



**HAL**  
open science

## North Atlantic winter cyclones starve seabirds

Manon Clairbaux, Paul Mathewson, Warren Porter, Jérôme Fort, Hallvard Strøm, Børge Moe, Per Fauchald, Sebastien Descamps, Hálfán Helgason, Vegard Bråthen, et al.

► **To cite this version:**

Manon Clairbaux, Paul Mathewson, Warren Porter, Jérôme Fort, Hallvard Strøm, et al.. North Atlantic winter cyclones starve seabirds. *Current Biology - CB*, 2021, 31 (17), pp.3964-3971.e3. 10.1016/j.cub.2021.06.059 . hal-03346886

**HAL Id: hal-03346886**

**<https://hal.science/hal-03346886v1>**

Submitted on 16 Oct 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **North Atlantic winter cyclones starve seabirds**

2  
3 Manon Clairbaux<sup>1\*</sup>, Paul Mathewson<sup>2</sup>, Warren Porter<sup>2</sup>, Jérôme Fort<sup>3</sup>, Hallvard Strøm<sup>4</sup>, Børge  
4 Moe<sup>5</sup>, Per Fauchald<sup>5</sup>, Sebastien Descamps<sup>4</sup>, Hálf dán Helgason<sup>4</sup>, Vegard S. Bråthen<sup>5</sup>,  
5 Benjamin Merkel<sup>6</sup>, Tycho Anker-Nilssen<sup>5</sup>, Ingar S. Bringsvor<sup>7</sup>, Olivier Chastel<sup>8</sup>, Signe  
6 Christensen-Dalsgaard<sup>5</sup>, Jóhannis Danielsen<sup>9</sup>, Francis Daunt<sup>10</sup>, Nina Dehnhard<sup>5</sup>, Kjell Einar  
7 Erikstad<sup>5, 11</sup>, Alexey Ezhov<sup>12</sup>, Maria Gavrilov<sup>13, 14</sup>, Yuri Krasnov<sup>12</sup>, Magdalene Langset<sup>5</sup>, Svein  
8 H. Lorentsen<sup>5</sup>, Mark Newell<sup>10</sup>, Bergur Olsen<sup>9</sup>, Tone K. Reiertsen<sup>5</sup>, Geir Systad<sup>5</sup>, Thorkell L.  
9 Thórarinsson<sup>15</sup>, Mark Baran<sup>16</sup>, Tony Diamond<sup>16</sup>, Annette L. Fayet<sup>17</sup>, Michelle G  
10 Fitzsimmons<sup>18</sup>, Morten Frederiksen<sup>19</sup>, Hugh G. Gilchrist<sup>20</sup>, Tim Guilford<sup>17</sup>, Nicholas P.  
11 Huffeldt<sup>19, 21</sup>, Mark Jessopp<sup>22</sup>, Kasper L. Johansen<sup>19</sup>, Amy Lee Kouwenberg<sup>23</sup>, Jóhannis .F.  
12 Linnebjerg<sup>19</sup>, Heather L. Major<sup>24</sup>, Laura McFarlane Tranquilla<sup>23</sup>, Mark Mallory<sup>25</sup>, Flemming  
13 R. Merkel<sup>19</sup>, William Montevecchi<sup>26</sup>, Anders Mosbech<sup>19</sup>, Aevan Petersen<sup>27</sup>, David Grémillet<sup>8,</sup>  
14 <sup>28\*</sup>

15 <sup>1</sup> CEFE, Univ Montpellier, CNRS, EPHE, IRD, Univ Paul Valéry Montpellier 3, Montpellier,  
16 France

17 <sup>2</sup> Department of Integrative Biology, University of Wisconsin, Madison, WI, USA

18 <sup>3</sup> Littoral, Environnement et Sociétés (LIENSs), UMR7266 CNRS - La Rochelle Université, 2  
19 rue Olympe de Gouges, 17000 La Rochelle, France

20 <sup>4</sup> Norwegian Polar Institute, Fram Centre, P.O. Box 6606 Langnes, 9296 Tromsø, Norway

21 <sup>5</sup> Norwegian Institute for Nature Research - NINA, PO Box 5685 Torgarden, NO-7485  
22 Trondheim, Norway

23 <sup>6</sup> Akvaplan-niva AS, Fram Centre, P.O. Box 6606 Langnes, 9296 Tromsø, Norway

24 <sup>7</sup> Norwegian Ornithological Society, Sandgata 30 B, NO-7012 Trondheim, Norway

25 <sup>8</sup> Centre d'Etudes Biologiques de Chizé (CEBC), UMR 7372 CNRS/La Rochelle Univ,  
26 France

27 <sup>9</sup> Faroe Marine Research Institute, P.O. Box 3051, Nóatún 1, FO-110 Tórshavn, Faroe Islands

28 <sup>10</sup> UK Centre for Ecology & Hydrology, Bush Estate, Penicuik EH26 0QB, UK

29 <sup>11</sup> Centre for Biodiversity Dynamics, Department of Biology, Norwegian University of  
30 Science and Technology, 7491 Trondheim, Norway

31 <sup>12</sup> Murmansk Marine Biological Institute, 17 Vladimirkaya street, 183010 Murmansk, Russia

32 <sup>13</sup> Association Maritime Heritage, Saint Petersburg, Russia

33 <sup>14</sup> National Park Russian Arctic, 57 Sovetskikh Kosmonavtove Avenue, Archangelsk, Russia

34 <sup>15</sup> Northeast Iceland Nature Research Centre, Hafnarstétt 3, 640 Húsavík, Iceland

35 <sup>16</sup> Atlantic Laboratory for Avian Research, University of New Brunswick, P.O. Box 4400,  
36 Fredericton NB, Canada E3B 5A3

37 <sup>17</sup> Department of Zoology, University of Oxford, 11a Mansfield Road, Oxford OX1 3SZ, UK

38 <sup>18</sup> Wildlife Research Division, Environment and Climate Change Canada, 6 Bruce St., Mount  
39 Pearl, NL, Canada A1N 4T3

40 <sup>19</sup> Aarhus University, Dept. of Bioscience, Frederiksborgvej 399, 4000 Roskilde, Denmark

41 <sup>20</sup> National Wildlife Research Centre, Environment and Climate Change Canada, Ottawa

42 <sup>21</sup> Greenland Institute of Natural Resources, Kivioq 2, 3900 Nuuk, Greenland

43 <sup>22</sup> School of Biological, Earth and Environmental Sciences, University College Cork,  
44 Distillery Field, North Mall, Cork, Ireland

45 <sup>23</sup> Bird Studies Canada, Sackville, New Brunswick, Canada

46 <sup>24</sup> Department of Biological Sciences, University of New Brunswick, P.O. Box 5050, Saint  
47 John NB, Canada E2L 4L5

48 <sup>25</sup> Biology, Acadia University, 15 University Avenue, Wolfville, Nova Scotia, Canada, B4P  
49 2R6

50 <sup>26</sup> Psychology and Biology Departments, Memorial University of Newfoundland, St. John's,  
51 NL A1C 5S7, Canada

52 <sup>27</sup> Brautarland 2, 108 Reykjavik, Iceland

53 <sup>28</sup> Percy FitzPatrick Institute, DST/NRF Centre of Excellence, University of Cape Town,  
54 Rondebosch, South Africa

55 \* Lead contacts: clairbauxm@gmail.com or david.gremillet@cebc.cnrs.fr

## 56 **Summary**

57 Each winter the North Atlantic Ocean is the stage for numerous cyclones, the most severe  
58 ones leading to seabird mass-mortality events called 'winter wrecks' <sup>1-3</sup>. During those,  
59 thousands of emaciated seabird carcasses are washed ashore along European and North  
60 American coasts. Winter cyclones can therefore shape seabird population dynamics<sup>4,5</sup> by  
61 affecting survival rates as well as the body condition of surviving individuals and thus their  
62 future reproduction. However, most often the geographic origins of impacted seabirds and the  
63 causes of their deaths remain unclear<sup>6</sup>. We performed the first ocean-basin scale assessment  
64 of cyclone exposure in a seabird community, by coupling winter tracking data for ~1500  
65 individuals of five key North Atlantic seabird species (*Alle alle*, *Fratercula arctica*, *Uria*  
66 *aalge*, *Uria lomvia* and *Rissa tridactyla*) and cyclone locations. We then explored the  
67 energetic consequences of different cyclonic conditions using a mechanistic bioenergetics  
68 model<sup>7</sup> and tested the hypothesis that cyclones dramatically increase seabird energy  
69 requirements. We demonstrated that cyclones of high-intensity impacted birds from all  
70 studied species and breeding colonies during winter, but especially those aggregating in the

71 Labrador Sea, the Davis Strait, the surroundings of Iceland and the Barents Sea. Our broad-  
72 scale analyses suggested that cyclonic conditions do not increase seabird energy requirements,  
73 implying that they die because of the unavailability of their prey and/or their inability to feed  
74 during cyclones. Our study provides essential information on seabird cyclone exposure in a  
75 context of marked cyclone regime changes due to global warming<sup>8</sup>.

