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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[1]. Increased glacier-surface melt during the twentieth century[2,3] has contributed to ice-shelf collapse and the widespread acceleration[4], thinning and recession[5] of glaciers. Therefore, glaciers peripheral to the Antarctic Ice Sheet currently make a large contribution to eustatic sea-level rise[6,7], but future melting may be offset by increased precipitation[8]. 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. Focusing on Glacier IJR45 on James Ross Island, northeast Antarctic Peninsula, our modelling experiments show that this representative glacier is most sensitive to temperature change, not precipitation change. We determine that its most recent expansion occurred during the late Holocene 'Little Ice Age' and not during the warmer mid-Holocene, as previously proposed[9]. Simulations using a range of future Intergovernmental Panel on Climate Change 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 yr^{-1} in 2006[10]). They are likely to dominate contributions to sea-level rise over the next few decades (21 ± 12 mm by AD 2100 from Antarctic mountain glaciers and ice caps[11]), but there is large uncertainty about the magnitude of their future contribution[11]. This is partly because snow accumulation is increasing on the Antarctic Peninsula plateau[12–14], 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.

James Ross Island (Fig. 1) preserves a rare terrestrial record of Holocene glacier fluctuations[9,17–19] in a region of rapid warming[1,3,20], glacier recession and ice-shelf collapse[21]. Glacier IJR45 on Ulu Peninsula (Fig. 1c) underwent a 10 km re-advance sometime after ~4–5 cal. kyr BP (ref. 9), when air temperatures were 0.5 °C warmer than today[20] (Supplementary Information). Prince Gustav Ice Shelf was absent at this time[22], which is indicative of strong surface melt. Previous research indicates that this re-advance was driven by increased precipitation[9], suggesting that future increased precipitation may offset increased melting. However, this is contrary to currently observed glacier recession[5,21,23] during a period of warming and ice-shelf absence.

We used a high-resolution flowline model (Methods) to establish the primary controls on glacier behaviour in a terrestrial Antarctic Peninsula environment. Climate data from a highly resolved nearby ice core[20] allowed us to test the prevailing hypothesis that a warmer and wetter climate during the mid-Holocene encouraged the synchronous advance of glaciers on James Ross Island and the collapse of the Prince Gustav Ice Shelf[9]. We also used future climate forcings from regional climate model simulations to investigate likely changes in glacier mass balance and geometry over the next two centuries.

Response-time tests showed that the time taken to reach equilibrium is 240 to >1,000 years, depending on the temperature perturbation applied, but that the e-folding time (two-thirds of the time taken to reach equilibrium) ranged from 100 to 400 years depending on the temperature perturbation applied (Fig. 2a,b). Once the glacier begins to calve, the response time increases non-linearly. In our sensitivity experiments (Fig. 2c–g and Supplementary Fig. 7), changing the snow degree-day factor by ±20% resulted in a 0.12 km^3 (28.8%) difference in glacier volume, and a negligible difference in velocity. Increasing the degree-day factor of snow has a similar effect to decreasing the amount of precipitation, which is as expected because it melts the accumulated snow.

A relatively small 0.8 °C decrease in mean annual air temperature (MAAT) was sufficient to force a 10 km glacier advance and an increase in ice volume from 0.53 km^3 to 6.25 km^3 (Figs 2c and 3a and Supplementary Fig. 7). Further growth was limited by calving at the break in slope in Prince Gustav Channel (Figs 1d and 3a). The magnitude of the advance was controlled by the mass-balance gradient and the glacier's hypsometry; a small amount of cooling resulted in a large increase in accumulation area. In contrast, a ±20%

