Islands in the ice: Climate change impacts Antarctic biodiversity habitat

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Summary

Antarctic terrestrial biodiversity almost exclusively occurs in ice-free areas that cover less than 1% of the continent. Climate change will alter the extent and configuration of ice-free areas, yet the distribution and severity of these effects remain unclear. Here we quantify the impact of 21st century climate change on ice-free areas under two IPCC climate forcing scenarios using temperature-index melt modelling. Under the strongest forcing scenario, ice-free areas could expand by over 17,000 km^2 by the end of the century, close to a 25% increase. Most of this expansion will occur in the Antarctic Peninsula, where a three-fold increase in ice-free area could drastically change the availability and connectivity of biodiversity habitat. Isolated ice-free areas will coalesce, and while the impacts on biodiversity are uncertain, we hypothesise that they could eventually lead to increasing regional scale biotic homogenisation, the extinction of less competitive species and the spread of invasive species.

Climate change poses one of the greatest threats to biodiversity persistence worldwide[1]. The Antarctic Peninsula has experienced one of the most rapid temperature rises in the Southern Hemisphere[2,3]. This increase has recently paused, which is likely a consequence of short-term natural climate variability masking the longer-term human influence[4]. However, the anthropogenic signal is likely to become more pronounced over the 21st century, resulting in further significant warming across the Peninsula and wider Antarctic continent[5-7].

Considerable resources and research have been directed into studying and understanding the effects of climate change on the melting of the Antarctic ice-sheets and their contribution to global sea-level rise[8-10]. In comparison, until very recently, the impacts of climate change and associated ice melt on native Antarctic biodiversity have been largely overlooked[11]. Yet, a warming climate has the potential to cause substantial expansion of ice-free areas across Antarctica, possibly allowing some species to expand and even cross ancient biogeographical divides as ice-free areas begin to coalesce.

Ice-free Antarctica

Ice-free areas form isolated patches of habitat within a matrix of ice, analogous to islands in an ocean[12]. They manifest in many forms, including exposed mountain-tops (nunataks), cliffs, scree slopes, ice-free valleys, coastal oases and islands, ranging in size from less than 1 km^2 to thousands of km^2, and can be separated by merely metres to hundreds of kilometres[13,14]. The direct and indirect effects of climate change on ice-free areas have not yet been investigated across the broader continent, or even at a regional scale, leaving a significant gap in our understanding of climate change impacts on Antarctic species, ecosystems and their future conservation.

Comprising less than 1% of Antarctica[15,16], permanently ice-free areas are home to almost all the continent's biodiversity, including arthropods, nematodes, microbes, vegetation (vascular plants, lichen, fungi, moss and algae), rotifers, and tardigrades[17,18]. Ice-free areas also form essential breeding grounds for seals and seabirds. Until recently it was believed that Antarctic biodiversity underwent a major extinction event during the Last Glacial Maximum (LGM), subsequently colonising and expanding during the glacial recession[19,20]. However, geological and genetic studies suggest that many taxa persisted through the LGM and quite probably multiple glacial cycles, by contracting into refugia[19,21]. Springtails for example, are believed to have diversified during the late Miocene and have long since been separated by glacial barriers[22].

Many species are recorded from only a single region across the continent (including tardigrades, rotifers and nematodes[23]), or indeed even single ice-free areas (eg. the tardigrade *Mopsechiniscus franciscae* from Victoria Land[24] or the rotifer *Rhinoglena kutikovae* from the Bunger Hills, East Antarctica[25]). It is uncertain whether these species are limited to these patches due to lack of dispersal potential or opportunities, or whether we have limited understanding of their distribution owing to a deficiency of comprehensive surveys[18]. Regional differences in terrestrial fauna led to the identification of a broad geographic divide between the Antarctic Peninsula and the rest of the Antarctic mainland (the Gressitt Line[17]) and more recently the delineation of 16 biologically distinct regional units (Antarctic Conservation Biogeographic Regions – ACBRs or bioregions)[16,26]. Geographic isolation and lack of connectivity has largely sheltered terrestrial Antarctic biota from dispersing species and interspecific competition[12,18,27].

Abiotic factors, such as availability of water, energy (e.g. sunlight) and nutrients, are widely understood to be the major drivers of Antarctic species distributions and life histories[14,18, 23, 28], unlike many regions of the world (such as African savannah[29] or rainforests[30]), where predation and competition have more substantive impacts on species distributions. Antarctic biodiversity is also severely limited by physical barriers, such as expanses of ice and snow, which decrease dispersal opportunities between ice-free patches[14,20]. How Antarctic communities as a whole will cope with a changing climate and potential increases in habitat and biotic interactions remains largely unknown[13,18].

