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Circumpolar projections of Antarctic krill growth potential

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30 **Antarctic krill is a key species of important Southern Ocean food webs, yet how changes in**
31 **ocean temperature and primary production may impact their habitat quality remains poorly**
32 **understood. We provide a circumpolar assessment of the robustness of krill growth habitat to**
33 **climate change by coupling an empirical krill growth model with projections from a weighted**
34 **subset of IPCC Earth System Models. We find that 85% of the study area experienced only a**
35 **moderate change in Relative Gross Growth Potential (RGGP) ($\pm 20\%$) by 2100. However, a**
36 **temporal shift in seasonal timings of habitat quality may cause disjunctions between krill's**
37 **biological timings and the future environment. Regions likely to experience habitat quality decline**
38 **or retreat are concentrated near the northern limits of krill distribution and in the Amundsen-**
39 **Bellingshausen Sea region during autumn, meaning habitat will likely shift to higher latitudes in**
40 **these areas.**

41 Antarctic krill (*Euphausia superba*, hereafter krill) are an ecologically¹⁻⁴ and commercially^{5,6}
42 important species in the Southern Ocean, and yet qualitative reviews hypothesize that krill may be
43 vulnerable to projected oceanic warming as stenothermic crustaceans⁷⁻⁹. Previous projections have
44 suggested that ocean warming will cause favourable krill habitat to contract^{10,11}, resulting in possible
45 declines in abundance and/or biomass. Currently, oceanic warming is manifesting more rapidly in
46 regions of the Southern Ocean than the global average^{12,13}, but its effect on observed krill
47 abundance and distribution is a topic of debate¹⁴⁻¹⁸. Predicting the population response of krill to
48 climate change, and the ecological impacts of these changes, is therefore important to conservation
49 efforts and the management of the krill fishery⁸.

50 Projecting future changes in krill habitat requires knowledge of environmental drivers of
51 habitat quality. Existing empirically-based models describe krill growth as a function of two major
52 factors: temperature and food concentration (typically phytoplankton approximated by primary
53 production (PP) and/or chlorophyll-*a*)¹⁹⁻²¹. Thus, accurate estimates of these variables are required.
54 Recent advances in computing capacities now allow climate models to support the reasonable

55 representation of the carbon cycle within fully coupled Earth System Models (ESMs)²². However, it
56 remains difficult for modelled PP fields to reproduce current observations with a resolution and
57 accuracy sufficient for application to biological models^{23,24}.

58 Existing studies modelling future changes in krill habitat have so far explored future PP by
59 manipulating (i.e. % increase/decrease) satellite chlorophyll-*a* observations. For example, projected
60 changes in sea surface temperature (SST) and sea ice resulted in changes in spawning habitat
61 ranging from +51 to -83%, depending on changes in summer chlorophyll-*a* of +25 to -50%²⁵.
62 Increases in SST also resulted in mid-latitude (~55-65°S) declines in adult krill habitat quality, and
63 potentially biomass^{10,11}, although these declines could be partially mitigated by a 50% increase in
64 chlorophyll-*a*¹⁰. A wider analysis of Southern Ocean PP from the Coupled Model Intercomparison
65 Project 5 (CMIP5) ensemble suggests this mitigating interaction to be unlikely, reporting a
66 latitudinally-banded response to climate change with reduced PP in mid-latitude regions²⁶. Further
67 studies²⁷⁻³⁰ indicate that future changes in the timing of seasonal PP may result in a temporal
68 mismatch between the seasonal cycle of krill and food availability. Krill habitat is therefore highly
69 sensitive to future changes in PP, for which skilled model projections are needed¹¹.

70 We combine projections of both SST and chlorophyll-*a* to provide simulations of circumpolar
71 krill growth potential as a measure of adult krill habitat quality. To calculate growth potential we
72 built upon an existing method¹¹, forcing an empirical growth model²¹ for a 40mm krill with projected
73 seasonal climatologies for 2070-2099 from an ensemble of ESMs. To improve the ESM ensemble
74 performance for biological modelling applications, we developed an approach to select and weight
75 ESMs based on their skill at reproducing observation-based growth potential for the recent past.
76 Projections from the weighted subset are presented for two representative concentration pathways
77 (RCPs): RCP 4.5 and RCP 8.5. Relative gross growth potential (RGGP) projections are developed using
78 a krill length:mass relationship^{10,31,32}.