76 **Keywords:** At-sea distribution, Cyclones, Energy expenditure, GLS tracking, Seabird  
77 migration, Seascape ecology

## 78 **Results**

79 Cyclone-induced seabird mortality adds to other threats such as habitat loss, invasive  
80 species or interactions with fisheries, contributing to the general downward trend of the global  
81 seabird community<sup>9</sup> and making them one of the most threatened bird groups<sup>10</sup>. It is therefore  
82 essential to understand the causes of seabird mortality during cyclones, and to identify factors  
83 contributing to contrasting spatio-temporal mortality patterns at the seabird-community level.  
84 Multiple seabird species from different breeding colonies may inhabit different wintering  
85 areas<sup>11,12</sup>, and this may strongly affect the composition of seabird winter wrecks. In this  
86 context, community-wide analyses are lacking due to the technical difficulties of studying  
87 seabirds wintering far out at sea under harsh conditions.

### 88 *Winter cyclone exposure of the North Atlantic seabird community*

89 The North Atlantic Ocean and adjacent seas (100°W–100°E, 30°N–90°N, see Figure  
90 S1) is the stage for numerous winter cyclones (October to February) (see Figure S2), which  
91 are defined by the National Hurricane Center, as large-scale air masses that rotate around a  
92 center of low atmospheric pressure. Their locations between 2000 and 2016 were obtained  
93 from climatic reanalysis data (see STAR Methods). Using the Dvorak storm classification<sup>13</sup>  
94 we sorted them across their duration into one of the four classes of cyclone intensity defined  
95 (see STAR Methods). Calculating, for each month, the average number of cyclones of each

96 category for each 250 km grid cell, we demonstrated that a limited number of localized low  
97 intensity cyclones (Class 1 and 2) occurred mainly in the Baffin Bay, the Gulf of Maine and  
98 the Mediterranean Sea regions (see Data S1A). Class 3 cyclones were more numerous and  
99 widespread, particularly in October and November, and mainly occurred in the Baffin and  
100 Hudson bays, the Davis Strait, the Labrador Sea, east off Newfoundland, around Iceland and  
101 in the Barents Sea. Finally, Class 4 cyclones were observed in all winter months off west  
102 Iceland, the Norwegian coast and in the Barents Sea, whereas the Davis Strait and the  
103 Labrador Sea were only affected by Class 4 cyclones between December and February.

104 Winter bird locations were obtained from Global Location Sensors (GLS) deployed and  
105 retrieved during the breeding season on 1532 individuals from 39 breeding colonies across the  
106 North Atlantic Ocean (see STAR Methods and Table S1). We approximated core use areas  
107 for each colony and species during the winter months, calculating monthly utilization  
108 distributions (UD) with the BRB-MKDE software (<sup>14</sup>, see STAR Methods). To conclude on  
109 seabird cyclone exposure, we overlapped cyclone locations with core wintering areas of  
110 different seabird species and populations (see Figure 1, Data S1A-S1F), before calculating an  
111 average cyclone exposure index (see Figure 2 and STAR Methods).

112 Low intensity cyclones (Class 1 and 2) showed limited overlap with the seabird community.  
113 However, birds from all species and colonies were likely to encounter Class 3 and 4 cyclones  
114 during winter, with substantial inter-annual variability in the mean number of such events  
115 occurring within seabird core use areas (Figure 1 and Data S1B-S1F). Notably, seabirds from  
116 Canadian, Greenlandic and Icelandic colonies were exposed to Class 3 and 4 cyclones in the  
117 Davis Strait, the Labrador Sea and off Newfoundland, while Norwegian and Russian seabirds  
118 were likely impacted by those occurring in the Barents Sea. In contrast, Class 3 cyclones were  
119 fewer in the mid-west Atlantic Ocean and were more likely to spare seabirds wintering there  
120 (see Data S1A). Due to major seabird aggregation and the marked presence of Class 3 and 4

121 cyclones, areas such as the Labrador Sea, the Davis Strait, the vicinity of Iceland and the  
122 Barents Sea are predicted as sources of major winter wrecks (Figure 2).

123

#### 124 *Seabird energy requirements under cyclonic and non-cyclonic conditions*

125 Necropsies suggest that seabirds are lean after being exposed to high-intensity  
126 cyclones<sup>6,15</sup> and that the resulting mortality can be aggravated by mercury contamination<sup>16</sup>.  
127 Yet, we do not know whether they starve due to abnormally high-energy expenditure linked  
128 to harsh climatic conditions<sup>17</sup>, because of reduced foraging profitability and energy inputs, or  
129 because both these constraints synoptically affect their energy balance. Recent research has  
130 shown that seabirds wintering in the North Atlantic Ocean track environmental gradients to  
131 remain in an energetic steady state<sup>18-20</sup>, but how winter cyclones affect this delicate balance  
132 remains mysterious.

133 To test the hypothesis that cyclones dramatically increase seabird energy requirements, we  
134 modeled species-specific, monthly energy requirements for each winter between 2000 and  
135 2016 on a 1000km\*1000km area off North Newfoundland (see Figure S1), using the  
136 mechanistic model Niche Mapper<sup>TM</sup> (Porter & Mitchell, 2006, see STAR Methods) under  
137 four intensities of cyclones and under non-cyclonic conditions (see STAR Methods).  
138 Following the protocol used by Grémillet and colleagues<sup>21</sup>, we calculated how many days  
139 each of the five studied species could fast before dying, when exposed to Class 2, Class 3 and  
140 Class 4 cyclones in the studied area (see STAR Methods). Statistical analyses revealed several  
141 significant differences (Kruskal-Wallis,  $p < 0.05$ ) in seabird energy requirements (see Table 1)  
142 between the six categories of conditions tested (Class 1 to 4 cyclones, non-cyclonic conditions  
143 with usual seabird flight/diving activities, non-cyclonic conditions with cyclonic seabird  
144 flight/diving activities). In a very limited number of cases, cyclonic conditions led to  
145 increases (up to 36%) in seabird energy requirements in comparison with non-cyclonic

146 conditions with cyclonic flight/diving activities (post hoc Dunn's test,  $p < 0.05$ ). Surprisingly,  
147 we found that seabird energy requirements were generally similar or lower during cyclones,  
148 compared to non-cyclonic conditions (see Figure 3 and Data S1G-S1K). In particular, for  
149 little auks and black-legged kittiwakes, energy requirements were generally significantly  
150 lower during Class 2, 3 and 4 cyclones than during non-cyclonic conditions experienced with  
151 usual flight/diving activities (post hoc Dunn's test,  $p < 0.05$ ). Those differences were not  
152 significant for deep divers (except for Atlantic puffins in October and December under  
153 specific cyclonic conditions) (see Table 1). Further, seabird energy requirements were not  
154 significantly different during Class 1 cyclones than for non-cyclonic conditions experienced  
155 with usual flight/diving activities (post hoc Dunn's test,  $p < 0.05$ ).

156 Energy requirements under Class 2, Class 3 and Class 4 cyclones were not significantly  
157 different (see Data S1G-S1K) and these classes were therefore pooled when calculating  
158 fasting endurance. Between October and December, average fasting endurance was 2.2 days  
159 ( $\pm 0.1$ ) for little auk and 6.5 days ( $\pm 2.5$ ) for Atlantic puffins while black-legged  
160 kittiwakes, Brünnich's guillemots and common guillemots could fast 8.4 days ( $\pm 0.5$ ), 7.3  
161 days ( $\pm 0.06$ ) and 8.1 days ( $\pm 0.1$ ), respectively. With winter's advance, these durations  
162 dropped respectively to 1.6 days ( $\pm 0.1$ ), 4.6 days ( $\pm 0.6$ ), 6.4 days ( $\pm 0.5$ ), 5.9 days ( $\pm$   
163 0.6) and 6.3 days ( $\pm 0.7$ ), between January and February.