To determine the likelihood of climate induced ice melt around Antarctic ice-free areas we used a temperature-index modelling approach (see Methods), previously used to estimate ice melt in the European Alps, New Zealand and the Arctic[31,32]. We make projections for the year 2098 under two of the Representative Concentration Pathways (RCP4.5, 8.5[33]) adopted by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report[34] (AR5). By combining air temperature, radiation, projected precipitation changes and recently updated spatial layers of current ice-free area and ice coverage, we quantified, for the first time, the potential impacts of 21st century climate change on ice-free areas and present hypotheses on the associated implications for Antarctic terrestrial biota.

Changing Climate in the Antarctic

Across the Antarctic continent, it is the Antarctic Peninsula that shows the greatest projected future changes in climate by the end of the century (Fig. 1), perhaps not surprising given the rapid climate change already observed in this region[2,3,12]. Increases in degree days and the attendant ice melt are mostly restricted to coastal regions and are heavily concentrated around the Antarctic Peninsula (Fig. 1a). The greatest projected changes in precipitation are also over the Peninsula, potentially increasing by over 400 mm/yr in some areas (Fig. 1b).

Concomitant with these projected climate changes across the Peninsula are dramatic changes in ice coverage. Ice and snow melt largely reflect the projected change in degree days (Fig. 1c), and for most of the continent is predicted to be less than 1 m by the end of the century. In contrast, we predict over 5 m of melt in some Peninsula areas, where melt far outweighs the increasing precipitation. These results are consistent with ice sheet and surface mass balance (SMB) models of Antarctica[9,10,35]. For example, studies found increased SMB across most of the continent due to increased snowfall[9], decreased SMB and increased run-off in the Antarctic Peninsula[9], and triggering of extensive surface meltwater due to increasing summer air temperatures, leading to major retreat and thinning of outlet glaciers and ice shelves in the Antarctic Peninsula and across the West Antarctic Ice Sheet[10].