79 Evaluation of ESM selection and weighting approach

80 Assuming model biases remain consistent with time, selecting ESMs that most accurately
81 reproduce current climate can increase confidence in future projections³³. Yet reducing the number
82 of models contributing to a projection can limit predictive power. Of eleven CMIP5 ESMs that
83 contributed chlorophyll-*a* and SST for the relevant RCP scenarios, most produced seasonal SST
84 climatologies for the historical period (1960-1989) that closely matched Southern Ocean
85 observations (Extended Data Figs. 1-2). The observed variability in chlorophyll-*a* was typically
86 misrepresented by relatively simple biogeochemical models with high inter-model variation
87 (Standard Deviation axes, Extended Data Fig. 2). Since the krill growth model is highly sensitive to
88 changes in chlorophyll-*a*¹¹, spatial variability was also typically misrepresented in growth potential
89 (Fig. 1).

90 Our selection and weighting approach (see Methods) ensured that modelled growth
91 potential more closely matched observation-based variability than achieved using the full ensemble
92 mean (Fig. 1). Across all seasons, the weighted subset growth potential shows normalised root mean
93 square errors between 0.75 and 1 (0.6–1.2 for the full ensemble), correlation coefficients between
94 0.4 and 0.7 (0.1–0.7), and normalised standard deviations within ± 0.7 (± 0.9) of observation-based
95 growth potential. The models displayed seasonal variation in their skill, which was reflected in the
96 seasonal differences of the weightings (Supplementary Table 2).

97 Our weighting approach had the largest effect on chlorophyll-*a*, firstly because there was
98 higher inter-model variation in chlorophyll-*a* estimates. Secondly, the weighting acted largely on
99 growth potential variability, which originated primarily from variability in chlorophyll-*a* due to the
100 growth model sensitivity. A previous analysis²⁶ projected changes in maximum annual surface
101 phytoplankton under RCP 8.5, calculated for the CMIP5 multi-model mean. Here, using seasonal
102 chlorophyll-*a* calculated for the weighted ensemble mean, we see evidence of at least two
103 latitudinal bands of change under RCP 4.5 (spring) and RCP 8.5 (spring-summer), consistent with this

104 previous finding (Fig. 2b). However, our weighted subset projected localized decreases in
105 chlorophyll-*a* over the continental shelf in summer and generally more zonal structuring in the
106 manifested change.

107 Seasonal growth potential maps confirmed that, by prioritizing variability, the weighted
108 approach reproduced the observation-based growth potential with improved magnitude and
109 distribution relative to the full ensemble (Fig. 3). There were several regions that deviated from
110 observation-based values. Regions of expected limited growth upstream of the Kerguelen Plateau
111 and in the Amundsen Sea were not as well-resolved. In autumn, localised regions of growth
112 potential >4 mm month⁻¹ were underestimated, leading to an underestimation in spatial variability.
113 This was likely due to few models receiving high weighting in this season (Supplementary Table 2).
114 Additionally, known model biases in SST and sea ice result in growth areas extending into higher
115 latitudes than observed in winter and spring³⁴.

116 Projected krill habitat quality shifts in space and time

117 Projected changes in krill habitat quality (growth potential) and habitat area (the total area
118 where growth potential was positive) were evaluated between the recent past (1960-1989) and end
119 of the century (2070-2099) (Fig. 4, Supplementary Figs. 4-5). The major projected changes in growth
120 potential reflect the projections of the future environmental drivers (projected SST and chlorophyll-
121 *a*; Fig. 2). As with the historical climatology, future projections display seasonal variation but
122 seasonal differences between RCP scenarios were relatively minor. In spring, summer and winter,
123 RCP 8.5 resulted in slightly lower median growth potential than RCP 4.5 (Table 1). This was due to an
124 increase in SST and slight decline in chlorophyll-*a* in summer. Due to seasonal similarities, the results
125 of the two RCP scenarios are presented together.

126 Krill habitat quality is expected to improve in spring. Growth potential increased south of
127 60°S. Habitat area increased by 13% and 10% under RCP 4.5 and 8.5 respectively; the regions of krill
128 habitat expansion was concentrated on the continental shelf. This encroachment should be

129 considered alongside the known low sea ice bias in spring³⁴, which causes historical growth potential
130 to extend farther south than observed. This bias will likely propagate into future projections,
131 meaning habitat may not extend as far south as projected. While changes in krill habitat generally
132 varied by latitude, there were regional exceptions of increased growth: to the east of and including
133 the Weddell Sea under RCP 4.5, and the high latitude regions of the Bellingshausen and Amundsen
134 Seas under RCP 8.5.

