Aberystwyth University

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

Davies, Bethan J.; Golledge, Nicholas R.; Glasser, Neil F.; Carrivick, Jonathan L.; Ligtenberg, Stefan R. M.; Barrand, Nicholas E.; van den Broeke, Michiel R.; Hambrey, Michael J.; Smellie, John L.

Published in:
Nature Climate Change

DOI:
10.1038/NCLIMATE2369

Publication date:
2014

Citation for published version (APA):
Davies, B. J., Golledge, N. R., Glasser, N. F., Carrivick, J. L., Ligtenberg, S. R. M., Barrand, N. E., van den Broeke, M. R., Hambrey, M. J., & Smellie, J. L. (2014). Modelled glacier response to centennial temperature and precipitation trends on the Antarctic Peninsula. *Nature Climate Change*, *4*(11), 993-998. https://doi.org/10.1038/NCLIMATE2369

General rights
Copyright and moral rights for the publications made accessible in the Aberystwyth Research Portal (the Institutional Repository) are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the Aberystwyth Research Portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the Aberystwyth Research Portal

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

tel: +44 1970 62 2400
email: is@aber.ac.uk

Download date: 09. Jul. 2020

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. Glasser[1], Jonathan L. Carrivick[4], Stefan R.M. Ligtenberg[5], Nicholas E. Barrand[6], Michiel R. van den Broeke[5], Michael J. Hambrey[1], John L. Smellie[7],

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

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

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

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

[5]IMAU, Utrecht University, Utrecht, The Netherlands

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

[7]Department 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 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. 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 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. 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[9]. 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 2006[10]). 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[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, 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.

James Ross Island (Figure 1) preserves a rare terrestrial record of Holocene glacier fluctuations[9, 17, 18, 19] in a region of rapid warming[1, 3, 20], glacier recession and ice-shelf collapse[21]. Glacier IJR45 on Ulu Peninsula underwent a 10 km re-advance sometime after ~4-5 cal. ka BP[9], perhaps during a period that was 0.5°C warmer than today[20] (Supplementary Information, Figure 1c). Prince Gustav Ice Shelf was absent at this time[22], which is indicative of strong surface melt. Previous research indicates that this readvance 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 (RCM) 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 >1000 years, depending on the temperature perturbation applied, but that the *e-folding* time (two-thirds of the time taken to reach equilibrium) ranged from 100-1000 years depending on the temperature perturbation (Figure 2a, b). In our sensitivity experiments (Figure 2 b-g; Supplementary Figure 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 as 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 (Figures 2c, 3a, Supplementary Figure 7). Further growth was limited by calving at the break in slope in Prince Gustav Channel (Figures 1d, 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% change in mean annual precipitation was only sufficient to force a 0.8 km difference in glacier length and a difference in volume of 0.24 km^3 (Figures 2d, 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 because the gravitational driving stress increased as it grew thicker (Supplementary Figure 7k, p).

We investigated the influence of precipitation under different mean annual air temperatures (Figure 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 to 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 +1132%).

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 prolonging the melt season. Sensitivity analysis of the amplitude of precipitation seasonality

(Figure 3d, Supplementary Information) showed that increasing the proportion of precipitation falling during the summer months resulted in glacier recession (0.06 km^3 volume difference between minimum and maximum amplitudes). This is significant, as the observed increases in precipitation over the last 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 less at warmer temperatures (Figure 3e, 3f), as the accumulation area diminishes and precipitation increasingly falls as rain. At cooler temperatures, 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 (Figures 1b, 4a), which provides a temperature record[20] from 12 cal. ka BP to present and a thinning-corrected accumulation record from 1807 to 2007 AD[3]. This experiment reproduced a large readvance only during the cool period ca. 1.5 cal. ka BP. A small recession was observed during the period 3–5 cal. ka BP, during a +0.5°C warming (Figure 4b and animation in Supplementary Information).

While the accumulation record from the James Ross Island ice core appears to show no increase in accumulation with temperature (Supplementary Figure 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% to 7.3%[25]. In order 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 readvance. 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 (Figure 4b). None of these experiments drove a 10 km readvance from 2–5 cal. ka BP, even under extreme precipitation scenarios.

Our modelling experiments indicate that glaciers on Ulu Peninsula remained largely stable during Mid-Holocene time. From 2–5 cal. ka 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. ka BP. Glacier IJR45 began to advance after 1.5 cal. ka 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 readvance (~4.8 cal. ka BP[9]), and with records of ice-shelf expansion and glacier readvance at this time on the South Shetland Islands (1.5-1.0 cal. ka BP) and Livingston Island[26] (750 years ago). A glacier readvance at 1.5 cal. ka BP, during a cool period with ice-shelf re-formation[22] and glacier recession during warming, is also consistent with modern observations of glacier recession and ice-shelf collapse during warming.

