

1 **Cross-disciplinarity in the advance of Antarctic ecosystem research**

2

3

4 Gutt J<sup>1\*</sup>, Isla E<sup>2</sup>, Bertler N<sup>3</sup>, Bodeker GE<sup>4</sup>, Bracegirdle TJ<sup>5</sup>, Cavanagh RD<sup>5</sup>, Comiso JC<sup>6</sup>,  
5 Convey P<sup>5</sup>, Cummings V<sup>7</sup>, De Conto R<sup>8</sup>, DeMaster D<sup>9</sup>, di Prisco G<sup>10</sup>, d'Ovidio F<sup>11</sup>, Griffiths  
6 HJ<sup>5</sup>, Khan AL<sup>12</sup>, López-Martínez J<sup>13</sup>, Murray AE<sup>14</sup>, Nielsen UN<sup>15</sup>, Ott S<sup>16</sup>, Post A<sup>17</sup>, Ropert-  
7 Coudert Y<sup>18</sup>, Saucède T<sup>19</sup>, Scherer R<sup>20</sup>, Schiaparelli S<sup>21</sup>, Schloss IR<sup>22</sup>, Smith CR<sup>23</sup>, Stefels  
8 J<sup>24</sup>, Stevens C<sup>7</sup>, Strugnell JM<sup>25</sup>, Trimborn S<sup>1</sup>, Verde C<sup>10</sup>, Verleyen E<sup>26</sup>, Wall DH<sup>27</sup>, Wilson  
9 NG<sup>28</sup>, Xavier JC<sup>5,29</sup>

10

11 \* corresponding author, [julian.gutt@awi.de](mailto:julian.gutt@awi.de)

12

13 <sup>1</sup> Alfred Wegener Institute, Hemholtz Centre for Polar and Marine Research, PO Box  
14 120161, 27515 Bremerhaven, Germany, [julian.gutt@awi.de](mailto:julian.gutt@awi.de), [scarlett.trimborn@awi.de](mailto:scarlett.trimborn@awi.de)

15

16 <sup>2</sup> Institut de Ciències del Mar-CSIC, Passeig Marítim de la Barceloneta, 37-49, Barcelona  
17 08003, Spain, [isla@icm.csic.es](mailto:isla@icm.csic.es)

18

19 <sup>3</sup> Antarctic Research Centre, Victoria University and GNS Science, PO Box 600,  
20 Wellington, New Zealand; [nancy.bertler@vuw.ac.nz](mailto:nancy.bertler@vuw.ac.nz)

21

22 <sup>4</sup> Bodeker Scientific, 42 Russell Street, Alexandra 9320, Central Otago, New Zealand;  
23 [greg@bodekerscientific.com](mailto:greg@bodekerscientific.com)

24

25 <sup>5</sup> British Antarctic Survey, NERC, High Cross, Madingley Rd, Cambridge CB3 0ET, United  
26 Kingdom; [tjbra@bas.ac.uk](mailto:tjbra@bas.ac.uk), [rcav@bas.ac.uk](mailto:rcav@bas.ac.uk), [pcon@bas.ac.uk](mailto:pcon@bas.ac.uk), [hjg@bas.ac.uk](mailto:hjg@bas.ac.uk),  
27 [jxavier@zoo.uc.pt](mailto:jxavier@zoo.uc.pt)

28

29 <sup>6</sup> NASA Goddard Space Flight Center, Code 615, 8800 Greenbelt, 20 Road, Greenbelt, MD,  
30 20771 USA; [josefino.c.comiso@nasa.gov](mailto:josefino.c.comiso@nasa.gov)

31

32 <sup>7</sup> National Institute of Water and Atmospheric Research, 301 Evans Bay Parade, Greta  
33 Point, Wellington, New Zealand, [Vonda.Cummings@niwa.co.nz](mailto:Vonda.Cummings@niwa.co.nz),  
34 [Craig.Stevens@niwa.co.nz](mailto:Craig.Stevens@niwa.co.nz)

35

36 <sup>8</sup> Department of Geosciences, University of Massachusetts-Amherst, Amherst  
37 Massachusetts, 01003 USA, [deconto@geo.umass.edu](mailto:deconto@geo.umass.edu)

38

39 <sup>9</sup> Department of Marine, Earth and Atmospheric Sciences, North Carolina State  
40 University, Raleigh, NC 27695-8208, USA; [demaster@ncsu.edu](mailto:demaster@ncsu.edu)

41

42 <sup>10</sup> Institute of Biosciences and Bioresources, National Research Council, Via Pietro  
43 Castellino 111, IT-80131 Naples, Italy; [guido.diprisco@ibbr.cnr.it](mailto:guido.diprisco@ibbr.cnr.it),  
44 [cinzia.verde@ibbr.cnr.it](mailto:cinzia.verde@ibbr.cnr.it)

45

46 <sup>11</sup> Sorbonne Université (UPMC, Paris 6)/CNRS/IRD/MNHN, Laboratoire  
47 d'Océanographie et du Climat (LOCEAN), Institut Pierre Simon Laplace (IPSL), 75252  
48 Paris Cedex 05, France; [Francesco.dovidio@locean-ipsl.upmc.fr](mailto:Francesco.dovidio@locean-ipsl.upmc.fr)

49

50 <sup>12</sup> National Snow and Ice Data Center and Cooperative Institute for Research in  
51 Environmental Sciences, University of Colorado, Boulder, U.S.A.; [alia.khan@colorado.edu](mailto:alia.khan@colorado.edu)

52

53 <sup>13</sup> Universidad Autónoma de Madrid, Facultad de Ciencias, Dept. Geología y Geoquímica,  
54 28049 Madrid, Spain; [jeronimo.lopez@uam.es](mailto:jeronimo.lopez@uam.es)

55

56 <sup>14</sup> Division of Earth and Ecosystem Sciences, Desert Research Institute, 2215 Raggio  
57 Parkway, Reno, NV 89512, USA; [Alison.Murray@dri.edu](mailto:Alison.Murray@dri.edu)

58

59 <sup>15</sup> Hawkesbury Institute for the Environment, Western Sydney University, Locked Bag  
60 1979, Penrith NSW 2751, Australia; [U.Nielsen@westernsydney.edu.au](mailto:U.Nielsen@westernsydney.edu.au)

61

62 <sup>16</sup> Heinrich-Heine-Universität Düsseldorf, Institut für Botanik, Universitätsstraße 1,  
63 Gebäude 26.13, D-40225 Düsseldorf, Germany, [otts@uni-duesseldorf.de](mailto:otts@uni-duesseldorf.de)

64

65 <sup>17</sup> Geoscience Australia, GPO Box 378, Canberra, ACT 2601, Australia;  
66 [Alix.Post@ga.gov.au](mailto:Alix.Post@ga.gov.au)

67

68 <sup>18</sup> Centre d'Etudes Biologiques de Chizé Station d'Écologie de Chizé-La Rochelle CNRS  
69 UMR 7372, 79360 Villiers-en-Bois, France; [yan.ropert-coudert@cebc.cnrs.fr](mailto:yan.ropert-coudert@cebc.cnrs.fr)

70

71 <sup>19</sup> UMR 6282 Biogéosciences, Univ Bourgogne Franche-Comté, 6 boulevard Gabriel,  
72 21000 Dijon, France; [thomas.saucede@u-bourgogne.fr](mailto:thomas.saucede@u-bourgogne.fr)

73

74 <sup>20</sup> Department of Geology & Environmental Geosciences, Northern Illinois University,  
75 DeKalb, IL, 60115, USA; [reed@niu.edu](mailto:reed@niu.edu)

76

77 <sup>21</sup> DISTAV, Università degli Studi di Genova, C.so Europa 26, I-16132, Genova, Italy and  
78 Museo Nazionale dell'Antartide (Sede di Genova); [Stefano.Schiaparelli@unige.it](mailto:Stefano.Schiaparelli@unige.it)

79

80 <sup>22</sup> Instituto Antártico Argentino, Balcarce 290 (C1064AAF), Ciudad Autónoma de Buenos  
81 Aires & CONICET, Argentina and Institut des sciences de la mer de Rimouski, 310 Allée  
82 des Ursulines, Rimouski, QC G5L 3A1, Canada; [ireschloss@gmail.com](mailto:ireschloss@gmail.com)

83

84 <sup>23</sup> Department of Oceanography, University of Hawaii at Manoa, 1000 Pope, Honolulu, HI  
85 96822, USA; [craigsmi@hawaii.edu](mailto:craigsmi@hawaii.edu)

86

87 <sup>24</sup> University of Groningen, Groningen Institute for Evolutionary Life Sciences,  
88 Ecophysiology of Plants, PO Box 11103, 9700 CC Groningen, The Netherlands;  
89 [j.stefels@rug.nl](mailto:j.stefels@rug.nl)

90

91 <sup>25</sup> Marine Biology and Aquaculture, College of Science and Engineering, James Cook  
92 University, Townsville, Qld, 4811, Australia; [jan.strugnell@jcu.edu.au](mailto:jan.strugnell@jcu.edu.au)

93

94 <sup>26</sup> Ghent University, Biology Department, Research group Protistology and Aquatic  
95 Ecology, Campus Sterre, S8, Krijgslaan 281, B-9000 Ghent, Belgium;  
96 [Elie.Verleyen@UGent.be](mailto:Elie.Verleyen@UGent.be)

97

98 <sup>27</sup> School of Global Environmental Sustainability, Colorado State University, Fort Collins,  
99 CO 80523-1036, USA; [Diana.Wall@ColoState.edu](mailto:Diana.Wall@ColoState.edu)  
100

101 <sup>28</sup> Western Australian Museum, 49 Kew Street, Welshpool 6106, Western Australia,  
102 Australia, [Nerida.Wilson@museum.wa.gov.au](mailto:Nerida.Wilson@museum.wa.gov.au)  
103

104 <sup>29</sup> MARE - Marine and Environmental Sciences Centre, Faculty of Sciences and  
105 Technology, University of Coimbra, Portugal; [jccx@cantab.net](mailto:jccx@cantab.net)  
106

107 **Abstract**

108 The biodiversity, ecosystem services and climate variability of the Antarctic continent,  
109 and the Southern Ocean are major components of the whole Earth system. Antarctic  
110 ecosystems are driven more strongly by the physical environment than many other  
111 marine and terrestrial ecosystems. As a consequence, to understand ecological  
112 functioning, cross-disciplinary studies are especially important in Antarctic research.  
113 The conceptual study presented here is based on a workshop initiated by the Research  
114 Programme *Antarctic Thresholds – Ecosystem Resilience and Adaptation* of the *Scientific*  
115 *Committee on Antarctic Research*, which focussed on challenges in identifying and  
116 applying cross-disciplinary approaches in the Antarctic. Novel ideas, and first steps in  
117 their implementation, were clustered into eight themes, ranging from scale problems,  
118 risk maps, organism and ecosystem responses to multiple environmental changes, to  
119 evolutionary processes. Scaling models and data across different spatial and temporal  
120 scales were identified as an overarching challenge. Approaches to bridge gaps in  
121 research programmes included multi-disciplinary monitoring, linking biomolecular  
122 findings and simulated physical environments, as well as integrative ecological  
123 modelling. New strategies in academic education are proposed. The results of advanced  
124 cross-disciplinary approaches can contribute significantly to our knowledge of  
125 ecosystem functioning, the consequences of climate change, and to global assessments  
126 that ultimately benefit humankind.

127

128 **Keywords:** scaling, risk maps, response to environmental changes, sea-ice, multiple  
129 stressors, Southern Ocean

130

131

132 **Introduction**

133 The Antarctic continent, incorporating its surrounding Southern Ocean, overlying  
134 atmosphere, and its biosphere, is an integral component of the Earth system. As  
135 Antarctic ecosystems change, so do the services they provide to global ecosystems and  
136 humankind. In the context of this framework, cross-disciplinary science is essential to  
137 conducting Antarctic ecosystem research. Other than a few biological interactions, life in  
138 the Antarctic is driven by variations in the current physical environment and its history,  
139 including geological and chemical drivers (Convey et al. 2014, Gutt et al. 2015).  
140 Conversely, biological activity also modulates the physical environment. As a result, it is  
141 essential to (a) understand the response of the biosphere to climate change, taking into  
142 account species-specific adaptations to the specific environment, (b) estimate the  
143 proportion of endemic Antarctic biota in relation to the global biodiversity, and (c)  
144 quantify Southern Ocean contributions to global biogeochemical cycles, as well as other  
145 ecosystem services (Grant et al. 2013). Linking the physical and biological components  
146 of Antarctic ecosystems is also a key challenge since many parts of the Antarctic and  
147 Southern Ocean climate system are heterogeneous in space and time (Mayewski et al.  
148 2009, Turner et al. 2009, 2014, Jones et al. 2016), but descriptions of the physical  
149 environment, and associated modelling, often differ widely from those applied to  
150 biological processes.

151

152 As a consequence, Antarctic research is at the forefront of important scientific  
153 challenges, applying holistic approaches that combine systematic assessments of key  
154 physical predictors and key biota. Antarctic interdisciplinary research also helps to  
155 provide societal benefits by delivering new technologies and projections of potential  
156 impacts of the Antarctic environment to change and the impacts of those changes on

157 ecosystem goods and services. Challenges range from increasing the availability of  
158 quantitative information, such as increasing the number of studies and publicly available  
159 data sets, to more functional requirements such as developing new analytical tools and  
160 progressing our ability to resolve and simulate systems of greater complexity. Many of  
161 these challenges can only be tackled synergistically, and need to be addressed to provide  
162 a framework for future development of research in Antarctica, and elsewhere.

163

164 The Antarctic science community has made remarkable progress over the past 20 years.  
165 However, despite some outstanding exceptions, this has largely been achieved within  
166 single disciplines. It is not only the traditional structure of how scientific research is  
167 organised and funded that encourages single-discipline approaches, but it is also the  
168 extreme Antarctic environment, including difficulty of accessing support, that has  
169 resulted in generally narrow science programmes, and has led to the current silo  
170 structure of Antarctic research. Today we can sequence genes and modify genomes, and  
171 we can remotely observe area-wide temperature, sea-ice cover and primary production  
172 including their spatial patchiness and temporal dynamics from space, and make  
173 projections, for instance, of sea-ice cover for the next 100 years; we can also count  
174 penguins, seals and whales by satellites, drones, helicopters and airplanes, and we can  
175 survey marine habitats by remotely operated and autonomous vehicles. We can also  
176 conduct physiological and ecological experiments on terrestrial or marine  
177 environments, either *in situ*, or in the laboratory, by manipulating environmental  
178 variables. A drawback of such rapid and successful advances in single disciplines is that  
179 it leaves gaps in cross-disciplinary developments. To date, we are left with a mosaic of  
180 information that does not provide a coherent and robust picture of past, present and  
181 future Antarctic ecosystems. With access to emerging new technologies, the



182 collaboration of Antarctic biological, geological and physical scientists provides an  
183 exciting opportunity to develop a comprehensive assessment of future ecosystem  
184 vulnerabilities and resilience. But this is only likely to happen if scientists extend their  
185 research interests beyond their discipline and are encouraged to establish true  
186 interdisciplinary collaborations. To achieve this, historical barriers dividing distinct  
187 areas of expertise need to be removed so that a new era of research targeted at  
188 systematically addressing specific cross-disciplinary questions is ushered in. Biologists  
189 need support from the climate and physical research fields (including chemistry and  
190 geology) to solve the challenges of understanding complexity of real life systems. In turn,  
191 physicists benefit from approaches that address obvious requirements of society. Large  
192 international initiatives, once sufficiently developed, could in the future provide an  
193 appropriate 'home' for advanced cross-disciplinary research e.g. the *Southern Ocean*  
194 *Observing System* (SOOS; Rintoul et al. 2012), the *Polar Climate Predictability Initiative*  
195 (PCPI; <http://www.climate-cryosphere.org/wcrp/pcpi>, last access: 17 May 2017) or  
196 ongoing Scientific Research Programmes (SRP) of the *Scientific Committee on Antarctic*  
197 *Research* (SCAR). Even more promising, would be new truly cross-disciplinary SRPs to  
198 be developed in the near future.

199

200 In this sense, the *1st SCAR Antarctic and Southern Ocean Science Horizon Scan*  
201 (hereinafter the *SCAR Horizon Scan*; Kennicutt II et al. 2015,  
202 <http://www.scar.org/horizonscanning>, last access: 17 May 2017), was a key step to  
203 opening new doors. It provided discipline-clustered overarching science questions  
204 central to advancing science over the next two decades. The biology theme "*Life at the*  
205 *precipice*" centred on processes of various biota (see also Xavier et al. 2016). However,  
206 besides nature conservation issues, the genomic, molecular and cellular basis of

207 adaptation of organisms to their environment, was the only other biological challenge  
208 highlighted in one of the published versions (Kennicutt II et al. 2014). Life in Antarctica  
209 and the Southern Ocean is always shaped by various non-biological drivers, but  
210 modulated and propagated through biological interactions (Gutt et al. 2013a, Convey et  
211 al. 2014). Hence, the status of ecosystems can only be evaluated if environmental  
212 requirements of organisms are related to the chemical-physical constraints of their  
213 survival. The present conceptual study aims to contribute to this challenge by focussing  
214 on the urgency of cross-disciplinary approaches for the advance of Antarctic ecosystem  
215 research. The fact that assessments by organisations such as the *Intergovernmental*  
216 *Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES; Díaz et al. 2015)  
217 and the *Intergovernmental Panel on Climate Change* (IPCC; IPCC 2013) require  
218 scientifically reliable information on interactions between the biological and physical  
219 environment is clear evidence that such cross-disciplinary approaches are needed now.  
220 This information is also used for the development of future scenarios and, thus, related  
221 to socio-cultural, as well as socio-economic aspects.