135 In summer, there was an increase in habitat quality at high and low latitudes, and a decline
136 in the mid latitudes. Results for summer are the most robust, as the empirical growth model was
137 validated with summertime *in-situ* data. The net circumpolar effect of these changes on habitat area
138 resulted in a negligible increase under RCP 4.5 (+2%) and decrease under RCP 8.5 (-1%). Notably, the
139 Antarctic Peninsula (AP), a potential source population³⁵ for the Scotia Sea downstream, is in the
140 mid-latitude band of habitat quality decline, consistent with the banding pattern of changes in
141 chlorophyll-*a*. Regions of increased summer habitat quality include the eastern Weddell (15-45°W,
142 RCP 4.5) and western Ross Seas (160-180°E, RCP 4.5 and 8.5). Yet the Ross Sea is difficult to
143 accurately depict in ESMs³⁴, making projections here less certain.

144 Autumn displayed the greatest decline in habitat quality and area, especially under RCP 4.5.
145 This constituted the greatest difference between the RCP projections, but was likely due to a
146 difference in model weighting, rather than differences between the RCP scenarios themselves. One
147 of the best-performing (thus highly-weighted) models in autumn for the recent past (CMCC-CESM)
148 did not contribute RCP 4.5 projections to the CMIP5 archive. This suggests that our RCP 8.5 autumn
149 projection is more reliable. Autumn decreases in growth potential and habitat area (-28% under RCP
150 4.5, -19% under RCP 8.5) mainly occurred in sub-Antarctic regions, including the eastern and central
151 Pacific Ocean. These range contractions are attributed to warming SST (Fig. 2).

152 Finally, in winter small declines in already low growth potential are projected at low
153 latitudes due to warming SST while chlorophyll-*a* remains low. The net impact of these changes on
154 habitat area is negligible for RCP 4.5 (-3%) and results in a decline in RCP 8.5 (-10%).

155 In summary, projected krill habitat quality shifts towards higher latitudes mainly due to
156 rising SST. Habitat quality also shifts temporally as a function of changing SST and chlorophyll-*a*, by
157 improving in spring, declining in ecologically important regions in summer and declining overall in
158 autumn. Projected circumpolar changes in habitat area are relatively small, but positive in spring.

159 Management implications

160 The results of this study are relevant for future perspectives on krill fishery management,
161 which is overseen by the Commission for the Conservation of Antarctic Marine Living Resources
162 (CCAMLR). The krill fishery is the largest in the Southern Ocean, and its management is subdivided
163 into statistical subareas⁵. Here we present results of RGGP—a habitat quality metric based on
164 biomass rather than length^{10,31,32}—and its environmental drivers (Supplementary Tables 3-4).
165 Overall, 90% of CCAMLR subareas evaluated experienced a change in RGGP of less than 15% (Fig. 5).
166 This comprises subareas south of the Southern Antarctic Circumpolar Front (SACCF) but including
167 South Georgia (Subarea 48.3). The SACCF generally represents the northern limit of krill distribution,
168 except for South Georgia, which represents the upper limits of krill thermotolerance (~4°C)^{35,36}.

169 Across all seasons 40% of CCAMLR subareas projected increases in RGGP. Most of these are
170 attributed to SST increases in spring, changing historically cold areas to temperatures more
171 favourable for high growth. The three areas of greatest RGGP increase all demonstrate large
172 increases in chlorophyll-*a* (+25 – 175%), with only minor changes in SST (within 0.1°C). Therefore,
173 RGGP is projected to improve when changes in SST are either small and accompanied by increases in
174 chlorophyll-*a*, or when they beneficially increase historically low temperatures in spring.

175 Krill are most sensitive to changes in temperature at the upper limits of their
176 thermotolerance^{11,21}, hence areas exhibiting RGGP declines in excess of 20% were almost exclusively
177 towards the northern limits of krill distribution. Declines in most of these regions were still relatively
178 moderate, for example during autumn under RCP 4.5 in the Bellingshausen Sea (Subarea 88.3, -21%),
179 and during summer under RCP 8.5 around South Georgia (-23%). These RGGP declines had different
180 environmental drivers, with a decrease in chlorophyll-*a* (-50%) and increase in SST (+1.7°C), and an
181 increase in SST (+1.8°C) respectively.

182 Discussion

183 Refining an ESM ensemble in a novel way allows the circumpolar projection of krill habitat
184 quality. We found a temporal shift of habitat quality in the Antarctic Peninsula, with habitat
185 improving in spring and declining in summer and autumn. This could have important implications for
186 krill reproduction and population size, as the tip of the AP is both an important spawning ground for
187 krill within the Southwest Atlantic sector³⁷ and a major fishing ground for krill³⁵.