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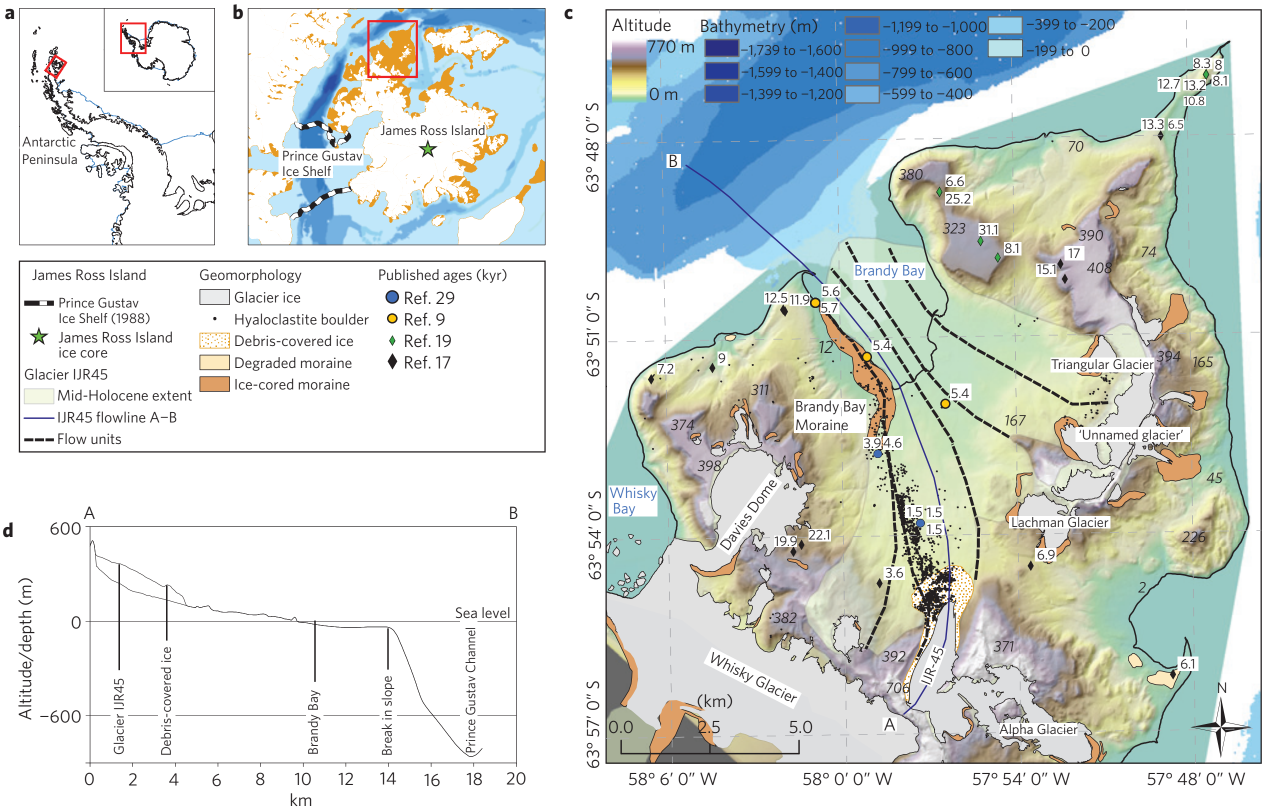

Figure 1 | Study context. a, The Antarctic Peninsula. **b**, James Ross Island, location of the ice-core drilling site, and Prince Gustav Ice Shelf in 1988. The red square shows the location of **c**. **c**, Ulu Peninsula with published radiocarbon ages (circles)[9,29] and cosmogenic nuclide ages (diamonds)[17,19], Brandy Bay Moraine and boulder train. The plan view along line A–B is shown. Spot heights are in italics. The digital elevation model was produced by the Czech Geological Survey[28]. Bathymetric data are from the Antarctic and Southern Ocean Data Portal of the Marine Geoscience Data System. **d**, Cross-section of flowline A–B.