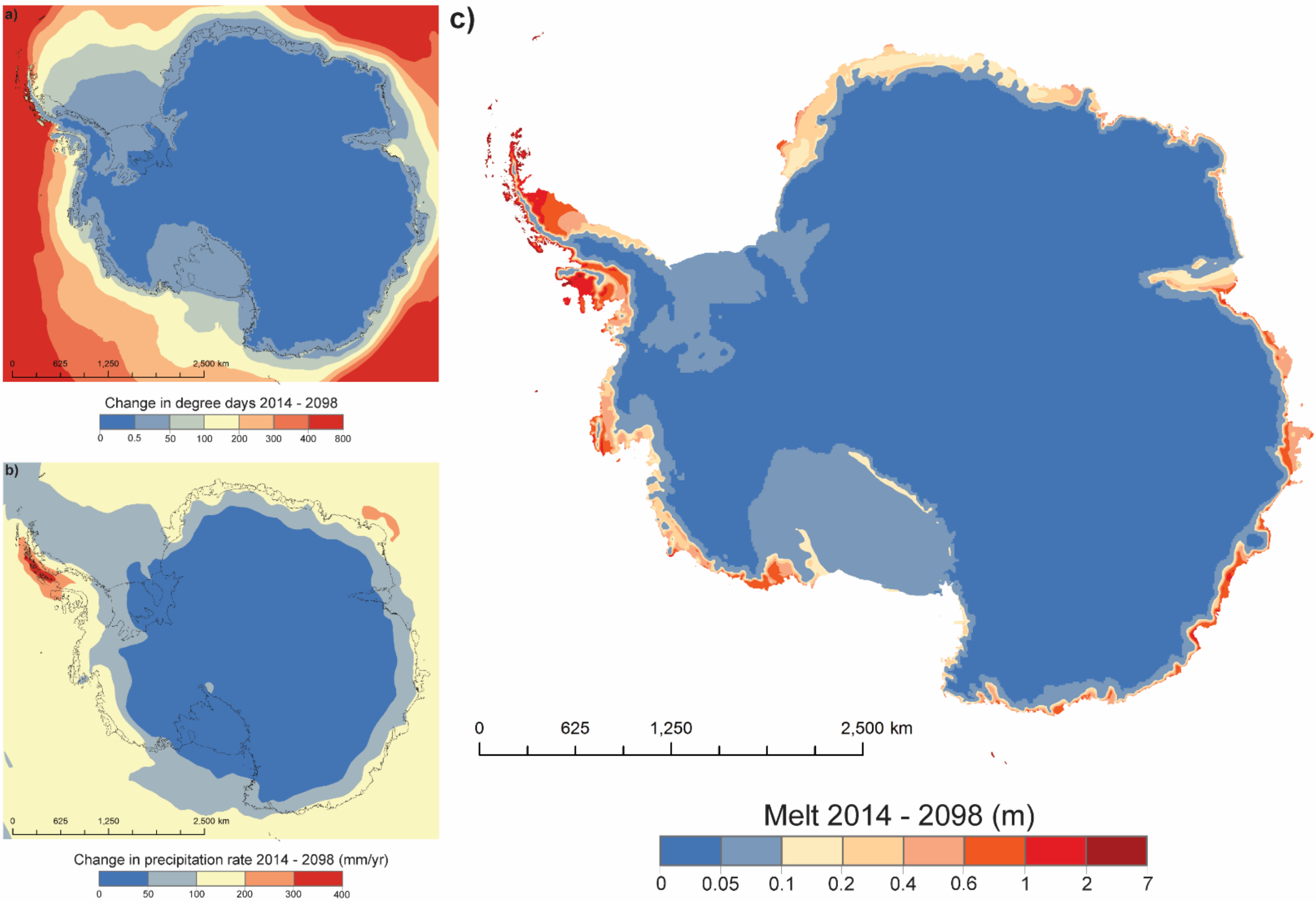
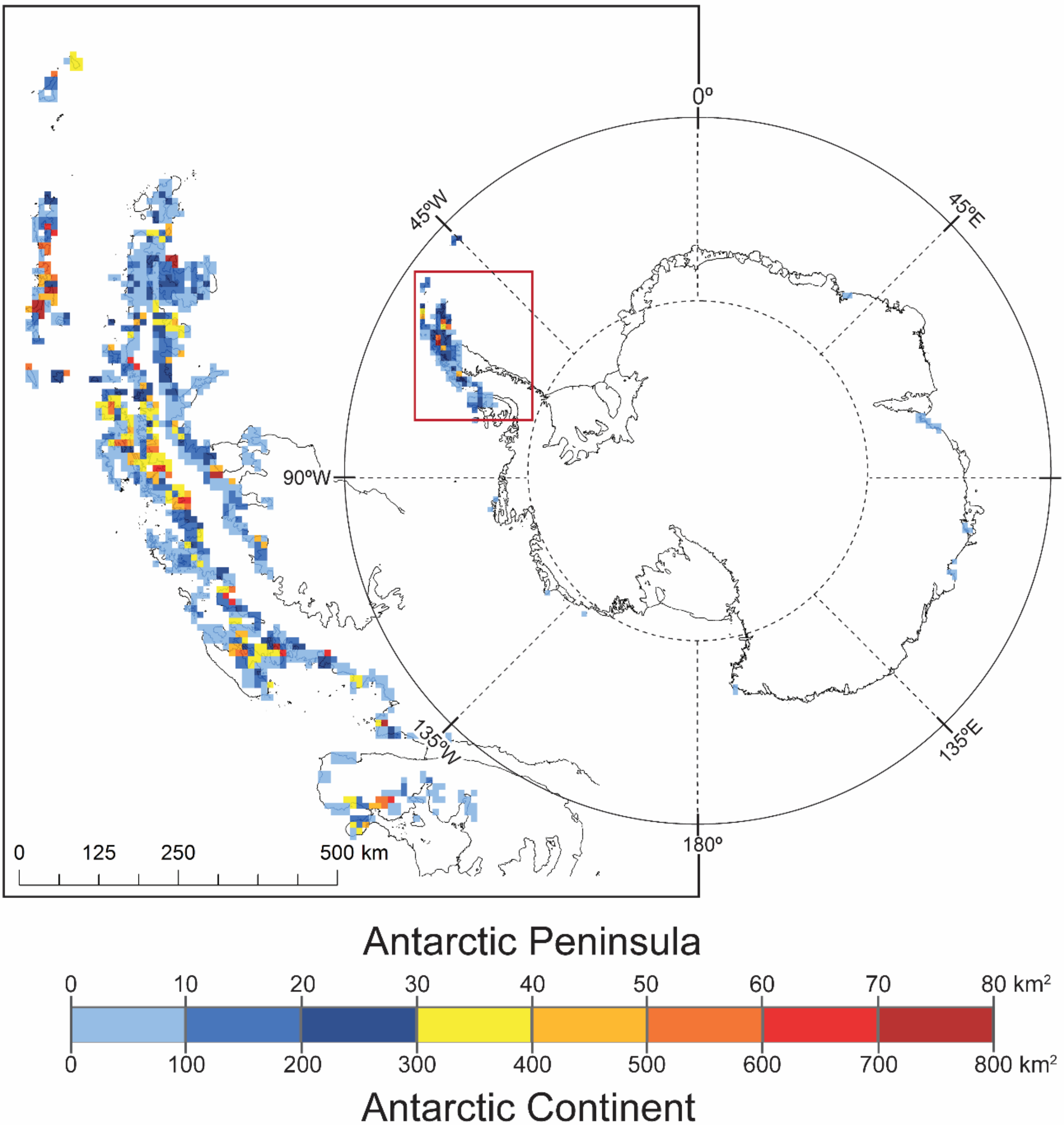


Figure 1. Projected 21st century climate change between 2014 and 2098 under RCP8.5, showing ***a)*** the change in degree days, ***b)*** the change in precipitation rate (mm/yr), and ***c)*** projected melt (m) using mean melt coefficients (see Methods). RCP4.5 is provided in Extended Data Fig. 1.