188 Temporal shifts could influence krill population dynamics by offsetting the synchronization
189 of krill life history to the annual cycle of the Antarctic environment^{11,30}. In a stable climate,
190 synchronization allows krill to efficiently utilise seasonally-available food sources that facilitate
191 growth, reproduction and overwintering³⁸. A temporal shift in habitat quality could therefore create
192 a timing mismatch. In this same AP region, modelling showed spawning habitat to be highly affected
193 by future changes in the timing of sea-ice advance²⁵. Furthermore, recent laboratory work suggests
194 that krill lack the plasticity to adapt to temporal shifts, as the seasonal physiological cycle of krill is
195 entrained by light regime^{28,29}.

196 In a typical reproductive season, food in late-winter to early spring is important to allow krill
197 to prepare for reproduction, while PP during summer is critical for completion of the reproductive
198 cycle³⁸. Our projections show that while krill may have a good start to maturation early in the
199 season, the subsequent decline in habitat condition may negatively affect reproductive performance

200 due to the exponential relationship between adult size and fecundity^{35,39}. Decreases in projected
201 summer growth potential around the AP (-1 to -2 mm month⁻¹, -3 to -6 mm over the season) would
202 translate into an exponential decrease in regional fecundity.

203 We also found a spatial shift in habitat quality towards higher latitudes. Northern regions
204 where temperature increases begin to rise above krill thermotolerance^{11,21} also showed associated
205 decreases in projected chlorophyll-*a*; the exception being South Georgia during summer under RCP
206 4.5. Previous regional-scale modelling work¹⁰ hypothesized that increases in ocean PP might mitigate
207 the increased physiological consequences of rising SST for krill. Our results suggest that projected
208 changes in chlorophyll-*a* and SST will more likely have a negative synergistic effect in low latitudes,
209 while beneficial increases in chlorophyll-*a* and SST in high latitudes may have a positive synergistic
210 effect for krill growth.

211 Particularly high krill growth potential increases were projected for the eastern Weddell and
212 western Ross seas in summer, which we have placed within the context of large-scale climate
213 processes altering two major growth drivers (SST and chlorophyll-*a*). However, regional-scale
214 hydrographic features, such as the Antarctic Slope Current (ASC)⁴⁰ and Ross Gyre⁴¹, are likely to have
215 significant implications for habitat quality and growth potential; for example, variability in the
216 strength of the ASC between years and the associated influx of Circumpolar Deep Water. Antarctic
217 shelf and along-shelf processes are generally not well-represented in the coarse grid scales of CMIP5
218 models^{40,42,43} but this will likely improve with future simulations undertaken on finer-scale grids.

219 Similarly, our results compile seasonal climatologies, however the Southern Annular Mode
220 (SAM) and the El Niño Southern Oscillation (ENSO) are known drivers of interannual variability in
221 physical processes likely to impact krill growth potential¹⁵. Observational studies have linked positive
222 SAM and strong ENSO events with decreases in krill density and recruitment, hypothesizing that
223 these events degraded the quality of sea-ice habitat for overwintering krill^{15,17,44,45}. Under
224 anthropogenic forcing, CMIP5 models generally project an increasingly positive SAM⁴⁶ and possibly

225 more El Niño events⁴⁷. Therefore, a consideration of modes of climactic variability (i.e. ENSO and
226 SAM), and their role in hydrographic and sea-ice variability, is needed to obtain more confident
227 projections of krill habitat in these regions^{1,48}.

228 Food availability (represented by chlorophyll-*a*) is a primary driver of krill distribution and
229 growth^{11,19,21}. The chlorophyll-*a* projections obtained using our weighted subset approach present
230 broad-scale similarities, but some key regional differentiation, with those using an unweighted
231 ensemble mean²⁶. Our findings indicate the unweighted mean underrepresents historical growth
232 potential (and chlorophyll-*a*). Consequently, the weighting approach adopted here improves our
233 confidence for this biological application. Overall, a central message across studies is that PP
234 projections show important seasonal variability in responses to future change.

235 Our results suggest possible changes in the availability of krill to the fishery. Currently, most
236 fishing activities occur around the AP and south Scotia Sea (Subareas 48.1 and 48.2 respectively)⁴⁹.
237 During recent years the fishery around the AP usually reaches its catch limits in the middle of fishing
238 season (*i.e.*, mid-autumn)⁵⁰, triggering a management rule to move to a different spatial unit.
239 Projected regional changes in RGGP – an increase in spring and decline in summer and autumn –
240 may lead to shifts in the distribution and timing of fishing effort.