The most recent readvance 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 last 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 1980 to 2200 AD, 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 2200 AD) and ECHAM5 (to 2100 AD). All four simulations predict warming over the next 100-200 years in the Antarctic Peninsula (Figure 4c), but RACMO2 forced by ECHAM5 show less warming and less snowfall over this region (Figure 4d; see Supplementary Information for discussion). All model runs predicted a reduction in glacier volume, with glacier lengths at 2100 AD ranging from 3.8 km (ECHAM5 E1) to 2.8 km (HadCM3 A1B). By 2200 AD, the glacier was predicted to be just 0.5 km long with a volume of 0.03 km^3 (HadCM3 A1B; Figure 4c). 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 (e.g., ref. [21]). Since both are increasing[2], summer melting will become increasingly 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 readvance occurred during a warmer but wetter period, around 4-5 ka BP[9, 19, 26], suggesting that increased precipitation in the future would offset glacier melt due to higher air temperatures. We reject the hypotheses that 1) the glacier readvanced during the Holocene in response to increased precipitation, and 2) 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.

References

1. Turner J, Colwell SR, Marshall GJ, Lachlan-Cope TA, Carelton AM, Jones PD*, et al.* Antarctic climate change during the last 50 years. *International Journal of Climatology* 2005, **25:** 279-294.

2. Barrand NE, Vaughan DG, Steiner N, Tedesco M, Kuipers Munneke P, van den Broeke MR*, et al.* Trends in Antarctic Peninsula surface melting conditions from observations and regional climate modeling. *Journal of Geophysical Research: Earth Surface* 2013, **118**(1)**:** 315-330.

3. Abram NJ, Mulvaney R, Wolff EW, Triest J, Kipfstuhl S, Trusel LD*, et al.* Acceleration of snow melt in an Antarctic Peninsula ice core during the Twentieth Century. *Nature Geosci* 2013, **6:** 404-411.

4. Pritchard HD, Vaughan DG. Widespread acceleration of tidewater glaciers on the Antarctic Peninsula. *Journal of Geophysical Research-Earth Surface* 2007, **112**(F3)**:** F03S29, 01-10.

5. Cook AJ, Fox AJ, Vaughan DG, Ferrigno JG. Retreating glacier fronts on the Antarctic Peninsula over the past half-century. *Science* 2005, **308**(5721)**:** 541-544.

6. Hock R, de Woul M, Radic V, Dyurgerov M. Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution. *Geophysical Research Letters* 2009, **36:** L07501.

7. Gardner AS, Moholdt G, Cogley JG, Wouters B, Arendt AA, Wahr J*, et al.* A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009. *Science* 2013, **340**(6134)**:** 852-857.

8. Uotila P, Lynch AH, Cassano JJ, Cullather RI. Changes in Antarctic net precipitation in the 21st Century based on Intergovernmental Panel on Climate Change (IPCC) model scenarios. *Journal of Geophysical Research* 2007, **112:** D10107.

9. Hjort C, Ingólfsson Ó, Möller P, Lirio JM. Holocene glacial history and sea-level changes on James Ross Island, Antarctic Peninsula. *Journal of Quaternary Science* 1997, **12:** 259-273.

10. Meier MF, Dyurgerov MB, Rick UK, O'Neel S, Pfeffer WT, Anderson RS*, et al.* Glaciers Dominate Eustatic Sea-Level Rise in the 21st Century. *Science* 2007, **317**(5841)**:** 1064-1067.

11. Radic V, Hock R. Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. *Nature Geosci* 2011, **4**(2)**:** 91-94.

12. Thomas ER, Marshall GJ, McConnell JR. A doubling in snow accumulation in the western Antarctic Peninsula since 1850. *Geophysical Research Letters* 2008, **35**(1)**:** L01706.

13. Turner J, Lachlan-Cope T, Colwell S, Marshall GJ. A positive trend in western Antarctic Peninsula precipitation over the last 50 years reflecting regional and Antarctic-wide atmospheric circulation changes. *Annals of Glaciology* 2005, **41**(1)**:** 85-91.

14. Krinner G, Magand O, Simmonds I, Genthon C, Dufresne JL. Simulated Antarctic precipitation and surface mass balance at the end of the twentieth and twenty-first centuries. *Climate Dynamics* 2007, **28**(2-3)**:** 215-230.