Emerging ice-free area

We predict that melt across the Antarctic continent will lead to the emergence of between 2,100 and 17,267 km^2 of new ice-free area by the end of this century (Extended Data Table 1), with the upper bound representing nearly a 25% increase in total area. More than 85% of this new ice-free area will emerge in the North Antarctic Peninsula bioregion, with some also emerging along the East Antarctic coastline (Fig. 2). For the Peninsula, this could mean an almost three-fold increase of total ice-free area under the most severe scenario (RCP8.5), which the globe is on track to meet if emissions are not substantially reduced[36,]

The South Orkney Islands are projected to become completely ice-free in five of the six melt scenarios (Fig. 3), with a global temperature rise beyond 2° C leading to a 4-fold increase in ice-free area for this bioregion (contrast with RCP2.6 in Extended Data Fig. 3 and Extended Data Table 2, where the bioregion is scarcely affected). This will result in a complete transformation of the physical environment, with the emergence of new habitat providing new dispersal and colonisation opportunities for the region's biota and possibly non-native species.



142 **Figure 2.** New Antarctic ice-free area (km^2) predicted to emerge between 2014 and 2098 143 under the climate forcing scenario RCP8.5 using 'mean' melt coefficients to determine the 144 melt rate. Grid cell resolution is 50 km in the continental map and 10 km in the Antarctic 145 Peninsula inset. 'Mean' melt scenario for RCP4.5 in Extended Data Fig. 2.