241 A southward shift in krill habitat will also have consequences for dependent predators.
242 Species that are highly mobile and able to track changes in prey distribution may be less impacted
243 than those that are tied to land-based colonies with restricted foraging ranges. This is especially
244 relevant for predators breeding on sub-Antarctic islands, which rely on krill availability in low-mid
245 latitudes^{11,51-54}. South Georgia, for example, has a krill-dominated marine food web^{53,55} and our
246 results suggest a decline in RGGP in this region. While CMIP5 models do not resolve mesoscale
247 processes that are likely important to PP around South Georgia, even a high-PP future scenario also
248 produced declines in RGGP at low latitudes¹⁰. Yet RGGP cannot be directly translated into changes in
249 prey availability as it is a measure of relative habitat quality. RGGP is generally related to krill

250 density, but this relationship is complex and contains caveats^{11,31}. Methods for developing explicit
251 projections of krill biomass are therefore needed for accurate predictions of impacts on predators.

252 Future krill habitat projections can build upon our method in several ways. A growth model
253 validated with *in-situ* data from all seasons (not only summer) would be valuable²¹, and there is
254 potential to use a more biologically realistic carbon-based krill growth model⁵⁶. The life cycle of krill
255 is complex, with different habitats utilized at different life-history stages^{25,57,58}, and habitat quality in
256 autumn-winter is considered of key importance in determining larval survival and juvenile
257 recruitment⁵⁹⁻⁶¹. Sea ice is thought to play a crucial role^{25,57,58}, serving as an overwintering habitat
258 for larval krill^{62,63}, and supplying an important food source via sea-ice biota^{64,65}. Krill recruitment and
259 abundance have both been linked to sea-ice extent^{14,59,66}, with the latter projected to decrease
260 about 25% by 2100⁶⁷. However, while sea-ice extent is projected to decline, observational and
261 modelling studies examining other favourable ice characteristics (e.g. optimal thickness to promote
262 light for sea-ice algae⁶⁸; sea-ice ridging to provide refuge⁶³) have found that future habitat may
263 expand^{62,69}.

264 Our study provides a robust and quantitative assessment of future habitat quality, using a
265 temperature- and food-related growth model that was empirically derived for krill sampled in the
266 20-60 mm length range. This provides a habitat quality estimate of individuals already *recruited* into
267 the population. Since key knowledge gaps currently preclude a holistic quantitative assessment
268 (incorporating sea ice or multiple other drivers such as ocean acidification^{7,70-73}) there is a clear need
269 for developing our largely qualitative understanding of sea-ice impacts on recruitment into
270 quantitative relationships. Trait-based modelling^{9,74} of the complete life-cycle is one feasible
271 approach to connect impacts on early life stages with growth and population dynamics.

272 In conclusion, our findings are relevant to the conservation of a globally important
273 ecosystem and the management of the Southern Ocean's largest fishery. They provide an important
274 step in developing capacity to quantify climate change impacts on Southern Ocean ecosystems and
275 outlines pathways to address key uncertainties.

276 Tables

277 **Table 1 | Median growth potential and model projection envelope.**

278 The median of all grid-cell growth potential values from the weighted subset mean, for each season
 279 and CMIP5 scenario. The analogous medians from the weighted subset 10% and 90% quantiles are
 280 shown in parentheses to illustrate the envelope of the projections (See Appendix B in
 281 Supplementary Information for an explanation of the projection envelope, and its associated
 282 Supplementary Figures 1-3 for spatial patterning).

283

<i>growth potential (mm month⁻¹)</i>	<i>Spring</i>	<i>Summer</i>	<i>Autumn</i>	<i>Winter</i>
<i>Historical</i>	2.00 (-1.12 – 5.64)	3.87 (3.83–5.44)	1.30 (0.36 – 2.89)	-1.14 (-2.07 – 0.68)
<i>RCP 4.5</i>	2.84 (0.36 – 5.58)	3.94 (3.77– 5.19)	-0.20* (-0.42 – 1.14)	-1.02 (-1.58– 0.64)
<i>RCP 8.5</i>	2.24 (-0.40 – 5.65)	3.45 (3.35 – 5.09)	0.67 (0.16 – 2.08)	-1.35 (-2.02 – -0.43)

284

285 *One of the highest weighted models for this season was not contributed to the CMIP5 RCP 4.5
 286 scenario (Supplementary Table 2). Therefore, the median projection is not consistent with those of
 287 the other two scenarios, as the underlying weighting mechanism is vastly different.