## 164 **Discussion**

165 We demonstrated that seabirds wintering in areas such as the Labrador Sea, the Davis  
166 Strait, the vicinity of Iceland and the Barents Sea, are particularly exposed to cyclones.  
167 Crucially, our broad-scale analyses led us to reject our hypothesis: climatic conditions  
168 experienced by seabirds during cyclones generally did not enhance their energy requirements.  
169 These results suggest that seabird mortality during winter high intensity cyclones is likely  
170 caused by starvation due to the unavailability of prey and/or their incapacity to feed.



171 *Mechanistic insights into storms impacts on seabirds*

172 Our surprising conclusion regarding death causes in seabirds exposed to cyclones is in  
173 agreement with a study conducted on greater flamingos (*Phoenicopterus roseus*) during cold  
174 spells in the Camargue, France<sup>22</sup>: Thousands of flamingos died, not because of hypothermia  
175 but due to inaccessible food in frozen salt pans. Conversely, our results contrast with former  
176 modeling work which pointed to weather-induced energetic bottlenecks in seabirds wintering  
177 in the North Atlantic Ocean<sup>17</sup>. Birds were predicted to experience markedly higher  
178 thermoregulatory costs in December, because of lower air and water temperatures, and higher  
179 wind speeds. Yet this previous study investigated seabird energetics at the scale of months,  
180 whereas cyclones affect them at the scale of days. In this context, little auks appear as  
181 particularly vulnerable to fasting induced by cyclones, because of low lipid reserves and high  
182 mass-specific energy expenditure, likely explaining extensive and recurrent winter wrecks on  
183 North American coasts near their main wintering grounds<sup>23,24</sup>. Other species were predicted to  
184 cope with relatively longer fasts, but remain vulnerable to prolonged cyclonic conditions  
185 especially at the end of winter. Therefore, recurrent cyclones affecting a specific area/seabird  
186 population are predicted as strong drivers of winter wrecks.

187 What exactly prevents seabirds from feeding during cyclonic conditions remains unclear. One  
188 possibility is that cyclones may enhance water turbidity, decrease underwater light intensity,  
189 and perturb prey patches and vertical migration. Potentially disrupting water stratification,  
190 cyclones may modify prey aggregation and negatively impact seabird foraging efficiency<sup>25</sup>.  
191 Therefore, this ‘washing-machine effect’ could strongly affect seabirds feeding within the 50  
192 upper meters of the water column, such as black-legged kittiwakes and little auks in our  
193 study. Further, cyclones and associated disturbances alter underwater soundscapes and thus  
194 constrain the detection of acoustic cues by seabirds, being from conspecifics, prey or  
195 predators<sup>26,27</sup>. Prey could also occur deeper in the water column during cyclones as already

196 observed for some elasmobranchs or teleosts<sup>28,29</sup>, but how this impacts pursuit-diving species  
197 such as puffins and guillemots, is not known. By continuing to dive during cyclones, deep  
198 divers such as guillemots and puffins potentially take the risk of using energy reserves in an  
199 attempt to track inaccessible prey. However, common and Brünnich's guillemots have been  
200 observed switching their diet during strong winds, from schooling fish to amphipods or  
201 smaller sandeels, potentially targeting prey that required less underwater searching<sup>30,31</sup>.  
202 Alternatively, cyclones may shift alcid away from their preferred prey patches and into  
203 unprofitable foraging habitats<sup>32</sup>. Overall, even if starvation may be the main driver of seabird  
204 winter wrecks, we cannot exclude others causes of mortality, such as drowning<sup>6</sup>, or collision  
205 with reefs and rocky coastlines (Mark Baran, personal comm) or inland stranding<sup>32</sup>.

#### 206 *Potential limitations*

207 Despite these advances, we recommend caution in interpreting our results as they are based  
208 on reanalyzed environmental data and on thermodynamic modeling. Notably, measuring  
209 empirical data is nearly impossible during cyclones. This calls for the use of modeling  
210 approaches to characterize these climatic events and their energy consequences for seabirds,  
211 but also constrains model outputs. This lack of in-situ measurements influenced  
212 NicheMapper<sup>TM</sup> simulations in two main ways. First, the behavior of pelagic seabirds is hard  
213 to assess under cyclonic conditions, and the animal module mainly relies on the assumption  
214 that North Atlantic seabirds significantly reduce flying and/or diving during cyclones. On a  
215 worldwide scale, while many seabird species exhibit avoidance behavior seeking coastal  
216 shelter and/or reducing activity levels during high-intensity cyclones<sup>33</sup>, others, such as great  
217 frigatebirds (*Fregata minor*) take advantage of cyclonic winds to save energy while gliding  
218 over thousands of kilometers<sup>34</sup>. Such extreme gliders, which occur in the tropics and Southern  
219 Ocean, are rarer in the North Atlantic, an area dominated by alcid species in terms of  
220 abundance<sup>35</sup>. This seabird family, which is morphologically adapted to using its wings for

221 underwater propulsion, has high wing-loading, and very limited capacity to ride strong winds.  
222 Thus, cyclonic conditions dramatically increase flight costs in alcids<sup>30</sup>, and therefore tend to  
223 prevent them from flying.

224 Second, since direct measurements of environmental data during cyclones were lacking at the  
225 spatio-temporal scales needed for our analyses, we depicted cyclonic conditions in the  
226 microclimate module using a limited number of reconstructed data at a broad scale,  
227 potentially missing other relevant differences between non-cyclonic and cyclonic conditions.

228 Finally, due to a lack of available information, we only modeled the effects of temperature,  
229 wind speed and reduced activity on heat loss and energy requirements during cyclones,  
230 omitting other variables such as wind gust speed, water velocity, wave height, as well as other  
231 conditions potentially affecting seabird thermoregulation and thus their energy requirements.

232 For example, localized wind gusts, sea spray and high-speed precipitation could all reduce  
233 plumage insulation, thereby increasing seabird heat loss and energy requirements. Further, tall  
234 waves could require the birds to dive more frequently, increasing energy requirements. Thus,  
235 current predictions on seabird energy requirements during cyclones should be interpreted as  
236 likely conservative estimates. However, given the current lack of information, mechanistic  
237 models remain important tools to explore potential impacts, and to generate hypotheses that  
238 could be further investigated. Additional direct measurements could help to refine these  
239 modeling approaches and evaluate initial assumptions. For example, deploying electronic  
240 devices to study North Atlantic seabird 3D movements during cyclones is a key objective for  
241 future research, which will allow testing our assumption that these animals are less active  
242 under passing cyclones. Such deployments will also help infer additional energetic costs in  
243 seabirds floating across rough seas, especially if they try to dive under each wave and/or to  
244 stay in the same area rather than drifting away with surface currents (up to 2.5 m.s<sup>-1</sup> under  
245 Class-4 cyclones<sup>36</sup>). Finally, future efforts will allow researchers to take into account inter-

246 and intra-individual morphological, physiological and behavioral variability across winter in  
247 seabird energetic modeling, improving output accuracy.

248 Despite these limitations, our study provides essential new knowledge, notably on the  
249 vulnerability of wintering seabirds to high intensity cyclones in the Labrador Sea, off  
250 Newfoundland, off southern Greenland, around Iceland, off the Norwegian coast and in the  
251 Barents Sea. These results are supported by the numerous seabird winter wrecks observed  
252 across years on beaches close to those areas<sup>2,6,23,24,37</sup> (and Flemming Ravn Merkel personal  
253 communication about Brünnich's guillemot wrecks in south Greenland). Yet, as GLS-tracking  
254 is based on individuals who survived the non-breeding period, we cannot exclude the  
255 possibility that wrecked individuals wintered in different locations with higher cyclone  
256 exposure, even though seabirds are highly gregarious, also at sea. Further, the localization and  
257 study of winter wrecks on beaches is impacted by oceanic currents carrying seabird carcasses,  
258 and by the accessibility of these beaches to observers. This potentially leads to spatio-  
259 temporal mismatches between seabird wrecks as perceived by researchers and the general  
260 public, and areas of major winter high intensity cyclone impacts on seabirds offshore. Such a  
261 mismatch may explain why we found limited overlap between seabird winter distributions  
262 and cyclones in the Eastern Atlantic, despite the fact that large winter wrecks have regularly  
263 been recorded along the shores of Western Europe.