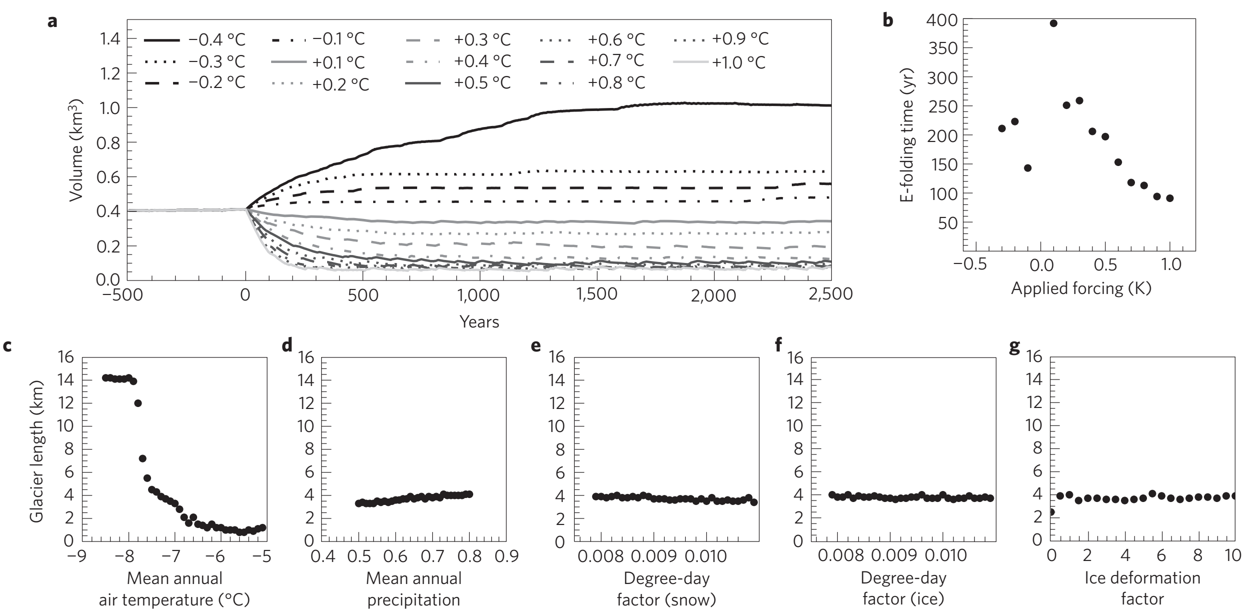

Figure 2 | Response-time and sensitivity test results. a,**b**, Response-time tests showing that, provided it does not start to calve, IJR45 reaches a dynamic equilibrium after ~500 years (**a**) and has an e-folding time of 90–400 years, depending on the perturbation (**b**). **c**–**g**, Sensitivity test results, with the change in glacier length arising from perturbations to MAAT, mean annual precipitation, snow and ice degree-day factors and flow-enhancement coefficient (ice-deformation factor).

change in mean annual precipitation was sufficient to force only a 0.8 km difference in glacier length and a difference in volume of 0.24 km^3 (Figs 2d and 3b). Velocity arising from ice deformation and basal sliding increased under warmer air temperatures as more of the bed reached pressure melting point and as the glacier ice softened. The glacier also accelerated under lower temperatures