15. Barrand NE, Hindmarsh RCA, Arthern R, Williams CR, Mouginot J, Scheuchl B*, et al.* Computing the volume response of the Antarctic Peninsula Ice Sheet to warming scenarios to 2200. *Journal of Glaciology* 2013, **59**(215)**:** 397-409.

16. Ligtenberg SRM, van de Berg WJ, van den Broeke MR, Rae JGL, van Meijgaard E. Future surface mass balance of the Antarctic ice sheet and its influence on sea level change, simulated by a regional atmospheric climate model. *Climate Dynamics* 2013, **41**(3-4)**:** 867-884.

17. Glasser NF, Davies BJ, Carrivick JL, Rodés A, Hambrey MJ, Smellie JL*, et al.* Ice-stream initiation, duration and thinning on James Ross Island, northern Antarctic Peninsula. *Quaternary Science Reviews* 2014, **86:** 78-88.

18. Davies BJ, Glasser NF, Carrivick JL, Hambrey MJ, Smellie JL, Nývlt D. Landscape evolution and ice-sheet behaviour in a semi-arid polar environment: James Ross Island, NE Antarctic Peninsula. In: Hambrey MJ, Barker PF, Barrett PJ, Bowman VC, Davies BJ, Smellie JL*, et al.* (eds). *Antarctic Palaeoenvironments and Earth-Surface Processes*, vol. 381. Geological Society, London, Special Publications, volume 381: London, 2013, pp 353-395.

19. Johnson JS, Bentley MJ, Roberts SJ, Binney SA, Freeman SPHT. Holocene deglacial history of the north east Antarctic Peninsula - a review and new chronological constraints. *Quaternary Science Reviews* 2011, **30**(27-28)**:** 3791-3802.

20. Mulvaney R, Abram NJ, Hindmarsh RCA, Arrowsmith C, Fleet L, Triest J*, et al.* Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history. *Nature* 2012, **489:** 141-144.

21. Davies BJ, Carrivick JL, Glasser NF, Hambrey MJ, Smellie JL. Variable glacier response to atmospheric warming, northern Antarctic Peninsula, 1988–2009. *The Cryosphere* 2012, **6:** 1031-1048.

22. Pudsey CJ, Murray JW, Appleby P, Evans J. Ice shelf history from petrographic and foraminiferal evidence, Northeast Antarctic Peninsula. *Quaternary Science Reviews* 2006, **25**(17-18)**:** 2357-2379.

23. Engel Z, Nývlt D, Láska K. Ice thickness, areal and volumetric changes of Davies Dome and Whisky Glacier in 1979-2006 (James Ross Island, Antarctic Peninsula). *Journal of Glaciology* 2012, **58**(211)**:** 904-914.

24. Golledge N, Hubbard A, Bradwell T. Influence of seasonality on glacier mass balance, and implications for palaeoclimate reconstructions. *Climate Dynamics* 2010, **35**(5)**:** 757-770.

25. Huybrechts P. Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles. *Quaternary Science Reviews* 2002, **21**(1-3)**:** 203-231.

26. Hall BL. Holocene glacial history of Antarctica and the sub-Antarctic islands. *Quaternary Science Reviews* 2009, **28**(21-22)**:** 2213-2230.

27. Bentley MJ, Hodgson DA, Smith JA, Ó Cofaigh C, Domack EW, Larter RD*, et al.* Mechanisms of Holocene palaeoenvironmental change in the Antarctic Peninsula region. *Holocene* 2009, **19**(1)**:** 51-69.

28. Björck S, Olsson S, Ellis-Evans C, Håkansson H, Humlum O, de Lirio JM. Late Holocene palaeoclimatic records from lake sediments on James Ross Island, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology* 1996, **121**(3-4)**:** 195-220.

29. Nývlt D, Šerák L. James Ross Island - Northern Part. Topographic Map 1:25 000. Praha: Czech Geological Survey; 2009.

30. Golledge NR, Levy RH. Geometry and dynamics of an East Antarctic Ice Sheet outlet glacier, under past and present climates. *J Geophys Res* 2011, **116**(F3)**:** F03025.

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 information should be addressed to BJD.