#### 264 *Seabird storm exposure under climate change*

265 It is well-established that seabirds experience direct and indirect negative stressors from  
266 global warming<sup>38</sup>. Since the 1970s, the frequency and intensity of the strongest tropical  
267 cyclones in the North Atlantic have increased markedly<sup>39</sup>. Considering future North Atlantic  
268 cyclone regimes, there are still uncertainties but model outputs predict some common  
269 features: There will be fewer cyclones in the future, but the frequency of the strongest ones is  
270 predicted to increase with global warming<sup>39</sup>. Moreover, cyclone tracks will likely shift

271 northwards under climate change<sup>40</sup>, increasing the storminess of Western Europe<sup>41</sup> and of the  
272 high Arctic<sup>42,43</sup>. Since storm activity is positively correlated to the magnitude of seabird  
273 wrecks<sup>44,45</sup> and the North Atlantic Ocean seabird community is also predicted to shift  
274 northwards, following its prey base<sup>46</sup>, we infer that this community will become even more  
275 susceptible to mass mortality caused by winter wrecks. This might be particularly marked in  
276 areas such as the Bay of Biscay, the North Sea, the Norwegian and the Barents Seas. In this  
277 context, our study provides an essential conceptual and methodological framework to identify  
278 the vulnerability of specific populations to cyclone events at the scale of the North Atlantic  
279 Ocean.

## 280 **Acknowledgements**

281 We warmly thank the many fieldworkers involved in this study. Data collection in Norway,  
282 including Svalbard and Jan Mayen, was supported by the Norwegian seabird program  
283 SEAPOP ([www.seapop.no/en](http://www.seapop.no/en)). Thanks to the SEATRACK-program for making tracking data  
284 available for the analyzes (<http://seatrack.seapop.no/map/>). Fieldwork on little auks in  
285 Northwest Greenland was funded by the Bureau of Minerals and Petroleum, Greenland  
286 Government. The work on the Isle of May was also supported by the Natural Environment  
287 Research Council (Award NE/R016429/1 as part of the UK-SCaPE programme delivering  
288 National Capability). The New Brunswick Wildlife Trust Fund provided funding for GLS  
289 tags on Machias Seal Island. We thank the University of New Brunswick, the Federal  
290 Government of Canada, the Government of Greenland and the Danish Ministry of  
291 Environment and Food. Thanks to the Polar Continental Shelf Program of Natural Resources  
292 Canada (Grant 213-08), and core funding from Environment and Climate Change Canada.  
293 Thanks also to the French Polar Institute Paul Emile Victor for funding the ADACLIM  
294 program (IPEV program 388 to D. Grémillet et J. Fort) and the ORNITHO-ENDOCRINO  
295 program (IPEV program 330 to O. Chastel). We thank Simon Benhamou and Benjamin

296 Robira for their help with BRB-MKDE, Doris Gomez, Christine Andraud and Aurélie  
297 Tournié for their valuable help regarding feather reflectivity measurements and Katherine  
298 Brownlie for carcass measurements. We thank Kyle Elliott (McGill University, Canada) and  
299 Sarah Wanless (Center for Ecology and Hydrology, UK) for their help when assessing the  
300 seabird behavior during cyclones and Antoine Chabrolle for our discussion regarding winter  
301 wreck phenomena. This is a contribution to the Excellence Chair ECOMM funded by the  
302 Region Nouvelle Aquitaine.

### 303 **Author Contributions**

304 Conceived and designed the project: D.G., J.F, M.C. Software developers and data providers:  
305 W.P, P.M, J.F, H.S, B.M, P.F, S.D, H.H, V.S.B, B.M, T.A-N, I.S.B, O.C, S.C-D, J.D, F.D,  
306 N.D, K.E.E, A.E, M.G, Y.K, M.L, S.H.L, M.N, B.O, T.K.R, G.S, T.L.T, M.B, T.D, A.L.F,  
307 M.G.F, M.F, H.G.G, T.G, N.P.H, M.J, K.L.J, A.L.K, J.F.L, L.MT, M.M, F.R.M, W.M, A.M,  
308 A.P, D.G. Analyzed the data: M.C. Wrote the paper: M.C., D.G. All authors reviewed the  
309 manuscript.

### 310 **Declaration of interests**

311 The authors declare no competing interests.

### 312 **Figures**

**Figure 1: Average number of cyclones within the core use areas of common guillemot from different colonies between 2000 and 2016 in October.** Colonies abbreviations: Bjørnøya (BJ), Cape Gorodetskiy (CG), Faroe Islands (FI), Grimsey (GR), Hjelmsøya (HJ), Hornøya (HO), Jan Mayen (JM), Langanes and Skjalfandi (LaS), Latrabjarg (LA), Sklinna (SK). Error bars correspond to standard deviations capturing the variation between years. Results for other species, colonies and months are provided in Data S1B-S1F.

**Figure 2: Mean cyclone exposure index across the North Atlantic Ocean during winter.** See STAR Methods for details on index calculation.

313

**Figure 3: Average energy requirements for little auks (A) and Atlantic puffins (B) in the studied area off Newfoundland for each wintering month under cyclonic and non-cyclonic conditions between 2000 and 2016.** Error bars were halved for clarity reasons and correspond to standard deviations capturing between-year variation. Results for other species are presented in Data S1G-Data S1K.

314 **Tables**

315 **Table 1: Results of Kruskal-Wallis tests.** Comparisons were made between mean energy  
 316 requirements per conditions tested (Class 1 to 4 cyclones, non-cyclonic conditions with usual seabird  
 317 flight/diving activities, non-cyclonic conditions with cyclonic seabird flight/diving activities), for each  
 318 species and each month. Statistical significant results ( $p < 0.05$ ) are indicated in bold.  $\chi^2$ , Chi square;  
 319 df., degrees of freedom; p, p.value. Outputs of the corresponding Dunn post hoc test are presented in  
 320 Data S1G-S1K.

	Little auks			Black-legged kittiwakes			Atlantic puffins			Common guillemots			Brünnich's guillemots		
	$\chi^2$	df	p	$\chi^2$	df	p	$\chi^2$	df	p	$\chi^2$	df	p	$\chi^2$	df	p
October	48.6	5	<b>&lt;0.0001</b>	50.4	5	<b>&lt;0.0001</b>	12.5	5	<b>0.029</b>	21.2	5	<b>&lt;0.0001</b>	6.98	5	0.223
November	48.8	5	<b>&lt;0.0001</b>	44.5	5	<b>&lt;0.0001</b>	10.1	5	0.072	8.70	5	0.122	9.98	5	0.076
December	38.6	5	<b>&lt;0.0001</b>	36.9	5	<b>&lt;0.0001</b>	26.7	5	<b>&lt;0.0001</b>	7.28	5	0.201	10.16	5	0.071
January	26.1	5	<b>&lt;0.0001</b>	25.8	5	<b>&lt;0.0001</b>	12.9	5	<b>0.024</b>	12.2	5	<b>0.032</b>	14.4	5	<b>0.013</b>
February	14.0	5	<b>0.016</b>	11.5	5	0.042	17.9	5	<b>0.003</b>	9.99	5	0.076	10.8	5	0.055

321

322 **STAR Methods**

323 ***Resources Availability***

324 *Lead contact*

325 Further information and requests for resources and reagents should be directed to and will be  
 326 fulfilled by the lead contact, Manon Clairbaux (clairbauxm@gmail.com).

327 *Materials availability*

328 This study did not generate new unique reagents.

329 *Data and code availability*

- 330 • Environmental variables, bird and cyclone location are publicly available online.  
 331 Physiological, behavioral and morphological characteristic of the species studied are  
 332 available in the Table S2.

- 333 • All original code has been deposited at (<http://dx.doi.org/10.17632/rzszt9fpt4.1>) and is  
334 publicly available as of the date of publication. DOIs are listed in the key resources  
335 table.
- 336 • Any additional information required to reanalyze the data reported in this paper is  
337 available from the lead contact upon request.

### 338 ***Experimental Model and Subject details***

339 We focused on the winter distribution of five seabird species (little auk (*Alle alle*),  
340 Atlantic puffin (*Fratercula arctica*), common guillemot (*Uria aalge*), Brünnich’s guillemot  
341 (*Uria lomvia*) and black-legged kittiwake (*Rissa tridactyla*)). These species, which account  
342 for ca. 75% of the total number of seabirds breeding along the North Atlantic Ocean<sup>35</sup> are also  
343 among the most severely hit by winter high-intensity cyclones<sup>2,3</sup>. Bird locations were obtained  
344 from Global Location Sensors (GLS) deployed and retrieved during the breeding season for  
345 1532 individuals from 39 breeding colonies across the North Atlantic Ocean (see Figure S1  
346 and Table S1). Birds were caught at the nest according to ethical approval from each  
347 country’s appropriate organization.

