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## Modelled glacier response to centennial temperature and precipitation trends on the Antarctic Peninsula

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The northern Antarctic Peninsula is currently undergoing rapid atmospheric warming<sup>1</sup>. Increased glacier-surface melt during the Twentieth Century<sup>2,3</sup> has contributed to ice-shelf collapse and the widespread acceleration<sup>4</sup>, thinning, and recession<sup>5</sup> of glaciers. Glaciers peripheral to the Antarctic Ice Sheet currently therefore make a large contribution to eustatic sea-level rise<sup>6,7</sup>, but future melting may be offset by increased precipitation<sup>8</sup>. Here we assess glacier-climate relationships both during the past and into the future, using ice core and geological data and glacier and climate numerical model simulations. Focussing on Glacier IJR45, James Ross Island, northeast Antarctic Peninsula, our modelling experiments show that this representative glacier is most sensitive to temperature change, not precipitation change. Consequently, we determine that its most recent expansion occurred during the late Holocene 'Little Ice Age' and not during the warmer mid-Holocene, as previously hypothesised<sup>9</sup>. Together with future simulations using a range of IPCC climate scenarios, these modelling experiments suggest that future increases in precipitation are unlikely to offset atmospheric warming-induced melt of peripheral Antarctic Peninsula glaciers.

This paper analyses surface mass balance and ice-flow sensitivities to changes in temperature and precipitation on glaciers around the northern Antarctic Peninsula. Our study is motivated by observations that glaciers and ice caps around the peripheries of the large ice sheets have short response times and high climate sensitivity, and are known to significantly contribute to sea-level rise<sup>6,7</sup> (1.1 mm a<sup>-1</sup> in 2006<sup>10</sup>). They are likely to dominate contributions to sea level rise over the next few decades (21±12 mm by 2100 AD from Antarctic mountain glaciers and ice caps<sup>11</sup>), but there is large uncertainty about the magnitude of their future contribution<sup>11</sup>. This is partly because snow accumulation is increasing on the Antarctic Peninsula plateau<sup>12,13,14</sup>, which may offset increased surface melt caused by higher air temperatures<sup>8,15,16</sup>. Improving projections of glacier behaviour requires a better understanding of the relative sensitivities to these changes.

40 James Ross Island (Figure 1) preserves a rare terrestrial record of Mid-Holocene glacier fluctuations<sup>9,17,</sup>  
41 <sup>18,19</sup> in a region of rapid warming<sup>1,3,20</sup>, glacier recession and ice-shelf collapse<sup>21</sup>. Glacier IJR45 on Ulu  
42 Peninsula underwent a 10 km re-advance sometime after ~4-5 cal. ka BP<sup>9</sup> (Supplementary Information,  
43 Figure 1c), during a period that was 0.5°C warmer than today<sup>20</sup>. Prince Gustav Ice Shelf was absent at this  
44 time<sup>22</sup>, which is indicative of strong surface melt. Previous workers suggested that this readvance was driven  
45 by increased precipitation<sup>9</sup>, which suggests that future increased precipitation may offset increased melting.  
46 However, this is contrary to currently observed glacier recession<sup>5,21,23</sup> during a period of warming and ice-  
47 shelf absence.

48 We used a high-resolution flowline model (Methods) to establish the primary controls on glacier  
49 behaviour in a terrestrial Antarctic Peninsula environment. Climate data from a highly resolved nearby ice  
50 core<sup>20</sup> allowed us to test the prevailing hypothesis that a warmer and wetter climate during the Mid-  
51 Holocene encouraged the synchronous advance of glaciers on James Ross Island and the collapse of the  
52 Prince Gustav Ice Shelf<sup>9</sup>. Next, we used future climate forcings from regional climate model (RCM)  
53 simulations to investigate likely changes in glacier mass balance and geometry over the next two centuries.

54 Response-time tests showed that the time taken to reach equilibrium is 240 to >1000 years, depending  
55 on the temperature perturbation applied, but that the *e-folding* time (two-thirds of the time taken to reach  
56 equilibrium) ranged from 91 years for a +1.0°C temperature increase to 487 years for a -0.4°C decrease  
57 (Figure 2a, b). In our sensitivity experiments (Figure 2 b-g; Supplementary Figure 7), changing the snow  
58 degree-day factor by ±20% resulted in a 0.12 km<sup>3</sup> (28.8%) difference in glacier volume, and a negligible  
59 difference in velocity. Increasing the snow degree day factor has a similar effect as decreasing the amount of  
60 precipitation, which is as expected because it melts the accumulated snow.