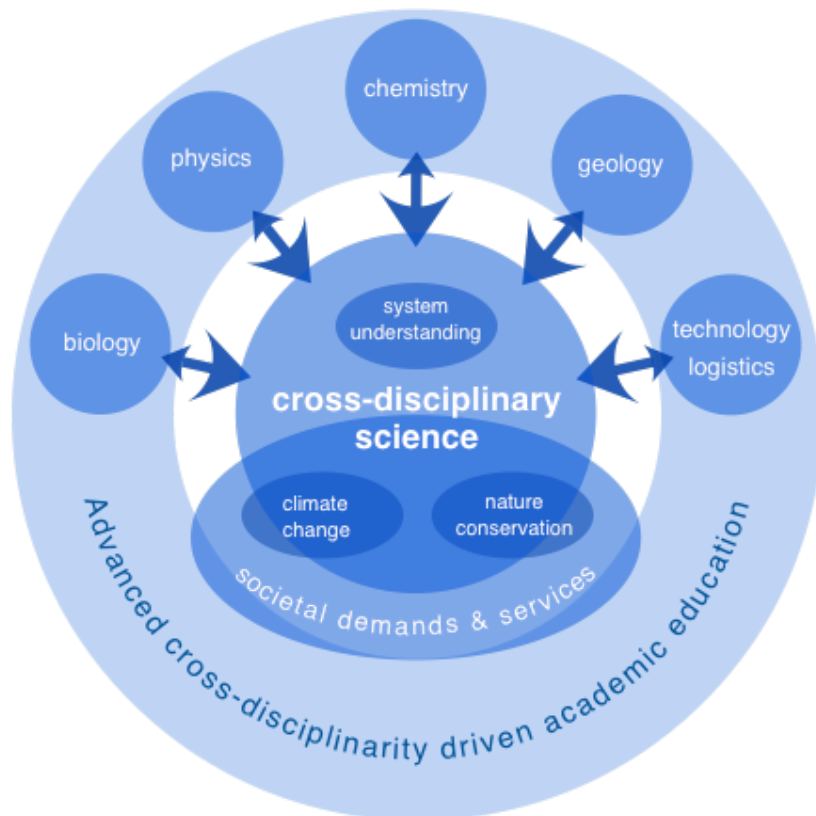
222

223 The timing of such initiatives to improve inter-disciplinary approaches to Antarctic  
224 science is appropriate, because the quality and quantity of spatially and temporally  
225 explicit data on the state of the Antarctic environment has increased enormously in the  
226 past few years. This refers especially to variables that are relevant as global change  
227 stressors of ecosystems, including freshwater availability, sea-ice extent, atmosphere  
228 and ocean temperature change, and to other anthropogenic impacts, such as fishing and  
229 the introduction of non-indigenous species. Major advances have also recently been  
230 achieved in application of molecular markers to study the taxonomy, diversity and  
231 distribution of taxa. In addition, the availability of new and historic biogeographic data

232 uploaded to repositories and made publicly available allows insights into large-scale  
233 biodiversity patterns (Terauds et al. 2012, De Broyer et al. 2014) and potentially to  
234 assess the role of contemporary and historical processes in shaping these patterns  
235 (Convey et al. 2008). Projections of expected future changes for single physical  
236 environmental variables, and populations of a very few iconic Antarctic species, have  
237 been developed (e.g. Jenouvrier 2009, Bracegirdle & Stephenson 2012). In essence,  
238 enormous single-disciplinary advances happened in the past five to ten years, and  
239 included a transition to a new generation of SCAR SRPs (Bergstrom et al. 2006, Gutt et al.  
240 2013a, Verde et al. 2016).

241

242 As a legacy of the *SCAR Horizon Scan*, a workshop was initiated by the SCAR SRP  
243 *Antarctic Thresholds – Ecosystem Resilience and Adaptation* (AnT-ERA,  
244 <http://www.scar.org/srp/ant-era>, last access: 17 May 2017; Gutt et al. 2013a). The  
245 workshop focussed on "*Interactions between Biological and Environmental Processes in*  
246 *the Antarctic*". The core aim of this workshop was to exchange novel ideas among  
247 scientists to gain an improved understanding of the focal questions generated by the  
248 *SCAR Horizon Scan*. The first steps towards implementation of these new ideas and  
249 questions were also discussed. These can serve as a basis for research proposals in a  
250 second step of project realisation. In addition, underrepresented cross-disciplinary  
251 concepts that had been difficult to implement in the past were highlighted. Various  
252 developments within disciplines were also discussed, because answering cross-  
253 disciplinary questions still demands specific disciplinary knowledge (for a general  
254 illustration of this concept see Fig. 1). The overarching aim of this paper is to present the  
255 intellectual output of this brainstorming workshop with a focus on the most striking  
256 novel ideas for cross-disciplinary studies in Antarctica and the Southern Ocean.



257

258 **Figure 1: Schematic view of how to achieve advanced cross-disciplinary research.**

259 Different scientific disciplines can contribute through cross-disciplinary coordination  
 260 and management to improved scientific and societal approaches. This strategy includes  
 261 modern cross-disciplinary academic education.

262

263 To identify the fields most urgently requiring focus, the outcomes of the workshop were  
 264 clustered into eight themes according to an informal survey among the participants.  
 265 Apart from sea-ice, the themes were purposely not ecosystem-specific. The authors are  
 266 aware that this clustering, necessary for the dissemination of novel ideas, is somewhat  
 267 arbitrary. As a result, overlaps exist between the selected themes. Theme 1 on upscaling  
 268 and downscaling is considered to cover overarching approaches, which are applicable to  
 269 all other themes. Despite an attempt to cover a very broad scientific scope, the authors  
 270 accept that this paper does not and cannot claim to represent a complete overview but

271 rather the identification of leading novel research themes from, and for, the Antarctic  
272 scientific community.

273

274 The workshop was held in September 2015 at the Institute of Marine Sciences in  
275 Barcelona, Spain. SCAR SRPs and research initiatives, which contributed to this  
276 conceptual study in addition to AnT-ERA, were *State of the Antarctic Ecosystem* (AntEco,  
277 <http://www.scar.org/srp/anteco>, last access: 17 May 2017), *Antarctic Climate Change in*  
278 *the 21st Century* (AntClim21, <http://www.scar.org/srp/antclim21>, last access: 17 May  
279 2017), *Antarctic Climate Change and the Environment* (ACCE,  
280 <http://www.scar.org/ssg/physical-sciences/acce>, last access: 17 May 2017),  
281 *Biogeochemical Exchange Processes at Sea Ice Interfaces* (BEPSII,  
282 <http://www.scar.org/ssg/life-sciences/bepsii>, last access: 17 May 2017), *Past Antarctic*  
283 *Ice Sheet Dynamics* (PAIS, <http://www.scar.org/srp/pais>, last access: 17 May 2017),  
284 *Expert Group on Birds And Marine Mammals* (EGBAMM, [http://www.scar.org/ssg/life-](http://www.scar.org/ssg/life-sciences/bamm)  
285 [sciences/bamm](http://www.scar.org/ssg/life-sciences/bamm), last access: 17 May 2017), and *Integrating Climate and Ecosystem*  
286 *Dynamics in the Southern Ocean* (ICED, Murphy et al. 2008,  
287 <http://www.iced.ac.uk/index.htm>, last access: 17 May 2017).

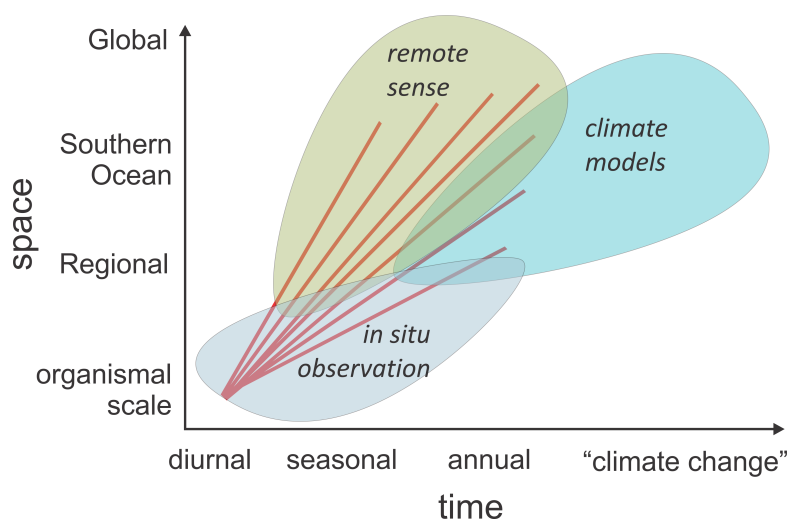
288

289

290 **1. Theme 1: Spatio-temporal scales: upscaling and downscaling in climate change**  
291 **research.**

292 **1.2 Background and justification.**

293



294

295 **Figure 2: Spatio-temporal perspective of research approaches to understanding**

296 **multi-scale ecosystems.** Currently climate modelling, remote sensing and in situ

297 observations occupy the distinct regions of understanding. The EPIC approach

298 (Ensemble Projections Incorporating Climate model uncertainty) is an example of a class

299 of approaches that seeks to take predictions, contextualise with what is known about

300 variability and determine implications at smaller scales (Lewis et al. 2017).

301

302 Climate change fundamentally operates over a range of spatial scales and involves

303 multiple variables in addition to air temperature, i.e. impacts extend beyond the often-

304 used term 'global warming'. Responses of biological systems to climate change, and

305 more widely to all aspects of environmental variability and change, can operate over a

306 broad range of temporal scales, from diurnal through to evolutionary, and spatial scales

307 from square or cubic metres with distinct biological patchiness to many kilometres

308 (Peck et al. 2006, Peck 2011, Blois et al. 2013). Biological responses, in turn, feed back

309 on climate so that the system must be viewed as multi-scale (e.g. Lavergne et al. 2010).

310

311 Multi-scale is a convenient term, but it is exceedingly challenging to implement in

312 Antarctic ecosystem studies. Required observations need to be carried out

313 simultaneously at a range of scales, and modelling needs to encompass a range of scales  
314 (e.g. Ådlandsvik & Bentsen 2007). Spatio-temporal is also a term that suggests a good  
315 understanding of the dynamics is required across multiple spatial and temporal scales  
316 but, again, this is not easily achieved (Fig. 2). The implication then is the requirement to  
317 know everything, everywhere and all the time – something patently impossible.  
318 Furthermore, making observations at high latitudes is logistically challenging. Often it is  
319 difficult to develop simultaneous spatial and temporal perspectives on a given process  
320 let alone interactions between processes (e.g. Sinclair et al. 2014). Simplistically, while  
321 the climate as a driver can be viewed as physical, it is clearly multi-disciplinary as it  
322 incorporates chemical and biological processes (Niiranen et al. 2013) that range across  
323 multiple scales.

324

325 This suggests effort must go into focusing on predictive skills for targeted questions,  
326 especially around connecting different spatial scales, both upscaling from small local  
327 scales to hemispheric scales, and downscaling from global to local scales. To aid such  
328 efforts, one needs to consider (a) what are the critical scales for linking biological  
329 responses to climate and where do current knowledge gaps lie, (b) what data are needed  
330 to more effectively link biology and climate, relevant to what is to be predicted, (c) how  
331 and what simulation tools (models) can be best used to upscale and downscale biological  
332 responses. Connecting these scales will be a necessary component of almost all aspects  
333 considering ecological change in relation to climate in Antarctica. In terms of research  
334 structure, it is useful to identify what can be produced in an overarching sense,  
335 irrespective of the ecology in question, and what needs to be process-specific.

336

337 The overarching aim of upscaling should be a comprehensive and spatially explicit large-  
338 scale knowledge of responses of ecosystems to environmental change derived, in part,  
339 from localised data (e.g. Sinclair et al. 2014). Downscaling should lead to a better system  
340 understanding by focussing on a comprehensive understanding of interactions between  
341 selected biological and non-biological variables. This is predominantly based on detailed  
342 observational data, which are also needed to advance ecosystem modelling and  
343 projections but primarily not including spatial variability. However, downscaling must  
344 focus on scenarios that are representative of larger components of the Antarctic  
345 environment, including the ecosystem i.e. extending approaches applied by Rickard et al.  
346 (2010) to contribute to a whole ecosystem view.

347

## 348 **1.2 Questions.**

- 349 1. Projections of future changes in climate are best generated using global climate  
350 models, which generally simulate atmosphere, ocean and cryosphere changes at  
351 quite a coarse grid spacing (e.g. horizontal 100 km x 100 km); how efficiently (i.e.  
352 what scales can be transitioned in each step), and to what extent, can climate model  
353 outputs be usefully downscaled?
- 354 2. What key elements are missing from these large-scale climate models both  
355 structurally (e.g. ice shelves and their cavities) or in regards to parameterizations  
356 (i.e. parameterization of sub-grid-scale processes)? This approach recognises that  
357 climate projections, remote sensing and *in situ* observations do not always span the  
358 same spatio-temporal scales (Fig. 2).
- 359 3. How interconnected are scientific disciplines (physics, biology, chemistry,  
360 geology/sedimentology) when transitioning various scales?



361 4. Is upscaling the simple reverse of downscaling, and vice versa? If not, what are the  
362 fundamental differences?

363

### 364 **1.3 First steps towards implementation.**

365 First, goals need to be defined to enable models to work sufficiently as tools to  
366 understand how change will manifest itself in biological/ecological systems. To define  
367 and then achieve these goals, a clear dialogue between observational and modelling  
368 communities needs to be established and maintained.

- 369 • Biology must be parameterized well, including definitions of key parameters, to  
370 inform cross-disciplinary models.
- 371 • Models from different disciplines should be embedded within each other by  
372 bridging fundamental differences in biological and physical spatio-temporal data.
- 373 • A quantified differentiation between realistic variability of the climate system  
374 ('noise') and scales not captured by the models ('aliasing') should be developed.
- 375 • Specific biophysical systems need to be identified as logical, tractable starting-  
376 points for an overall project.
- 377 • Taking a system view, minimum standards for adequately defining and describing  
378 the system should be identified.
- 379 • Observational gaps and first-principle models can provide a set of tools for  
380 conducting thought experiments.

381

## 382 **2. Theme 2: Risk maps and ecoregions.**

### 383 **2.1 Background and justification.**

384 Our current understanding of Antarctic biodiversity has been catalysed by the growing  
385 discovery of its rich ecological diversity and complex biogeography (Convey et al. 2008,

386 2014, Terauds et al. 2012, Gutt et al. 2013b, Chown et al. 2015). In parallel, projections  
387 to 2100 suggest faster rates of change with higher amplitude of physical changes than  
388 previously experienced (IPCC 2013, Bracegirdle & Stephenson 2012). This includes, in  
389 particular, changes in melt-water flux, ocean and atmospheric circulation, sea-ice extent  
390 and thickness, stratospheric ozone concentrations, and CO<sub>2</sub> fluxes, as well as changes in  
391 the frequency and strength of patterns of change such as the El Niño - Southern  
392 Oscillation, the Southern Annular Mode and the Pacific Decadal Oscillation. Despite  
393 significant uncertainties that remain, it is apparent that in addition to currently-  
394 observed changes, projected changes in the physical environment will have a  
395 considerable effect on the distribution of organisms due to geographical shifts and  
396 disappearance of suitable habitats, and on ecosystem functioning.

397

398 Ecoregions are strongly cohesive and recognizable areas determined by unique  
399 biological assemblages and abiotic (climatic) environments, delimited with distinct but  
400 dynamic boundaries (Spalding et al. 2007, Koubbi et al. 2010, Bailey 2014). They include  
401 habitat suitability, i.e. maps reporting current availability of optimal conditions for  
402 species and communities. Risk maps constitute essential tools for conservation planning  
403 by designating Antarctic Specially Protected Areas (ASPAs) and Marine Protected Areas  
404 (MPAs). They also provide a baseline for establishing key sites for environmental  
405 monitoring, assessing ecosystem vulnerabilities, and predicting the consequences of  
406 future scenarios on biodiversity (Constable et al. 2014, Gutt et al. 2015). Ecoregions can  
407 be used as operational areas on which ecological scenarios of highest risk of biodiversity  
408 loss and functional shifts can be formulated to produce risk maps (i.e. maps forecasting  
409 areas where changes are more likely to occur) and to provide current baselines as  
410 reference points for climate changes, to assess human impacts on the continent. Species

411 and community distributional data suitable to produce such maps are still scarce.  
412 However, for some study sites and in some case studies, the quality of data enables such  
413 assessments and models (e.g. Nkem et al. 2006, Pinkerton et al. 2010). Initiatives such as  
414 the OBIS-ENV-DATA pilot project, established to combine biological, physical and  
415 chemical data sets within the same repository, are a major step forward in this direction,  
416 being similar to the approach of the research programme *Antarctic Terrestrial Observing*  
417 *System* (ANTOS; <http://www.scar.org/ssg/life-sciences/antos>, last access: 17 May  
418 2017). The US Long Term Ecological Research Sites of the McMurdo Dry Valleys  
419 (terrestrial) and Palmer Station on the Antarctic Peninsula (marine), and the French  
420 Long Term Ecological Research PROTEKER observatory at the Kerguelen Islands, are  
421 examples of long-term field monitoring of physical processes and ecosystem change.