### 348 ***Method details***

#### 349 *Locations and characteristics of North Atlantic cyclones during winter*

350 According to the National Hurricane Center, cyclones are defined as large-scale air  
351 masses that rotate around a center of low atmospheric pressure. Their locations were obtained  
352 from the ‘Northern Hemisphere Cyclone Locations and Characteristics from NCEP/NCAR  
353 Reanalysis Data, Version 1’ online dataset<sup>47</sup>. Locations were calculated using the updated  
354 Serreze (1997)<sup>48</sup> algorithm on daily Sea Level Pressure from the National Center for  
355 Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR)  
356 Reanalysis data set in a 250 km grid. We focused on winter cyclones (October to February) in  
357 the North Atlantic and adjacent seas (100°W–100°E, 30°N–90°N) between 2000 and 2016.



358 Using the Dvorak storm classification<sup>13</sup> on the cyclone central pressure we defined four  
359 classes of cyclone intensity (> 1009 hPa = Class 1; 1005-1009 hPa = Class 2; 987-1005 hPa =  
360 Class 3; < 987 hPa = Class 4) and classified each cyclone in the studied area across its  
361 duration. Finally, for each month, we calculated the average number of cyclones of each  
362 category that occurred between 2000 and 2016 for each 250 km grid cell.

### 363 *Winter distribution of seabirds*

364 Two locations per day were obtained through the recorded light levels by Global  
365 Location Sensors for each individual with an accuracy of +/- 200 km<sup>49,50</sup>. We focused on  
366 locations acquired during the winter period (October to February) and removed locations  
367 obtained during the two weeks on either side of the equinoxes<sup>49</sup> as well as spurious locations  
368 and those falling on land. For each species, we then calculated monthly utilization  
369 distributions (UD) for each individual using the BRB-MKDE software (<sup>14</sup>, March 2018  
370 version for location in decimal degrees with hmin=250 km) before averaging by seabird  
371 colony and species. To avoid that some individuals drive the UD of the colony, we performed  
372 a kernel stability analysis and for each month, we only considered individuals which had a  
373 sufficiently large number of locations to satisfy this stability criteria. To perform this stability  
374 analysis we calculated for each individual and for each month (n/4) UD, with n the total  
375 number of locations (after quality and equinoxes checks) for the individual and month  
376 considered: the first UD was calculated with 4 locations, the second 8, the third one 12, etc.  
377 until the total number of locations was included. Then, for each individual and for each  
378 month, we calculated the percentage of overlap between each UD and the UD obtained  
379 considering all the locations. Finally, for each species, we plot for each month the individual  
380 percentage of overlap against the number of locations included in the UD calculation and we  
381 visually determined the minimum number of locations needed to reach a high overlap  
382 percentage for the maximum of individuals. This threshold was set at 30 locations for little

383 auks and black-legged kittiwakes and was set at 20 locations for Atlantic puffins, common  
384 and Brunnich's guillemots. Therefore individuals having less locations than the number  
385 needed wasn't considered when averaging UD by colony and species.

386 We then used 25% utilization kernels to approximate areas of core use for each colony and  
387 species during the winter months (see Data S1A). For each month, we calculated the average  
388 number of cyclones of each category that occurred between 2000 and 2016 within each  
389 colony core use areas (Figure 1 and Data S1B-S1F). Finally, we interpolated each colony's  
390 UD on a 250 km grid before calculating, for each pixel, the following cyclone exposure index  
391 (CEI) for each wintering month:

$$392 \quad CEI(i,j) = NC(i,j) \times UDT(i,j)$$

393 where  $NC(i,j)$  is the average number of cyclones between 2000 and 2016 within the pixel  $i$  for  
394 the month  $j$  and  $UDT(i,j)$  is the sum, all species considered, of average UD of each colony for  
395 the pixel  $i$  and the month  $j$ . The monthly cyclone exposure indexes were then averaged to  
396 obtain a unique index for the wintering period (see Figure 2).

### 397 *Modeling seabird energy requirements under non-cyclonic and cyclonic conditions*

398 We used the mechanistic model Niche Mapper<sup>TM</sup> 7 to calculate energy requirements  
399 for each species under cyclonic and non-cyclonic conditions for each wintering month. Niche  
400 Mapper<sup>TM</sup> is based on a microclimate model and an animal module: the microclimate model  
401 calculates hourly environmental conditions for the near surroundings of the bird and the  
402 animal module uses the resulting outputs together with bird morphological, behavioral and  
403 physiological properties to estimate the metabolic rate needed by the bird to maintain its body  
404 temperature at a given time with a specific behavioral time budget. We focused on a 1000 km  
405 x 1000 km area off North Newfoundland (see Figure S1) where the five seabird species  
406 aggregate during winter. This area experienced numerous cyclones during the winter months  
407 between 2000 and 2016 (see Figure S3). For each of them, we extracted environmental

408 characteristics (sea surface temperature, air temperature and relative humidity), before  
409 averaging the values obtained by intensity class for each winter month (see Figure S4) to  
410 parameterize the microclimate module of Niche Mapper<sup>TM</sup>. For each cyclone, we extracted  
411 corresponding sea surface temperatures using the NOAA High Resolution SST dataset  
412 provided by the NOAA/OAR/ESRL PSL  
413 (<https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html#detail>)<sup>51</sup>. The  
414 corresponding air temperature and relative humidity were extracted from the NCEP/NCAR  
415 Reanalysis dataset previously used to define cyclone locations (see above). We set the wind  
416 speed of each cyclone according to its intensity (5-13 m.s<sup>-1</sup> = Class 1; 13.1-17 m.s<sup>-1</sup>= Class 2;  
417 17.1-32.5 m.s<sup>-1</sup> = Class 3; > 32.6 m.s<sup>-1</sup> = Class 4) using the Dvorak classification<sup>13</sup>. We then  
418 averaged the values obtained by intensity class to calculate mean environmental characteristic  
419 of each class for each winter month between 2000 and 2016. Finally, for each year, non-  
420 cyclonic conditions were defined by calculating the daily mean characteristics of each month  
421 using the same environmental dataset after excluding cyclone days. Wind speeds were  
422 obtained from the NCEP/NCAR Reanalysis data set. All environmental data used were  
423 interpolated in a 250 km grid. Mean environmental conditions encountered during cyclonic  
424 and non-cyclonic events are presented in Figure S4.

425 Once we had parameterized the microclimate model of Niche Mapper<sup>TM</sup>, we parameterized its  
426 animal module to obtain seabird daily energy requirements. As this module had already been  
427 parameterized to model energy expenditure in little auks, Brünnich's guillemots and common  
428 guillemots<sup>17,52</sup>, we re-used most Niche Mapper<sup>TM</sup> input values. Missing values and values  
429 required to parameterize Niche Mapper<sup>TM</sup> for black-legged kittiwakes and Atlantic puffins,  
430 were sourced from the literature (see Table S2) and obtained through dedicated  
431 measurements. Specifically, we set the proportion of time spent flying per day during winter  
432 under non-cyclonic conditions to 9%, 11.8%, 5.7% and 4.5% for little auks, black-legged

433 kittiwakes, Atlantic puffins and guillemots, respectively<sup>17,53–55</sup>. Further, under those  
434 conditions, we considered that those species spent respectively, 24%, 18.8%, 16.9% and 16%  
435 of the day diving during winter<sup>17,52,53,56</sup>. Feather reflectivity was measured with a double beam  
436 spectrophotometer (CARY 5000 UV-VIS-NIR, Agilent, USA) with a deuterium-tungsten-  
437 mercury light source. We used an integrative sphere to measure spectral and diffuse  
438 reflectance with a 1 nm resolution across all wavelengths between 300 and 2500 nm. This  
439 range covers approximately 98% of the solar spectrum that reaches the Earth's surface.  
440 Reflectance spectra relative to a Spectralon white standard were then computed with the Cary  
441 WinUV software. For each species, measurements were made on one ventral and dorsal patch  
442 for six individuals. We then calculated the reflectivity of each sample following the methods  
443 of Medina et al.<sup>57</sup>. For each species, the results were averaged across patches. Other  
444 morphological properties such as body dimensions were measured on adult bird carcasses of  
445 five Atlantic puffins and four black-legged kittiwakes collected on Ré Island (France) during  
446 February 2014. All Niche Mapper input data are available in Table S2.