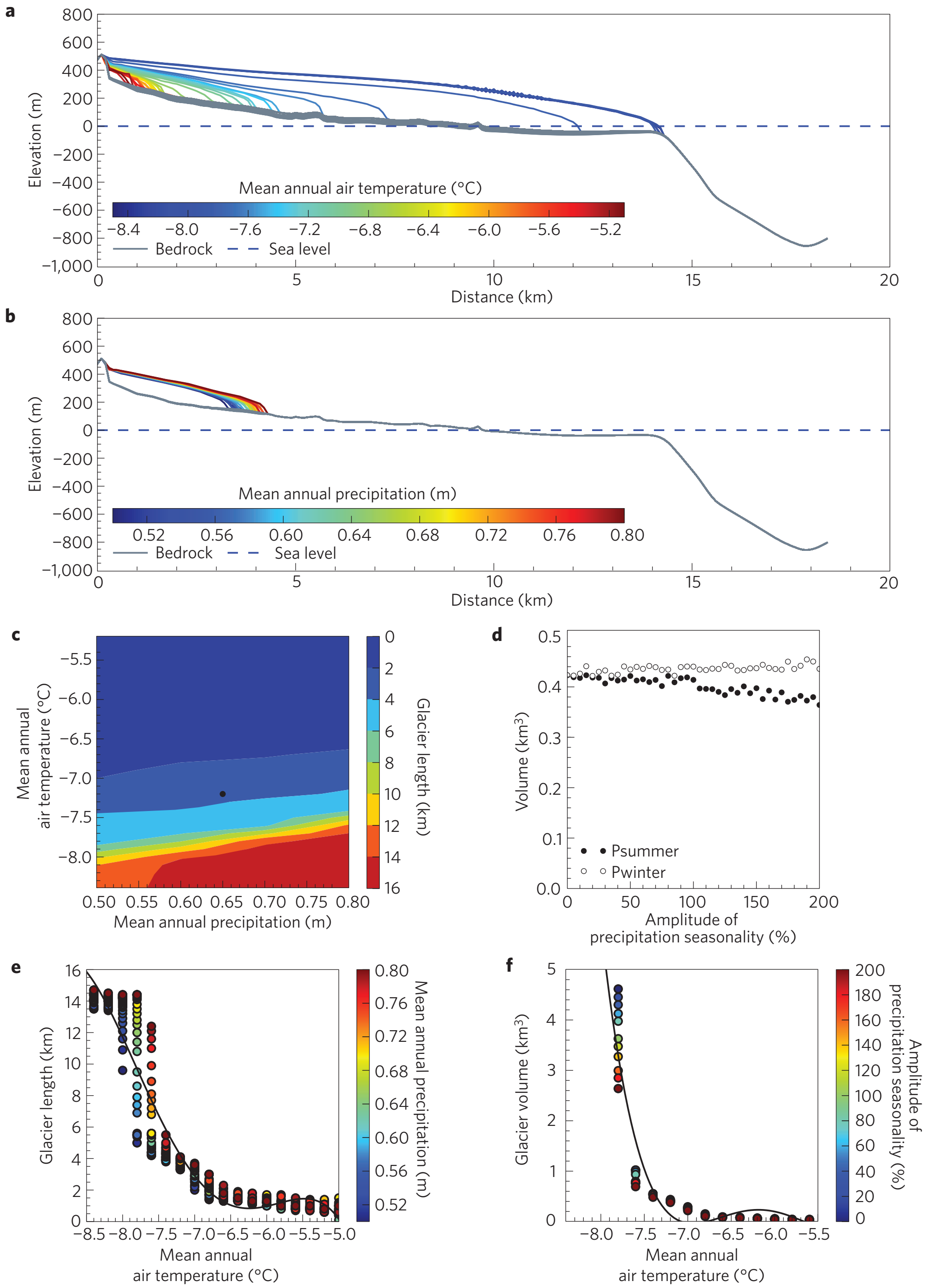

Figure 3 | Temperature and precipitation sensitivity experiments. a, Change in glacier profile under MAATs ranging from −8.5 °C to −5.2 °C. **b**, Change in glacier profile following −20% to +20% perturbations in mean annual precipitation (0.65 m yr^{-1}). **c**, Analysis of simultaneous temperature and precipitation changes on glacier length. Point indicates current climate. **d**, Effect of amplitude of precipitation seasonality on glacier volume. **e**, Temperature versus length. The influence of precipitation becomes greater with cooler temperatures. **f**, Analysis of simultaneous temperature and amplitude of summer precipitation seasonality changes. The influence of summer precipitation seasonality becomes greater under colder temperatures.

because the gravitational driving stress increased as it grew thicker (Supplementary Fig. 7k,p).

We investigated the influence of precipitation under different MAATs (Fig. 3c). Depending on the amount of precipitation, a MAAT of −6.2 °C (a 1 °C warming) resulted in the glacier shrinking to between 1.6 km and 1.1 km long with a volume ranging from 0.055 km^3 to 0.079 km^3, a change of −85.1% to −89.9% compared with modern values. A MAAT of −5.2 °C (a 2 °C warming) resulted in glacier lengths of between 0.6 and 1.4 km and a volume of 0.0167 km^3–0.033 km^3 (−93.8% to −96.9%) under minimum and maximum precipitation scenarios. However, at −8.0 °C (a 0.8 °C cooling), glacier length ranged from 9.6 to 14.4 km, and volume ranged from 2.90 km^3 to 6.54 km^3 (+447% to +1,132%).