422

423 The long-term objective of this theme is to produce risk maps. They must cover  
424 biologically relevant scales and derive from field observations. This can reach the scale  
425 of the entire Antarctic continent and the Southern Ocean using airborne and satellite  
426 remote sensing techniques. The overarching aim is to define at-risk ecoregions in order  
427 to provide the best possible scientific basis to protect unique, vulnerable and valuable  
428 ecosystems in Antarctica and the Southern Ocean.

429

## 430 **2.2 Questions.**

- 431 1. What are the most important anthropogenic and natural impacts for species  
432 distribution and regional biodiversity?
- 433 2. Where are the locations expected to be most impacted by future environmental  
434 changes and how do these correlate with hot-spots and cold-spots in vulnerability to  
435 environmental changes?

- 436 3. Which non-linear changes and thresholds will have a critical impact on  
437 biophysical/biological processes, for instance, changes in liquid water availability  
438 and increased ecosystem connectivity on land as a result of increased glacial melt  
439 and changes in precipitation?
- 440 4. What is the regional risk for the introduction of non-native species and their likely  
441 impacts on natural ecosystems, i.e. increase in access, exceeding thresholds in  
442 survivable conditions for endemic species, development of suitable conditions for  
443 non-native species, human traffic, as well as atmospheric transport?
- 444 5. To what extent does environmental change alter the effectiveness of dispersal  
445 mechanisms, source/sink dynamics and the potential for both native and non-native  
446 species to spread through e.g. aeolian and oceanic currents and processes?
- 447 6. When did current trends of change commence and are there signs of acceleration?  
448

### 449 **2.3 First steps towards implementation.**

450 A first step towards understanding the impact of physical changes on life in Antarctica  
451 would be high-resolution temporal observations of ecosystem drivers. These are to be  
452 measured within a monitoring network able to help refine models to quantify and deal  
453 with expected uncertainties. Recent efforts by PAGES (PAGES 2ka Consortium 2013) to  
454 develop regional reconstructions of changes in temperature (Stenni et al. 2017) and  
455 snow accumulation over the past 2,000 years (Thomas et al. 2017) are useful efforts to  
456 identify climatic regions and to assess their current trends in view of the recent climate  
457 variability. Such networks should be established further particularly in rapidly changing  
458 regions and, for comparative purposes, in regions expected to remain stable. To quantify  
459 the likely impacts based on currently-available information and models, it will be

460 important to develop and apply new metrics and evaluation tools such as the *Earth*  
461 *System Model Evaluation Tool* (ESMValTool; Davin et al. 2016).

462

463 A stronger collaboration of biologists, physical oceanographers and climate modellers,  
464 will allow us to more robustly identify key regions and locations that are vulnerable to  
465 future change including improved abilities to map biological communities, determine  
466 species ranges, and physiological vulnerabilities or robustness. These could serve as the  
467 foci of intensive comparisons between modelling and observations to fill in missing data  
468 gaps. Once this monitoring network is established, it will be possible to develop  
469 benchmarks and to understand sensitivity to thresholds for species and communities  
470 that are likely to face environmental changes in the future. Up- and downscaling (see 1.  
471 Theme 1) is likely to play an important role for this approach. Emphasis should be  
472 placed on estimating when and where rapid and especially non-linear changes will  
473 occur, as this could lead to identification of biologically relevant thresholds or ecological  
474 tipping points (Nielsen & Wall 2013, Fountain et al. 2016). This task can only be  
475 achieved by establishing an internationally cooperative and geographically  
476 comprehensive and robust monitoring system to produce a reference baseline and  
477 understanding relevant to ecological processes in this context.

478

### 479 **3. Theme 3: Organism responses, resilience and thresholds.**

#### 480 **3.1 Background and justification.**

481 Understanding the impacts of Antarctic climate change on marine and terrestrial  
482 organisms ultimately depends on understanding the specific tolerance of species to  
483 changes in their current environment. To define where and when organisms will first  
484 experience conditions that threaten their future persistence therefore requires intimate

485 knowledge of species traits and their tolerances. However, in broad terms, organisms  
486 that have high specificity for habitats and, thus, low resilience to change in specific  
487 properties, e.g. sea-ice, or other environmental demands such as a specific food  
488 preference, will likely be the 'losers' of anthropogenic change. By contrast, species  
489 endowed with the adequate physiological plasticity and/or being able to count on  
490 genetic evolution may be 'winners' in future climates, although they may not be able to  
491 compete with non-native species in the longer term.

492

493 According to Schofield et al. (2010), the conservation and management of polar marine  
494 populations (Simmonds & Isaac 2007) requires an elucidation of the causes and impacts  
495 of marine ecosystem changes. These studies will only succeed if they can accommodate  
496 the concepts of time-dependent species modifications by natural selection  
497 (microevolution) and phenotypic plasticity. Species and ecosystems may undergo  
498 sudden shocks in response to external changes falling in the proximity of their  
499 thresholds or tipping points. When environmental changes exceed a threshold or tipping  
500 point, life, ranging from a single cell to ecosystems, may rearrange and reach an  
501 alternative stable state (Nielsen & Wall 2013).

502

503 Besides altered food availability, the temperature variability may be a major factor in  
504 dictating responses, especially of Antarctic organisms, to environmental change. For  
505 example, terrestrial plants exposed to seasonal temperature variations exhibit higher  
506 physiological plasticity than Antarctic fish, which are exposed to year-round relatively  
507 stable temperatures. For terrestrial organisms water is recognised as the main driver of  
508 biodiversity processes in the Antarctic (Convey et al. 2014).

509

510 The objective of this theme is to highlight the fact that knowledge on species-specific  
511 traits and environmental requirements is essential for most, if not all, approaches to  
512 assess the response of species and thresholds, as well as the resilience of ecosystems to  
513 environmental change.

514

### 515 **3.2 Questions.**

516 1. When and where are environmental changes in Antarctica and the Southern Ocean  
517 projected to surpass natural variability of the climate system; when and where will  
518 such changes exceed tolerance limits of key species?

519 2. To what extent can potential biological responses and tipping points be extrapolated  
520 from the fossil record, genetics, and physiology?

521 3. To what extent can functional groups/key species be used to develop  
522 useful/informative systems models, and can these models predict the impacts of  
523 environmental change?

524 4. What are the likely range shifts in existing species and where will invasive species  
525 become established under future environmental conditions, e.g. due to changes in  
526 vectors such as currents, winds, frontal zones, running water, permafrost, humans,  
527 sea-ice extent?

528 5. What are the most urgent interfaces, where physiologists and geneticists in  
529 particular, must work together with physical scientists to ensure that information  
530 generated is equally relevant across disciplines and as ecologically relevant as  
531 possible?

532

533

534

### 535 **3.3 First step towards implementation.**

536 Modern distribution patterns of a wide range of Antarctic organisms can be assessed  
537 from existing biodiversity databases, such as [www.biodiversity.aq](http://www.biodiversity.aq). Through  
538 collaboration with oceanographers, chemists, sea-ice scientists, geologists, glaciologists  
539 and modellers, distribution patterns can be mapped against environmental datasets to  
540 define the realised environmental envelope of single species and communities.  
541 Additional information on the physiological and ecological limits of an organism or  
542 tissue can be obtained through genetics, advanced biomolecular methods, such as  
543 transcriptomics (e.g., Sadowsky et al. 2016), and implemented in ecological concepts,  
544 models and biogeographical projections (Kearney & Porter 2009, Chevin et al. 2010,  
545 Pörtner & Gutt 2016). All these approaches could usefully include comparative studies  
546 along gradients in terrestrial, limnetic and marine systems, such as between fjords of the  
547 Antarctic Peninsula and northwards to the South Shetland and South Orkney Islands and  
548 to the sub-Antarctic. Physical models of predicted environmental change should be used  
549 to target those regions that will reach predicted thresholds first, so that monitoring  
550 programmes can be established to detect non-linear changes in populations, including  
551 the establishment of invasive species (see also 2. Theme 2). Environmental variability  
552 and change at biologically relevant scales needs to be identified and tracked (e.g.  
553 ANTOS-type programmes), to accurately advise biological, physical, and Earth science  
554 studies. System models will need to include features such as cascade effects, food webs,  
555 changes to ecosystem function and services, points of no return, new stable/equilibrium  
556 states, highly resilient versus non-resilient assemblages and evolution.

557

558 To understand which organisms are likely to be impacted, where thresholds may be  
559 crossed, and where the consequences of change are likely to be strongest, the upper and



560 lower tolerance limits controlling their distribution are to be defined. For example,  
561 geographic ranges have been analysed for selected species using existing database  
562 records (see Barnes et al. 2009); a next step would be to take known species ranges and  
563 plot these against the oceanographic, chemical and physical properties to develop more  
564 accurate species environmental requirements. In parallel, the ecophysiology of  
565 ecological key species must be studied because knowing only their current distribution  
566 without further system understanding is obviously not sufficient to model their future  
567 distribution. Environmental envelope modelling, such as illustrated in a preliminary way  
568 in the study of Hughes et al. (2013) assessing the potential current limits to the  
569 distribution of the maritime Antarctic non-native terrestrial midge *Eretmoptera*  
570 *murphyi*, illustrate the potential utility of geographic range modelling both under  
571 current and future climate scenarios. One of the biggest challenges is to integrate  
572 biomolecular data into ecological distribution models (Gutt et al. 2012).

573

574 Only a collective and a cooperative effort from coordinated and cross-disciplinary  
575 research groups in conducting large-scale meta-studies will encompass the sources and  
576 bias of variability (time and space scale), helping to reach a breadth of knowledge and  
577 avoid the risk of under- or overestimating the impact of climate change on biodiversity.

578

579

580 **4. Theme 4: Ecosystem response to natural climate variability and anthropogenic**  
581 **change: studying the response to multiple stressors.**

582 **4.1 Background and justification.**

583 Ecosystems are almost always shaped by several environmental parameters, and in the  
584 Antarctic, biological interactions are not as relevant as in other ecosystems, e.g. tropical

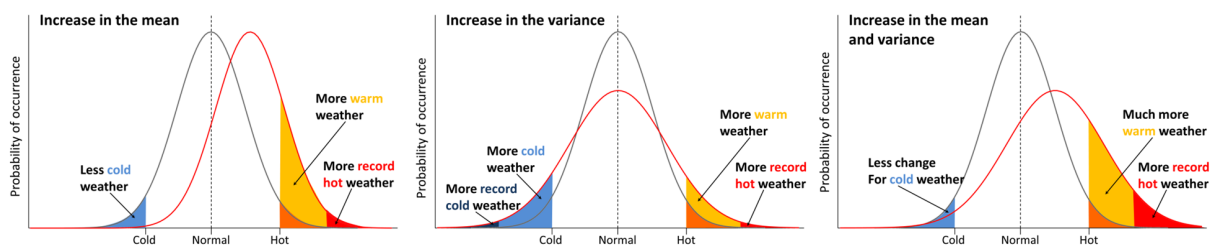
585 rainforests and coral reefs. Only rarely it is easy to identify the most important physical  
586 driver, e.g. water availability for terrestrial vegetation. Pelagic species, for instance, are  
587 exposed to increasing carbonate undersaturation due to ocean acidification (OA), which  
588 is driven by atmospheric CO<sub>2</sub> concentration, pressure and temperature. Since under OA  
589 marine organisms need more energy to maintain their calcium-based shells and  
590 skeletons, OA is never the problem alone; it is always accompanied by temperature,  
591 pressure and food/nutrient availability. For Antarctic benthic species on the deeper  
592 continental shelf, it is not possible to identify only one or two major natural drivers.  
593 Relationships to depth for instance, may relate to associated changes in temperature,  
594 pressure, dissolved oxygen, food availability and depth of iceberg scour. Climate change  
595 and its impacts on ecosystems includes not only include temperature increases, but is a  
596 phenomenon comprising temperature, wind, quality and quantity of precipitation, and is  
597 related to the ozone hole causing increased UV-B radiation. In addition to natural and  
598 indirect anthropogenic drivers such as climate change and OA, all the aforementioned  
599 ecosystems are or were exposed to direct anthropogenic impacts, such as whaling and  
600 fishing, local pollution, invasion of alien species, soundscape changes and terrestrial  
601 habitat loss (Tin et al. 2009).

602

603 Timescales associated with complex ecological processes, briefly described above, range  
604 from nanoseconds (cellular processes) to millions and billions of years (species  
605 evolution). When studying the effects of long-term trends and variability in climate on  
606 ecosystems, scaling climate change projections to biologically relevant temporal and  
607 spatial scales is challenging. Quantifying the extent to which changes in climate push  
608 Antarctic ecosystems beyond the natural variability (e.g. daily to seasonal variation) to  
609 which they have adapted (Fig. 3) requires a combined physical and biological

610 perspective. Although increases in temperature or changes in water availability may be  
611 important drivers of Antarctic ecosystems (Convey et al. 2014), exposure to novel  
612 climates could have much greater impacts. To predict the potential impacts of climate  
613 change it is therefore necessary to assess the severity of such events of the past and  
614 presence beyond intrinsic variability. For the physical Antarctic climate system, the  
615 Amundsen Sea Low is the most variable region of the global atmosphere, which must be  
616 taken into account when considering potential future envelopes of change in the  
617 physical system (Hawkins et al. 2016). Long-term sampling can determine the 'baseline  
618 variability', but this is limited in the extent to which it can inform projections of  
619 anthropogenic climate change.

620



621

622 **Figure 3: Environmental shifts and response of species occurrence.** A change in  
623 climate at any location can be considered as a shift in the probability density function  
624 (PDF) of the climate variable of interest, such as temperature, a change in the width of  
625 the PDF, or some combination of both. While a shift in the PDF to higher temperatures  
626 may be small ( $\sim 1^\circ\text{C}$ ), the increase in the number of days when maximum temperatures  
627 exceed some threshold can be a factor of 2 or 3 larger. Since biological systems are more  
628 likely to respond to the severity, duration and frequency of such extreme events,  
629 attention must be paid to the tails of the distributions of climate states when considering  
630 biological responses to climate change.

631

632

633

634 The objective of this theme is to find solutions to disentangle cause-effect relationships,  
635 and multiple global change stressors. The real challenge therefore, is to identify intrinsic  
636 and extrinsic biotic responses using statistical methods, which permit the design of  
637 hypothesis-driven multiple-stressor experiments as well as provide adequate  
638 parameterization in global ocean-climate models.

639

#### 640 **4.2 Questions.**

641 1. What methods are available to detect trends beyond natural variability in climate  
642 time series?

643 2. To what extent does past climate variability moderate species' responses to  
644 anthropogenic climate change?

645 3. How can outputs from projections from Earth System Models be tailored to match the  
646 spatial and temporal scales required to understand biological system responses?

647 4. How can statistical models be used to design robust multiple global-change stressor  
648 experiments?

649 5. What is the real contribution of biological CO<sub>2</sub> uptake of the Southern Ocean to the  
650 global CO<sub>2</sub> budget and what is its variability in space and time, in the present and  
651 future?

652

#### 653 **4.3 First steps towards implementation.**

654 To better assess Antarctic ecosystem responses to climate change, large ensembles of  
655 climate model simulations are required. They allow better quantification of future  
656 climate envelopes (Fig. 3) and the definition of ranges of stress, which must then be  
657 applied at ecologically relevant temporal and spatial scales. As they are now just

658 becoming available, they provide novel research opportunities, for example, the *Large*  
659 *Ensemble Community Project* (Kay et al. 2015). Changes in ecosystems may then  
660 potentially feedback on the climate system. This requires (a) better communication  
661 between the biology and climate physics communities, and (b) techniques that provide  
662 two-way connections between climate models and ecosystems at the relevant spatial  
663 and temporal scales. Semi-empirical models can help to identify which variables, i.e.  
664 environmental factors, are most relevant to determine the response of the biological  
665 system to changes in key climate variables, and thereby contribute to better  
666 understanding of cause-effect relationships.

