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

Bethan J. Davies^{1,2*†}, Nicholas R. Golledge^{2,3}, Neil F. Glasser¹, Jonathan L. Carrivick⁴, Stefan R.M. Ligtenberg⁵, Nicholas E. Barrand⁶, Michiel R. van den Broeke⁵, Michael J. Hambrey¹, John L. Smellie⁷,

¹Centre for Glaciology, Department of Geography and Earth Sciences, Aberystwyth University, Penglais Campus, Aberystwyth SY23 3DB, UK

²Antarctic Research Centre, Victoria University of Wellington, Wellington, New Zealand

³GNS Science, Avalon, Lower Hutt 5011, New Zealand

⁴School of Geography, University of Leeds, Leeds, UK

⁵IMAU, Utrecht University, Utrecht, The Netherlands

⁶School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

⁷Department of Geology, University of Leicester, Leicester, UK

*Email: bethan.davies@rhul.ac.uk

†Now at: Centre for Quaternary Research, Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK.

The northern Antarctic Peninsula is currently undergoing rapid atmospheric warming¹. Increased glacier-surface melt during the Twentieth Century^{2,3} has contributed to ice-shelf collapse and the widespread acceleration⁴, thinning, and recession⁵ of glaciers. Glaciers peripheral to the Antarctic Ice Sheet currently therefore make a large contribution to eustatic sea-level rise^{6,7}, but future melting may be offset by increased precipitation⁸. 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 hypothesised⁹. Simulations using a range of future IPCC climate scenarios indicate 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 contribute significantly to sea-level rise^{6,7} (1.1 mm a⁻¹ in 2006¹⁰). 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 caps¹¹), but there is large uncertainty about the magnitude of their future contribution¹¹. This is partly because snow accumulation is increasing on the Antarctic Peninsula plateau^{12,13,14}, which may offset increased surface melt caused by higher air temperatures^{8,15,16}. Improving projections of glacier behaviour requires a better understanding of the relative sensitivities of glaciers to these changes.

39 James Ross Island (Figure 1) preserves a rare terrestrial record of Holocene glacier fluctuations^{9, 17, 18, 19}
40 in a region of rapid warming^{1, 3, 20}, glacier recession and ice-shelf collapse²¹. Glacier IJR45 on Ulu Peninsula
41 underwent a 10 km re-advance sometime after ~4-5 cal. ka BP⁹, perhaps during a period that was 0.5°C
42 warmer than today²⁰ (Supplementary Information, Figure 1c). Prince Gustav Ice Shelf was absent at this
43 time²², which is indicative of strong surface melt. Previous research indicates that this readvance was driven
44 by increased precipitation⁹, suggesting that future increased precipitation may offset increased melting.
45 However, this is contrary to currently observed glacier recession^{5, 21, 23} during a period of warming and ice-
46 shelf absence.

47 We used a high-resolution flowline model (Methods) to establish the primary controls on glacier
48 behaviour in a terrestrial Antarctic Peninsula environment. Climate data from a highly resolved nearby ice
49 core²⁰ allowed us to test the prevailing hypothesis that a warmer and wetter climate during the Mid-
50 Holocene encouraged the synchronous advance of glaciers on James Ross Island and the collapse of the
51 Prince Gustav Ice Shelf⁹. We also used future climate forcings from regional climate model (RCM) simulations
52 to investigate likely changes in glacier mass balance and geometry over the next two centuries.

53 Response-time tests showed that the time taken to reach equilibrium is 240 to >1000 years, depending
54 on the temperature perturbation applied, but that the *e-folding* time (two-thirds of the time taken to reach
55 equilibrium) ranged from 100-1000 years depending on the temperature perturbation (Figure 2a, b). In our
56 sensitivity experiments (Figure 2 b-g; Supplementary Figure 7), changing the snow degree-day factor by
57 ±20% resulted in a 0.12 km³ (28.8%) difference in glacier volume, and a negligible difference in velocity.
58 Increasing the degree-day factor of snow has a similar effect as decreasing the amount of precipitation,
59 which is as expected because it melts the accumulated snow.