447 There is limited information about the behavior of seabirds under cyclonic conditions. Yet,  
448 we benefited from personal field observations performed by a wide range of North Atlantic  
449 seabird experts (e.g., most authors of this publication, as well as Dr. Kyle Elliott and Prof  
450 Sarah Wanless, see Table S3). Those led us to assume that the seabird species considered in  
451 our study react to winter cyclones by reducing their flight activity to zero when wind speeds  
452 exceed 15 m.s<sup>-1</sup> (corresponding to cyclones of Class 2, 3 and 4). In surface-feeding black-  
453 legged kittiwakes, we also assumed that conditions experienced, when wind speeds exceed  
454 this threshold, precluded them from diving and feeding. Further, for little auks diving in the  
455 upper 30 m of the water column<sup>58</sup>, we assumed that birds are also severely impacted by those  
456 cyclonic conditions, as the water here is too perturbed for them to dive and prey on  
457 zooplankton. In contrast, deeper diving species such as puffins and guillemots, which can dive

458 down to 75 and 250 m, respectively<sup>59,60</sup>, may still manage to feed<sup>31</sup>. Therefore, seabirds were  
459 modeled as resting at the surface of water when they did not fly and/or dive. Moreover, flight  
460 and diving activities were assumed to remain unchanged under cyclone of Class 1 (for which  
461 wind speeds are below 13 m.s<sup>-1</sup>, see above).

462 Using climatic, morphological and behavioral information as stated above, we modeled  
463 species-specific, monthly energy requirements for each winter between 2000 and 2016, under  
464 four intensities of cyclones and under non-cyclonic conditions. To disentangle the effects of  
465 changes in behavior (decreased flight/diving activities) and of weather conditions on bird  
466 energy requirements during cyclones, we also calculated those requirements for each species  
467 under non-cyclonic conditions, setting behavioral parameters as those displayed during a  
468 cyclone with wind speed > 15 m.s<sup>-1</sup>.

#### 469 *Estimation of fasting endurance*

470 Fasting endurance was calculated for each species under Class 2, Class 3 and Class 4 cyclonic  
471 conditions in the studied area off Newfoundland for each winter months using the method  
472 described in<sup>21</sup>. In this particular context, we assumed that none of the species could feed  
473 under cyclonic conditions even if deep divers continued diving. The energy requirement to be  
474 supplied was calculated previously using Niche Mapper<sup>TM</sup> (see above). The amount of energy  
475 available was calculated as the masses of lipids and proteins that could be metabolized during  
476 a prolonged fast (95% and 25%, respectively<sup>61</sup>), converted into energy (caloric equivalents  
477 39.3 and 18.0·kJ·g<sup>-1</sup>, respectively<sup>62</sup>). The body fat and protein contents of each species are  
478 indicated in Table S2. Integrating daily body component losses through an iterative  
479 procedure, we calculated the maximal duration of fasting that lipid and protein reserves could  
480 sustain before one of them was used up. We assumed that lipids and proteins accounted for 75  
481 and 25% of the energy expenditure until 3/4 of lipid reserves were used. They then accounted  
482 for 63 and 37%, respectively<sup>61,63</sup>.

483 ***Quantification and Statistical Analysis***

484 Monthly mean energy requirements per condition tested (Class 1 to 4 cyclones, non-cyclonic  
485 conditions with usual seabird flight/diving activities, non-cyclonic conditions with cyclonic  
486 seabird flight/diving activities) were compared for each species using a Kruskal-Wallis test  
487 (Table 1). When this test was significant ( $p < 0.05$ ), a posthoc Dunn's test was conducted ( $p$   
488 values adjusted with the Benjamini-Hochberg method) to conclude on the difference between  
489 energy requirements experienced under cyclonic and non-cyclonic conditions (Data S1G-  
490 S1K).

491 **Excel file**

492 **References**

- 493
- 494 1. Anker-Nilssen, T., Harris, M.P., Kleven, O., and Langset, M. (2017). Status, origin,  
495 and population level impacts of Atlantic Puffins killed in a mass mortality event in  
496 southwest Norway early 2016. *Seabird* 30, 1–14.
  - 497 2. Camphuysen, C.J., Wright, P.J., Leopold, M., Hüppop, O., and Reid, J.B. (1999). A  
498 review of the causes, and consequences at the population level, of mass mortality of  
499 seabirds. *ICES Coop. Res. Rep.* 232, 51–56.
  - 500 3. Farque, P.-A. (2014). Échouage massif d'oiseaux marins durant l'hiver 2014 sur la  
501 façade atlantique.
  - 502 4. Frederiksen, M., Daunt, F., Harris, M.P., and Wanless, S. (2008). The demographic  
503 impact of extreme events: stochastic weather drives survival and population dynamics  
504 in a long-lived seabird. *J. Anim. Ecol.* 77, 1020–1029.
  - 505 5. Guéry, L., Descamps, S., Hodges, K.I., Pradel, R., Moe, B., Hanssen, S.A., Erikstad,  
506 K.E., Gabrielsen, G.W., Gilchrist, H.G., Jenouvrier, S., et al. (2019). Winter  
507 extratropical cyclone influence on seabird survival: variation between and within  
508 common eider *Somateria mollissima* populations. *Mar. Ecol. Prog. Ser.* 627, 155–170.
  - 509 6. Morley, T.I., Fayet, A.L., Jessop, H., Veron, P., Veron, M., Clark, J., and Wood, M.J.  
510 (2016). The seabird wreck in the Bay of Biscay and Southwest Approaches in 2014: A  
511 review of reported mortality.
  - 512 7. Porter, W.P., and Mitchell, J.W. (2006). Method and system for calculating the spatial-  
513 temporal effects of climate and other environmental conditions on animals.
  - 514 8. Christensen, J.H., Kanikicharla, K.K., Aldrian, E., An, S. II, Albuquerque Cavalcanti,

- 515 I.F., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., et al. (2013).  
516 Climate phenomena and their relevance for future regional climate change.
- 517 9. Grémillet, D., Ponchon, A., Paleczny, M., Palomares, M.-L.D., Karpouzi, V., and  
518 Pauly, D. (2018). Persisting worldwide seabird-fishery competition despite seabird  
519 community decline. *Curr. Biol.* 28, 1–5.
- 520 10. Dias, M.P., Martin, R., Pearmain, E.J., Burfield, I.J., Small, C., Phillips, R.A., Yates,  
521 O., Lascelles, B., Borboroglu, P.G., and Croxall, J.P. (2019). Threats to seabirds: A  
522 global assessment. *Biol. Conserv.* 237, 525–537.
- 523 11. Frederiksen, M., Descamps, S., Erikstad, K.E., Gaston, A.J., Gilchrist, H.G., Grémillet,  
524 D., Johansen, K.L., Kolbeinsson, Y., Linnebjerg, J.F., Mallory, M.L., et al. (2016).  
525 Migration and wintering of a declining seabird, the thick-billed murre *Uria lomvia*, on  
526 an ocean basin scale: Conservation implications. *Biol. Conserv.* 200, 26–35.
- 527 12. Fayet, A.L., Freeman, R., Anker-Nilssen, T., Diamond, A., Erikstad, K.E., Fifield, D.,  
528 Fitzsimmons, M.G., Hansen, E.S., Harris, M.P., Jessopp, M., et al. (2017). Ocean-wide  
529 drivers of migration strategies and their influence on population breeding performance  
530 in a declining seabird. *Curr. Biol.* 27, 3871–3878.
- 531 13. Dvorak, V. (1984). Tropical cyclone intensity analysis using satellite data. NOAA  
532 Tech Rep. NESDIS 11, 47.
- 533 14. Benhamou, S. (2011). Dynamic approach to space and habitat use based on biased  
534 random bridges. *PLoS One* 6.
- 535 15. Jones, P.H., Barrett, C.F., Mudge, G.P., and Harris, M.P. (1984). Physical condition of  
536 auks beached in eastern Britain during the wreck of February 1983. *Bird Study* 31, 95–  
537 98.
- 538 16. Fort, J., Lacoue-Labarthe, T., Nguyen, H.L., Boué, A., Spitz, J., and Bustamante, P.  
539 (2015). Mercury in wintering seabirds, an aggravating factor to winter wrecks? *Sci.*  
540 *Total Environ.* 527–528, 448–454.
- 541 17. Fort, J., Porter, W.P., and Grémillet, D. (2009). Thermodynamic modelling predicts  
542 energetic bottleneck for seabirds wintering in the northwest Atlantic. *J. Exp. Biol.* 212,  
543 2483–2490.
- 544 18. Amélineau, F., Fort, J., Mathewson, P.D., Speirs, D.C., Courbin, N., Perret, S., Porter,  
545 W.P., Wilson, R.J., and Grémillet, D. (2018). Energyscapes and prey fields shape a  
546 North Atlantic seabird wintering hotspot under climate change. *R. Soc. Open Sci.*  
547 5:171883.
- 548 19. Fort, J., Beaugrand, G., Grémillet, D., and Phillips, R.A. (2012). Biologging, remotely-  
549 sensed oceanography and the continuous plankton recorder reveal the environmental  
550 determinants of a seabird wintering hotspot. *PLoS One* 7.
- 551 20. Clairbaux, M., Cheung, W., Mathewson, P., Porter, W., Courbin, N., Fort, J., Strøm,