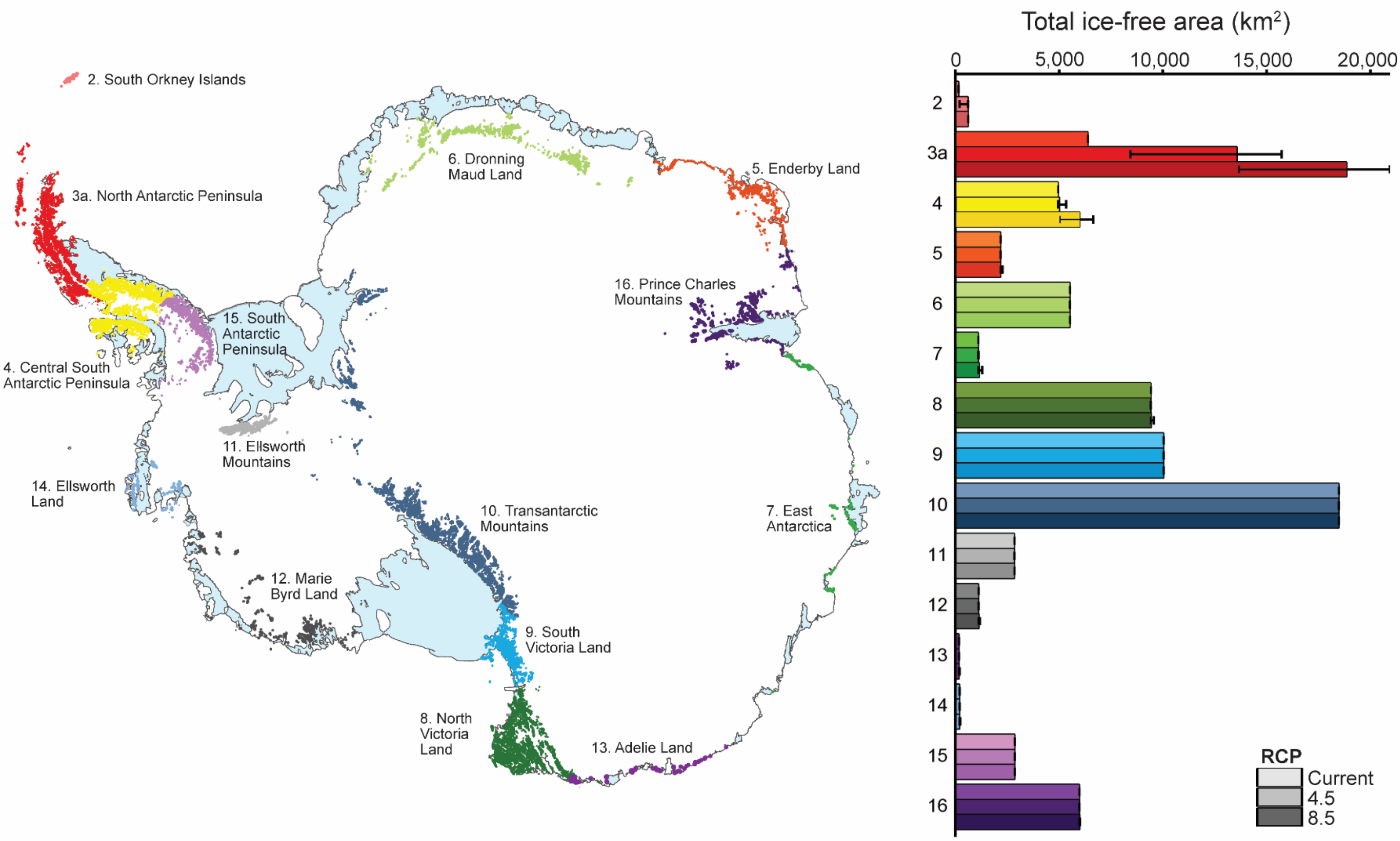


Figure 3. Current and future ice-free area (km^2) in each Antarctic Conservation Biogeographic Region, with future estimates provided for two different climate change scenarios (RCP4.5, RCP8.5) using the model subset ensemble mean (see Methods). Bars represent total area using the mean ice melt coefficients, whilst error bars represent the lower and upper bounds respectively (lowest and highest ice melt coefficients). Bar colours correspond to map locations of bioregions. Full-ensemble Ensemble Regression mean model results are shown in Extended Data Fig. 3.

The Transantarctic Mountains (ACBR 10) currently contain the largest amount of ice-free area on a bioregional scale (Fig. 3, Extended Data Table 3 and 4), yet even under RCP8.5, this bioregion is likely to experience very little change by the end of the century. In contrast, ice-free area in the North Antarctic Peninsula (ACBR 3a) will undergo substantial expansion (Fig. 3, Extended Data Table 3 and 4) and our predictions indicate that in the future it could contain the largest amount of ice-free area of any bioregion (Fig. 3, Extended Data Table 3). The spatial changes exhibited by the North Antarctic Peninsula are depicted in Figure 4, illustrating the mass expansion of ice-free area under climate change. There will also be some change in the South Orkney Islands (ACBR 2), the Central-south Antarctic Peninsula (ACBR 4) and East Antarctica (ACBR 7), but little change across most other bioregions (Extended Data Table 3).

The number of individual ice-free patches in Antarctica are projected to decrease by nearly 3,000 as patches coalesce (marked reductions in the North Antarctic Peninsula and South Orkney Islands, and smaller reductions across bioregions 4, 5 and 16; Extended Data Table 3), which is also consistent with an increase in mean patch size (Extended Data Table 3). In the North Antarctic Peninsula, mean patch area increases significantly by the end of the century under RCP4.5 and RCP8.5 (Fig. 5. a; Supplementary Table 1), the total ice-free area could increase by a maximum of >9,000 km^2 under RCP4.5, and >14,500 km^2 under RCP8.5 (upper bound: Fig. 5. b) and number of patches decreases with the severity of the RCP scenario (Fig. 5. c). Distance to nearest neighbouring ice-free area decreases in some bioregions due to edge melt (expansion of existing patches, e.g. ACBR 2 and 7) but increases in other bioregions as nearby patches coalesce (yet this still reduces distance to the neighbour that is currently considered the closest e.g. ACBR 3a; Fig 5. d, Extended Data Table 3). However, in both cases these changes portend an increasingly connected landscape with reduced isolation of ice-free patches. This is in striking contrast to a trend of decreasing connectivity and increasing habitat fragmentation frequently seen in response to climate change and anthropogenic impacts across the rest of the globe[37,38].