667

668

## 669 **5. Theme 5: Interactions between biological and climate processes - Antarctic top** 670 **predators and food webs.**

### 671 **5.1 Background and justification.**

672 Ecosystem processes occurring in the vast expanses of the Southern Ocean, including  
673 under the sea-ice and ice shelves, remain difficult to examine with conventional methods  
674 (e.g. surveys from research ships, remote sensing). However, this region is regularly  
675 visited by a wide range of species that cover most of the uncharted volume of the  
676 Southern Ocean: from penguins and albatrosses to seals and cetaceans; from the  
677 continental shelf through the deep-sea to the northernmost limits (and beyond) of the  
678 Southern Ocean. With the advent of animal-embarked data-recording technology (bio-  
679 logging, Ropert-Coudert & Wilson 2005), these foraging animals have been turned into  
680 living probes, scouting the environment and delivering not only biological information  
681 on their ecology, but also a wealth of physical information on parts of the Antarctic  
682 environment that are still poorly studied. As an illustration of this, CTD profiles obtained

683 by data recorders attached to elephant seals (*Mirounga leonina*) are achieving more than  
684 simply complementing those given by Argo floats: they are doubling the dataset (Roquet  
685 et al. 2014). In this domain, prospects for future cross-disciplinary studies (e.g. bridging  
686 biology, oceanography, engineering, physics) are booming as the type of data that can be  
687 acquired by animal-embarked technology benefits from progression in, for example, the  
688 mobile phone industry. New sensors measuring dissolved oxygen, bioluminescence, sea-  
689 ice thickness, acoustic signals, amongst others, are set to help physical oceanographers,  
690 biochemists, plankton biologists and trophic ecologists, to address the questions below.  
691 Cameras attached to the heads of seals and penguins provide direct insights in their  
692 feeding behaviour and food preferences, as well as additional information on under ice-  
693 shelf habitats, e.g. isopods living attached to the ice subsurface.

694

695 The overarching scientific aim of combining biological and physical methods and  
696 approaches is to identify the major drivers of top predator populations, the position and  
697 functioning of regions of ecological importance, and to predict their development under  
698 climate change. A mechanistic understanding of the biophysical processes controlling  
699 trophic chains in the Southern Ocean is needed for assessing the impact of climate  
700 change scenarios – which are expressed in terms of physical changes - to marine  
701 populations. In turn, this knowledge should support the deployment of conservation  
702 actions, like the establishment of marine protected areas.

703

## 704 **5.2 Questions.**

705 1. What are the biotic and abiotic mechanisms controlling energy and biomass flow  
706 from primary producers to top predators at various temporal and spatial scales, and

- 707 change according to shifts in the physical environment? What are the spatio-  
708 temporal scales and key locations associated with these mechanisms?
- 709 2. How can dynamic multi-scale food-web models (biomass and carbon-based) be  
710 constructed that include physical and biological data, as well as threats (human  
711 impacts, pollution, fisheries)?
- 712 3. What is happening under the sea-ice and ice shelves: new sensors to help us  
713 understand physical and biological processes in habitats that are beyond the reach  
714 of traditional methods?
- 715 4. What are the key biophysical mechanisms through which climate change will impact  
716 marine ecosystems?

### 717 **5.3 First steps towards implementation.**

718 In this context, the assemblage of a network to maximize usage of  
719 chemical/physical/biological, multi-scale data collected by top predators is a priority.  
720 An additional goal of such a network would be to maintain a state-of-the-art survey of  
721 progress in monitoring technologies so as to inform users of animal-embarked devices  
722 from the physical and biological sciences of the latest trends in sensor development.  
723 Continuity is particularly important in these years, in which the anthropogenic signal of  
724 climate change is emerging. Enhanced collaboration between research disciplines  
725 should be favoured through the organization of dedicated programmes/surveys that  
726 would integrate a wide range of expertise, as well as cross-disciplinary fora that would  
727 emphasize data sharing, homogenization and centralization. Finally, urgent questions on  
728 the current state and future of the well-being of Antarctic top predators demands the  
729 integration of the data obtained from modern sensor development and use by advanced  
730 modelling techniques, including the simulation of the dynamics of trophic interactions.  
731 In terms of scales, satellite observations are now opening a new frontier, allowing for

732 the first time mapping of the environment at a scale that approaches the resolution of  
733 animal telemetry. Thanks to Synthetic Aperture Radar and visible imaging, the details of  
734 complex landscapes like the ice margin are now accessible. In the open ocean, activities  
735 such as the *Surface Water and Ocean Topography* mission will soon provide fine-scale  
736 details of ocean circulation, making it possible to reconstruct the physical context at the  
737 resolution of the behavioural switches of marine predators.

738

739

## 740 **6. Theme 6: Impact of changing ice sheet dynamics on circumpolar, nearshore, and** 741 **off-shore environments.**

### 742 **6.1 Background and justification.**

743 Anthropogenic pressure forces the Antarctic ice shelves and glaciers to retreat and  
744 consequently modify the coastal and continental shelf ecosystems. For example,  
745 phytoplankton blooms in recently opened water areas and the subsequent downward  
746 fluxes of fresh organic matter set conditions for the benthic recolonization of the seabed  
747 (Bertolin & Schloss 2009, Sañé et al. 2011). Glacier melt run-off releases sediment and  
748 nutrients into the water column, which can both stimulate and hamper photosynthesis  
749 and also affect benthic life (e.g., clogging, burying) (Sahade et al. 2015). Massive icebergs  
750 calving from the ice shelves can scour the sea floor to several hundred metres in depth  
751 and remove benthic life from it on their way, but also stimulate life in the pelagic realm  
752 (Gutt et al. 2011, 2013c). They can also affect large areas of the continental shelf, where  
753 pelagic life would otherwise flourish (Arrigo et al. 2002, Vernet et al. 2012). At the same  
754 time, melting glaciers and receding ice fronts may result in the exposure of new ice-free  
755 land as well as intertidal zones, which in turn may support terrestrial and limnetic  
756 ecosystem development.



757

758 The developmental trajectories of these new ecosystems obviously depend on a  
759 multitude of factors. These include the bioavailability of nutrients, the connectivity with  
760 existing ecosystems affecting colonization dynamics, microclimatic conditions and biotic  
761 interactions, such as soil formation processes and nutrient remineralisation by  
762 microbes. The effect of physical and chemical parameters on these newly emerged  
763 ecosystems is also expected to vary through time. For example, liquid water may  
764 become increasingly available in a particular region due to direct meltwater input from  
765 retreating glaciers, while conditions may become drier over longer timescales when the  
766 ice front further retreats and local sources of water become exhausted. Many of these  
767 processes have been occurring more extensively in recent decades (e.g. Favero-Longo et  
768 al. 2012) and opened the opportunity to study them for the first time in the history of  
769 science.

770 With a trend of increasing ice shelf disintegration and glacial retreat, other discrete  
771 regime shifts in coastal waters are expected over the coming decades, and the direction  
772 of these regime shifts may change in a second phase thereafter, their impact on the  
773 terrestrial, near-shore and off-shore ecosystems must be addressed and their effect and  
774 direction in which they may change in the future must be anticipated. Such studies can  
775 also incorporate large field experiments aimed at assessing the general resilience or  
776 vulnerability of Antarctic ecosystems.

777

## 778 **6.2 Questions.**

779 1. What is/was the effect of ice-shelf collapse, glacier retreat and iceberg scouring in  
780 the past, present and future on benthic marine, intertidal and terrestrial biodiversity  
781 and nutrient cycles, e.g. biological storage, release, sequestration, and

- 782 remineralization of nutrients over space and time, including the devastation of  
783 benthic assemblages through iceberg scour, and fast-ice occurrence?
- 784 2. What is the contribution of nutrients (e.g., iron fertilization) from icebergs and wind  
785 from exposed land surfaces to local and regional primary production in a changing  
786 pelagic environment?
- 787 3. How do fjord/coastal ecosystems drivers (e.g., meltwater and glacial sediment  
788 inputs, light regime) and ecological responses change along the Western Antarctic  
789 Peninsula (WAP) and other regions with obvious climate gradients?
- 790 4. What are the timescales and dynamics (continuous versus episodic, local versus  
791 regional) of climate shifts around the Antarctic continent, and how will these shifts  
792 be reflected in under-ice shelf, fjord and sea-ice shaped ecosystems?
- 793 5. Which Holocene climate-change ice-shelf and sea-ice processes, and their biological  
794 responses, are mirrored by sediment characteristics, which, in turn, affect (other)  
795 biological processes, especially at the sea floor?
- 796 6. How will the glacier-retreat affect the appearance of more connected habitats shape  
797 the diversity of terrestrial and limnetic ecosystems, and what will be the short- and  
798 longer-term effects of changing physical, chemical and (micro-) climatic conditions  
799 on these ecosystems and their functioning?
- 800 7. How important are microbial microfilms in the recolonization of ice-devastated  
801 benthic habitats and what is the role of the early-life history for the recruitment of  
802 invaders?

803

### 804 **6.3 First steps towards implementation.**

805 Improved approaches of upscaling (see 1. Theme 1) have to be applied because glacier  
806 and ice-shelf disintegration is a local phenomenon but the expected impact is regional. It

807 is important also to apply downscaling techniques, e.g. to understand the consequences  
808 of higher turbidity for pelagic and benthic organisms and to date significant sediment  
809 layers. Emphasis has to be placed onto the dynamics of cryosphere-ocean interactions  
810 (e.g., ice-shelf and marine ice sheet collapse) and ice-sheet processes (e.g., rapid melting,  
811 glacial erosion, pulsed iceberg inputs) to be studied through modelling and  
812 observational surveys (Scambos et al. 2003) as well as documentation of past changes  
813 (Scherer et al. 1998; 2016). This especially refers to biologically relevant changes e.g.  
814 water mass characteristics, rather than the recently emphasized physical changes, such  
815 as sea-level increase. Cross-disciplinary studies can be supported by more  
816 sedimentological results acting as an archive for recent processes in the water column,  
817 e.g. transitions from sub-ice shelf to sea-ice ecosystems in response to climate forcing  
818 (Sañé et al. 2013). Better dating of Antarctic marine sediments will benefit more than  
819 studies focussing on ice-related habitats. Biological studies under areas of permanent ice  
820 (sea ice and ice shelves) provide a technical challenge but are broadly significant.  
821 Currently-available technology, such as autonomous underwater vehicles and crawlers  
822 can provide valuable, previously almost non-existent, information across broader scales  
823 and with higher spatial resolution than that obtained through drilling cores. Good  
824 results might also be achieved when remotely operated vehicles are deployed through  
825 drill holes. The application of swarms of autonomous probes using collective intelligence  
826 might solve the problem of obtaining results that are representative for large areas. This  
827 is especially important since these areas are highly relevant to understanding ecosystem  
828 functioning, including feedback processes between life in the ocean, the cryosphere and  
829 the atmosphere. Modelling and long-term observations of ice dynamics and the  
830 relationship to climate forcing (applying ecologically relevant spatial and temporal  
831 scales) improve predictions of the impact of the behaviour of ice bodies on marine

832 ecosystems. A better understanding of environmental and biological processes induced  
833 by small-scale upwelling around marine glacier termini and around grounded as well as  
834 floating icebergs will allow the assessment of some still fragmentary knowledge on  
835 polar-specific ecological processes. Terrestrially relevant information can be obtained  
836 from monitoring studies, in combination with space-for-time substitution approaches, in  
837 which glacier forefields can be used to study the short- and longer-term effects of  
838 receding glaciers on the interplay between biological processes and nutrient and carbon  
839 dynamics in soils, wetlands and lake ecosystems.

840

841

842 **7. Theme 7: Sea-ice ocean and sea-ice atmosphere boundary layers - impact of**  
843 **changes on primary production and other biological processes.**

844 **7.1 Background and justification.**

845 Trends over recent decades in Antarctic sea-ice distribution contrast dramatically with  
846 what is happening in the Arctic. While Arctic sea-ice extent has been reaching record  
847 lows, satellite data have shown that sea-ice extent had been increasing around  
848 Antarctica since the satellite era started in 1979, with the extent exceeding  $2 \times 10^7$  km<sup>2</sup>  
849 for the first time in 2014. In 2016/17, however, the recent record Antarctic summer low  
850 highlights the possibility of a switch to future declines in sea ice extent  
851 ([http://nsidc.org/arcticseaicenews/2017/01/low-sea-ice-extent-continues-in-both-](http://nsidc.org/arcticseaicenews/2017/01/low-sea-ice-extent-continues-in-both-poles/)  
852 [poles/](http://nsidc.org/arcticseaicenews/2017/01/low-sea-ice-extent-continues-in-both-poles/), last access: 17 May 2017). However, there are large mid-term regional  
853 differences, with slight increases in the Ross Sea area and off East Antarctica and  
854 extensively declining ice cover in the Bellingshausen/Amundsen Seas (Comiso et al.  
855 2017). Variation in sea-ice cover may be associated with large-scale atmosphere-ocean  
856 features like the Southern Annular Mode and the El Niño–Southern Oscillation (Kwok et

857 al. 2016), identified by the decline in ice cover during 2015 and 2016. Currently, the  
858 majority of simulations conducted as part of the *Coupled Model Intercomparison Projects*  
859 (CMIP) indicate ice-extent trends that are the opposite of what is currently happening.  
860 The reasons for this are difficult to identify and could simply be a consequence of  
861 different timings in natural ocean cycles. Irrespective of the ultimate explanation, the  
862 model-observation differences appear to be associated with inability to reproduce  
863 observed trends in surface temperature in the ice covered and surrounding regions  
864 (Comiso et al. 2017).

865

866 The ecology and productivity of the Southern Ocean are strongly influenced by the sea-  
867 ice cover (Smith & Comiso 2008). Sea ice causes the replacement of surface water  
868 through vertical mixing during the growth period when dense water is formed, gets  
869 submerged and is replaced by nutrient-rich water from below. During ice retreat, the  
870 melt-water forms a stable surface layer that is exposed to abundant sunlight and  
871 becomes an ideal platform for photosynthesis. With algal biomasses 1000 times higher  
872 than pelagic concentrations, sea-ice forms a rich support for higher trophic levels. It  
873 seeds pelagic blooms and the high sedimentation rates of ice algae fuel benthic  
874 communities (Riebesell et al. 1991, Isla et al. 2009). Hence, sea-ice-associated  
875 communities also form the basis of Antarctic marine life. Reductions in the extent and  
876 timing of sea-ice around the WAP since 1979 have been associated with phytoplankton  
877 community spatial shifts (Montes-Hugo et al. 2009) and with shifts from a krill-  
878 dominated to a salp-dominated community (Atkinson et al. 2004). Such changes may  
879 have important cascading effects on higher trophic levels (Schofield et al. 2010).

880

881 Sea-ice biogeochemistry is a new and growing scientific discipline. Due to its large  
882 heterogeneity in time and space, sea-ice is a difficult medium to study and from which to  
883 construct a generalized view of state parameters, let alone of quantitative process rates.  
884 Sea-ice is an important mediator in the carbon-cycle, driving carbon exchange from  
885 atmosphere to ocean and vice versa due to extreme and specific physical, chemical and  
886 biological processes in the ice matrix (VanCoppenolle et al. 2013). Sea-ice also  
887 contributes to the dynamics of other climate-relevant gases, such as dimethyl sulfide  
888 (Tison et al. 2010) and halocarbons, and to the oxidative capacity of the cold Antarctic  
889 atmosphere (Simpson et al. 2007). Many processes are still unknown and may be very  
890 different across long regional gradients, making it a challenge to advance our  
891 understanding of the system. Close collaboration between field scientists and modellers  
892 is needed to bring this field of research forward (Steiner et al. 2016).

893

894 Given the above, sea-ice as a habitat and driver is highlighted here because (a) sea-ice  
895 biogeochemistry potentially contributes to the global C-cycle and is important for the  
896 Antarctic marine foodweb, (b) this highly relevant issue was not identified in the  
897 questions of the *SCAR Horizon Scan*, (c) sea-ice – primary production relationships are  
898 not yet well understood.

899

## 900 **7.2 Questions.**

- 901 1. What methods are available to model movement of sea-ice on a bay-scale? How can  
902 these models/results feed climate models?
- 903 2. Can physical modellers help with predicting small-scale features like leads, ridges,  
904 first-year ice versus multi-year ice, floe drift and polynya development?

- 905 3. Which are the important predictors of climate gas fluxes and heat exchange between  
906 ocean, sea-ice and atmosphere?
- 907 4. How can information on historical shifts in sea-ice extent be improved (e.g. through  
908 sediment records or time-series of pelagic species biomass) to match with ongoing  
909 changes detected from satellite data and model simulations of periods further back in  
910 time?
- 911 5. What is the contribution of sea-ice to the global C-cycle in general and specifically to  
912 SO biology?
- 913 6. What happens with the coastal and offshore blooms when ice disappears?
- 914 7. What is the role of ice-shelf cavities on sea-ice growth and under-ice habitat  
915 structure? How will this change when ocean water warms?

916

### 917 **7.3 First steps towards implementation.**

918 Since seasonality is perhaps the most important characteristic of Antarctic sea-ice, year-  
919 round studies are needed to understand the high temporal variability of biogeochemical  
920 processes and feedbacks with climate. Modellers should become involved in the  
921 development of such field experiments at an early stage, so as to collect field data that  
922 can be directly implemented in models. The challenge will be to develop a set of tools  
923 useful for future projections on the impact of sea-ice on the regional carbon/primary  
924 production cycle. This can be done by using scenarios of both rapid sea-ice melt-back  
925 and more stable sea-ice cover in coupled models, thereby taking account of the  
926 uncertainty in future projections (models project significant melt, observations so far  
927 indicate only regional melt).