- 552 H., Moe, B., Fauchald, P., Descamps, S., et al. (2021). Meeting Paris agreement  
553 objectives will temper seabird winter distribution shifts in the North Atlantic Ocean.  
554 *Glob. Chang. Biol.*, 1–13.
- 555 21. Grémillet, D., Kuntz, G., Gilbert, C., Woakes, A.J., Butler, P.J., and Maho, Y. I.  
556 (2005). Cormorants dive through the Polar night. *Biol. Lett.* *1*, 469–471.
- 557
- 558
- 559 22. Deville, A.-S., Labaude, S., Robin, J.-P., Bechet, A., Gauthier-Clerc, M., Porter, W.,  
560 Fitzpatrick, M., Mathewson, P., and Grémillet, D. (2014). Impacts of extreme climatic  
561 events on the energetics of long-lived vertebrates: the case of the greater flamingo  
562 facing cold spells in the Camargue. *J. Exp. Biol.* *217*, 3700–3707.
- 563 23. Stenhouse, I.J., and Montevecchi, W.A. (1996). Winter distribution and wrecks of little  
564 auks (dovekies) *Alle a. alle* in the Northwest Atlantic. *Sula* *10*, 219–228.
- 565 24. Lucas, Z., Horn, A., and Freedman, B. (2012). Beached bird surveys on Sable Island,  
566 Nova Scotia, 1993 to 2009, show a decline in the incidence of oiling. *Proc. Nov.*  
567 *Scotian Inst. Sci.* *47*, 91–129.
- 568 25. Meyer, X., MacIntosh, A.J.J., Chiaradia, A., Kato, A., Ramírez, F., Sueur, C., and  
569 Ropert-Coudert, Y. (2020). Oceanic thermal structure mediates dive sequences in a  
570 foraging seabird. *Ecol. Evol.* *10*, 6610–6622.
- 571 26. Hansen, K.A., Maxwell, A., Siebert, U., Larsen, O.N., and Wahlberg, M. (2017). Great  
572 cormorants (*Phalacrocorax carbo*) can detect auditory cues while diving. *Sci. Nat.*  
573 *104*, 45.
- 574 27. Thiebault, A., Charrier, I., Aubin, T., Green, D.B., and Pistorius, P.A. (2019). First  
575 evidence of underwater vocalisations in hunting penguins. *PeerJ* *2019*, 1–16.
- 576 28. Udyawer, V., Chin, A., Knip, D.M., Simpfendorfer, C.A., and Heupel, M.R. (2013).  
577 Variable response of coastal sharks to severe tropical storms : environmental cues and  
578 changes in space use. *Mar. Ecol. Prog. Ser.* *480*, 171–183.
- 579 29. Patterson, W.F.I., Watterson, C.J., Shipp, R.L., and Cowan, J.H.J. (2001). Movement  
580 of tagged red snapper in the Northern Gulf of Mexico. *Trans. Am. Fish. Soc.* *130*, 533–  
581 545.
- 582 30. Elliott, K.H., Chivers, L.S., Bessey, L., Gaston, A.J., Hatch, S.A., Kato, A., Osborne,  
583 O., Ropert-Coudert, Y., Speakman, J.R., and Hare, J.F. (2014). Windscape shape  
584 seabird instantaneous energy costs but adult behavior buffers impact on offspring.  
585 *Mov. Ecol.* *2*, 17.
- 586 31. Finney, S.K., Wanless, S., and Harris, M.P. (1999). The effect of weather conditions on  
587 the feeding behaviour of a diving bird, the common guillemot *Uria aalge*. *J. Avian*



- 588 Biol. 30, 23–30.
- 589 32. Wiley, J.W., and Wunderle, J.M. (1993). The effects of hurricanes on birds, with  
590 special reference to Caribbean islands. *Bird Conserv. Int.* 3, 319–349.
- 591 33. Wilkinson, B.P., Satgé, Y.G., Lamb, J.S., and Jodice, P.G.R. (2019). Tropical cyclones  
592 alter short-term activity patterns of a coastal seabird. *Mov. Ecol.* 7, 1–11.
- 593 34. Weimerskirch, H., Bishop, C., Jeanniard-du-Dot, T., Prudor, A., and Sachs, G. (2016).  
594 Frigate birds track atmospheric conditions over months-long transoceanic flights.  
595 *Science (80-. )*. 353, 74–78.
- 596 35. Barrett, R.T., Chapdelaine, G., Anker-Nilssen, T., Mosbech, A., Montevecchi, W.A.,  
597 Reid, J.B., and Veit, R.R. (2006). Seabird numbers and prey consumption in the North  
598 Atlantic. *ICES J. Mar. Sci.* 63, 1145–1158.
- 599 36. Chang, Y.C., Chu, P.C., Centurioni, L.R., and Tseng, R.S. (2014). Observed near-  
600 surface currents under four super typhoons. *J. Mar. Syst.* 139, 311–319.
- 601 37. McFarlane Tranquilla, L., Hedd, A., Burke, C., Montevecchi, W.A., Regular, P.M.,  
602 Robertson, G.J., Stapleton, L.A., Wilhelm, S.I., Fifield, D.A., and Buren, A.D. (2010).  
603 High Arctic sea ice conditions influence marine birds wintering in Low Arctic regions.  
604 *Estuar. Coast. Shelf Sci.* 89, 97–106.
- 605 38. Sydeman, W., Poloczanska, E., Reed, T., and Thompson, S.A. (2015). Climate change  
606 and marine vertebrates. *Science (80-. )*. 350, 171–193.
- 607 39. IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working*  
608 *Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on*  
609 *Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)].*
- 610 40. Tamarin-Brodsky, T., and Kaspi, Y. (2017). Enhanced poleward propagation of storms  
611 under climate change. *Nat. Geosci.* 10, 908–913.
- 612 41. Wolf, J., Woolf, D., and Bricheno, L. (2020). Impacts of climate change on storms and  
613 waves relevant to the coastal and marine environment around the UK. *MCCIP Sci.*  
614 *Rev.*, 132–157.
- 615 42. Akperov, M., Rinke, A., Mokhov, I.I., Semenov, V.A., Parfenova, M.R., Matthes, H.,  
616 Adakudlu, M., Boberg, F., Christensen, J.H., Dembitskaya, M.A., et al. (2019). Future  
617 projections of cyclone activity in the Arctic for the 21st century from regional climate  
618 models (Arctic-CORDEX). *Glob. Planet. Change* 182.
- 619 43. Benestad, R.E., Parding, K.M., Isaksen, K., and Mezghani, A. (2016). Climate change  
620 and projections for the Barents region: What is expected to change and what will stay  
621 the same? *Environ. Res. Lett.* 11.
- 622 44. Tavares, D.C., De Moura, J.F., and Siciliano, S. (2016). Environmental predictors of  
623 seabird wrecks in a tropical coastal area. *PLoS One* 11, 1–20.