288 Figure Legends

289 **Fig. 1 | Taylor diagram assessing individual model performance in projecting growth potential**

290 **against observation-based values for selection and weighting scheme.** Available models in the full
 291 ensemble are plotted with circles, while the weighted subset and unweighted full ensemble mean
 292 are plotted in squares. Models not pictured have negative correlation and are outside the plotting
 293 range. Statistics for the Taylor diagram were calculated from the area-weighted seasonal surface
 294 averages of growth potential. Observation-based growth potential was calculated using the average
 295 of the SeaWiFS⁷⁵ and Johnson et al.⁷⁶ chlorophyll datasets. For each season, models that fell outside

296 the red line boundary were not included in the weighting scheme. Weighting was then assigned
297 based on weighting scheme 4 (see Methods and Supplementary Table 2).

298 **Fig. 2 | Changes in future environmental drivers projected by the weighted subset for RCP**
299 **scenarios 4.5 and 8.5. a) sea surface temperature, b) chlorophyll-a.** Change is defined as the
300 projected climatology minus the historical. The black contour delineates where the projected change
301 = 0.

302 **Fig. 3 | Evaluating the performance of the weighted subset.** Mean growth potential calculated
303 using seasonal averages of (columns left to right): satellite observation datasets binned to the same
304 $1^{\circ}\times 1^{\circ}$ grid as the ESMs (chlorophyll was the mean between SeaWiFS⁷⁵ and Johnson et al.⁷⁶ datasets),
305 the weighted multi-model mean of the model subset, and the unweighted mean of the full
306 ensemble. The seasonal climatologies were averaged from 1997-2010 for observation data, and
307 from 1960-1989 (the “historical” time-period) for CMIP5 climate models. The black contour
308 delineates where SST = -1°C , below which the empirical krill growth model²¹ has not been validated
309 with *in-situ* data and therefore represents extrapolation. Black meridional lines on maps delineate
310 ocean basin sectors⁹.

311 **Fig. 4 | The projected change in krill growth potential between each RCP scenario and the**
312 **historical scenario.** The red contour delineates regions where growth potential is positive for each
313 RCP projection. Note that in summer the red contour hugs the coastline, indicating the entire
314 Southern Ocean exhibits growth in all situations. These projections represent the weighted subset
315 mean. Black meridional lines on maps delineate ocean basin sectors⁹.

316 **Fig. 5 | The projected relative gross growth potential (RGGP) in CCAMLR management areas.**
317 “Relative” refers to the ratio between each RCP scenario and the historical scenario. The dark grey
318 contour represents the location of the SACCF⁷⁷, which with the exception of South Georgia, marks
319 the northern boundary for krill distribution³⁵. The contour for the SACCF was accessed using the
320 raadtools⁷⁸ package.

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502

503 Methods

504 Circumpolar growth potential calculated from an ensemble of available CMIP5 ESMs was
505 assessed against observation-based growth potential using seasonal Taylor diagrams. This
506 assessment produced a weighted model subset with greater skill at reproducing krill growth. This
507 weighted subset was then applied to future projections for two Intergovernmental Panel on Climate
508 Change (IPCC) climate change scenarios, or representative concentration pathways (RCPs): 4.5,
509 where climate policy works to reduce emissions and radiative forcing stabilized shortly after 2100,
510 and 8.5, a “business as usual scenario” where emissions continue to rise on their current
511 trajectories⁷⁹. All analyses were performed in the R statistical computing environment⁸⁰.

512 Krill growth potential and biomass models

513 To model seasonal growth potential using ESM outputs, we built upon a previous study
514 which modelled current growth potential from satellite observations¹¹. The following empirical
515 model deriving daily growth rate (DGR, mm d⁻¹) was used²¹:

$$DGR = a + b \times Length + c \times Length^2 + \left[d \times \frac{chlorophyll}{e + chlorophyll} \right] + f \times SST \quad (1) \\ + g \times SST^2 + error$$

516 The *in-situ* data originally used to develop the empirical growth model²¹ represent only one region
517 within the circumpolar range of krill, for one season (summer, a season of high growth rates for krill)
518 and within a specific temperature range (-1— 5°C). As data on krill growth outside of these
519 conditions are sparse, it is uncertain whether we can reliably extrapolate these calculations as actual
520 growth values. A recent study¹⁹ has shown that within the same season and temperature limits, the
521 growth model produces realistic circumpolar krill growth habitat distributions. This precedent allows
522 us to reasonably assume that these relationships will hold in general. We consider daily growth rate
523 to thus more accurately represent growth potential, a measure of habitat quality that can be used
524 for comparative purposes.