928

929 Improvements can be made through small-scale modelling of ice movement, formation  
930 and melting by combining weather data with sea-ice extent. To resolve small-scale  
931 features in sea-ice relevant to gas- and heat-exchange processes, statistical distribution  
932 models need to be developed from satellite data that can then be extrapolated to the  
933 regional scale. In order to improve modelling of biogeochemical cycles in sea-ice and the  
934 coupling between sea-ice and ocean, benthos as well as atmosphere, there is an urgent  
935 need for more studies of inter-annual variability using time series of biogeochemical  
936 parameters.

937

938

939 **8. Theme 8: Evolution of biota in relation to glaciation history, marine and**  
940 **terrestrial glacial refugia, trans-Antarctic seaways and connectivity.**

941 **8.1 Background and justification.**

942 Antarctic biota are a reservoir for evolutionary novelty, including adaptations to a  
943 unique environment following natural selection over millions of years in response to  
944 past climate changes and tectonic events (Clarke & Crame 1989, Poulin et al. 2002,  
945 Convey et al. 2008, 2009, Fraser et al. 2012, Strugnell et al. 2008, Wilson et al. 2013).  
946 The break-up of Gondwana led to the geographic isolation of the continent, the  
947 formation of the Southern Ocean and in particular the Antarctic Circumpolar Current,  
948 and accelerated the development of continental-scale Antarctic ice sheets (Zachos et al.  
949 2001). Over time, repeated glacial-interglacial cycles have resulted in a wide range of  
950 environmental conditions as well as changes in the connectivity among habitats. These  
951 include the formation of seaways (e.g. between the Ross and the Weddell Seas; Barnes &  
952 Hillenbrand 2010, Strugnell et al. 2012), large fluctuations in sea level, periods of higher  
953 discharge of freshwater and icebergs into the Southern Ocean, increased liquid water



954 availability in terrestrial regions, and a higher surface area of ice-free habitats during  
955 warm periods (De Conto & Pollard 2016). During glacial maxima, both marine and  
956 terrestrial (including limnetic and microbial) biota appear to have survived in glacial  
957 refugia (Allcock et al. 2011, Convey et al. 2008, 2009, Pugh & Convey 2008, Vyverman et  
958 al. 2010, Fraser et al. 2012), as revealed by both recent molecular studies (see Allcock &  
959 Strugnell 2012 for review) and classical biogeographic analyses (Terauds et al. 2012)  
960 although the nature and locations of these refugia are still poorly understood (Lyons et  
961 al. 2016). Most terrestrial habitats are extremely isolated. Potential refugial locations  
962 are poorly localised at anything less than regional scale, although in some areas there is  
963 evidence for refugia being located in volcanic and other geothermal areas (Fraser et al.  
964 2014). Marine habitats seem to be more connected, although dispersal limitation  
965 between regions appears to be present. Biogeographic and phylogeographic patterns are  
966 often in conflict due to the presence of cryptic species, or a poor understanding of  
967 taxonomy (e.g. Díaz et al. 2011, Brasier et al. 2016), so generalities of distributions are  
968 not yet well-understood. Thus, historical processes have left a clear imprint on the  
969 contemporary diversity and distribution of biota in Antarctica and resulted in a high  
970 incidence of endemism, geographic structuring of populations, evolution in isolation,  
971 and clear bioregionalization patterns even at small spatial scales in both multicellular  
972 and microbial organisms (Convey et al. 2014). Moreover, this particular evolutionary  
973 history has also led to biological differences between habitats in Antarctica and  
974 comparable counterparts in the Arctic (Fraser et al. 2012, Pointing et al. 2015). Changes  
975 in the permafrost, active layer, freshwater availability and groundwater circulation have  
976 important connections with ecosystem processes. Old permafrost can be an interesting  
977 repository of microbes, metabolic products and biodiversity (Gilichinsky et al. 2007).  
978 Biological comparison of taxa inhabiting the two polar regions pinpoints the differences

979 in evolutionary histories between the two systems. As a result, for instance, Arctic fish  
980 have higher biodiversity (Mecklenburg et al. 2010).

981

982 Despite this unique biological constellation, it is becoming increasingly evident that the  
983 human influence on biological colonization into and within Antarctica is already high  
984 and is only likely to increase in the future, challenging the governance and  
985 environmental management mechanisms of the *Antarctic Treaty System* (Frenot et al.  
986 2005, Tin et al. 2009, Convey et al. 2012, Chown et al. 2012, Hughes et al. 2015). Robust  
987 knowledge of the evolutionary background of recent life in the Southern Ocean and  
988 Antarctica is essential to assess its contribution to global biodiversity and ecosystem  
989 functioning and to provide reliable estimates of the consequences of projected  
990 anthropogenic climate change and other environmental changes.

991

## 992 **8.2 Questions.**

- 993 1. What strategies allowed biota to persist during glacial cycles, where and when did  
994 glacial refugia exist?
- 995 2. Does any generality exist in these processes between marine, terrestrial and  
996 limnetic systems or between large groups of organisms, or are they all unique?
- 997 3. Is it possible to reliably predict (remotely) where suitable habitats exist today, and  
998 how will these habitats change under climate-change scenarios and in which  
999 direction, towards higher or lower complexity?
- 1000 4. How connected are regions at present and have they been in the past in terms of  
1001 both colonization and also other biological processes and ecosystem functions (e.g.,  
1002 nutrient flows between and among terrestrial and marine ecosystems), what  
1003 mechanisms connect them and on what timescales?

1004 5. Under which environmental conditions will regionally extinct species/taxa re-  
1005 colonize?

1006 6. Will new species appear for the first time in Antarctica and the Southern Ocean and  
1007 what will future colonization processes be?

1008 7. What is the genetic diversity of Antarctic organisms and can improved constraints  
1009 on the timing of key evolutionary events be generated and, resulting from this,  
1010 insights into the long-term drivers of taxa distribution provided?

1011

### 1012 **8.3 First steps towards implementation.**

1013 There is a particular need for improved spatial coverage of biodiversity surveys and for  
1014 molecular phylogenies across more taxonomic groups, including links to non-Antarctic  
1015 regions and taxa, and to sample under-represented areas (e.g. sub-ice environments).

1016 This can only be achieved by increased sample and data exchange between national  
1017 programmes and individual scientists. Substantial advances in biogeographic

1018 understanding with an evolutionary background, however, will involve correlating  
1019 biodiversity distribution, occurrence of ecological key species and communities as well

1020 as ecosystem functions with evolutionary physical drivers. The integration of  
1021 bioinformatics and taxonomic skills will facilitate (a) the combination of classical

1022 approaches and state-of-the-art molecular techniques to reveal cryptic species diversity  
1023 and (b) large-scale barcoding initiatives of taxa based on molecular markers. These

1024 biodiversity assessments should be interlinked with climate modelling, and physical and  
1025 geosciences, including programmes aimed at monitoring environmental properties as

1026 part of large-scale networks, which will enable disentanglement of the drivers of  
1027 present-day diversity patterns. There is thus a particular need for developing finer-

1028 resolution glaciological, oceanographic, paleogeographic, atmospheric/climate

1029 reconstructions and models to study biological processes at biologically relevant scales.  
1030 These multidisciplinary programmes are required to achieve congruence between  
1031 geological and molecular and fossil-based estimates of evolutionary events, including  
1032 adaptive radiations, range expansions and contraction colonization events and regional  
1033 extinctions.

1034

1035

### 1036 **Discussion**

1037 Most ecosystems on the Antarctic continent and in the Southern Ocean are unique, and  
1038 vary greatly in their connectivity to other ecosystems on the planet. However, they all  
1039 are exposed to the high spatial and temporal variability of the physical climate  
1040 environment. The connection between Antarctic biological and non-biological systems  
1041 can be divided into the exposure of biota to environmental impact and the response of  
1042 life at all levels of organization to it, which contributes significantly to the functioning of  
1043 the entire Earth system. Thus, knowledge about Antarctic ecosystem functions arising  
1044 from question-based research is essential to understand these unique ecosystems in a  
1045 global context (di Prisco et al. 2012).

1046

1047 The aim of this conceptual study, built on the impetus provided by the *SCAR Horizon*  
1048 *Scan*, was to identify new science directions focussing on cross-disciplinarity, resulting  
1049 in a variety of questions, and to suggest the first steps towards their implementation.

1050 Most of the themes presented herein are polar / Antarctic specific but a few can be  
1051 applied to any biological system independent of global region or specific environmental  
1052 conditions, for instance the up- and downscaling challenges (1. Theme 1).

1053

1054 In this discussion overarching challenges are identified to find a certain generality  
1055 among the questions from the different themes. This type of clustering could provide an  
1056 extended basis for science managers and scientists to plan the realization of novel  
1057 approaches.

1058

1059 (A) Cross-disciplinary **bridging of methodological incompatibilities** between physical  
1060 and biological sciences, with respect to scales, is urgently needed. In an ecosystem  
1061 research approach both disciplines have the common aim to provide an Antarctic-wide  
1062 system understanding and to provide reliable results, which are representative of larger  
1063 areas, extended periods, or scientific phenomena, e.g. formation of deep water or  
1064 biological CO<sub>2</sub> uptake. If the desired Antarctic-wide geographical cover is not achievable  
1065 directly, it may instead be feasible through remote-sensing approaches or the  
1066 application of upscaling methods. All disciplines also require detailed insights into  
1067 system processes, where downscaling approaches help. Despite this common ground,  
1068 biological and non-biological disciplines often differ in important details. The following  
1069 requirements are therefore suggested: (1) a conformity of spatial and temporal scales  
1070 and resolution at which data are to be acquired and which should serve for up- and  
1071 downscaling approaches. Biological approaches generally demand *a priori* higher spatial  
1072 and temporal resolution than physical approaches, e.g. intermediate to small-scale krill  
1073 swarming behaviour is highly relevant as well as short-term and rare extreme events,  
1074 which can erase sessile benthic assemblages in a short period of time, which is hardly  
1075 traceable by physical scientists or biologists. (2) Biological data should be implemented  
1076 in interdisciplinary cause-and-effect relationships because biological phenomena  
1077 depend on the physical environment. Physical oceanographic information of biological  
1078 relevance, for instance changes in up- and down-welling, must be traced back to their

1079 source, in this case changes in wind regimes, to make spatial and temporal predictions  
1080 possible. Temperature increase throughout the entire water column can be the  
1081 consequence of horizontal and vertical shifts of water masses and also directly of  
1082 atmospheric warming. Changes in ocean pH follow increased atmospheric CO<sub>2</sub> levels in a  
1083 complex cause and effect relationship. Biologists also need specific information from the  
1084 sediments, groundwater and soil, e.g. age and biogeochemical characteristics, in order to  
1085 explain recruitment processes and optimum or limiting conditions for all life stages of  
1086 benthic, terrestrial or limnetic organisms. Less frequently, e.g. in the case of biological  
1087 production of climate-related gases, the situation is reversed. Biologists must provide  
1088 estimates of the uptake of CO<sub>2</sub> and production of climate gases mostly by marine  
1089 primary producers in order to improve regional and global climate models. Such  
1090 knowledge is essential for future projections including both the response of organisms,  
1091 communities and ecosystems to environmental change and the effects of life on the  
1092 atmosphere and ocean.

1093

1094 (B) Other complex questions centre around **learning from the past to understand the**  
1095 **present and predict the future**. This refers to the research on the molecular and  
1096 physiological adaptation of organisms to stable or changing environmental conditions  
1097 (3. Theme 3) and on attempts to correlate large-scale geotectonic and climate events  
1098 with evolutionary processes (8. Theme 8). Firstly, fundamental differences between  
1099 understanding biological processes and correspondingly driven cross-disciplinary and  
1100 physical as well as geological approaches are to be recognized. For instance, adaptations  
1101 over the past  $25 \times 10^6$  years are key to understanding lethal temperature thresholds that  
1102 have existed until the present day. If this threshold was exceeded even for a short period  
1103 of time at any point on this long time axis, the individual, population or even species may

1104 have become extinct. Knowledge of physical events that happened a few million years  
1105 ago can improve our understanding of the present environment but -in contrast to  
1106 biological adaptation- the weather of today is independent of the climate e.g.  $1 \times 10^6$   
1107 years ago. As a consequence, studies linking long-term environmental and biological  
1108 processes demand especially detailed knowledge, for instance on the timing of  
1109 geotectonic events that happened a long time ago to answer large-scale biogeographic  
1110 questions on the relationships between isolation and speciation. Also important in this  
1111 context is robust knowledge of the pace and amplitude of natural paleoclimate  
1112 variability in order to assess tolerance limits of species in a today's changing climate and  
1113 the potential of microevolution to cope with such changes. Finally, high-resolution  
1114 records of the recent past (i.e. the past 200 to 2000 years) allow us to determine when  
1115 observed trends started, what the amplitude of change / variability is that the modern  
1116 ecosystem has experienced and thus survived, and whether the current change is  
1117 accelerating.

1118

1119 (C) A main driver of the intensification of cross-disciplinary approaches must be the  
1120 pressing demand of **developing future scenarios** for ecosystems. Projections for cryo-  
1121 pelagic systems including marine primary production, are unimaginable without large-  
1122 scale and detailed knowledge of sea-ice dynamics. The development of benthic  
1123 communities can only be predicted if physical impacts on these systems can also be  
1124 predicted. In this context, important factors can include patterns and trends of iceberg  
1125 disturbance, altered sea-ice conditions or changes in turbidity associated with terrestrial  
1126 runoff. As a consequence of the latter, light attenuation, primary production and food  
1127 availability in shallow water are affected. General linkages between atmospheric and  
1128 biological traits are well known, such as the influence of precipitation or wind regimes

1129 on terrestrial ecosystem components. If such relationships are non-linear, as most are,  
1130 detailed knowledge on physical/chemical and biological interactions is essential for  
1131 understanding them and in quantifying future projected change. This refers especially to  
1132 the role of the Southern Ocean as a biological source or sink of CO<sub>2</sub>.

1133

1134 (D) Another major prerequisite to encourage cross-disciplinary cooperation is to  
1135 **highlight its added value** for scientific and applied purposes. The value of cross-  
1136 disciplinary approaches lie in bringing different disciplines together and tackling  
1137 questions and challenges, which cannot be answered through single-disciplinary  
1138 approaches. Such interactions often demand compromises within each respective  
1139 discipline. Notwithstanding the value and progress of fundamental single-disciplinary  
1140 research, a broader system understanding is demanded by society. Marine ecosystem  
1141 services play an increasing role especially in the IPBES and also in the IPCC assessments.  
1142 The value of terrestrial ecosystem protection in Antarctica is well recognised although  
1143 yet to be properly achieved (Chown et al. 2017). A recent and first notable success for  
1144 the Southern Ocean is the designation of the Ross Sea Marine Protected Area by the  
1145 *Commission for the Conservation of Antarctic Marine Living Resources*, following smaller  
1146 predecessors of marine *Antarctic Specially Protected Areas* and *Vulnerable Marine*  
1147 *Ecosystems*. Further progress in this direction is expected from the *Antarctic Treaty*  
1148 *System* and its *Committee for Environmental Protection* supported with scientific  
1149 expertise through SCAR and its SRPs.

1150

1151 (E) The necessity of **comparative studies**, an approach which is not generally novel but  
1152 remains rare in Antarctic research, is particularly important, especially in a cross-  
1153 disciplinary context. Useful comparisons can be made between ecosystem functioning in



1154 areas subject to intensive versus little environmental change, shallow water versus  
1155 deep-sea regions, and terrestrial coastal areas of deglaciation versus near-shore marine  
1156 systems under the same stress regime. Antarctic-Arctic polar comparisons are generally  
1157 beneficial in the context of understanding ecosystem functioning especially under  
1158 climate change stress, for instance in the framework of the *International Polar Year -*  
1159 *Evolution and Biodiversity in the Antarctic* programme *Team-Fish* (Christiansen 2012).  
1160 The fastest environmental changes on Earth, accompanied by sea-ice decline, are  
1161 occurring in the Arctic and at the WAP. Predictions from the cross-disciplinary  
1162 comparative approach can help in answering questions on response of polar marine  
1163 organisms, for instance type and extent of new species distributions, the relationship  
1164 between primary production and climate and the capacity to develop resilience to  
1165 ongoing global warming. This seems to be especially valuable when predictions for one  
1166 system, for instance the Arctic, can be ground-truthed through monitoring programmes  
1167 for reliability and then, after necessary modification be applied to the Antarctic. A polar  
1168 comparison would also considerably improve assessment of the potential of adaptation  
1169 as a result of evolution under two quite different polar scenarios.

1170

1171 (F) **Monitoring** or long-term observations provide the basis for comparisons of  
1172 significant ecological changes or background variability in time and support most of the  
1173 Themes 2-7; especially important is the integration of biological with atmospheric,  
1174 glaciological, oceanographic, and geological measurements.