Precipitation seasonality can exert a significant control on glacier mass balance[24], because summer precipitation may fall as rain, particularly in relatively warm locations such as the northern Antarctic Peninsula. Warming on summer-precipitation glaciers may therefore result in decreased snow accumulation, as well as

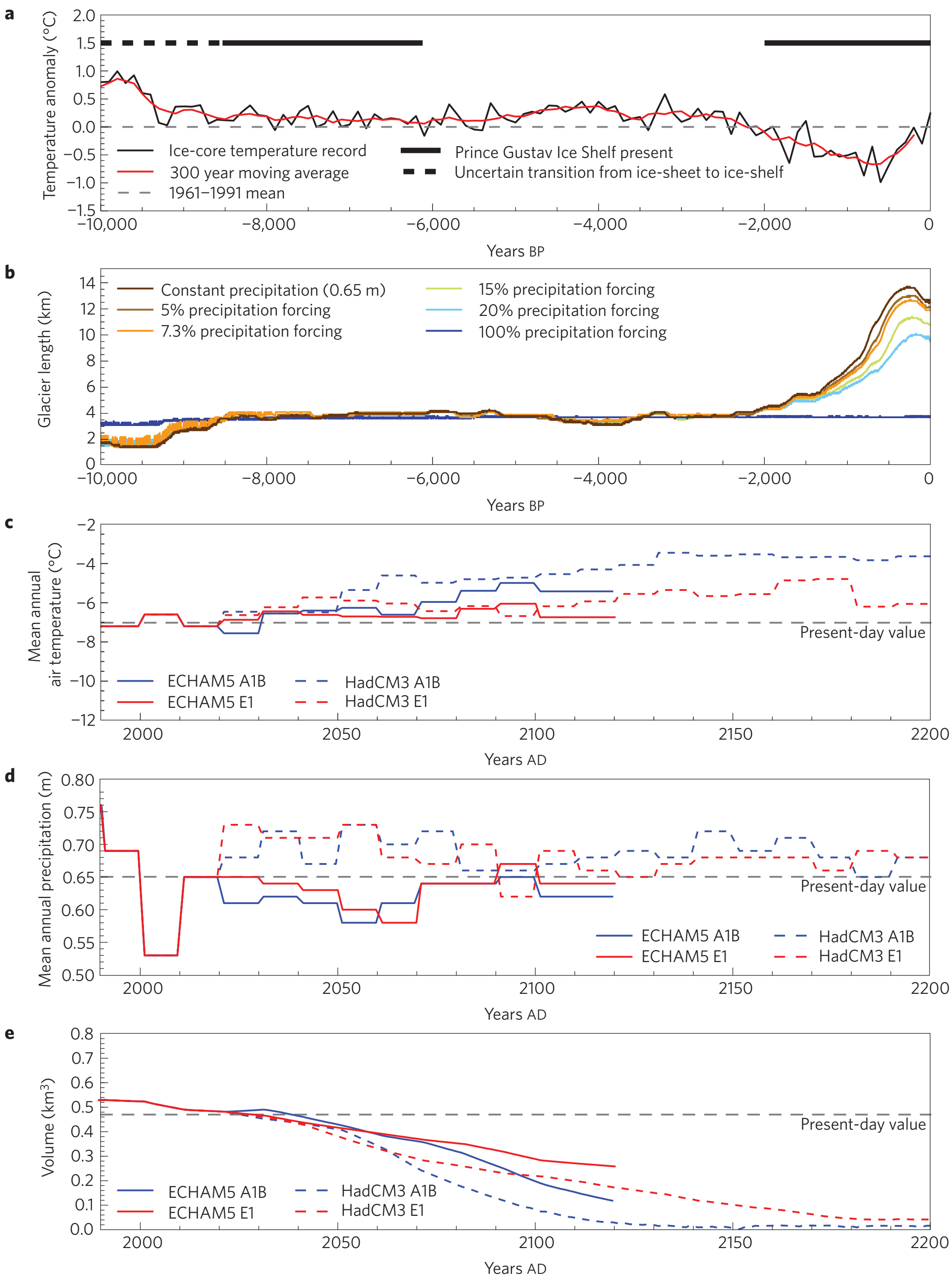

Figure 4 | Holocene and future simulations of glacier length. a, MAAT anomaly during the Holocene from the James Ross Island ice core[3,20]. The presence of Prince Gustav Ice Shelf is indicated by the thick black line. **b**, Change in glacier length as forced by the ice-core temperature record. Precipitation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

prolonging the melt season. Sensitivity analysis of the amplitude of precipitation seasonality (Fig. 3d and Supplementary Information) showed that increasing the proportion of precipitation falling during the summer months resulted in limited glacier recession (0.06 km^3 volume difference between minimum and maximum amplitudes). This is significant, as the observed increases in precipitation over the past five decades have mostly been in summer[13], and this trend is set to continue[14].

Together, these experiments show that the influence of both precipitation and precipitation seasonality is greater at cooler temperatures (Fig. 3e,f), as the accumulation area grows and precipitation increasingly falls as snow. Glacier expansion is eventually limited by calving at the break of slope in Prince Gustav Channel.

Time-dependent simulations were forced by the James Ross Island ice core (Figs 1b and 4a), which provides a temperature record[20] from 12 cal. kyr BP to present and a thinning-corrected accumulation record from AD 1807 to 2007[3]. This experiment reproduced a large re-advance only during the cool period about 1.5 cal. kyr BP. A small recession was observed during the period 3–5 cal. kyr BP, during a +0.5 °C warming (Fig. 4b and Supplementary Movie).