60 A relatively small 0.8°C decrease in mean annual air temperature (MAAT) was sufficient to force a 10 km
61 glacier advance and an increase in ice volume from 0.53 km³ to 6.25 km³ (Figures 2c, 3a, Supplementary
62 Figure 7). Further growth was limited by calving at the break in slope in Prince Gustav Channel (Figures 1d,
63 3a). The magnitude of the advance was controlled by the mass-balance gradient and the glacier's
64 hypsometry; a small amount of cooling resulted in a large increase in accumulation area. In contrast, a ±20%
65 change in mean annual precipitation was only sufficient to force a 0.8 km difference in glacier length and a
66 difference in volume of 0.24 km³ (Figures 2d, 3b). Velocity arising from ice deformation and basal sliding
67 increased under warmer air temperatures as more of the bed reached pressure melting point and as the
68 glacier ice softened. The glacier also accelerated under lower temperatures because the gravitational driving
69 stress increased as it grew thicker (Supplementary Figure 7k, p).

70 We investigated the influence of precipitation under different mean annual air temperatures (Figure
71 3c). Depending on the amount of precipitation, a MAAT of -6.2°C (a 1°C warming) resulted in the glacier
72 shrinking to between 1.6 km and 1.1 km long with a volume ranging from 0.055 km³ to 0.079 km³, a change
73 of -85.1% to -89.9% compared with modern values. A MAAT of -5.2°C (a 2°C warming) resulted in glacier
74 lengths of between 0.6 and 1.4 km and a volume of 0.0167 km³ to 0.033 km³ (-93.8% to -96.9%) under
75 minimum and maximum precipitation scenarios. However, at -8.0°C (a 0.8°C cooling), glacier length ranged
76 from 9.6 to 14.4 km, and volume ranged from 2.90 km³ to 6.54 km³ (+447% to +1132%).

77 Precipitation seasonality can exert a significant control on glacier mass balance²⁴, because summer
78 precipitation may fall as rain, particularly in relatively warm locations such as the northern Antarctic
79 Peninsula. Warming on summer-precipitation glaciers may therefore result in decreased snow accumulation,
80 as well as prolonging the melt season. Sensitivity analysis of the amplitude of precipitation seasonality

81 (Figure 3d, Supplementary Information) showed that increasing the proportion of precipitation falling during
82 the summer months resulted in glacier recession (0.06 km³ volume difference between minimum and
83 maximum amplitudes). This is significant, as the observed increases in precipitation over the last five
84 decades have mostly been in summer¹³, and this trend is set to continue¹⁴.

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

89 Time-dependent simulations were forced by the James Ross Island ice core (Figures 1b, 4a), which
90 provides a temperature record²⁰ from 12 cal. ka BP to present and a thinning-corrected accumulation record
91 from 1807 to 2007 AD³. This experiment reproduced a large readvance only during the cool period ca. 1.5
92 cal. ka BP. A small recession was observed during the period 3–5 cal. ka BP, during a +0.5°C warming (Figure
93 4b and animation in Supplementary Information).

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

103 Our modelling experiments indicate that glaciers on Ulu Peninsula remained largely stable during Mid-
104 Holocene time. From 2–5 cal. ka BP, ice-shelf collapse and a small amount of glacier recession occurred
105 during a 0.5°C warming. The ice-shelf reformed following rapid cooling starting 2 cal. ka BP. Glacier IJR45
106 began to advance after 1.5 cal. ka BP, reaching its maximum Holocene position around 300 years ago, before
107 rapid recession to its most recent position. This interpretation is consistent with radiocarbon ages that
108 provide an upper limit for the readvance (~4.8 cal. ka BP⁹), and with records of ice-shelf expansion and
109 glacier readvance at this time on the South Shetland Islands (1.5-1.0 cal. ka BP) and Livingston Island²⁶ (750
110 years ago). A glacier readvance at 1.5 cal. ka BP, during a cool period with ice-shelf re-formation²² and glacier
111 recession during warming, is also consistent with modern observations of glacier recession and ice-shelf
112 collapse during warming.