1175

1176 The *SCAR Horizon Scan* (Kennicutt II et al. 2014, 2015) was the major catalyst leading to  
1177 the brain-storming approach of the 2015 Barcelona workshop. A coarse comparison  
1178 between the *SCAR Horizon Scan* and the '*Barcelona*' outcomes show a certain overlap but

1179 also differences. A true comparison is difficult because, despite an interdisciplinary  
1180 background, most *SCAR Horizon Scan* questions are dominated by one scientific  
1181 discipline, whilst our approach herein attempted to build bridges between disciplines.  
1182 Scale issues, considered either as a scientifically challenging approach or methodological  
1183 problem to be solved, are especially highlighted in this study. Compared to the *SCAR*  
1184 *Horizon Scan*, various aspects of sea-ice research are well represented by the '*Barcelona*'  
1185 questions. Considerable overlap exists between both studies in climate-change relevant  
1186 themes, whilst questions focussing on primarily climate-change independent ecosystem  
1187 functioning are more strongly represented in this study. In this study, an attempt was  
1188 also made to provide first ideas on how to answer the questions, and societal  
1189 requirements by intergovernmental panels and platforms, which are outlined in the  
1190 introduction. While the *SCAR Horizon Scan* (Kennicutt II et al. 2015) and the *Council of*  
1191 *Managers of National Antarctic Programs* (COMNAP, Kennicutt II et al. 2016)  
1192 emphasized technological challenges, below we make also some general  
1193 recommendations about which developments in science strategies that could strengthen  
1194 cross-disciplinary research in Antarctica.

1195

1196 The progress of cross-disciplinary development is largely a matter of science structural  
1197 management (Fig. 1). This includes alignment of the scientist's 'attitude', funding  
1198 strategies that genuinely engage with cross-disciplinary proposals, logistic organisation,  
1199 especially in the less accessible Antarctic areas, and the recognition and adoption of the  
1200 most valuable approaches concurrent with discarding outdated traditions. Most of the  
1201 techniques required for advanced cross-disciplinary studies already exist (e.g. Poorter et  
1202 al. 2017). They are often expensive and some are under (continual) development often  
1203 driven by single-disciplinary projects, such as drilling through ice shelves for physical

1204 oceanography purposes or deep-sea sampling (Brandt et al. 2016). Other technologies,  
1205 such as biomolecular methods, are developed beyond the communities of Antarctic  
1206 researchers but must be adapted to the specific polar conditions. Society, which also  
1207 drives research budgets, increasingly demands detailed and open information, which  
1208 can arise only from cross-disciplinary cooperation. Thus, the conditions for working in  
1209 synergy with holistic approaches are currently favourable for expanding such research  
1210 effort, which must be further developed along with advances in highly specialized fields  
1211 of research. Within the science community, good question-driven science management  
1212 will be a key for the success of more advanced cross-disciplinary studies. Major progress  
1213 towards such visions may be catalysed by a better implementation of a whole-system  
1214 vision in academic education, introducing more cross-disciplinary university courses  
1215 and even academic degrees.

1216

1217 **Acknowledgements:**

1218 Thanks are due to the Institute of Marine Sciences in Barcelona, Spain, for hosting the  
1219 workshop. Participants of the workshop in addition to the authors were: O. Schofield, F.  
1220 Jopp, S. Imura, M. England.

1221 **Funding:**

1222 In addition to the employers of the authors this study was funded by: SCAR SRPs AnT-  
1223 ERA, AntClim21 and AntEco.

1224

1225 **Contributions to the manuscript:** Julian Gutt and Enrique Isla developed the general  
1226 concept, including introduction and conclusion; all authors contributed. In addition, G. E.  
1227 Bodeker, N. G. Wilson, T. Bracegridle and P. Convey contributed to significant linguistic  
1228 improvements. The following authors (abbreviated by first and surnames) contributed

1229 substantially to the specific Themes: Theme 1: CS, JG, PC; Theme 2: NB, SS, ALK, DHW,  
1230 TS; Theme 3: AP, CV, HJG, GdP, UNN, VC; Theme 4: AEM, CRS, GEB, IRS, JG, ST, TJB, UNN;  
1231 Theme 5: JCX, YR-C; Theme 6: DDM, EI, EV, IRS, JG; Theme 7: AEM, GdP, JCC, JMS, JS,  
1232 NGW, RDC, RS, TJB, VC; Theme 8: EV, SO, PC, JS, NGW, SS, DDM, JL-M.  
1233

1234 **References**

1235

1236 Ådlandsvik, B. & Bentsen, M. 2007. Downscaling a twentieth century global climate  
1237 simulation to the North Sea. *Ocean Dynamics*, **57**, 453-466.

1238

1239 Allcock, A.L., Barratt, I., Eléaume, M., Linse, K., Norman, M.D., Smith, P.J., Steinke, D.,  
1240 Stevens, D.W. & Strugnell, J.M. 2011. Cryptic speciation and the circumpolarity debate: a  
1241 case study on endemic Southern Ocean octopuses using the *coxI* barcode of life. *Deep-Sea*  
1242 *Research II – Topical Studies in Oceanography*, **58**, 242-248.

1243

1244 Allcock, A.L. & Strugnell, J.M. 2012. Southern Ocean diversity: new paradigms from  
1245 molecular ecology. *Trends in Ecology and Evolution*. 10.1016/j.tree.2012.05.009.

1246

1247 Arrigo, K.R., van Dijken, G.L., Ainley, D.G., Fahnestock, M.A. & Marcus, T. 2002. Ecological  
1248 impact of a large Antarctic iceberg. *Geophysical Research Letters*, **29**,  
1249 10.1029/2001GL014160.

1250

1251 Atkinson, A., Siegel, V., Pakhomov, E. & Rothery, P. 2004. Long-term decline in krill  
1252 stock and increase in salps within the Southern Ocean. *Nature*, **432**, 100-103.

1253

1254 Bailey, R.G. 2014. *Ecoregions. The Ecosystem Geography of the Oceans and Continents*.  
1255 New York: Springer-Verlag, 2<sup>nd</sup> edition, ISBN 978-1-4939-3706-6, 180 pp.

1256

1257 Barnes, D.K.A., Griffiths H.J. & Kaiser S. 2009. Geographical range shift responses to  
1258 climate change by Antarctic benthos: where we should look. *Marine Ecology Progress*  
1259 *Series*, **393**, 13-26.

1260

1261 Barnes, D.K.A. & Hillenbrand, C.D. 2010. Faunal evidence for a late quaternary trans-  
1262 Antarctic seaway. *Global Change Biology*, **16**, 3297-3303.

1263

1264 Bergstrom, D.M, Convey, P. & Huiskes, A.H.L., eds. 2006. Trends in Antarctic Terrestrial  
1265 and Limnetic Ecosystems: Antarctica as a Global Indicator. Dordrecht: Springer.

1266

1267 Bertolin, M.L. & Schloss, I.R. 2009. Phytoplankton production after the collapse of the  
1268 Larsen A Ice Shelf, Antarctica. *Polar Biology*, **32**, 1435-1446.

1269

1270 Blois, J.L., Zarnetske, P.L., Fitzpatrick, M.C. & Finnegan, S. 2013. Climate change and the  
1271 past, present, and future of biotic interactions. *Science*, **341**, 499-504.

1272

1273 Bracegirdle, T. & Stephenson, D. 2012. Higher precision estimates of regional polar  
1274 warming by ensemble regression of climate model projections. *Climate Dynamics*,  
1275 10.1007/s00382-012-1330-3.

1276

1277 Brandt, A., Gutt, J., Hildebrandt, M., Pawlowski, J., Schwendner, J., Soltwedel, T. &  
1278 Thomsen, L. 2016. Cutting the umbilical: new technological perspectives in benthic  
1279 deep-sea research. *Journal of Marine Science and Engineering*, **4**, 36,  
1280 10.3390/jmse4020036.

1281

1282 Brasier, M.J., Wiklund, H., Neal, L., Jeffreys, R., Linse, K., Ruhl, H., & Glover, A.G. 2016. DNA  
1283 barcoding uncovers cryptic diversity in 50% of deep-sea Antarctic polychaetes. *Royal*  
1284 *Society Open Science*, **3**(11), 160432.

1285

1286 Chevin, L.M., Lande, R. & Mace, G.M. 2010. Adaptation, Plasticity and Extinction in a  
1287 Changing Environment: Towards a Predictive Theory. *Public Library of Science - Biology*,  
1288 **8**, e1000357, 10.1371/journal.pbio.1000357.

1289

1290 Chown, S.L., Lee, J. E., Hughes, K.A., Barnes, J., Barrett, P.J., Bergstrom, D.M., Convey, P.,  
1291 Cowan, D.A., Crosbie, K., Dyer, G., Frenot, Y., Grant, S.M., Herr, D., Kennicutt II, M.C.,  
1292 Lamers, M., Murray, A., Possingham, H.P., Reid, K., Riddlel, M.J., Ryan, P.G., Sanson, L.,  
1293 Shaw, J.D., Sparrow, M.D., Summerhayes, C., Terauds, A., & Wall, D.H. 2012. Challenges to  
1294 the future conservation of the Antarctic. *Science*, **337**, 158–159.

1295

1296 Chown, S.L., Huiskes, A.H.L., Gremmen, N.J.M., Lee, J.E., Terauds, A., Crosbie, K., Frenot, Y.,  
1297 Hughes, K.A., Imura, S., Kiefer, K., Lebouvier, M., Raymond, B., Tsujimotoi, M., Ware, C.,  
1298 Van de Vijver, B. & Bergstrom, D.M. 2012. Continent-wide risk assessment for the  
1299 establishment of nonindigenous species in Antarctica. *Proceedings of the National*  
1300 *Academy of Sciences of the United States of America*, **109**, 4938–4943

1301

1302 Chown, S.L., Clarke, A., Fraser, C.I., Cary, S.C., Moon, K.L. & McGeoch, M.A. 2015. The  
1303 changing form of Antarctic biodiversity. *Nature*, **522**, 431-438.

1304

1305 Chown, S.L., Brooks, C.M., Terauds, A., Le Bohec, C., van Klaveren-Impagliazzo, C.,  
1306 Whittington, J.D., Butchart, S.H.M., Coetzee, B.W.T., Collen, B., Convey, P., Gaston, K.J.,

1307 Gilbert, N., Gill, M., Höft, R., Johnston, S., Kennicutt II, M.C., Kriesell, H.J., Le Maho, Y.,  
1308 Lynch, H.J., Palomares, M., Puig-Marcó, R., Stoett, P. & M.A. McGeoch, M.A. 2017.  
1309 Antarctica and the strategic plan for biodiversity. *PLoS Biology*, **15(3)**, e2001656.  
1310 10.1371/journal.pbio.2001656.  
1311  
1312 Christiansen, J.S. 2012. The TUNU-programme: Euro-Arctic marine fishes – Diversity and  
1313 adaptation. In: di Prisco, G. & Verde, C., eds. *Adaptation and Evolution in Marine*  
1314 *Environments - The Impacts of Global Change on Biodiversity, vol 1, Series "From Pole to*  
1315 *Pole"*. Berlin: Springer, 35-73.  
1316  
1317 Clarke, A. & Crame, J.A. 1989. The origin of the Southern Ocean marine fauna. In Crame,  
1318 J.A., ed. *Origins and Evolution of the Antarctic biota*. London: The Geological Society,  
1319 Special Publications, **47**, 253-268.  
1320  
1321 Comiso, J.C., Gersten, R., Stock, L., Turner J., Perez G. & Cho K. 2017. Positive trends in the  
1322 Antarctic sea ice cover and associated changes in surface temperature. *Journal of*  
1323 *Climate*, 10.1175/JCLI-D-0408.1.  
1324  
1325 Constable, A.J., Melbourne-Thomas, J., Corney, S.P., Arrigo, K.R., Barbraud, C., Barnes,  
1326 D.K.A., Bindoff, N.L., Boyd, P.W., Brandt, A., Costa, D.P., Davidson, A.T., Ducklow, H.W.,  
1327 Emmerson, L., Fukuchi, M., Gutt, J., Hindell, M.A., Hofmann, E.E., Hosie, G.W., Iida, T.,  
1328 Jacob, S., Johnston, N.M., Kawaguchi, S., Kokubun, N., Koubbi, P., Lea, M.-A., Makhado, A.,  
1329 Massom, R.A., Meiners, K., Meredith, M.P., Murphy, E.J., Nicol, S., Reid, K., Richerson, K.,  
1330 Riddle, M.J., Rintoul, S.R., Smith Jr, W.O., Southwell, C., Stark, J.S., Sumner, M., Swadling,  
1331 K.M., Takahashi, K.T., Trathan, P.N., Welsford, D.C., Weimerskirch, H., Westwood, K.J.,



1332 Wienecke, B.C., Wolf-Gladrow, D., Wright, S.W., Xavier, J.C. & Ziegler, P. 2014. Climate  
1333 change and Southern Ocean ecosystems I: how changes in physical habitats directly  
1334 affect marine biota. *Global Change Biology*, 10.1111/gcb.12623.

1335

1336 Convey, P., Gibson, J.A.E., Hillenbrand, C.D., Hodgson, D.A., Pugh, P.J.A., Smellie, J.L. &  
1337 Stevens, M.I. 2008. Antarctic terrestrial life - challenging the history of the frozen  
1338 continent? *Biological Reviews*, **83**, 103-117.

1339

1340 Convey, P., Stevens, M.I., Hodgson, D.A., Smellie, J.L., Hillenbrand, C.D., Barnes, D.K.A.,  
1341 Clarke, A., Pugh, P.J.A., Linse, K. & Cary, S.C. 2009. Exploring biological constraints on the  
1342 glacial history of Antarctica. *Quaternary Science Reviews*, **28**, 3035-3048.

1343

1344 Convey, P., Hughes, K.A. & Tin, T. 2012. Continental governance and environmental  
1345 management mechanisms under the Antarctic Treaty System: sufficient for the  
1346 biodiversity challenges of the next century? *Biodiversity*, **13**, 234-248.

1347

1348 Convey, P., Chown, S.L., Clarke, A., Barnes, D.K.A., Bokhorst, S., Cummings, V., Ducklow,  
1349 H.W., Frati, F., Green, T.G.A., Gordon, S., Griffiths, H.J., Howard-Williams, C., Huiskes,  
1350 A.H.L., Laybourn-Parry, J., Lyons, W.B., McMinn, A., Morley, S.A., Peck, L.S., Quesada, A.,  
1351 Robinson, S.A., Schiaparelli, S. & Wall, D.H. 2014. The spatial structure of Antarctic  
1352 biodiversity. *Ecological Monographs*, **84**, 203-244.

1353

1354 Davin, E.L., Phillips, A.S., van Uft, L.H. & Williams, K.D. 2016. ESMValTool (v1. 0)-a  
1355 community diagnostic and performance metrics tool for routine evaluation of Earth  
1356 system models in CMIP. *Geoscientific Model Development*, **9**, 1747.

1357  
1358 De Broyer, C., Koubbi, P., Griffiths, H.J., Raymond, B., d'Udekem d'Acoz, C., Van de Putte,  
1359 A.P., Danis, B., David, B., Grant, S., Gutt, J., Held, C., Hosie, G., Huettmann, F., Post, A. &  
1360 Ropert-Coudert, Y. 2014. *Biogeographic Atlas of the Southern Ocean*. Cambridge: SCAR,  
1361 498 pp.

1362  
1363 De Conto, R.M., & Pollard, D. 2016 Contribution of Antarctica to past and future sea-level  
1364 rise. *Nature*, **531**, 591-597.

1365  
1366 De Pooter, D., Appeltans, W., Bailly, N., Bristol, S., Deneudt, K., Eliezer, M., Fujioka, E.,  
1367 Giorgetti, A., Goldstein, P., Lewis, M., Lipizer, M., Mackay, K., Marin, M., Moncoiffé, G.,  
1368 Nikolopoulou, S., Provoost, P., Rauch, S., Roubicek, A., Torres, C., van de Putte, A.,  
1369 Vandepitte, L., Vanhoorne, B., Vinci, M., Wambiji, N., Watts, D., Klein Salas, E. &  
1370 Hernandez, F. 2017. Toward a new data standard for combined marine biological and  
1371 environmental datasets - expanding OBIS beyond species occurrences. *Biodiversity Data*  
1372 *Journal*, **5**, e10989, 10.3897/BDJ.5.e10989.

1373  
1374 di Prisco, G., Convey, P., Gutt, J., Cowan, D., Conlan, K. & Verde, C. 2012. Understanding  
1375 and protecting the world's biodiversity: The role and legacy of the SCAR programme  
1376 "Evolution and Biodiversity in the Antarctic". *Marine Genomics*, **8**, 3-8.

1377  
1378 Díaz, A., Féral, J.P., David, B., Saucède, T. & Poulin, E. 2011. Evolutionary pathways among  
1379 shallow and deep-sea echinoids of the genus *Sterechinus* in the Southern Ocean. *Deep*  
1380 *Sea Research Part II – Topical Studies in Oceanography*, **58**, 205-211.

