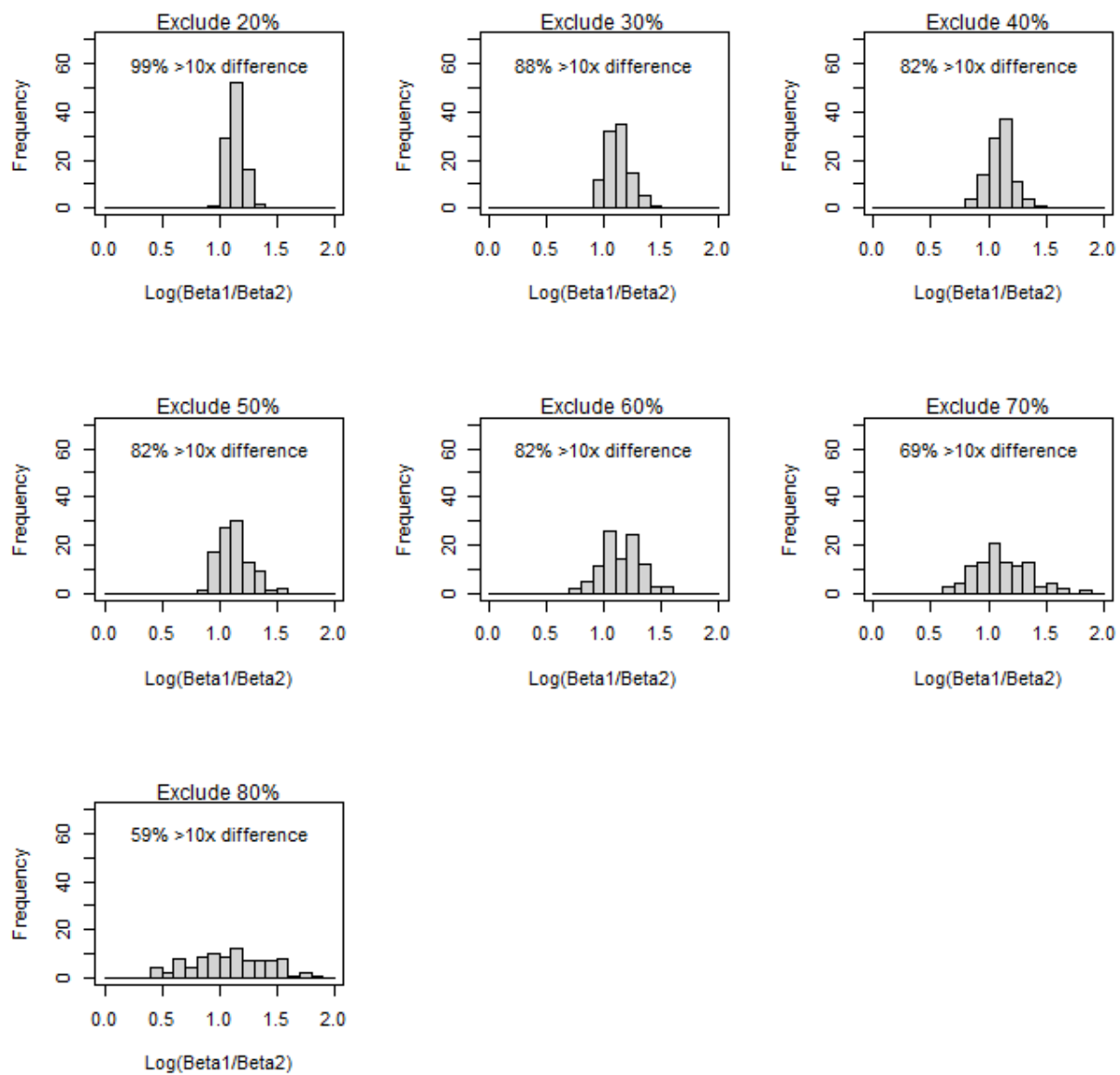
181   *Tag power*

182

183   Failure of telemetry instruments can arise from technical and mechanical failure of the
184   tag, tag shedding or removal by the animal, and premature animal death. Power failure
185   associated with bad batteries is the number one cause of failure, accounting for roughly 50% of
186   all technical failures [9].