Acknowledgements

This work was funded by the UK Natural Environment Research Council (NERC) under the Antarctic Funding Initiative grant (NE/F012942/1), awarded to NFG and MJH, and a SCAR (Scientific Committee for Antarctic Research) Fellowship awarded to BJD to visit the Antarctic Research Centre, Victoria University of Wellington. Transport logistics and fieldwork on James Ross Island were supported by the British Antarctic Survey, and we thank the captain and crew of the *RRS Ernest Shackleton* and the *RRS James Clark Ross* for their support. We thank Alan Hill for his field logistical support. We thank the Czech Geological Survey for providing topographical and glaciological data. Dr Nerilie Abram provided a thinning and ice-flow corrected ice-core accumulation record from the 2007 James Ross Island ice core (1807-2007 AD). We also acknowledge the Netherlands Polar Program of NWO/ALW and the ice2sea project, funded by the European Commission's 7th Framework Programme through grant number 226375, ice2sea manuscript number 174.

Author contributions

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

Competing financial interests

The authors declare no competing financial interests.

Figures

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. Red box shows location of panel 'c'. (c) Ulu Peninsula with published radiocarbon ages (circles)[9, 28] 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 DEM was produced by the Czech Geological Survey[29]. 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) Response time tests showing that IJR45 reaches a dynamic equilibrium after ~400 years and (b) has an *e-folding* time of 100-1000 years, depending on the perturbation. (c-g) Sensitivity test results, with the change in glacier length arising from perturbations to mean annual air temperature, precipitation, snow and ice degree-day factors and flow enhancement coefficient (ice deformation factor).

Figure 3. Temperature and precipitation sensitivity experiments. (a) Change in glacier length following a -1.5°C to +2°C perturbation in mean annual air temperature (-7.2°C). (b) Change in length following a ±20% perturbation in mean annual precipitation (0.65 m a^{-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.

Figure 4. Holocene and future simulations of glacier length. (a) Mean annual air temperature 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) Plot of temperature and (d) precipitation changes simulated by RACMO2 under four different forcing scenarios. (e) Resultant change in glacier volume.

Methods

Glaciological input data. Glaciological input data include ice thickness[23], velocity, mean annual air temperature, topography[29] and bathymetry (Figure 1). The most recent readvance was reconstructed from our own geological data[17, 18] (Figure 1) and from published calibrated radiocarbon[9, 28] 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 summarised 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 (Figure 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 (Table S3; Methods), and was then dynamically calibrated using temperature and accumulation data over the last 160 years from the James Ross Island ice core[3, 20] (cf. Figure 1b). Small adjustments were made to the degree-day factors until the glacier replicated observed recession and thinning rates over the last 30 years[23] (Supplementary Information). The glacier stabilised in a position that matched present-day velocity and geometry, thus increasing confidence in model initialisation.