1381

1382 Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A.,  
1383 Adhikari, J.R., Arico, S., Báldi, A., Bartuska, A., Baste, I.A., Bilgin, A., Brondizio, E., Chan,  
1384 K.M.A., Figueroa, V.E., Duraiappah, A., Fischer, M., Hill, R., Koetz, T., Leadley, P., Lyver, P.,  
1385 Georgina, M., Mace, G.M., Martin-Lopez, B., Okumura, M., Pacheco, D., Pascual, U., Pérez,  
1386 E.S., Reyers, B., Roth, E., Saito, O., Scholes, R.J., Sharma, N., Tallis, H., Thaman, R., Watson,  
1387 R., Yahara, T., Hamid, Z.A., Akosim, C., Al-Hafedh, Y., Allahverdiyev, R., Amankwah, E.,  
1388 Asah, S.T., Asfaw, Z., Bartus, G., Brooks, L.A., Caillaux, J., Dalle, G., Darnaedi, D., Driver, A.,  
1389 Erpul, G., Escobar-Eyzaguirre, P., Failler, P., Fouda, A.M.M., Fu, B., Gundimeda, H.,  
1390 Hashimoto, S., Homer, F., Lavorel, S., Lichtenstein, G., Mala, W.A., Mandivenyi, W.,  
1391 Matczak, P., Mbizvo, C., Mehrdadi, M., Metzger, J.P., Mikissa, J.B., Moller, H., Mooney, H.A.,  
1392 Mumby, P., Nagendra, H., Nesshöver, C., Oteng-Yeboah, A.A., Pataki, G., Roué, M., Rubis, J.,  
1393 Schultz, M., Smith, P., Sumaila, R., Takeuchi, K., Thomas, S., Verma, M., Yeo-Chang, Y. &  
1394 Zlatanova, D. 2015. The IPBES Conceptual Framework - connecting nature and people.  
1395 *Current Opinion in Environmental Sustainability*, **14**, 1–16, 10.1016/j.cosust.2014.11.002  
1396  
1397 Favero-Longo, S.E., Worland, M.R., Convey, P., Piervittori, R., Guglielmin, M. & Cannone,  
1398 N. 2012. Primary succession of lichen and bryophyte communities following glacial  
1399 recession on Signy Island, South Orkney Islands, maritime Antarctic. *Antarctic Science*,  
1400 **24**, 323-336.  
1401  
1402 Fountain, A.G., Saba, G., Adams, B., Doran, P., Fraser, W., Gooseff, M., Obryk, M., Priscu,  
1403 J.C., Stammerjohn, S., & Virginia, R.A. 2016. The Impact of a large-scale climate event on  
1404 Antarctic ecosystem processes. *BioScience*, **66**, 848-863.  
1405

1406 Fraser, C.I., Nikula, R., Ruzzante, D.E. & Waters, J.M. 2012. Poleward bound: biological  
1407 impacts of Southern Hemisphere glaciation. *Trends in Ecology and Evolution*, **27**, 462-  
1408 471.

1409

1410 Fraser, C.I., Terauds, A., Smellie, J., Convey, P. & Chown, S.L. 2014. Geothermal activity  
1411 helps life survive glacial cycles. *Proceedings of the National Academy of Sciences of the*  
1412 *United States of America*, **111**, 5634-5639.

1413

1414 Frenot, Y., Chown, S. L., Whinam, J., Selkirk, P. M., Convey, P., Skotnicki, M. & Bergstrom,  
1415 D. M. 2005. Biological invasions in the Antarctic: extent, impacts and implications.  
1416 *Biological Reviews*, **80**, 45-72.

1417

1418 Gilichinsky, D.A., Wilson, G.S., Friedmann, E.I., McKay, C.P., Sletten, R.S., Rivkina, E.M.,  
1419 Vishnivetskaya, T.A., Erokhina, L.G., Ivanushkina, N.E., Kochkina, G.A., Shcherbakova,  
1420 V.A., Soina, V.S., Spirina, E.V., Vorobyova, E.A., Fyodorov-Davydov, D.G., Hallet, B.,  
1421 Ozerskaya, S.M., Sorokovikov, V.A., Laurinavichyus, K.S., Shatilovich, A.V., Chanton, J.P.,  
1422 Ostroumov, V.E. & Tiedje, J.M. 2007. Microbial populations in Antarctic permafrost:  
1423 biodiversity, state, age, and implication for astrobiology. *Astrobiology*, **7**, 275-311.

1424

1425 Grant, S.M., Hill, S.L., Trathan, P.N. & Murphy, E.J. 2013. Ecosystem services of the  
1426 Southern Ocean: trade-offs in decision-making. *Antarctic Science*, **25**, 603-617,  
1427 [10.1017/S0954102013000308](https://doi.org/10.1017/S0954102013000308).

1428

1429 Gutt, J., Barratt, I., Domack, E., d'Udekem d'Acoz, C., Dimmler, W., Grémare, A., Heilmayer,  
1430 O., Isla, E., Janussen, D., Jorgensen, E., Kock, K.-H., Lehnert, L.S., López-González, P.,

1431 Langner, S., Linse, K., Manjón-Cabeza, M.E., Meißner, M., Montiel, A., Raes, M., Robert, H.,  
1432 Rose, A., Sañé Schepisi, E., Saucède, T., Scheidat, M., Schenke, H.-W., Seiler, J. & Smith, C.  
1433 2011. Biodiversity change after climate-induced ice-shelf collapse in the Antarctic. *Deep-*  
1434 *Sea Research II- Topical Studies in Oceanography*, **58**, 74-83.

1435

1436 Gutt, J., Zurell, D., Bracegridle, T.J., Cheung, W., Clarke, M.S., Convey, P., Danis, B., David,  
1437 B., De Broyer, C., di Prisco, G., Griffiths, H., Laffont, R., Peck, L., Pierrat, B., Riddle, M.J.,  
1438 Saucède, T., Turner, J., Verde, C., Wang, Z. & Grimm, V. 2012. Correlative and dynamic  
1439 species distribution modelling for ecological predictions in the Antarctic: a cross-  
1440 disciplinary concept. *Polar Research*, **31**, 11091, 10.3402/polar.v31i0.11091.

1441

1442 Gutt, J., Adams, B., Bracegirdle, T., Cowan, D., Cummings, V., di Prisco, G., Gradinger, R.,  
1443 Isla, E., McIntyre, T., Murphy, E., Peck, L., Schloss, I., Smith, C., Suckling, C., Takahashi, A.,  
1444 Verde, C., Wall, D.H. & Xavier, J. 2013a. Antarctic Thresholds - Ecosystem Resilience and  
1445 Adaptation a new SCAR-Biology Programme. *Polarforschung*, **82**, 147-150.

1446

1447 Gutt, J., Griffiths, H.J. & Jones, C.D. 2013b. Circum-polar overview and spatial  
1448 heterogeneity of Antarctic macrobenthic communities. *Marine Biodiversity*, **43**, 481-487,  
1449 10.1007/s12526-013-0152-9.

1450

1451 Gutt, J., Cape, M., Dimmler, W., Fillinger, L., Isla, E., Lieb, V., Lundälv, T. & Pulcher, C.  
1452 2013c. Shifts in Antarctic megabenthic structure after ice-shelf disintegration in the  
1453 Larsen area east of the Antarctic Peninsula. *Polar Biology*, **36**, 895-906.

1454

1455 Gutt, J., Bertler, N., Bracegirdle, T.J., Buschmann, A., Comiso, J., Hosie, G., Isla, E., Schloss,  
1456 I.R., Smith, C.R., Tournadre, J. & Xavier, J.C. 2015. The Southern Ocean ecosystem under  
1457 multiple climate stresses - an integrated circumpolar assessment. *Global Change Biology*,  
1458 **21**, 1434-1453, 10.1111/geb.12794.

1459

1460 Hawkins, E., Smith, R.S., Gregory, J.M. & Stainforth D.A. 2016. Irreducible uncertainty in  
1461 near-term climate projections. *Climate Dynamics*, **46**, 3807, 10.1007/s00382-015-2806-  
1462 8.

1463

1464 Hughes, K.A., Worland, M.R., Thorne, M.A.S., & Convey, P. 2013. The non-native  
1465 chironomid *Eretmoptera murphyi* in Antarctica: erosion of the barriers to invasion.  
1466 *Biological Invasions*, **15**, 269-281.

1467

1468 Hughes, K.A., Pertierra, L.R., Molina-Montenegro, M.A. & Convey, P. 2015. Biological  
1469 invasions in Antarctica: what is the current status and can we respond? *Biodiversity and*  
1470 *Conservation*, **24**, 1031-1055.

1471

1472 IPCC 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working*  
1473 *Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

1474 Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y.,  
1475 Bex, V. & Midgley, P.M. eds. Cambridge: Cambridge University Press,  
1476 10.1017/CBO9781107415324.

1477

1478 Isla, E., Gerdes, D., Palanques, A., Gili, J.-M., Arntz, W.E. & König-Langlo, G. 2009.  
1479 Downward particle fluxes, wind and a phytoplankton bloom over a polar continental  
1480 shelf: A stormy impulse for the biological pump. *Marine Geology*, **259**, 59-72.  
1481  
1482 Jenouvrier, S., Caswell, H., Barbraud, C., Holland, M. & Strøve, J. 2009. Demographic  
1483 model and IPCC climate projections predict the decline of an emperor penguin  
1484 population. *Proceedings of the National Academy of Sciences of the United States of*  
1485 *America*, **106**, 1844–1847, 10.1073/pnas.0806638106.  
1486  
1487 Jones, J.M., Gille, S.T., Goosse, H., Abram, N.J., Canziani, P.O., Charman, D.J., Clem, K.R.,  
1488 Crosta, X., de Lavergne, C. & Eisenman, I. 2016. Assessing recent trends in high-latitude  
1489 Southern Hemisphere surface climate. *Nature Climate Change*, **6**, 917-926, 2016.  
1490  
1491 Kay, J.E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J., Bates, S.,  
1492 Danabasoglu, G., Edwards, J., Holland, M. Kushner, P., Lamarque, J.-F., Lawrence, D.,  
1493 Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L. & M. Vertenstein  
1494 2015. The Community Earth System Model (CESM) Large Ensemble Project: A  
1495 Community Resource for Studying Climate Change in the Presence of Internal Climate  
1496 Variability. *Bulletin of the American Meteorological Society*, **96**, 1333-1349,  
1497 10.1175/BAMS-D-13-00255.1.  
1498  
1499 Kearney, M. & Porter, W. 2009. Mechanistic niche modelling: combining physiological  
1500 and spatial data to predict species ranges. *Ecology Letters*, **12**, 1–17, 10.1111/j.1461-  
1501 0248.2008.01277.x  
1502

1503 Kennicutt II, M.C., Cassano, J.J., Liggett, D., Massom, R., Peck, S., Rintoul, S.R., Storey,  
1504 J.W.V., Vaughan, D.G., Wilson, T.J. & Sutherland, W.J. 2014. Six priorities for Antarctic  
1505 science. *Nature*, **512**, 23-25.

1506

1507 Kennicutt II, M.C., Chown, S.L., Cassano, J.J., Liggett, D., Peck, L.S., Massom, R., Rintoul,  
1508 S.R., Storey, J., Vaughan, D.G., Wilson, T.J., Allison, I., Ayton, J., Badhe, R., Baeseman, J.,  
1509 Barrett, P.J., Bell, R.E., Bertler, N., Bo, S., Brandt, A., Bromwich, D., Cary, S.C., Clark, M.S.,  
1510 Convey, P., Costa, E.S., Cowan, D., DeConto, R., Dunbar, R., Elfring, C., Escutia, C., Francis,  
1511 J., Fricker, H.A., Fukuchi, M., Gilbert, N., Gutt, J., Havermans, C., Hik, D., Hosie, G., Jones, C.,  
1512 Kim, Y.D., Le Mahon, Y., Lee, S.H., Leppe, M., Leychenkov, G., Li, X., Lipenkov, V., Lochte, K.,  
1513 López-Martínez, J., Lüdecke, C., Lyons, W., Marensi, S., Miller, H., Morozova, P., Naish, T.,  
1514 Nayak, S., Ravindra, R., Retamales, J., Ricci, C.A., Rogan-Finnemore, M., Ropert-Coudert,  
1515 Y., Samah, A.A., Sanson, L., Scambos, T., Schloss, I.R., Shiraishi, K., Siegert, M.J., Simões, J.C.,  
1516 Storey, B., Sparrow, M.D., Wall, D.H., Walsh, J.C., Wilson, G., Winther, J.G., Xavier, J.C., Yang,  
1517 H. & Sutherland, W.J. 2015. A roadmap for Antarctic and Southern Ocean science for the  
1518 next two decades and beyond. *Antarctic Science*, **27**, 3-18,  
1519 10.1017/S0954102014000674.

1520

1521 Kennicutt II, M.C., Kim, Y. & Rogan-Finmore, M. 2016. Antarctic roadmap challenges.  
1522 Council of Managers of National Antarctic Programs (COMNAP); ISBN 978-0-473-35673-  
1523 6 (pdf).

1524

1525 Koubbi, P., Ozouf-Costaz, C., Goarant, A., Moteki, M., Hulley, P.A., Causse, R., Dettai, A.,  
1526 Duhamel, G., Pruvost, P., Tavernier, E., Prost, A.L., Beaman, R.J., Rintoul, S.R., Hirawake, T.,  
1527 Hirano, D., Ishimaru, T., Riddle, M. & Hosie G. 2010. Estimating the biodiversity of the



1528 East Antarctic shelf and oceanic zone for ecoregionalisation: Example of the  
1529 ichthyofauna of the CEAMARC (Collaborative East Antarctic Marine Census) CAML  
1530 surveys. *Polar Science*, **4**, 115-133.

1531

1532 Kwok, R., Comiso, J.C., Lee, T. & Holland, P.R. 2016. Linked trends in the South Pacific sea  
1533 ice edge and Southern Oscillation Index. *Geophysical Research Letters*, **43**,  
1534 10.1002/2016GL070655.

1535

1536 Lavergne, S., Mouquet, N., Thuiller, W. & Ronce, O. 2010. Biodiversity and climate  
1537 change: integrating evolutionary and ecological responses of species and communities.  
1538 *Annual Review of Ecology, Evolution, and Systematics*, **41**, 321-350.

1539

1540 Lewis, J., Bodeker, G.E., Tait, A. & Kremser, S. 2017. A method to encapsulate model  
1541 structural uncertainty in ensemble projections of future climate. *Geoscientific Model  
1542 Development Discussions*, 10.5194/gmd-2017-5136.

1543

1544 Lyons, W.B., Deuerling, K., Welch, K.A., Welch, S.A., Michalski, G., Walters, W.W., Nielsen,  
1545 U., Wall, D.H., Hogg, I. & Adams, B.J. 2016. The soil geochemistry in the Beardmore  
1546 Glacier Region, Antarctica: Implications for terrestrial ecosystem history. *Scientific  
1547 Reports (Nature)*, **6**, 10.1038/srep26189.

1548

1549 Mayewski, P.A., Meredith, M.P., Summerhayes, C.P., Turner, J., Worby, A., Barrett, P.J.,  
1550 Casassa, G., Bertler, N.A., Bracegirdle, T., Naveira Garabato, A.C. & Bromwich, D. 2009.  
1551 State of the Antarctic and Southern Ocean climate system. *Reviews of Geophysics*, **47**, RG  
1552 1003/2009, 10.1029/2007RG000231.

1553

1554 Mecklenburg, C.W., Møller, P.R. & Steinke, D. 2010. Biodiversity of arctic marine fishes:  
1555 taxonomy and zoogeography. *Marine Biodiversity*, 10.1007/s12526-010-0070-z.

1556

1557 Montes-Hugo, M., Doney, S.C., Ducklow, H.W., Fraser, W., Martinson, D., Stammerjohn,  
1558 S.E. & Schofield O. 2009. Recent Changes in Phytoplankton Communities Associated with  
1559 Rapid Regional Climate Change Along the Western Antarctic Peninsula. *Science*, **323**,  
1560 1470-1473.

1561

1562 Murphy, E.J., Cavanagh, R.D., Johnston, N.M., Reid, K. & Hofmann, E.E. 2008. *Integrating*  
1563 *Climate and Ecosystem Dynamics (ICED): Science Plan and Implementation Strategy*.  
1564 GLOBEC Report No. 25.

1565

1566 Nielsen, U.N. & Wall, D.H. 2013. The future of soil invertebrate communities in polar  
1567 regions: different climate change responses in the Arctic and Antarctic? *Ecology Letters*,  
1568 **16**, 409–419.

1569

1570 Niiranen, S., Yletyinen, J., Tomczak, M.T., Blenckner, T., Hjerne, O., MacKenzie, B.R.,  
1571 Müller-Karulis, B., Neumann, T. & Meier, H.E. 2013. Combined effects of global climate  
1572 change and regional ecosystem drivers on an exploited marine food web. *Global Change*  
1573 *Biology*, **19**, 3327-3342.

1574

1575 Nkem, J.N., Virginia, R.A., Barrett, J.E., Wall, D.H. & Li, G. 2006. Salt tolerance and survival  
1576 thresholds for two species of Antarctic soil nematodes. *Polar Biology*, **29**, 643–651.

1577

1578 PAGES 2ka Consortium 2013. Continental-scale temperature variability during the past  
1579 two millennia. *Nature Geoscience*, **6**, 339-346, 10.1038/ngeo1797, 2013.