187   We examined the battery voltages of tags used in this study at the time of their last
188   transmission and over the duration of the deployment prior to each tag's last transmission to
189   assess the likelihood that battery failure was a factor in the rate of tag loss. We find this to be
190   unlikely.

191   Data were available for the tags released on Adélie penguins in 2018 (main manuscript
192   Table 1). Note that this subset of tags was manufactured at the same time as all tags released in
193   2017, but these were shelved for one full year due to logistical problems that prevented their
194   deployment until 2018. This shelving might be expected to increase the likelihood of power
195   failure in these 29 tags. However, battery voltages at the time of last transmission remained in
196   "normal" operating ranges for these tags (P. O'Flaherty, pers. comm. 2020). A significant linear
197   trend ($F_{1,17}$=9.7, p=0.006) in the relationship between voltage and duration (figure S9) indicates
198   that tags lost early in their deployment presumably had sufficient power for future
199   transmissions. Moreover, final battery voltages were within a narrow range of values that were
200   comparable to the mean transmission voltages of these batteries. A paired t-test indicates no
201   difference between mean and final transmission voltages (t_{18}=1.47, p=0.16), suggesting that
202   there was no sudden drop-off in voltage at the time of the last transmission. Together, these
203   results suggest that battery failure was not the cause of tag failure in this study.

204

205   **Figure S9**. Relationship between (a) final battery voltage and deployment duration (regression
206   line is included for reference) and (b) mean battery voltage and final battery voltage (1:1 line
207   included for reference).
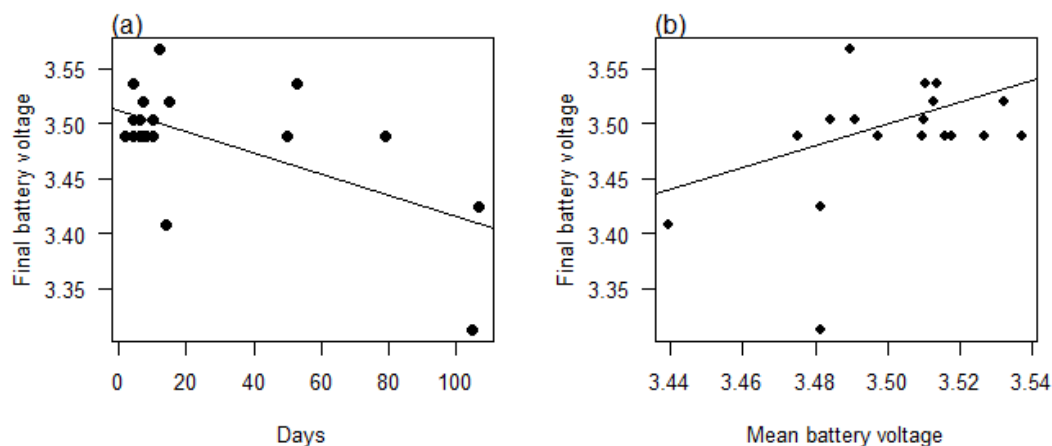
208   *Bioenergetics, body condition, and tag effects*

209

210   Body condition and increased energy expenditures owing to tagging effects may affect

211   subsequent survival within a post-fledging bottleneck. To assess likely impacts of these two

212   factors on our results, we used the bioenergetics model [10] described previously and used in

213   the main manuscript. We note that the bioenergetics model [10] was developed originally for

214   breeding, adult Adélie penguins, but is here applied to simulate recently fledged penguins.

215   Ontogenetic changes in metabolic rates may cause fledgling energetics to differ from those of

216   adults, but we proceed with published parameterizations [10] given a lack of fledgling-specific

217   parameter estimates at this time. Here, we simulated three no-ration scenarios and three half-

218   ration scenarios to compare mass loss of birds with different initial weights. We repeated the

219   simulations for a range of multipliers for energy expenditure that may arise from the additional

220   drag generated by an externally attached tag [4]. Specifically, we tested 10% and 30% increases

221   in energy expenditure to assess sensitivity of weight loss during the bottleneck period, noting

222   that these multipliers bracket an up-to 20% increase in tag-induced swimming expenditures

223   reported [11] for Magellanic penguins (*Spheniscus magellanicus*).