- 624 45. Tavares, D.C., Moura, J.F., Merico, A., and Siciliano, S. (2020). Mortality of seabirds  
625 migrating across the tropical Atlantic in relation to oceanographic processes. *Anim.*  
626 *Conserv.* *23*, 307–319.
- 627 46. Beaugrand, G., Conversi, A., Atkinson, A., Cloern, J., Chiba, S., Fonda-Umani, S.,  
628 Kirby, R.R., Greene, C.H., Goberville, E., Otto, S.A., et al. (2019). Prediction of  
629 unprecedented biological shifts in the global ocean. *Nat. Clim. Chang.* *9*, 237–243.
- 630 47. Serreze, M. (2009). Northern Hemisphere Cyclone Locations and Characteristics from  
631 NCEP/NCAR Reanalysis Data, Version 1.
- 632 48. Serreze, M.C., Carse, F., Barry, R.G., and Rogers, J.C. (1997). Icelandic low cyclone  
633 activity: Climatological features, linkages with the NAO, and relationships with recent  
634 changes in the Northern hemisphere circulation. *J. Clim.* *10*, 453–464.
- 635 49. Lisovski, S., Hewson, C.M., Klaassen, R.H.G., Korner-Nievergelt, F., Kristensen,  
636 M.W., and Hahn, S. (2012). Geolocation by light: Accuracy and precision affected by  
637 environmental factors. *Methods Ecol. Evol.* *3*, 603–612.
- 638 50. Phillips, R.A., Silk, J.R.D., Croxall, J.P., Afanasyev, V., and Briggs, D.R. (2004).  
639 Accuracy of geolocation estimates for flying seabirds. *Mar. Ecol. Prog. Ser.* *266*, 265–  
640 272.
- 641 51. Reynolds, R.W., Smith, T.M., Liu, C., Chelton, D.B., Casey, K.S., and Schlax, M.G.  
642 (2007). Daily high-resolution-blended analyses for sea surface temperature. *J. Clim.*  
643 *20*, 5473–5496.
- 644 52. Fort, J., Steen, H., Strøm, H., Tremblay, Y., Grønningsæter, E., Pettex, E., Porter,  
645 W.P., and Grémillet, D. (2013). Energetic consequences of contrasting winter  
646 migratory strategies in a sympatric Arctic seabird duet. *J. Avian Biol.* *44*, 255–262.
- 647 53. McKnight, A., Irons, D.B., Allyn, A.J., Sullivan, K.M., and Suryan, R.M. (2011).  
648 Winter dispersal and activity patterns of postbreeding black-legged kittiwakes *Rissa*  
649 *tridactyla* from Prince William Sound, Alaska. *Mar. Ecol. Prog. Ser.* *442*, 241–253.
- 650 54. Shoji, A., Elliott, K., Fayet, A., Boyle, D., Perrins, C., and Guilford, T. (2015).  
651 Foraging behaviour of sympatric razorbills and puffins. *Mar. Ecol. Prog. Ser.* *520*,  
652 257–267.
- 653 55. Burke, C.M., and Montevecchi, W.A. (2018). Taking the bite out of winter : Common  
654 murres (*Uria aalge*) push their dive limits to surmount energy constraints. *Front. Mar.*  
655 *Sci.* *5*, 1–13.
- 656 56. Dunn, R.E., Wanless, S., Green, J.A., Harris, M.P., and Daunt, F. (2019). Effects of  
657 body size, sex, parental care and moult strategies on auk diving behaviour outside the  
658 breeding season. *J. Avian Biol.*
- 659 57. Medina, I., Newton, E., Kearney, M.R., Mulder, R.A., Porter, W.P., and Stuart-Fox, D.  
660 (2018). Reflection of near-infrared light confers thermal protection in birds. *Nat.*

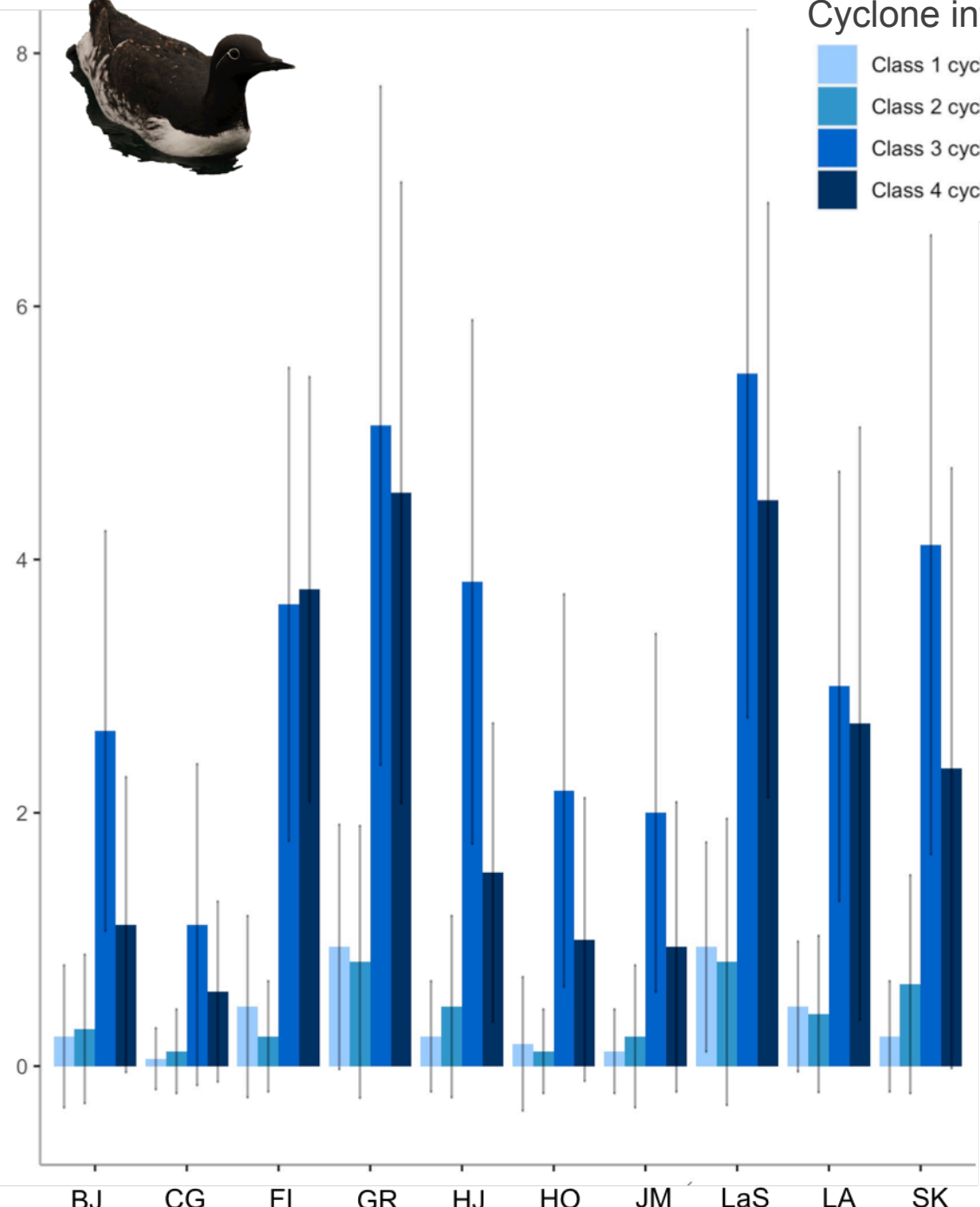
- 661 Commun. 9:3610, 1–7.
- 662 58. Amélineau, F., Grémillet, D., Bonnet, D., Bot, T. Le, and Fort, J. (2016). Where to  
663 forage in the absence of sea ice? Bathymetry as a key factor for an arctic seabird. PLoS  
664 One 11, 1–19.
- 665 59. Burger, A., and Simpson, M. (1986). Diving depths of Atlantic puffins and common  
666 murre. Auk 103, 828–830.
- 667
- 668 60. Chimienti, M., Cornulier, T., Owen, E., Bolton, M., Davies, I.M., Travis, J.M.J., and  
669 Scott, B.E. (2017). Taking movement data to new depths: Inferring prey availability  
670 and patch profitability from seabird foraging behavior. Ecol. Evol. 7, 10252–10265.
- 671 61. Belkhou, R., Cherel, Y., Heitz, A., Robin, J.-P., and Le Maho, Y. (1991). Energy  
672 contribution of proteins and lipids during prolonged fasting in the rat. Nutr. Res. 11,  
673 365–374.
- 674 62. Schmidt-Nielsen, K. (1990). Animal physiology, adaptation and environment. 4th edn.  
675 Cambridge.
- 676 63. Cherel, Y., and Groscolas, R. (1999). Relationships between nutrient storage and  
677 nutrient utilisation in long-term fasting birds and mammals. In 22 Int. Ornithol. Congr.,  
678 Durban:17-34. Johannesburg: BirdLife South Africa. Birds, R. H. (eds) Adams, N.J. &  
679 Slotow, ed., pp. 1–14.
- 680

Average number of cyclones within the core use areas between 2000 and 2016



### Cyclone intensity

- Class 1 cyclone
- Class 2 cyclone
- Class 3 cyclone
- Class 4 cyclone



Colonies