Whereas the accumulation record from the James Ross Island ice core seems to show no increase in accumulation with temperature (Supplementary Fig. 5), and thus a temperature–precipitation dependence of 0%, a dependence of up to 50% has been reported elsewhere on the Antarctic Peninsula[12,13]. The generally held value is 5–7.3% (ref. 25). To explore a range of possible climatic scenarios, we increased precipitation by 5%, 7.3%, 15%, 20% and 100% for every 1 °C increase in temperature to test the hypothesis that a warmer but wetter climate was responsible for the mid-Holocene re-advance. This change in precipitation fed the glacier during warm periods and starved it during cool periods, dampening the glacier's response and resulting in progressively smaller fluctuations (Fig. 4b). None of these experiments drove a 10 km re-advance from 2 to 5 cal. kyr BP, even under extreme precipitation scenarios.

Our modelling experiments indicate that glaciers on Ulu Peninsula remained largely stable during mid-Holocene time. From 2 to 5 cal. kyr BP, ice-shelf collapse and a small amount of glacier recession occurred during a 0.5 °C warming. The ice shelf reformed following rapid cooling starting 2 cal. kyr BP. Glacier IJR45 began to advance after 1.5 cal. kyr BP, reaching its maximum Holocene position around 300 years ago, before rapid recession to its most recent position. This interpretation is consistent with radiocarbon ages that provide an upper limit for the re-advance (∼4.8 cal. kyr BP (ref. 9)), and with records of ice-shelf expansion and glacier re-advance at this time on the South Shetland Islands (1.5–1.0 cal. kyr BP) and Livingston Island[26] (750 years ago). A glacier re-advance from 1.5 to 0.3 cal. kyr BP, during a cool period with ice-shelf re-formation[22], and with glacier recession during warming, is consistent with modern observations.

The most recent re-advance of Glacier IJR45 therefore occurred during the Neoglacial period, or 'Little Ice Age'. Evidence for the 'Little Ice Age' around the Antarctic continent is patchy[27], and glacier response is poorly understood. Few terrestrial records of glacier advances have been dated to this time[27]. Our study is the first in this region to convincingly show glacier advance during a period of strong cooling during the past millennium. Further, our findings suggest that, rather than being more extensive during similar climates in the past, as was previously argued, glacier minima similar to present have been experienced at multiple times during the Holocene.