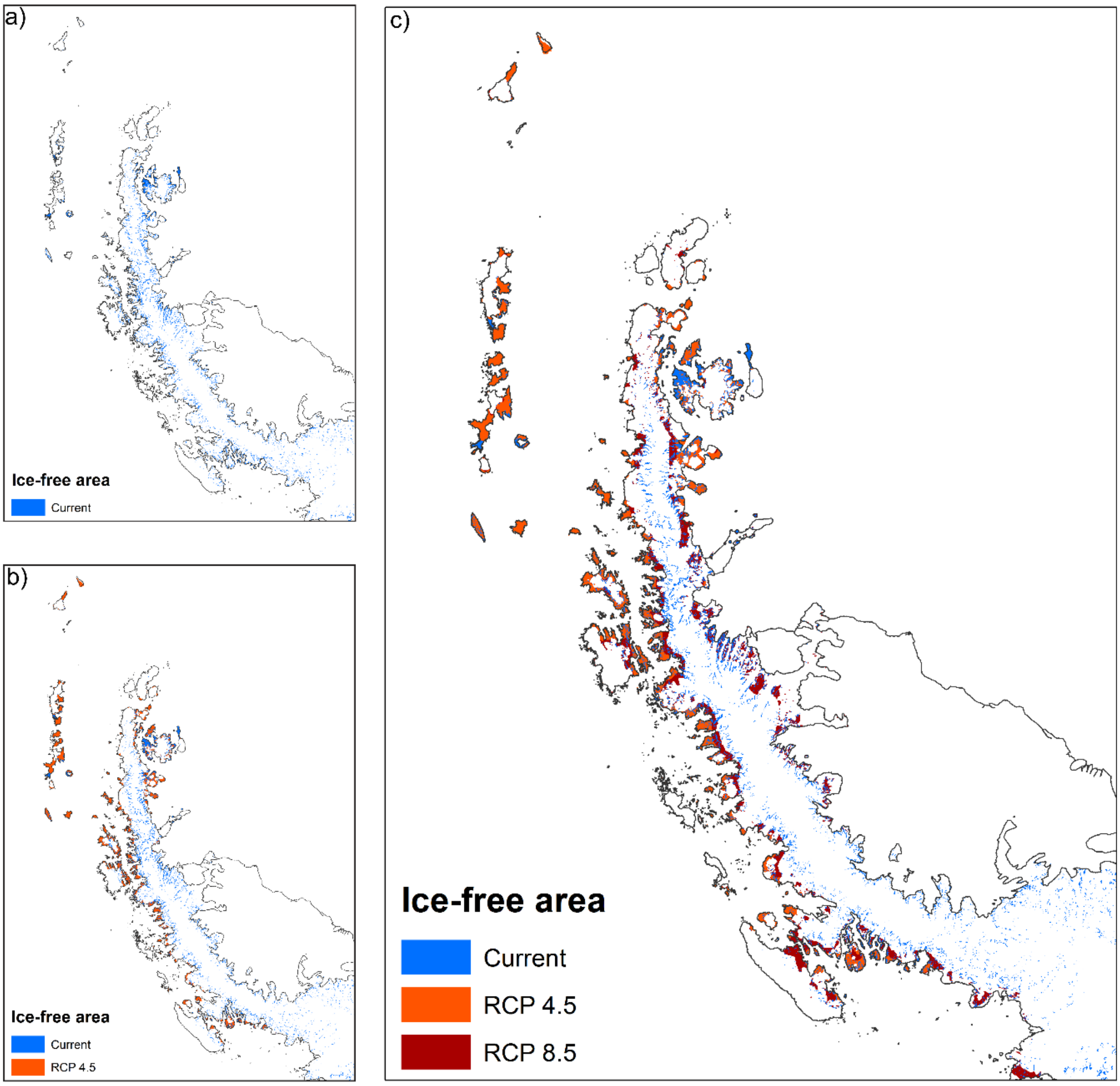


Figure 4. Projected cumulative changes in ice-free area size and distribution for North Antarctic Peninsula (ACBR 3a) by the year 2098 under two climate change scenarios; **a)** current, **b)** RCP4.5, **c)** RCP8.5