224   We used initial weights estimated as: 1) the mean mass of our tagged Adélie penguins

225   (3.76 kg) to address our study results; 2) the historical mean mass of fledglings at our study site

226   (3.16 kg) to assess an average individual; and 3) the lower 25th quantile of fledgling mass at our

227   study site (2.9 kg) to assess a poor-condition fledgling.

228   Given no rations, fledgling birds at each initial mass are predicted to reach levels

229   associated with low recruitment within the bottleneck period (vertical dashed line in figure

230   S10), with the smallest birds eating no rations achieving the lowest critical mass in 10 days.

231   Half-rations extend the period to attaining critical mass threshold by 10 to 17 days depending

232   on initial mass.

233   **Figure S10**. Mass loss over time assuming no rations (dashed lines) or half rations (solid lines)
234   for three different initial masses. The blue lines represent simulations presented in the main
235   text.
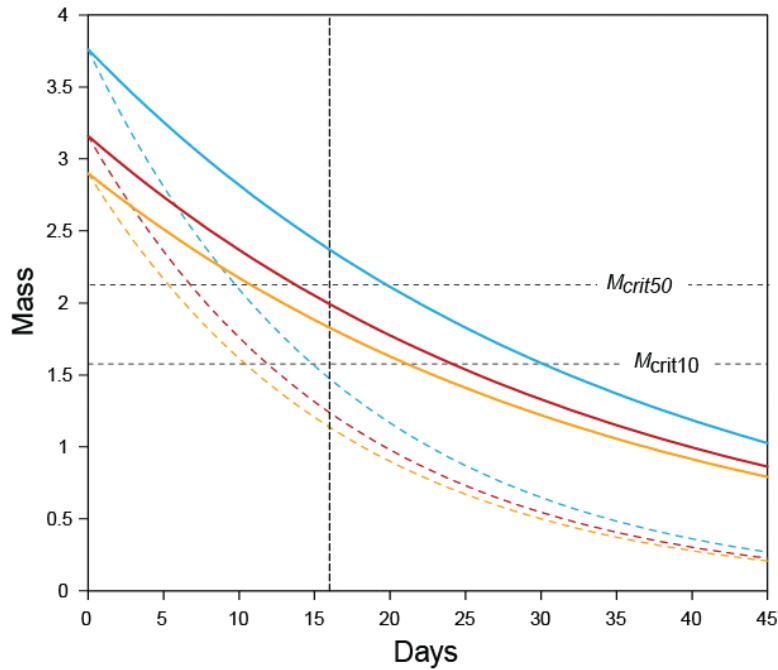
236
237
238   Simulations of mass over time were sensitive to increases in tag-induced energy
239   expenditure, with more rapid loss predicted with increasing effects of tags on necessary energy
240   expenditures (figure S11). The results suggest that no-ration birds reach critical masses 0-1 day
241   sooner at 10% increases in expenditures, and 1-2 days sooner at 30% increases in expenditure.
242   Half-ration birds reach critical masses 1-2 days sooner at 10% increases and up to a week earlier
243   at 30% increases in expenditures. Generally, the results suggest that birds less than average size
244   on rations <50% are likely to reach critical thresholds within the bottleneck period.