61 A relatively small 0.8°C decrease in mean annual air temperature (MAAT) was sufficient to force a 10 km  
62 advance and a growth in ice volume from 0.53 km<sup>3</sup> to 6.25 km<sup>3</sup> (Figures 2c, 3a). Further growth was limited  
63 by calving at the break in slope in Prince Gustav Channel (Figures 1d, 3a). The magnitude of the advance was  
64 controlled by the mass-balance gradient and the glacier's hypsometry; a small amount of cooling resulted in  
65 a large increase in accumulation area. In contrast, a ±20% change in mean annual precipitation was only  
66 sufficient to force a 0.8 km difference in glacier length and a difference in volume of 0.24 km<sup>3</sup> (Figures 2d,  
67 3b). Velocity arising from ice deformation and basal sliding increased under warmer air temperatures as  
68 more of the bed reached pressure melting point and as the glacier ice softened. The glacier also accelerated  
69 under lower temperatures because the gravitational driving stress increased as it grew thicker  
70 (Supplementary Figure 7m, s).

71 We investigated the influence of precipitation under different mean annual air temperatures (Figure  
72 3c). Depending on the amount of precipitation, a MAAT of -6.2°C (a 1°C warming) resulted in the glacier  
73 shrinking to between 1.6 km and 1.1 km long with a volume ranging from 0.055 km<sup>3</sup> to 0.079 km<sup>3</sup>, a change  
74 of -85.1% to -89.9% compared with modern values. A MAAT of -5.2°C (a 2°C warming) resulted in glacier  
75 lengths of between 0.6 and 1.4 km and a volume of 0.0167 km<sup>3</sup> to 0.033 km<sup>3</sup> (-93.8% to -96.9%) under  
76 minimum and maximum precipitation scenarios. However, at -8.0°C (a 0.8°C cooling), glacier volume ranged  
77 from 2.90 km<sup>3</sup> to 6.54 km<sup>3</sup> (+447% to +1132%).

78 Precipitation seasonality can exert a significant control on glacier mass balance<sup>24</sup>, because summer  
79 precipitation may fall as rain, particularly in relatively warm locations such as the northern Antarctic  
80 Peninsula. Warming on summer-precipitation glaciers may therefore result in decreased snow accumulation,  
81 as well as prolonging the melt season. Sensitivity analysis of the amplitude of precipitation seasonality

82 (Figure 3d, Supplementary Information) showed that increasing the proportion of precipitation falling during  
83 the summer months resulted in glacier recession ( $0.06 \text{ km}^3$  volume difference between minimum and  
84 maximum amplitudes). This is significant, as the observed increases in precipitation over the last five  
85 decades have mostly been in summer<sup>13</sup>, and this trend is set to continue<sup>14</sup>.

86 Together, these experiments show that the influence of both precipitation and precipitation seasonality  
87 is less at warmer temperatures (Figure 3e, 3f), as the accumulation area diminishes and precipitation  
88 increasingly falls as rain. At cooler temperatures, glacier expansion is eventually limited by calving at the  
89 break of slope in Prince Gustav Channel.

90 Time-dependent simulations were forced by the James Ross Island ice core (Figures 1b, 4a), which  
91 provides a temperature record<sup>20</sup> from 12 cal. ka BP to present and a thinning-corrected accumulation record  
92 from 1807 to 2007 AD<sup>3</sup>. This experiment reproduced a large readvance only during the cool period ca. 1.5  
93 cal. ka BP. A small recession was observed during the period 3–5 cal. ka BP, during a  $+0.5^\circ\text{C}$  warming (Figure  
94 4b and animation in Supplementary Information).

95 While the accumulation record from the James Ross Island ice core appears to show no increase in  
96 accumulation with temperature (Supplementary Figure 5), and thus a temperature-precipitation  
97 dependence of 0%, a dependence of up to 50% has been reported elsewhere on the Antarctic Peninsula<sup>12, 13</sup>.  
98 The generally held value is 5% to 7.3%<sup>25</sup>. In order to explore a range of possible climatic scenarios, we  
99 increased precipitation by 5%, 7.3%, 15%, 20% and 100% for every  $1^\circ\text{C}$  increase in temperature to test the  
100 hypothesis that a warmer but wetter climate was responsible for the Mid-Holocene readvance. This change  
101 in precipitation fed the glacier during warm periods and starved it during cool periods, dampening the  
102 glacier's response and resulting in progressively smaller fluctuations (Figure 4b). None of these experiments  
103 drove a 10 km readvance from 2–5 cal. ka BP, even under extreme precipitation scenarios.