1580

1581 Peck, L.S., Convey, P. & Barnes, D.K.A. 2006. Environmental constraints on life histories  
1582 in Antarctic ecosystems: tempos, timings and predictability. *Biological Reviews*, **81**, 75-  
1583 109.

1584

1585 Peck, L.S. 2011. Organisms and responses to environmental change. *Marine Genomics*, **4**,  
1586 237-243.

1587

1588 Pinkerton, M.H., Smith, A.N., Raymond, B., Hosie, G.W., Sharp, B., Leathwick, J.R. &  
1589 Bradford-Grieve, J.M. 2010. Spatial and seasonal distribution of adult *Oithona similis* in  
1590 the Southern Ocean: predictions using boosted regression trees. *Deep Sea Research Part*  
1591 *I: Oceanographic Research Papers*, **57**, 469-485.

1592

1593 Pointing, S.B., Budel, B., Convey, P., Gillman, L.N., Korner, C., Leuzinger, S. & Vincent, W.F.  
1594 2015. Biogeography of photoautotrophs in the high polar biome. *Frontiers in Plant*  
1595 *Science*, **6**, art 692.

1596

1597 Pörtner, H.O. & Gutt, J. 2016. Impacts of climate variability and change on (marine)  
1598 animals: physiological underpinnings and evolutionary consequences. *Integrative and*  
1599 *Comparative Biology*, **56**, 31-44.

1600

1601 Poulin, E., Palma, A.T. & Feral, J.P. 2002. Evolutionary versus ecological success in  
1602 Antarctic benthic invertebrates. *Trends in Ecology and Evolution*, **17**, 218-222.

1603

1604 Pugh, P.J.A. & Convey, P. 2008. Surviving out in the cold: Antarctic endemic invertebrates  
1605 and their refugia. *Journal of Biogeography*, **35**, 2176-2186.

1606

1607 Rickard, G.J., Roberts, M.J., Williams, M.J., Dunn, A. & Smith, M.H. 2010. Mean circulation  
1608 and hydrography in the Ross Sea sector, Southern Ocean: representation in numerical  
1609 models. *Antarctic Science*, **22**, 533-558.

1610

1611 Riebesell, U., Schloss, I. & Smetacek, V. 1991. Aggregation of algae released from melting  
1612 sea ice: implications for seeding and sedimentation. *Polar Biology*, **11**, 239-248.

1613

1614 Rintoul, S., Sparrow, M., Meredith, M., Wadley, V., Speer, K., Hofmann, E., Summerhayes,  
1615 C., Urban, E., Bellerby, R., Ackley, S., Alverson, K., Ansorge, I., Aoki, S., Azzolini, R., Beal, L.,  
1616 Belbeoch, M., Bergamasco, A., Biuw, M., Boehme, L., Budillon, G., Campos, L., Carlson, D.,  
1617 Cavanagh, R., Charpentier, E., Chul Shin, H., Coffin, M., Constable, A., Costa, D., Cronin, M.,  
1618 De Baar, H., De Broyer, C., De Bruin, T., De Santis, L., Butler, E., Dexter, P., Drinkwater, M.,  
1619 England, M., Fahrbach, E., Fanta, E., Fedak, M., Finney, K., Fischer, A., Frew, R., Garzoli, S.,  
1620 Gernandt, H., Gladyshev, S., Gomis, D., Gordon, A., Gunn, J., Gutt, J., Haas, C., Hall, J.,  
1621 Heywood, K., Hill, K., Hindell, M., Hood, M., Hoppema, M., Hosie, G., Howard, W., Joiris, C.,  
1622 Kaleschke, L., Kang, S., Kennicutt, M., Klepikov, A., Lembke-Jene, L., Lovenduski, N., Lytle,  
1623 V., Mathieu, P., Moltmann, T., Morrow, R., Muelbert, M., Murphy, E., Naganobu, M.,  
1624 Naveira Garabato, A., Nicol, S., O'Farrell, S., Ott, N., Piola, A., Piotrowicz, S., Proctor, R.,  
1625 Qiao, F., Rack, F., Ravindra, R., Ridgway, K., Rignot, E., Ryabinin, V., Sarukhanian, E.,  
1626 Sathyendranath, S., Schlosser, P., Schwarz, J., Smith, G., Smith, S., Southwell, C., Speich, S.,  
1627 Stambach, W., Stammer, D., Stansfield, K., Thiede, J., Thouvenot, E., Tilbrook, B.,

1628 Wadhams, P., Wainer, I., Willmott Puig, V., Wijffels, S., Woodworth, P., Worby, T. &  
1629 Wright S. 2012. *The Southern Ocean observing system: Initial science and implementation*  
1630 *strategy*. SCAR and SCOR, ISBN: 978-0-948277-27-6.  
1631  
1632 Ropert-Coudert, Y. & Wilson, R.P. 2005. Trends and perspectives in animal-attached  
1633 remote sensing. *Frontiers in Ecology and Evolution*, **3**(8), 437–444. 10.1890/1540-  
1634 9295(2005)003[0437:TAPIAR][2.0.CO](#);2.  
1635  
1636 Roquet, F., Williams, G., Hindell, M. A., Harcourt, R., McMahon, C., Guinet, C., Charrassin,  
1637 J.-B., Reverdin, G., Boehme, L., Lovell, P. & Fedak, M. 2014. A Southern Indian Ocean  
1638 database of hydrographic profiles obtained with instrumented elephant seals. *Scientific*  
1639 *Data*, **1**, 140028. 10.1038/sdata.2014.28.  
1640  
1641 Sadowsky, A., Mettler-Altmann, T. & Ott, S. 2016. Metabolic response to desiccation  
1642 stress in strains of green algal photobionts (*Trebouxia*) from two Antarctic lichens of  
1643 southern habitats. *Phycologia*, **55** (6), 703–714.  
1644  
1645 Sahade, R., Lagger, C., Torre, L., Momo, P., Monien, P., Schloss, I., Barnes, D. K. A., Servetto,  
1646 N., Tarantelli, S., Zamboni, N. & Abele, D. 2015. Climate change and glacier retreat drive  
1647 shifts in an Antarctic benthic ecosystem. *Science Advances*, 10.1126/sciadv.1500050.  
1648  
1649 Sañé, E., Isla, E., Grémare, A., Gutt, J., Vétion, G. & DeMaster, D.J. 2011. Pigments in  
1650 sediments beneath a recently collapsed ice shelves: the case of Larsen A and B shelves,  
1651 Antarctic Peninsula. *Journal of Sea Research*, **65**, 94–102.  
1652

1653 Sañé, E., Isla, E., Bárcena, M.A. & DeMaster, D. 2013. A shift in the biogenic silica of  
1654 sediment in the Larsen B continental shelf, off the eastern Antarctic Peninsula, resulting  
1655 from climate change. *Public Library of Science One*, **8**, e52632.  
1656 10.1371/journal.pone.0052632.  
1657  
1658 Scambos, T., Hulbe, C. & Fahnestock, M. 2003. Climate-induced ice shelf disintegration in  
1659 the Antarctic Peninsula. *In: Domack, E. W., Leventer, A., Burnett, A., Bindschadler, R. A.,*  
1660 *Convey, R. & Kirby, M. eds. Antarctic Peninsula climate variability: historical and*  
1661 *paleoenvironmental perspectives*. Washington DC: American Geophysical Union, 79-92.  
1662  
1663 Scherer, R.P., Aldahan, A., Tulaczyk, S., Kamb, B., Engelhardt, H. & Possnert, G. 1998.  
1664 Pleistocene collapse of the West Antarctic Ice Sheet. *Science*, **281**(373), 82-85.  
1665  
1666 Scherer, R.P., De Conto, R. M., Pollard, D. & Alley, R. B. 2016. Windblown Pliocene  
1667 diatoms and East Antarctic ice sheet retreat. *Nature Communications*, **7**, 12957,  
1668 10.1038/ncomms12957.  
1669  
1670 Schofield, O., Ducklow, H.W., Martinson, D.G., Meredith, M.P., Moline, M.A. & Fraser, W.R.  
1671 2010. How do polar marine ecosystems respond to rapid climate change? *Science*, **328**,  
1672 1520-1523.  
1673  
1674 Simmonds, M.P. & Isaac, S.J. 2007. The impacts of climate change on marine mammals:  
1675 early signs of significant problems. *Oryx*, **41**, 19-26.  
1676

1677 Simpson, W.R., von Glasow, R., Riedel, K., Anderson, P., Ariya, P., Bottenheim, J., Burrows,  
1678 J., Carpenter, L.J., Frieß, U., Goodsite, M.E., Heard, D., Hutterli, M., Jacobi, H.-W., Kaleschke,  
1679 L., Neff, B., Plane, J., Platt, U., Richter, A., Roscoe, H., Sander, R., Shepson, P., Sodeau, J.,  
1680 Steffen, A., Wagner, T., & Wolff, E. 2007. Halogens and their role in polar boundary-layer  
1681 ozone depletion. *Atmospheric Chemistry and Physics*, **7**, 4375–4418.

1682

1683 Sinclair, K.E., Bertler, N.A., Bowen, M.M. & Arrigo, K.R. 2014. Twentieth century sea-ice  
1684 trends in the Ross Sea from a high-resolution, coastal ice-core record. *Geophysical*  
1685 *Research Letters*, **41**, 3510-3516.

1686

1687 Smith, Jr. W. & Comiso, J.C. 2008. The influence of sea ice on primary production in the  
1688 Southern Ocean: A satellite perspective. *Journal of Geophysical Research*, **113**, C05S93,  
1689 10.1029/2007JC004251.

1690

1691 Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., Ferdaña, Z.A., Finlayson, M., Halpern,  
1692 B.S., Jorge, M.A., Lombana, A., Lourie, S.A., Martin, K.D., McManus, E., Molnar, J., Recchia,  
1693 C.A. & Roberston, J. 2007. Marine ecoregions of the world: a bioregionalization of coastal  
1694 and shelf areas. *BioScience*, **57**, 573e583.

1695

1696 Steiner, N., Deal, C., Lannuzel, D., Lavoie D., Massonnet, F., Miller, L.A., Moreau, S., Popova,  
1697 E., Stefels, J. & Tedesco, L. 2016. What sea-ice biogeochemical modellers need from  
1698 observers. *Elementa: Science of the Anthropocene*, **4**, 10.12952/journal.elementa.000084.

1699

1700 Stenni, B., Curran, M.A.J., Abram, N.J., Orsi, A., Goursaud, S., Masson-Delmotte, V.,  
1701 Neukom, R., Divine, D., van Ommen, T., Steig, E.J., Dixon, D.A., Thomas, E.R., Bertler, N.A.,

1702 Isaksson, E., Ekaykin, A., Frezzotti, M. & Werner, M. under review. Antarctic climate  
1703 variability at regional and continental scales over the last 2,000 years. *Climate of the Past*  
1704 *Discussion*, 10.5194/cp-2017-40. [www.clim-past-discuss.net/cp-2017-40/](http://www.clim-past-discuss.net/cp-2017-40/)  
1705  
1706 Strugnell, J., Rogers, A.D., Prodöhl, P.A., Collins, M.A. & Allcock, A.L. 2008. The  
1707 thermohaline expressway: the Southern Ocean as a centre of origin for deep-sea  
1708 octopuses. *Cladistics*, **24**, 853-860.  
1709  
1710 Strugnell, J., Cherel, Y., Cooke, I.R., Gleadall, I.G., Hochberg, F.G., Ibáñez, C.M., Jorgensen,  
1711 E., Laptikhovskiy, V.V., Linse, K., Norman, M., Vecchione, M., Voight, J.R. & Allcock, A.L.  
1712 2011. The Southern Ocean: Source and sink? *Deep-Sea Research II – Topical Studies in*  
1713 *Oceanography*, **58**, 196-204.  
1714  
1715 Strugnell, J.M., Watts, P.C., Smith, P.J. & Allcock, A.L. 2012. Persistent genetic signatures  
1716 of historic climatic events in an Antarctic octopus. *Molecular Ecology*, **21**, 2775-2787,  
1717 10.1111/j.1365-294X.2012.05572.x.  
1718  
1719 Terauds, A., Chown, S.L., Morgan, F., Peat, H.J., Watts, D.J., Keys, H., Convey, P. &  
1720 Bergstrom, D.M. 2012. Conservation biogeography of the Antarctic. *Diversity and*  
1721 *Distributions*, **18**, 726-741.  
1722  
1723 Thomas, E.R., van Wessem, J.M., Roberts, J., Isaksson, E., Schlosser, E., Fudge, T.,  
1724 Vallelonga, P., Medley, B., Bertler, N., van de Broeke, M.R., Dixon, D.A., Frezzotti, M.,  
1725 Stenni, B., Curran, M., & Ekaykin, A.A. under review. Review of regional Antarctic snow



1726 accumulation over the past 1000 years. *Climate of the Past Discussion*, 10.5194/cp-  
1727 2017-18. [www.clim-past-discuss.net/cp-2017-18/](http://www.clim-past-discuss.net/cp-2017-18/)  
1728  
1729 Tin, T., Fleming, Z., Hughes, K.A., Ainley, D., Convey, P., Moreno, C., Pfeiffer, S., Scott, J., &  
1730 Snape, I. 2009. Impacts of local human activities on the Antarctic environment: a review.  
1731 *Antarctic Science*, **21**, 3-33.  
1732  
1733 Tison, J.-L., Brabant, F., Dumont, I. & Stefels, J. 2010. High-resolution dimethyl sulfide and  
1734 dimethylsulfoniopropionate time series profiles in decaying summer first-year sea ice at  
1735 Ice Station Polarstern, western Weddell Sea, Antarctica. *Journal Geophysical Research*,  
1736 **115**, G04044, 10.1029/2010JG001427.  
1737  
1738 Turner, J., Bindschadler, R., Convey, P., di Prisco, G., Fahrbach, E., Gutt, J., Hodgson, D.,  
1739 Mayewski, P. & Summerhayes, C. eds. 2009. *Antarctic climate change and the*  
1740 *environment*. Cambridge: SCAR & Scott Polar Research Institute, 526pp.  
1741  
1742 Turner, J., Barrand, N.E., Bracegirdle, T.J., Convey, P., Hodgson, D., Jarvis, M., Jenkins, A.,  
1743 Marshall, G., Meredith, M.P., Roscoe, H., Shanklin, J., French, J., Goosse, H., Gutt, J., Jacobs,  
1744 S., Kennicutt II, M.C., Masson-Delmotte, V., Mayewski, P., Navarro, F., Robinson, S.,  
1745 Scambos, T., Sparrow, M., Summerhayes, C., Speer, K. & Klepikov, A. 2014. Antarctic  
1746 climate change and the environment: an update. *Polar Record*, **50**, 237-259.  
1747  
1748 Vancoppenolle, M., Meiners, K.M., Michel, C., Bopp, L., Brabant, F., Carnat, G., Delille, B.,  
1749 Lannuzel, D., Madec, G., Moreau, S., Tison, J.-L. & van der Merwe, P. 2013. Role of sea ice

1750 in global biogeochemical cycles: emerging views and challenges. *Quaternary Science*  
1751 *Reviews*, **79**, 207-230.

1752

1753 Verde, C., Giordano, D., Gutt, J. & di Prisco, G. 2016. Molecular-genetic studies of polar  
1754 biodiversity. *Biodiversity*, **17**, 1-3.

1755

1756 Vernet, M., Smith Jr., K.L., Cefarelli, A.O., Helly, J.J., Kaufmann, R.S., Lin, H., Long, D.G,  
1757 Murray, A.E., Robison, B.H., Ruhl, H.A., Shaw, T.J., Sherman, A.D., Sprintall, J., Stephenson  
1758 Jr., G.R., Stuart, K.M. & Twining, B.S. 2012. Islands of ice: Influence of free-drifting  
1759 Antarctic icebergs on pelagic marine ecosystems. *Oceanography*, **25**(3), 38–39,  
1760 [10.5670/oceanog.2012.72](https://doi.org/10.5670/oceanog.2012.72).

1761

1762 Vyverman W., Verleyen E., Wilmotte A., Hodgson D.A., Willems A., Peeters K., Van de  
1763 Vijver B, De Wever A. & Sabbe K. 2010. Evidence for widespread endemism among  
1764 Antarctic micro-organisms. *Polar Science*, **4**, 103-113.

1765

1766 Wilson, N.G., Maschek, J.A. & Baker, B.J. 2013. A species flock driven by predation?  
1767 Secondary metabolites support diversification of slugs in Antarctica. *Public Library of*  
1768 *Science One*, **8**(11), e80277, 10.1371/journal.pone.0080277.

1769

1770 Xavier, J.C., Brandt, A., Ropert-Coudert, Y., Badhe, R., Gutt, J., Havermans, C., Jones, C.,  
1771 Costa, E.S., Lochte, K., Schloss, I.R., Kennicutt II, M.C. & Sutherland, W.J. 2016. Future  
1772 challenges in Southern Ocean ecology research. *Frontiers in Marine Science*, **3**, article 94,  
1773 10.3389/fmars.2016.00094.

1774

1775 Zachos, J., Pagani, M., Sloan, L., Thomas, E. & Billups, K. 2001. Trends, rhythms, and  
1776 aberrations in global climate 65 Ma to present. *Science*, **292**, 686-693.