245   **Figure S11.** Simulation results for three different initial masses (M_o) that assume either no-
246   ration or half-ration and three multipliers for effects of tags on energy expenditures. Vertical
247   solid line marks the 16-day breakpoint identifying the bottleneck. Horizontal dashed and dotted
248   lines mark the critical weights identified in the main manuscript.
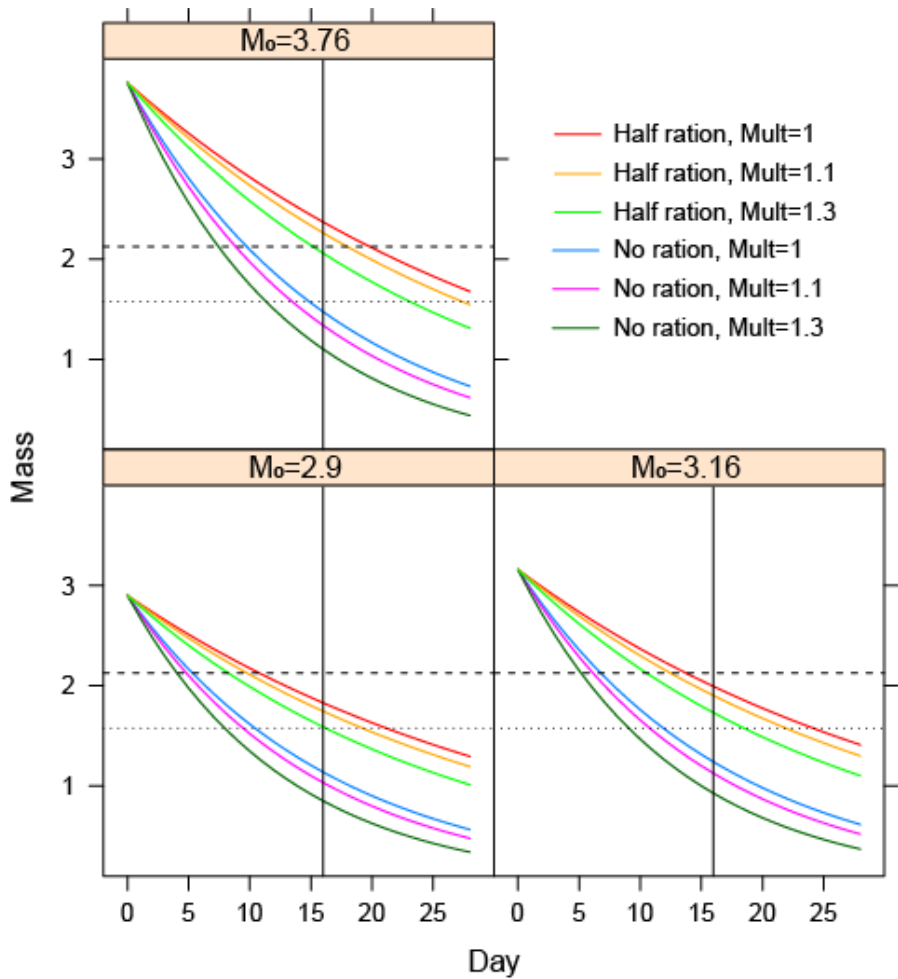
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250

251   We interpret these simulations to indicate that carrying a tag increases the likelihood of
252   mass loss that would lead to starvation or increased predation risk within the bottleneck
253   period, particularly for small individuals that do not feed.
254   Finally, historical data demonstrate that fledglings were of average (chinstraps) or
255   above-average (gentoo and Adélie) condition in our study (figure S12).

Figure S12.   Mean fledgling mass over time for Adélie penguins at Admiralty Bay, and for gentoo and chinstrap penguins at Cape Shirreff Livingston Islands. The year 2017 is marked with a vertical dashed line. Historical, species-specific mean weights are indicated by dotted horizontal lines.
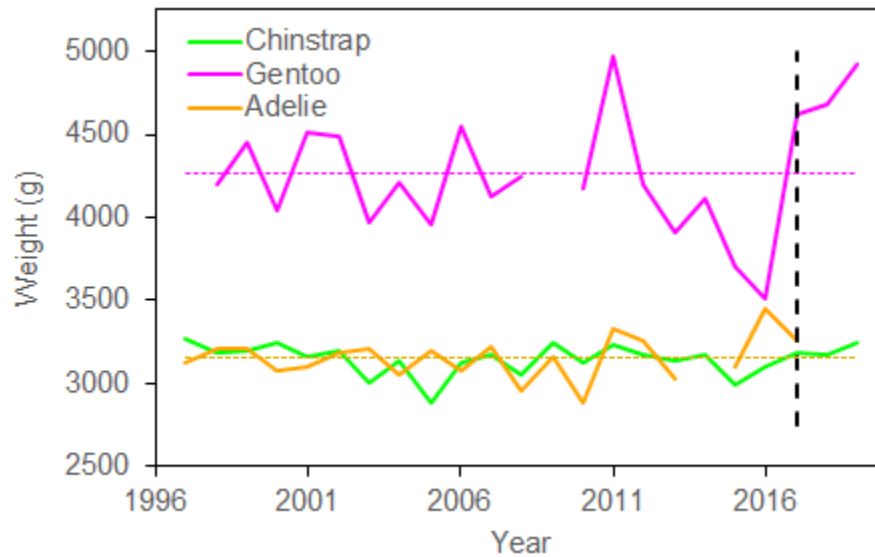
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