104 Our modelling experiments indicate that glaciers on Ulu Peninsula remained largely stable during Mid-  
105 Holocene time. From 2–5 cal. ka BP, ice-shelf collapse and a small amount of glacier recession occurred  
106 during a  $0.5^\circ\text{C}$  warming. The ice-shelf reformed following rapid cooling starting 2 cal. ka BP. Glacier IJR45  
107 began to advance after 1.5 cal. ka BP, reaching its maximum Holocene position around 300 years ago, before  
108 rapid recession to its most recent position. This interpretation is consistent with the radiocarbon ages  
109 providing an upper limit for the readvance ( $\sim 4.8$  cal. ka BP<sup>9</sup>), and with records of ice-shelf expansion and  
110 glacier readvance at this time on the South Shetland Islands (1.5-1.0 cal. ka BP) and Livingston Island<sup>26</sup> (750  
111 years ago). A glacier readvance at 1.5 cal. ka BP, during a cool period with ice-shelf re-formation<sup>22</sup> and glacier  
112 recession during warming, is also consistent with modern observations of glacier recession and ice-shelf  
113 collapse during warming.

114 The most recent readvance of Glacier IJR45 therefore occurred during the Neoglacial period, or “Little  
115 Ice Age”. Evidence for the “Little Ice Age” around the Antarctic continent is patchy<sup>27</sup>, and glacier response is  
116 poorly understood. Few terrestrial records of glacier advances have been dated to this time<sup>27</sup>. Our study is  
117 the first in this region to convincingly show glacier advance during a period of strong cooling during the last  
118 millennium. Further, our findings suggest that, rather than being more extensive during similar climates in  
119 the past, as was previously argued, glacier minima similar to present have been experienced at multiple  
120 times during the Holocene.

121 To assess the significance of these findings within the context of projected future climate scenarios, we  
122 performed time-dependent simulations from 1980 to 2200 AD, forced with climate outputs from the

123 regional atmospheric climate model RACMO2 (55 km horizontal resolution). We used the A1B and E1  
124 emissions scenarios<sup>16</sup> of the Intergovernmental Panel on Climate Change (IPCC), with lateral boundaries  
125 derived from two global climate models, HadCM3 (to 2200 AD) and ECHAM5 (to 2100 AD). All four  
126 simulations predict warming over the next 100-200 years in the Antarctic Peninsula (Figure 4c), but RACMO2  
127 outputs forced by ECHAM5 show less warming and less snowfall over Antarctica (Figure 4d; see  
128 Supplementary Information for discussion). All model runs predicted a reduction in glacier volume, with  
129 glacier lengths at 2100 AD ranging from 3.8 km (ECHAM5 E1) to 2.8 km (HadCM3 A1B). By 2200 AD, the  
130 glacier was predicted to be just 0.5 km long with a volume of 0.03 km<sup>3</sup> (HadCM3 A1B; Figure 4c). It is  
131 significant that all four simulations predict temperature increases but not precipitation increases, yet all four  
132 simulations led to a reduction in ice volume.

133 Glacier IJR45 is typical of many peripheral, land-terminating glaciers around the Antarctic Peninsula  
134 (e.g., refs.<sup>21</sup>), where surface melting is strongly controlled by MAAT and the positive degree-day sum. Since  
135 both are currently increasing<sup>2</sup>, summer melting will become increasingly important and these glaciers are  
136 expected to contribute significantly to sea-level rise over coming decades<sup>7</sup>. The surface mass-balance  
137 processes are also likely to be representative of regional tidewater glaciers draining the Antarctic Peninsula  
138 Ice Sheet. As with the gently sloping Glacier IJR45, the flat plateau on the Peninsula and the Mount  
139 Haddington Ice Cap renders these glaciers vulnerable to large changes in accumulation area following small  
140 temperature changes<sup>21</sup>. Furthermore, changes in precipitation seasonality, with increased snowfall largely  
141 occurring in summer months<sup>14</sup>, may exacerbate glacier recession over the next two centuries.

142 In conclusion, glacier modelling, spanning a range of past, present and future time intervals, shows that  
143 Glacier IJR45 has high sensitivity to air temperature and is less sensitive to precipitation. Glacier advance  
144 during past and future warm periods is therefore unlikely. Authors of previous studies have argued that this  
145 readvance occurred during a warmer but wetter period, around 4-5 ka BP<sup>9, 19, 26</sup>, suggesting that increased  
146 precipitation in the future would offset glacier melt due to higher air temperatures. We reject the  
147 hypotheses that 1) the glacier readvanced during the Holocene in response to increased precipitation, and 2)  
148 that increased precipitation over the next 200 years will offset increased glacier melt. The currently observed  
149 trends of glacier melting, recession and thinning across the Antarctic Peninsula are likely to continue  
150 throughout the next century.