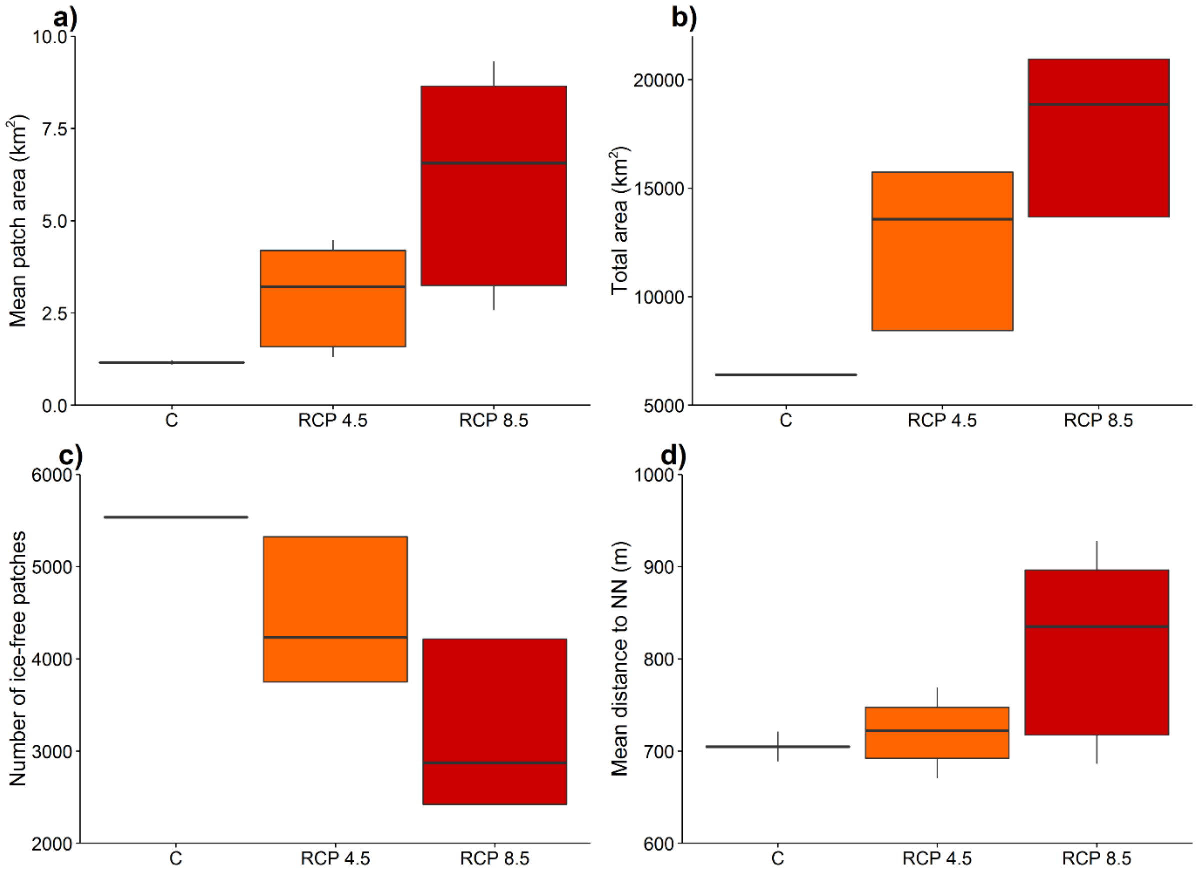


Figure 5. Ice-free area metrics for Antarctic Conservation Biogeographic Region 3a (North Antarctic Peninsula) under current climate conditions (C) and two different RCP scenarios (4.5, 8.5). **a)** mean area of ice-free patches (km^2), **b)** total ice-free area (km^2), **c)** number of ice-free patches, and **d)** mean distance to nearest neighbour (NN; m). Mid-line on box represents the 'mean' ice-melt coefficients, whilst bottom of box represents 'lower' bound, top of box represents 'upper' bound, and error bars represent standard error of the 'mean'.

Implications for biodiversity

Climate-driven expansion of ice-free area will uncover a substantial amount of potential new habitat for species and decrease the distance between patches, increasing connectivity. Despite the profound potential consequences for native fauna and flora, these impacts have scarcely been explored (see Olech and Chwedorzewska[39] for one example). Using existing biodiversity knowledge and considering all terrestrial taxa, we propose hypotheses on potential biodiversity impacts at various scales – from bioregional to species level.

Habitat expansion and increasing connectivity might generally be interpreted as a positive change for biodiversity[37], however, in Antarctica it is not known if the potential negative impacts will outweigh the benefits. While the expansion of available habitat and merging ice-free areas will undoubtedly enable some native species access to new resources and to colonise new space, the increasing connectivity could have destabilising impacts on ecological communities, for example via the spread of invasive species, which already pose a substantial threat to native biota[17,40]. Colonisation of newly exposed habitat has already been observed in the Antarctic Peninsula, where rocks recently exposed by snow melt have been subsequently colonised by *Rhizocarpon* lichens[41] or where the invasive grass *Poa annua* has colonised new ice-free land near Ecology Glacier[39]. Evidence from both the sub-Antarctic and Antarctic suggests *Poa annua* may begin to outcompete native species[40,42,43].

Within bioregions, (where there is often far less difference in taxonomic diversity than across bioregions[16,26]), native species may be able to establish new local populations or increase gene flow between existing populations. This has been demonstrated from previous glacial recessions, where populations of the formerly isolated springtail, *Gomphiocephalus hodgsoni,* in the McMurdo Dry Valleys (North Victoria Land) recolonised surrounding areas, increasing gene flow as the populations once again became sympatric[20]. However, as climate warms, metabolic studies suggest that some *G. hodgsoni* lineages may begin to outcompete others due to the genetic and physiological adaptations accumulated during allopatry, which in the long term could cause populations to homogenise as genetic variation is lost[20].

Antarctic climate change may produce both ‘winners’ and ‘losers’. For example, Adélie (*Pygoscelis adeliae*) and emperor (*Aptenodytes forsteri*) penguins are already contracting poleward with declines in sea ice extent[44], whilst the two vascular plants on the Antarctic Peninsula (*Colobanthus quitensis* and *Deschampsia antarctica*) are quickly expanding south with warming[17,45]. Microbial taxa may also benefit, where closer ice-free patches facilitate spore dispersal and a warming climate provides further opportunity for alien microbes to establish[45]. Other ‘winners’ will likely include non-native species[40,42,43].

The specialised biological traits of Antarctic species that give them the ability to adapt to environmental extremes in an isolated environment, put them at increased risk from invasive species[17,21], which are typically highly adaptable with rapid life-cycles[46]. Invasive species have the potential to increase competition in isolated regions, where native species may become subject to biological interactions they have not experienced for much of their evolutionary history[42]. The Antarctic Peninsula region already represents the highest risk for establishment of non-native species across the continent[40], and in fact, already contains the highest number of established non-native species[43]. Furthermore, the region is already experiencing severe glacial and ice-shelf retreat[47] and the subsequent exposure of new intertidal ice-free areas has been identified as a key conservation issue[11,48]. The increasing connectivity throughout the Antarctic Peninsula may even allow some species to cross bioregional boundaries, where large scale habitat expansion could eventually lead to localised homogenisation of terrestrial biodiversity across bioregions.