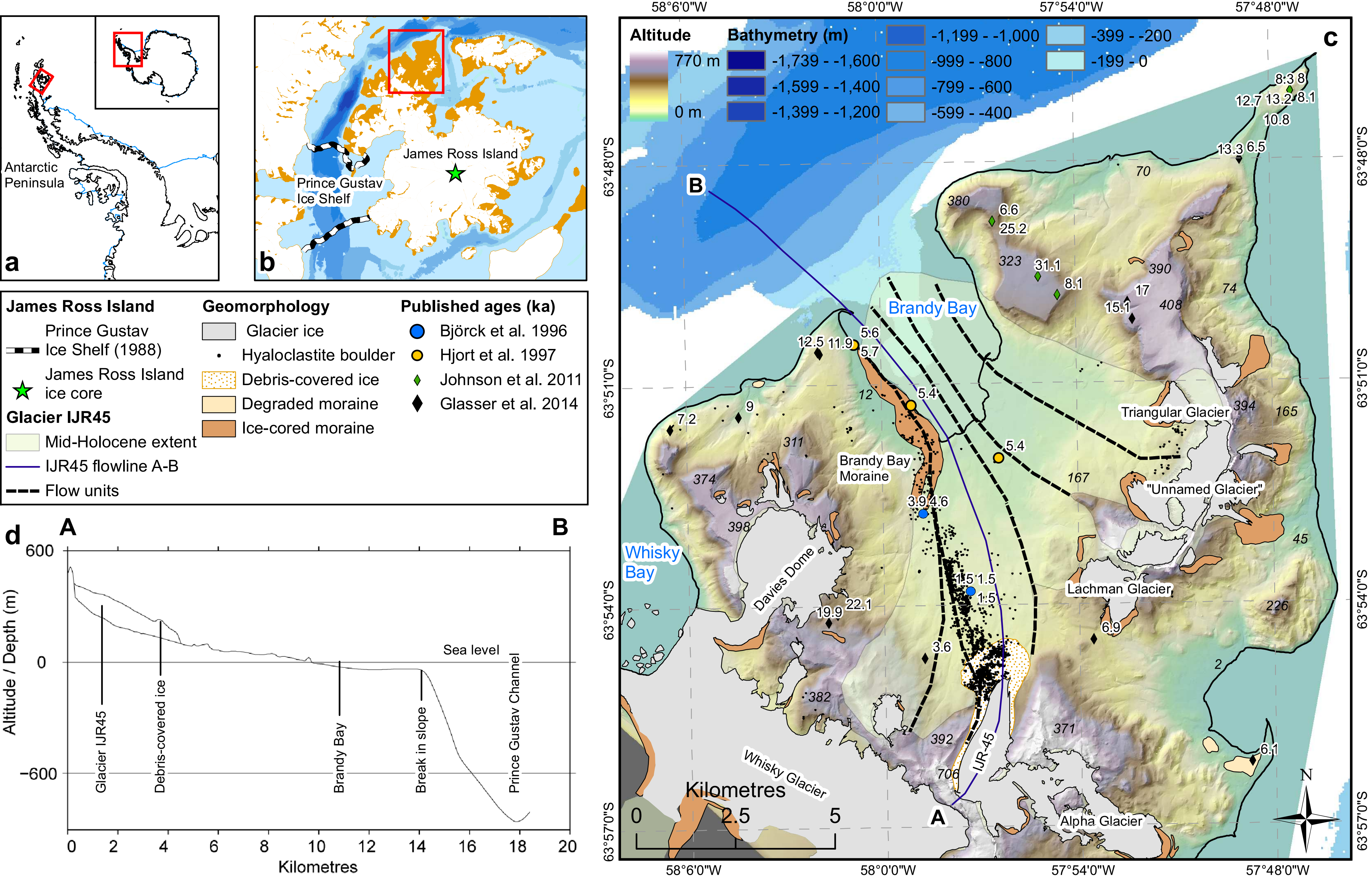
Response time tests performed at 0.1°C increments from -0.5°C to +1.0°C investigated time taken to reach equilibrium following perturbation. Sensitivity tests investigated glacier response to perturbations in mean annual air temperature, mean annual precipitation, snow and ice degree-day factors, precipitation 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 mean annual air temperatures 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 output from by regional atmospheric climate model (RACMO2), described in more detail in ref.[16] and the Supplementary Information.

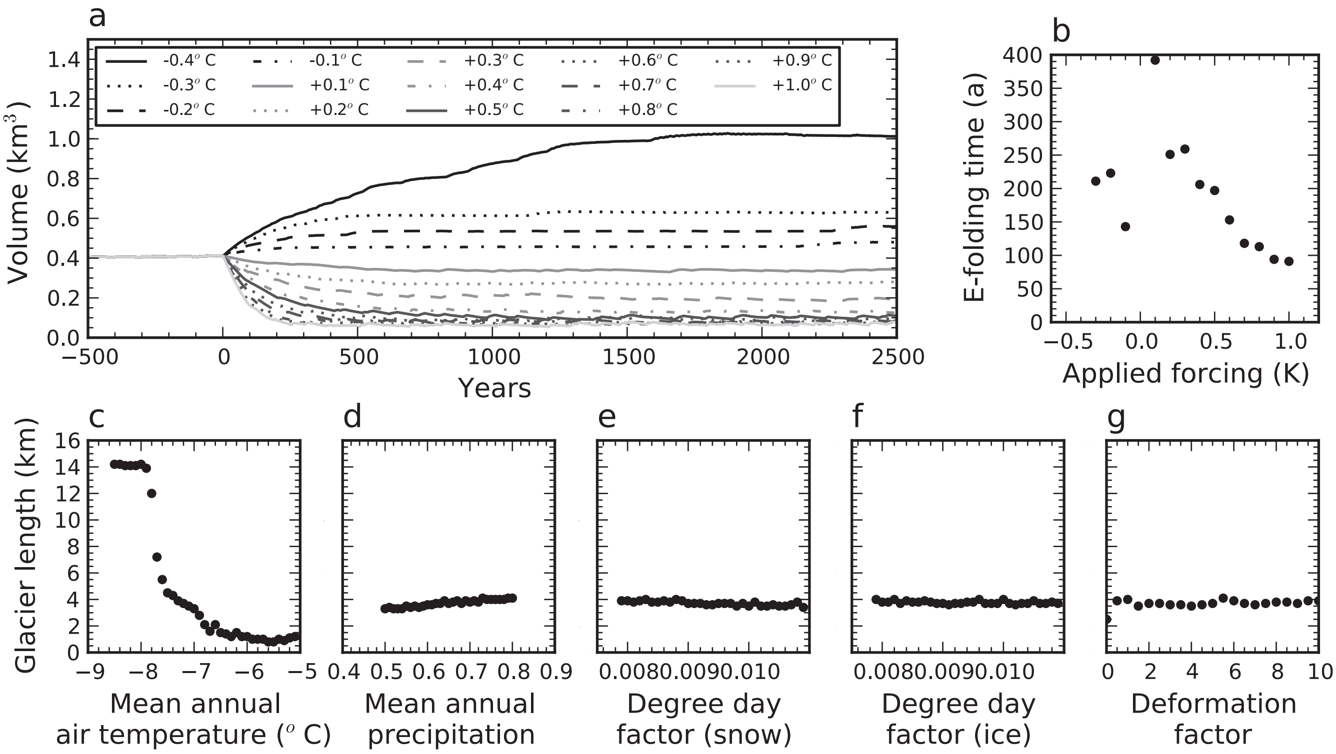
Experiment advantages and limitations. Advantages of this model domain are, firstly, that this is a simple model applied to one of the best observed and instrumented glaciers on the Antarctic Peninsula. Secondly, Glacier IJR45 is land-terminating and represents a well-constrained system that isolates 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 novel and original analysis of glacier-climate sensitivities in a critical, and rapidly changing, region. Thirdly, 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 (Figure 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.