525 All growth potential calculations were calculated using seasonal climatologies of SST and
526 surface chlorophyll. The empirical growth model was derived over an SST range between -1 and 5°C,
527 hence temperatures above this maximum were masked. However, after examining krill growth
528 predictions based on historical satellite observations, we concluded that limiting SST to above -1°C
529 excluded regions in the southern Ross Sea in summer, which are likely important whale foraging
530 areas for krill^{35,81}. Therefore we accepted regions with SST < -1°C, with the caveat that projections
531 for SST below this threshold have increased uncertainty. The -1°C SST contour is presented on maps
532 to identify these areas. For each cell, if SST was present and chlorophyll was absent, then chlorophyll
533 was set to 0 mg m⁻³, whereas if there was sea ice cover the cell was excluded from the calculation.

534 To calculate seasonal growth potential in mm month^{-1} , we assumed an individual krill with a
535 starting length of 40 mm, the observed mean length of adult krill³². Although previous analyses have
536 included other starting size classes^{10,11}, we found that projected differences between future and
537 historical epochs remained the same irrespective of starting length. For each day in the season, DGR
538 was calculated using the SST and chlorophyll fields, and then added to the previous length.

539 Growth potential, a metric based on length, was translated into gross growth potential
540 (GGP), a metric based on biomass. Biomass is more relevant when interpreting impacts on
541 dependant predators and the fishery, as it translates directly into the amount of energy consumed
542 by a predator or fishery yield. Since seasonal growth potential was presented as a monthly value,
543 GGP for a season is defined here as the dry mass of an individual krill at the end of a month in a
544 season divided by the beginning of the month in that season. It therefore represents the
545 proportional change in dry mass, with a value of 1 indicating that GGP remains constant. Krill length
546 (mm), derived using equation (1), was converted to dry mass (mg) using the following relationship¹⁰:

$$\log_{10}(Mass) = 3.89\log_{10}(Length) - 4.19 \quad (2)$$

547 SST and chlorophyll fields

548 Using equation 1, seasonal surface averages of growth were calculated for the observation-
549 based and model-based SST and chlorophyll fields summarized in Supplementary Table 1.

550 Seasonal surface averages of satellite observation-based datasets for SST and chlorophyll,
551 taken over the time-period of Dec 1997 to 2010 for the Southern Ocean (south of 50°S) were
552 accessed using the raadtools package⁷⁸. For SST, the OISST v2 daily dataset (1/4° horizontal
553 resolution) was used. For chlorophyll, the daily datasets (1/12° horizontal resolution) for both the
554 original SeaWiFS⁷⁵ and the Johnson et al.⁷⁶ corrected estimate of SeaWiFS were used. To calculate
555 growth potential, the OISST dataset was sampled to match the higher resolution chlorophyll
556 datasets using bilinear interpolation. Although the Johnson et al.⁷⁶ dataset is likely a more accurate

557 approximation of surface phytoplankton biomass⁷⁶, we elected to average the two chlorophyll
558 datasets when calculating observation-based growth potential to explicitly acknowledge that
559 satellite observations approximate truth with varying degrees of error (Extended Data Fig. 7). By
560 incorporating two different algorithms, the latter of which is tuned to *in-situ* chlorophyll estimates
561 taken from the Southern Ocean, we represent the variability surrounding our observation-based
562 benchmark (Extended Data Fig. 3).

563 ESMs used in this analysis included one ensemble member from most models in the CMIP5
564 archive that contributed sea surface temperature (tos in the IPCC shorthand) and chlorophyll (chl),
565 as well as NorESM1-ME, which contributed phyc (a carbon-based analogue of chl). In line with the
566 calculation used with NorESM1-ME, this was converted to chlorophyll using a constant carbon to
567 chlorophyll ratio of 60⁸² (Tjiputra, J. F., personal communication, Feb 1, 2019). Growth potential was
568 evaluated for 2 different IPCC climatologies: “historical” (1960-1989), which represents current
569 climate, and “future” (2070-2099). This latter climatology was calculated for two RCPs: RCP 4.5 and
570 RCP 8.5.