151

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### 259 **Additional information**

260 Supplementary information is available in the online version of the paper. Reprints and permissions  
261 information is available online at [www.nature.com/reprints](http://www.nature.com/reprints). Correspondence and requests for information  
262 should be addressed to BJD.

263

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275

### 276 **Author contributions**

277 BJD conducted fieldwork, planned and undertook the modelling, and led the writing and the compilation of  
278 the graphics and tables. NRG wrote the flowline model and contributed to the modelling effort. NFG  
279 conducted fieldwork and designed the original field-based project. JLC contributed to the original field-based  
280 project design and the fieldwork. MJH and JLS contributed to the original project design. NB, SRML and  
281 MRvdB provided projections of future climate around the Antarctic Peninsula. All authors contributed to the  
282 writing of the manuscript.

283

### 284 **Competing financial interests**

285 The authors declare no competing financial interests.



286

287 **Figures**

288 **Figure 1. Study context.** (a) The Antarctic Peninsula. (b) James Ross Island, location of the ice core drilling  
289 site, and Prince Gustav Ice Shelf in 1988. Red box shows location of panel 'c'. (c) Ulu Peninsula with  
290 published radiocarbon ages (circles)<sup>9,28</sup> and cosmogenic nuclide ages (diamonds)<sup>17,19</sup>, Brandy Bay Moraine  
291 and boulder train. The plan view along line A-B is shown. Spot heights are in italics. The DEM was produced  
292 by the Czech Geological Survey<sup>29</sup>. Bathymetric data are from the Antarctic and Southern Ocean Data Portal  
293 of the Marine Geoscience Data System. (d) Cross-section of flowline A-B.

294

295 **Figure 2. Response time and sensitivity test results.** (a) Response time tests showing that IJR45 reaches a  
296 dynamic equilibrium after ~400 years and (b) has an *e-folding* time of 100-200 years, depending on the  
297 perturbation. (c-g) Sensitivity test results, with the change in glacier length arising from perturbations to  
298 mean annual air temperature, precipitation, snow and ice degree-day factors and flow enhancement  
299 coefficient (ice deformation factor).

300

301 **Figure 3. Temperature and precipitation sensitivity experiments.** (a) Change in glacier length following a  
302 -1.5°C to +2°C perturbation in mean annual air temperature. (b) Change in glacier length following a ±20%  
303 perturbation in mean annual precipitation. (c) Analysis of simultaneous temperature and precipitation  
304 changes on glacier length. Point indicates current climate. (d) Effect of the amplitude of precipitation  
305 seasonality on glacier volume. (e) Temperature versus length, showing that the influence of precipitation  
306 becomes greater with cooler temperatures. (f) Analysis of simultaneous temperature and amplitude of  
307 summer precipitation seasonality changes. The influence of summer precipitation seasonality becomes  
308 greater under colder temperatures.

309

310 **Figure 4. Holocene and future simulations of glacier length.** (a) Mean annual air temperature anomaly  
311 during the Holocene from the James Ross Island ice core<sup>3,20</sup>. The presence of Prince Gustav Ice Shelf is  
312 indicated by the thick black line. (b) Change in glacier length as forced by the ice core temperature record.  
313 Precipitation is held constant at modern values, and variously forced at +5%, +7.3%, +15%, +20% and +100%  
314 for a 1°C rise in air temperature. (c) Plot of temperature and (d) precipitation changes predicted by RACMO2  
315 under four different forcing scenarios. (e) Resultant change in glacier volume.

316

317

## 318 Methods

319 **Glaciological input data.** Glaciological input data include measurements of ice thickness<sup>23</sup>, velocity, surface  
320 air temperature and topographical<sup>29</sup> and bathymetric data (Figure 1). The most recent readvance was  
321 reconstructed from our own geological data<sup>17, 18</sup> (Figure 1) and from published calibrated radiocarbon<sup>9, 28</sup> and  
322 cosmogenic nuclide ages<sup>17, 19</sup> (Supplementary Information).