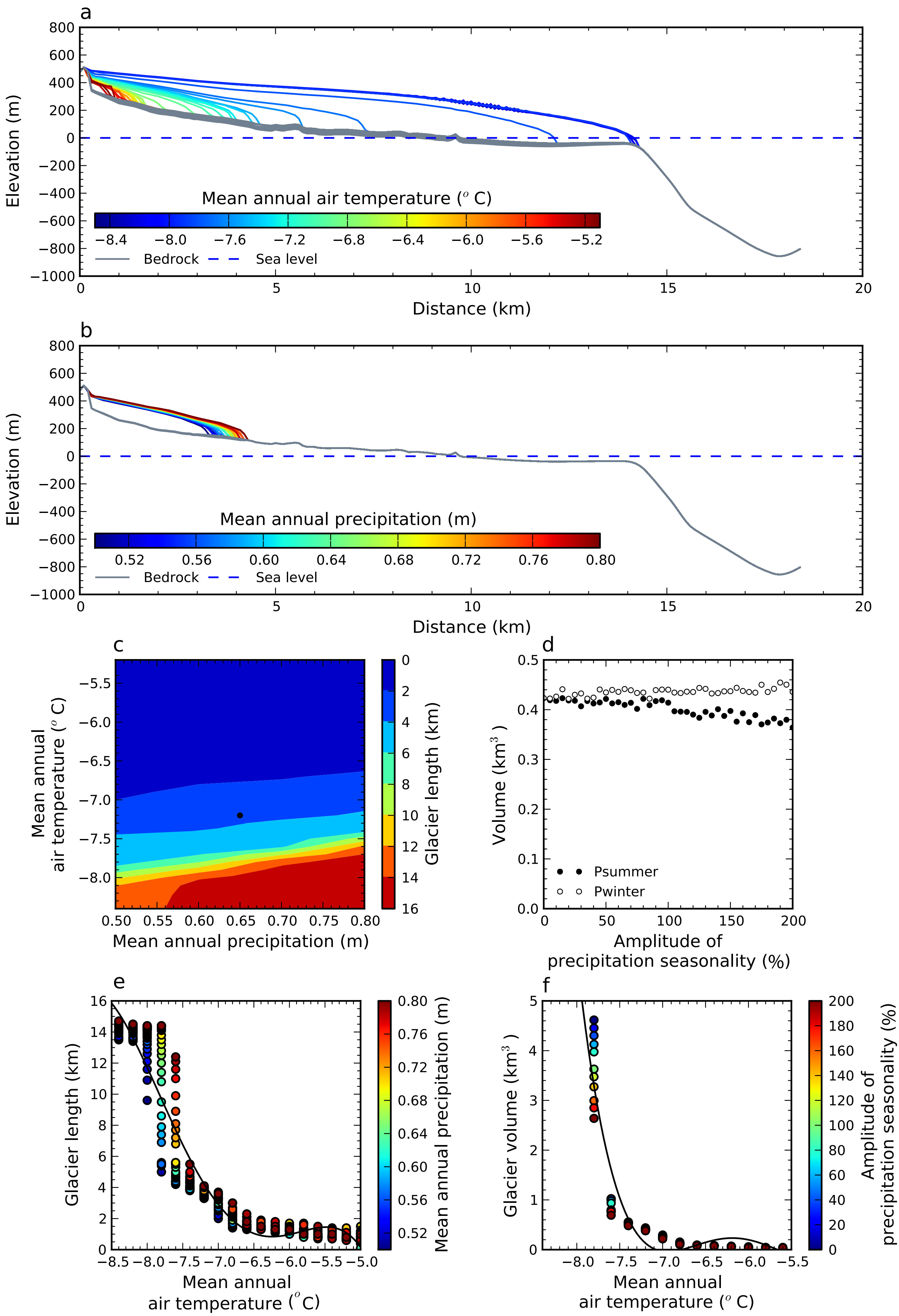
The 10,000 year Holocene experiment finishes with a glacier that is larger than that of the present day, but is rapidly receding. This is a limitation in the model; the enlarged modelled glacier is unable to respond fast enough to the rapidly increasing air temperatures.