571 Weighted subset selection

572 The weighted model subset was determined by evaluating the ability of each model to
573 reproduce observation-based growth potential for current climate conditions. For models, current
574 climate was represented by averaging seasonal outputs over 1960-1989. To allow direct comparison,
575 bilinear interpolation was used to re-grid the (eleven) model-based seasonal surface averages for
576 growth potential onto the same 1°x1° grid. These models were compared to observation-based
577 growth potential, also resampled to the same grid, using a seasonally split Taylor Diagram (Fig. 1).

578 We excluded models that had a normalized standard deviation $> \pm 0.5$ of observation-based
579 growth potential, and a correlation < 0.1 . Of the models that remained GFDL-ESM2G and GFDL-
580 ESM2M (2G and 2M respectively) were contributed by the same institution. They differed only in
581 their physical ocean component, and thus were not independent⁸³. To avoid pseudoreplication there

582 were two options: remove one of the models from the analysis, or weight them each as half. The
583 Taylor diagram shows that apart from standard deviation in spring, 2M more closely approaches
584 observed standard deviation and has higher correlation to observed growth potential than 2G. Since
585 the 2G model did not perform as well as 2M in most instances the first option was chosen and 2G
586 was removed from the analysis.

587 To weight the remaining models, 5 different weighting schemes were trialled (Extended Data
588 Fig. 4):

589
$$\text{Weighting scheme 1} = \frac{1}{x}$$

590
$$\text{Weighting scheme 2} = e^{-x\left(\frac{x}{0.1^2}\right)}$$

591
$$\text{Weighting scheme 3} = e^{-x\left(\frac{x}{0.15^2}\right)}$$

592
$$\text{Weighting scheme 4} = e^{-x\left(\frac{x}{0.2^2}\right)}$$

593
$$\text{Weighting scheme 5} = e^{-x\left(\frac{x}{0.25^2}\right)}$$

594 Where x is the standard deviation of the model (mm month^{-1}) under consideration (sd_{mod}), as
595 calculated for the growth potential Taylor diagram in Fig. 1. For the purposes of comparison, if
596 $\text{sd}_{\text{mod}} > 1$, then the value was reflected about the $\text{sd} = 1$ axis by subtracting it from 2.

597 Overall, we found that regardless of the specific weighting scheme, if models with a
598 standard deviation closer to observed were given higher weight, then the results were robust
599 (Extended Data Fig. 5). The greatest variation between weighting schemes occurred in autumn,
600 which was due to observed standard deviation being represented by a small proportion of the
601 models (Fig. 1). To select a weighting scheme, we again referenced a Taylor diagram that evaluated
602 weighting scheme performance at reproducing growth potential against observations (Extended
603 Data Fig. 6). Since the greatest variation between schemes occurred in autumn, we narrowed our

604 choice to the two schemes with standard deviations closest to 1: weighting schemes 3 & 4. Of these,
605 weighting scheme 4 was selected, as weighting scheme 3 greatly overestimated growth potential in
606 the Weddell, Amundsen and eastern Ross Seas.

607 **Future projections**

608 Future projections from the weighted subset were used to calculate a weighted multi-model
609 mean of seasonal krill growth potential for the RCP scenarios 4.5 and 8.5. This was then
610 implemented using equation 2 to calculate GGP. The relative change between historical and future
611 GGP is represented in this study as RGGP.

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631 **Author Contributions**

632 The study was developed by all authors. All authors supervised D.V.in conducting the
633 analyses, figure design and preparing the manuscript, as well as provided feedback and ideas in the
634 manuscript development.

635 **Competing Interests**

636 The authors declare no competing interests.

637 **Data Availability**

638 The data that support the findings of this study are publicly available at the Australian
639 Antarctic Data Centre, DOI: 10.26179/5e27c6584e0f8⁸⁴. The CMIP5 output is available from the
640 Earth System Grid Federation (<https://esgf-node.llnl.gov/projects/cmip5/>). In addition to being
641 retrievable using the raadtools package in R
642 (<https://github.com/AustralianAntarcticDivision/raadtools>), the satellite data can also be found at
643 (<https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C00844/html>)
644 for sea surface temperature, (<https://oceancolor.gsfc.nasa.gov/data/seawifs/>) for SeaWiFS⁷⁵
645 chlorophyll-*a*, and (https://data.aad.gov.au/metadata/records/AAS_4343_so_chlorophyll) for the
646 Johnson et al.⁷⁶ chlorophyll-*a* data.

647 **Code Availability**

648 The code relating to this study is available from the corresponding author on request.

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