323

324 **Numerical model description.** We used a one-dimensional, finite-difference glacier flowline model to  
325 investigate glacier-climate interactions on Ulu Peninsula, James Ross Island. The glacier model and its  
326 degree-day scheme have previously been described in detail<sup>24, 30</sup>, so are only summarised here. The model  
327 uses a forward explicit numerical scheme, implemented on a 100 m horizontal resolution staggered grid that  
328 spans the length and foreland of Glacier IJR45 into Prince Gustav Channel. Horizontal flux is calculated  
329 through a cross-sectional plane described by a symmetrical trapezoid, and incorporates a width-dependent  
330 shape factor. The model assumes no transfer of ice flux between adjacent, but dynamically independent,  
331 portions of the glacier. Velocity is determined by both the flow-enhancement coefficient (deformation  
332 factor), which accounts for the softening of the ice by impurities or contrasts in crystal orientation, and by  
333 basal sliding. Outliers in the velocity field are sensitive to transients in the model (short-term fluctuations  
334 that may be real or may be intermediate steps in the diffusion scheme).

335

336 **Modelling strategy and methods.** The flowline model was tuned to present-day conditions to reproduce  
337 observed glacier extent, volume and velocity (Table S3; Methods), and was dynamically calibrated using  
338 temperature and accumulation data over the last 160 years from the James Ross Island ice core<sup>3, 20</sup> (cf. Figure  
339 1b). Small adjustments were made to the degree-day factors until the glacier replicated observed recession  
340 and thinning rates over the last 30 years<sup>23</sup> (Supplementary Information). The glacier stabilised in a position  
341 that matched present-day velocity and geometry, thus increasing confidence in model initialisation.

342 Response time tests performed at 0.1°C increments from -0.5°C to +1.0°C investigated time taken to  
343 reach equilibrium following perturbation. Sensitivity tests investigated glacier response to perturbations in  
344 mean annual air temperature, mean annual precipitation, snow and ice degree-day factors, precipitation  
345 seasonality and flow-enhancement coefficient. Further, each incremental change in precipitation was run  
346 against each incremental change in temperature. Glacier sensitivity to summer precipitation seasonality  
347 under different mean annual air temperatures was also analysed. Subsequent time-dependent simulations  
348 used the tuned parameters to model Holocene and future glacier characteristics. Holocene accumulation  
349 and air temperatures were derived from the ice-core record<sup>3, 20</sup>. Future transient runs were forced by a  
350 regional climate model (RACMO2) (Supplementary Information).

351

352 **Experiment advantages and limitations.** Advantages of this model domain are, firstly, that this is a simple  
353 model applied to one of the best observed and instrumented glaciers on the Antarctic Peninsula. Secondly,  
354 Glacier IJR45 is land-terminating and represents a well-constrained system that isolates the controls on  
355 surface mass balance. Most notably, we are able to ignore the uncertainties associated with a more complex  
356 oceanic and tidewater glacier system. By restricting the number of assumptions and independent variables,  
357 we are able to present an entirely novel and original analysis of glacier-climate sensitivities in a critical, and  
358 rapidly changing, region. Thirdly, Holocene dynamics are well constrained by detailed geomorphological data  
359 and the ice core<sup>3, 20</sup>.

360            Limitations of the model include the debris-cover on the snout of the glacier (Figure 1c, d); the glacier  
361 bed is interpolated underneath the debris cover. The effect of the debris cover on ablation is taken into  
362 account by the degree-day factors. However, the debris cover is sparse, is likely to have accumulated only  
363 recently, and is not considered an important factor in this study. Measurements of temperature, velocity,  
364 accumulation and ablation are short (2-3 years). Glacier IJR45 receives a high volume of wind-blown snow,  
365 rendering precipitation lapse-rates calculated from accumulation recorded at sea level and at the summit of  
366 Mount Haddington inappropriate, as well of low confidence. Given the limited altitudinal range of this  
367 glacier and its forefield, the precipitation lapse rate is considered to be 0, and precipitation is distributed  
368 evenly across the glacier surface.

369            The 10,000 year Holocene experiment finishes with a glacier that is larger than that of the present day,  
370 but is rapidly receding. This is a limitation in the model; the enlarged modelled glacier is unable to respond  
371 fast enough to the rapidly increasing air temperatures.

372            As the forefield is very flat, adding mass from an adjoining flow unit could force a more rapid readvance.  
373 However, Glacier IJR45 needs to be relatively advanced before it would be affected by adjacent ice. During  
374 an advance, adjacent ice may have enhanced expansion, but with limited effect. If it did enhance an earlier  
375 advance during lesser cooling, it would logically also have to add to the biggest advance during the Late  
376 Holocene, so although adjacent ice may affect the absolute length of IJR45, it would not change the pattern  
377 of modelled response.