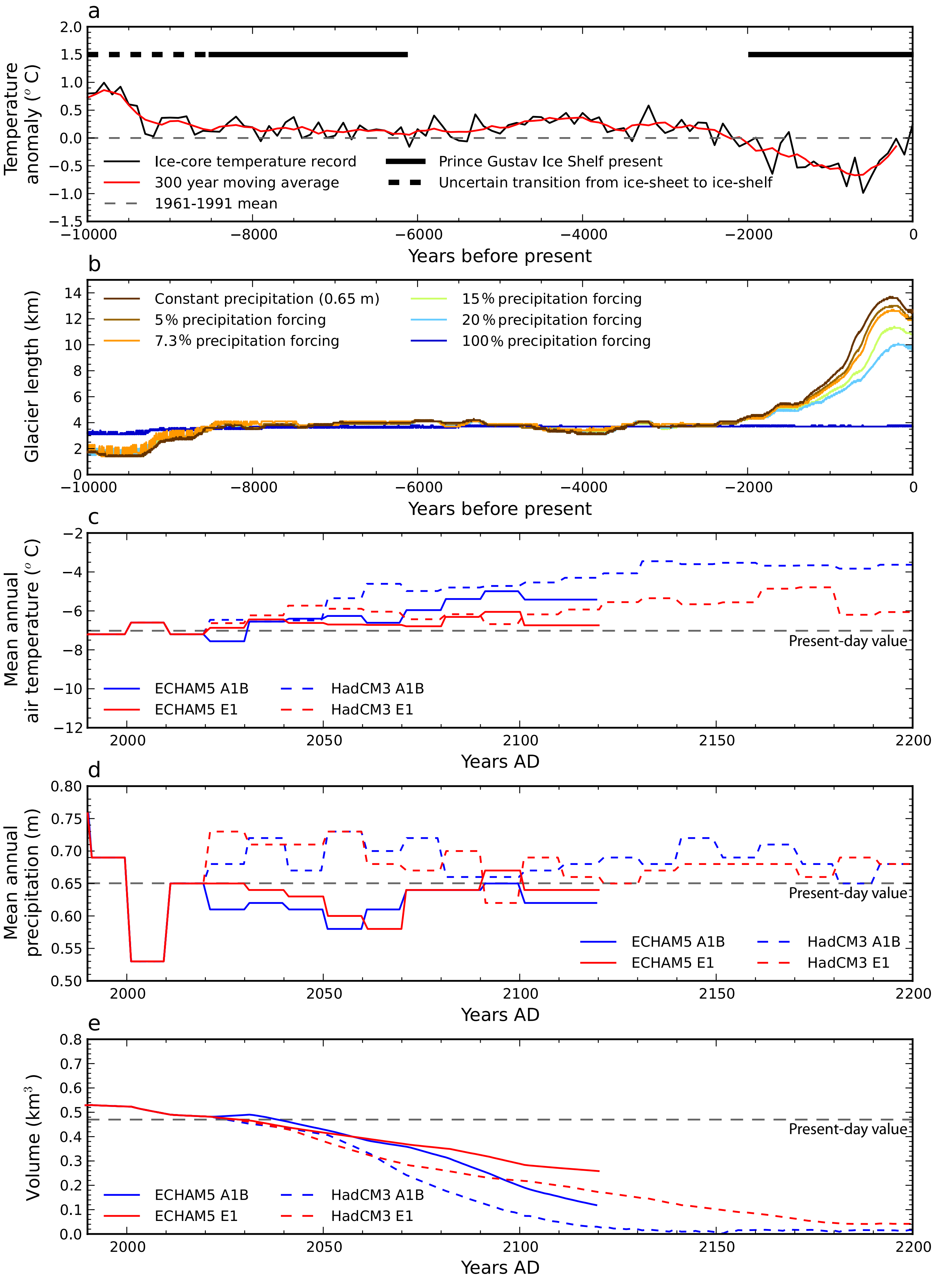
As the forefield is very flat, adding mass from an adjoining flow unit could force a more rapid readvance. However, Glacier IJR45 needs to be relatively advanced before it would be affected by adjacent ice. During an advance, adjacent ice may have enhanced expansion, but with limited effect. If it did 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.