113 The most recent readvance of Glacier IJR45 therefore occurred during the Neoglacial period, or “Little
114 Ice Age”. Evidence for the “Little Ice Age” around the Antarctic continent is patchy²⁷, and glacier response is
115 poorly understood. Few terrestrial records of glacier advances have been dated to this time²⁷. Our study is
116 the first in this region to convincingly show glacier advance during a period of strong cooling during the last
117 millennium. Further, our findings suggest that, rather than being more extensive during similar climates in
118 the past, as was previously argued, glacier minima similar to present have been experienced at multiple
119 times during the Holocene.

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

122 regional atmospheric climate model RACMO2 (55 km horizontal resolution). We used the A1B and E1
123 emissions scenarios¹⁶ of the Intergovernmental Panel on Climate Change (IPCC), with forcing at the lateral
124 boundaries derived from two global climate models, HadCM3 (to 2200 AD) and ECHAM5 (to 2100 AD). All
125 four simulations predict warming over the next 100-200 years in the Antarctic Peninsula (Figure 4c), but
126 RACMO2 forced by ECHAM5 show less warming and less snowfall over this region (Figure 4d; see
127 Supplementary Information for discussion). All model runs predicted a reduction in glacier volume, with
128 glacier lengths at 2100 AD ranging from 3.8 km (ECHAM5 E1) to 2.8 km (HadCM3 A1B). By 2200 AD, the
129 glacier was predicted to be just 0.5 km long with a volume of 0.03 km³ (HadCM3 A1B; Figure 4c). It is
130 significant that all four simulations predicted temperature increases but opposite precipitation trends, yet all
131 four simulations led to a reduction in ice volume.

132 Glacier IJR45 is typical of many peripheral, land-terminating glaciers around the Antarctic Peninsula,
133 where surface melting is strongly controlled by MAAT and the positive degree-day sum (e.g., ref.²¹). Since
134 both are increasing², summer melting will become increasingly important and these glaciers are expected to
135 contribute significantly to sea-level rise over coming decades⁷. The surface mass-balance processes are also
136 likely to be representative of regional tidewater glaciers draining the Antarctic Peninsula Ice Sheet. As with
137 the gently sloping Glacier IJR45, the flat plateau on the Peninsula and the Mount Haddington Ice Cap renders
138 these glaciers vulnerable to large changes in accumulation area following small temperature changes²¹.
139 Furthermore, changes in precipitation seasonality, with increased snowfall largely occurring in summer
140 months¹⁴, may exacerbate glacier recession over the next two centuries.

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

150

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257

258 **Additional information**

259 Supplementary information is available in the online version of the paper. Reprints and permissions
260 information is available online at www.nature.com/reprints. Correspondence and requests for information
261 should be addressed to BJD.

262

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274

275 **Author contributions**

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

282

283 **Competing financial interests**

284 The authors declare no competing financial interests.

285

286 **Figures**

287 **Figure 1. Study context.** (a) The Antarctic Peninsula. (b) James Ross Island, location of the ice core drilling
288 site, and Prince Gustav Ice Shelf in 1988. Red box shows location of panel 'c'. (c) Ulu Peninsula with
289 published radiocarbon ages (circles)^{9, 28} and cosmogenic nuclide ages (diamonds)^{17, 19}, Brandy Bay Moraine
290 and boulder train. The plan view along line A-B is shown. Spot heights are in italics. The DEM was produced
291 by the Czech Geological Survey²⁹. Bathymetric data are from the Antarctic and Southern Ocean Data Portal
292 of the Marine Geoscience Data System. (d) Cross-section of flowline A-B.