To assess the significance of these findings within the context of projected future climate scenarios, we performed time-dependent simulations from AD 1980 to 2200, forced with climate outputs from the regional atmospheric climate model RACMO2 (55 km horizontal resolution). We used the A1B and E1 emissions scenarios[16] of the Intergovernmental Panel on Climate Change (IPCC), with forcing at the lateral boundaries derived from two global climate models, HadCM3 (to AD 2200) and ECHAM5 (to AD 2100). All four simulations predict warming over the next 100–200 years in the Antarctic Peninsula (Fig. 4c), but RACMO2 forced by ECHAM5 shows less warming and less snowfall over this region (Fig. 4d and see Supplementary Information for discussion). All model runs predicted a reduction in glacier volume, with glacier lengths at AD 2100 ranging from 3.8 km (ECHAM5 E1) to 2.8 km (HadCM3 A1B). By AD 2200, the glacier was predicted to be just 0.5 km long with a volume of 0.03 km^3 (HadCM3 A1B; Fig. 4e). It is significant that all four simulations predicted temperature increases but opposite precipitation trends, yet all four simulations led to a reduction in ice volume.

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

In conclusion, glacier modelling, spanning a range of past, present and future time intervals, shows that Glacier IJR45 has high sensitivity to air temperature and is less sensitive to precipitation. Glacier advance during past and future warm periods is therefore unlikely. Authors of previous studies have argued that a re-advance occurred during a warmer but wetter period, around 4–5 kyr BP (refs 9,19,26), suggesting that increased precipitation in the future would offset glacier melt due to higher air temperatures. We reject the hypotheses that the glacier re-advanced during the mid-Holocene in response to increased precipitation, and that increased precipitation over the next 200 years will offset increased glacier melt. The currently observed trends of glacier melting, recession and thinning across the Antarctic Peninsula are likely to continue throughout the next century.

Methods

Glaciological input data. Glaciological input data include ice thickness[23], velocity, MAAT, topography[28] and bathymetry (Fig. 1). The most recent re-advance was reconstructed from our own geological data[17,18] (Fig. 1) and from published calibrated radiocarbon[9,29] and cosmogenic nuclide ages[17,19] (Supplementary Information).

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

Modelling strategy. The flowline model was tuned to present-day conditions to reproduce observed glacier extent, volume and velocity (Supplementary Table 3 and Methods), and was then dynamically calibrated using temperature and accumulation data over the past 160 years from the James Ross Island ice core[3,20] (Fig. 1b). Small adjustments were made to the degree-day factors until the glacier replicated observed recession and thinning rates over the past 30 years[23] (Supplementary Information). The glacier stabilized in a position that matched present-day velocity and geometry, thus increasing confidence in model initialization.

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

Experiment advantages and limitations. Advantages of this model domain are, first, that this is a simple model applied to one of the best observed and instrumented glaciers on the Antarctic Peninsula. Second, Glacier IJR45 is land-terminating and represents a well-constrained system that isolates the controls on surface mass balance. Most notably, we are able to ignore the uncertainties associated with a more complex oceanic and tidewater glacier system. By restricting the number of assumptions and independent variables, we are able to present an entirely new and original analysis of glacier–climate sensitivities in a critical, and rapidly changing, region. Third, Holocene dynamics are well constrained by detailed geomorphological data and the ice core[3,20].

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

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

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

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Author contributions

B.J.D. conducted fieldwork, planned and undertook the modelling, and led the writing and the compilation of the graphics and tables. N.R.G. wrote the flowline model and contributed to the modelling effort. N.F.G. conducted fieldwork and designed the original field-based project. J.L.C. contributed to the original field-based project design and the fieldwork. M.J.H. and J.L.S. contributed to the original project design. N.E.B., S.R.M.L. and M.R.v.d.B. provided projections of future climate around the Antarctic Peninsula. All authors contributed to the writing of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.J.D.

Competing financial interests

The authors declare no competing financial interests.