a
Antarctic Peninsula
b
Prince Gustav Ice Shelf
James Ross Island
James Ross Island
Prince Gustav Ice Shelf (1988)
James Ross Island ice core
Glacier IJR45
Mid-Holocene extent
IJR45 flowline A-B
Flow units
Geomorphology
Glacier ice
Hyaloclastite boulder
Debris-covered ice
Degraded moraine
Ice-cored moraine
Published ages (ka)
Björck et al. 1996
Hjort et al. 1997
Johnson et al. 2011
Glasser et al. 2014
c
Altitude
770 m
0 m
Bathymetry (m)
-1,739 - -1,600
-1,599 - -1,400
-1,399 - -1,200
-1,199 - -1,000
-999 - -800
-799 - -600
-599 - -400
-399 - -200
-199 - 0
Brandy Bay
Brandy Bay Moraine
Whisky Bay
Davies Dome
Whisky Glacier
Triangular Glacier
"Unnamed Glacier"
Lachman Glacier
Alpha Glacier
IJR-45
Kilometres
0
2.5
5
58°6'0"W
58°0'0"W
57°54'0"W
57°48'0"W
63°48'0"S
63°51'0"S
63°54'0"S
63°57'0"S
d
A
B
Altitude / Depth (m)
600
0
-600
Sea level
Glacier IJR45
Debris-covered ice
Brandy Bay
Break in slope
Prince Gustav Channel
Kilometres
0
2
4
6
8
10
12
14
16
18
20



a
b
c
d
e
f
g
Volume (km³)
Years
E-folding time (a)
Applied forcing (K)
Glacier length (km)
Mean annual air temperature (° C)
Mean annual precipitation
Degree day factor (snow)
Degree day factor (ice)
Deformation factor
-0.4° C
-0.3° C
-0.2° C
-0.1° C
+0.1° C
+0.2° C
+0.3° C
+0.4° C
+0.5° C
+0.6° C
+0.7° C
+0.8° C
+0.9° C
+1.0° C


a
Elevation (m)
Mean annual air temperature (^{o} C)
−8.4 −8.0 −7.6 −7.2 −6.8 −6.4 −6.0 −5.6 −5.2
Bedrock
Sea level
Distance (km)
b
Elevation (m)
Mean annual precipitation (m)
0.52 0.56 0.60 0.64 0.68 0.72 0.76 0.80
Bedrock
Sea level
Distance (km)
c
Mean annual air temperature (^{o} C)
Mean annual precipitation (m)
Glacier length (km)
d
Volume (km^3)
Psummer
Pwinter
Amplitude of precipitation seasonality (%)
e
Glacier length (km)
Mean annual air temperature (^{o}C)
Mean annual precipitation (m)
f
Glacier volume (km^3)
Mean annual air temperature (^{o} C)
Amplitude of precipitation seasonality (%)



a
Temperature anomaly (° C)
Ice-core temperature record
300 year moving average
1961-1991 mean
Prince Gustav Ice Shelf present
Uncertain transition from ice-sheet to ice-shelf
Years before present
b
Glacier length (km)
Constant precipitation (0.65 m)
5% precipitation forcing
7.3% precipitation forcing
15% precipitation forcing
20% precipitation forcing
100% precipitation forcing
Years before present
c
Mean annual air temperature (° C)
Present-day value
ECHAM5 A1B
ECHAM5 E1
HadCM3 A1B
HadCM3 E1
Years AD
d
Mean annual precipitation (m)
Present-day value
ECHAM5 A1B
ECHAM5 E1
HadCM3 A1B
HadCM3 E1
Years AD
e
Volume (km³)
Present-day value
ECHAM5 A1B
ECHAM5 E1
HadCM3 A1B
HadCM3 E1
Years AD