293

294 **Figure 2. Response time and sensitivity test results.** (a) Response time tests showing that IJR45 reaches a
295 dynamic equilibrium after ~400 years and (b) has an *e-folding* time of 100-1000 years, depending on the
296 perturbation. (c-g) Sensitivity test results, with the change in glacier length arising from perturbations to
297 mean annual air temperature, precipitation, snow and ice degree-day factors and flow enhancement
298 coefficient (ice deformation factor).

299

300 **Figure 3. Temperature and precipitation sensitivity experiments.** (a) Change in glacier length following a
301 -1.5°C to +2°C perturbation in mean annual air temperature (-7.2°C). (b) Change in length following a ±20%
302 perturbation in mean annual precipitation (0.65 m a⁻¹). (c) Analysis of simultaneous temperature and
303 precipitation changes on glacier length. Point indicates current climate. (d) Effect of amplitude of
304 precipitation seasonality on glacier volume. (e) Temperature versus length. The influence of precipitation
305 becomes greater with cooler temperatures. (f) Analysis of simultaneous temperature and amplitude of
306 summer precipitation seasonality changes. The influence of summer precipitation seasonality becomes
307 greater under colder temperatures.

308

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

315

316

317 **Methods**

318 **Glaciological input data.** Glaciological input data include ice thickness²³, velocity, mean annual air
319 temperature, topography²⁹ and bathymetry (Figure 1). The most recent readvance was reconstructed from
320 our own geological data^{17, 18} (Figure 1) and from published calibrated radiocarbon^{9, 28} and cosmogenic
321 nuclide ages^{17, 19} (Supplementary Information).

322

323 **Numerical model description.** We used a one-dimensional, finite-difference glacier flowline model to
324 investigate glacier-climate interactions on Ulu Peninsula, James Ross Island. The glacier model and its
325 degree-day scheme have previously been described in detail^{24, 30}, so are only summarised here. The model
326 uses a forward explicit numerical scheme, implemented on a 100 m horizontal resolution staggered grid that
327 spans the length and foreland of Glacier IJR45 into Prince Gustav Channel (Figure 1). Horizontal flux is
328 calculated through a cross-sectional plane described by a symmetrical trapezoid, and incorporates a width-
329 dependent shape factor. The model assumes no transfer of ice flux between adjacent, but dynamically
330 independent, portions of the glacier. Velocity is determined by both the flow-enhancement coefficient
331 (deformation factor), which accounts for the softening of the ice by impurities or contrasts in crystal
332 orientation, and by basal sliding. Outliers in the velocity field are sensitive to transients in the model.

333

334 **Modelling strategy.** The flowline model was tuned to present-day conditions to reproduce observed glacier
335 extent, volume and velocity (Table S3; Methods), and was then dynamically calibrated using temperature
336 and accumulation data over the last 160 years from the James Ross Island ice core^{3, 20} (cf. Figure 1b). Small
337 adjustments were made to the degree-day factors until the glacier replicated observed recession and
338 thinning rates over the last 30 years²³ (Supplementary Information). The glacier stabilised in a position that
339 matched present-day velocity and geometry, thus increasing confidence in model initialisation.

340 Response time tests performed at 0.1°C increments from -0.5°C to +1.0°C investigated time taken to
341 reach equilibrium following perturbation. Sensitivity tests investigated glacier response to perturbations in
342 mean annual air temperature, mean annual precipitation, snow and ice degree-day factors, precipitation
343 seasonality and flow-enhancement coefficient. Further, each incremental change in precipitation was run
344 against each incremental change in temperature. Glacier sensitivity to summer precipitation seasonality
345 under different mean annual air temperatures was also analysed. Subsequent time-dependent simulations
346 used the tuned parameters to model Holocene and future glacier characteristics. Holocene accumulation
347 and air temperatures were derived from the ice-core record^{3, 20}. Future transient runs were forced output
348 from by regional atmospheric climate model (RACMO2), described in more detail in ref.¹⁶ and the
349 Supplementary Information.

350

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

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

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

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