Given the minimal changes in degree days and precipitation (Fig. 1), ice-free areas across the rest of the Antarctic mainland will probably be largely unaffected by climate warming in this century, with some expansion projected only in East Antarctica. This implies minimal biodiversity impacts in these bioregions until climate driven temperature increases begin to substantially affect ice melt on mainland Antarctica[5,6]. Changing climate conditions may also begin to impact growth and movement of biota through changes in the distribution of energy, such as sunlight, radiation and wind[7,18]. For example, low temperatures are thought to limit Antarctic bryophyte reproduction, therefore an ameliorating climate will likely increase sporophyte production and dispersal opportunities for some species, ultimately influencing their potential distribution[49]. In light of the broad biological divide between the Peninsula and mainland Antarctica, entire groups of species south of the Gressitt Line[14,17] may be shielded from direct climate change impacts in this century. High levels of endemism could therefore be maintained in some parts of Antarctica, while the Peninsula regions begin to locally homogenise.

In the coming centuries, as the anthropogenic signal of climate change becomes more pronounced across the entire Antarctic continent[5,6], we might expect mainland Antarctica eventually to experience more substantial transformation of ice-free areas. Multiple century impacts of physical expansion of ice-free areas on native biodiversity have the potential to be severe, and mainland bioregions may be put at further risk of invasive species and increased competition, possibly leading to growing homogenisation and extinctions of terrestrial biodiversity across the entire continent. This highlights the need for continued monitoring and modelling of Antarctic ecosystems as climate change progresses and longer term projections become available. Although global emissions are currently tracking the highest greenhouse gas emissions scenario (RCP 8.5[36]), if emissions can be reduced, and anthropogenic temperature increases kept to <2°C (as per the Paris Agreement[50]), then the impacts on ice-free habitat and its dependent biodiversity are likely to be reduced.

Methods

Current Ice-free

Current ice-free areas were delineated using the recent spatial layers available in the Scientific Committee for Antarctic Research (SCAR) Antarctic Digital Database (ADD Version 7; www.add.scar.org). We used the 'medium resolution' rock-outcrop layer, equivalent to a 1:1 million scale, because this best matches the 1 km^2 resolution of the ice-thickness layer and spatially interpolated climate data (see below), enabling us to match future projections of ice melt with a map of currently ice-free areas.

Current Ice Thickness

Current ice thickness is required to determine how melt will impact the distribution of ice-free areas. We used the Bedmap2 'ice thickness' layer from the British Antarctic Survey, which gives ice thickness on a 1 km grid of Antarctica[51]. The Bedmap2 layer is generated from primary data (direct ice thickness measurements and satellite altimetry measurements) where available, and where unavailable, it was modelled using a 'thin ice' model (see ref. 51 for details).

Ice melt

There are several methods available for measuring changing ice in polar regions. Energy-balance models assess surface energy fluxes to determine the amount of energy available for melt[52]. Surface mass balance (SMB) studies, which focus on ice sheets and their contribution to sea level rise[8,9], subtract loss of snow and ice (sublimation, run off, erosion) from the accumulation through precipitation. These methods are usually applied at pan-continental ice sheet scales, often covering hundreds of kilometres and modelling gigatonnes of ice. In contrast, our biodiversity based focus is at the periphery of current ice-free areas, where ice can be orders of magnitudes thinner than most of the Antarctic Ice Sheet[51]. These areas are typically relatively small (kilometres to tens of kilometres).

A widely used method of measuring ice and snow melt on this type of regional or catchment scale is temperature-index modelling, which relies on the strong correlation between ice melt and air temperature[52]. Though a simplification of the complex 'energy-balance' methods incorporating heat flux and energy transfer, temperature-index models have been found to perform as well as and even out-perform energy-balance models on this scale and over longer time periods[31,52,53]. The good performance and relatively low data requirements of temperature-index modelling make it appropriate for our study and our focus on the ecological implications of change.

We used a temperature-index approach based on degree days and incorporating solar radiation[54]. The current configuration of ice-free areas (as defined by ADD v7) is a result of both climatic and other processes (such as glaciological history, wind, elevation, temperature and precipitation[55]). To isolate the effects of climate change from these other processes, we assume that the current configuration of ice-free areas is stable under current climatic conditions (temperature and precipitation), allowing us to attribute melt purely to differences in projected climate between now and 2098. We used the projected melt and the Bedmap2 ice thickness layer to determine which areas would melt under different climate forcing scenarios and combined these with the current ice-free areas to determine future configuration. For a simple overview of our methods, refer to Extended Data Fig. 4.

Current Degree Days

Three hourly air temperature records (mean of 2014 & 2015 temperatures, 10 km resolution) from the Antarctic Mesoscale Prediction System (AMPS[56]; http://www2.mmm.ucar.edu/rt/amps/) were used to calculate degree days for each day of the year according to equation (1). The European Centre for Medium Range Weather Forecasts (ECMWF) ERA-interim re-analysis data[57] was used to verify that 2014 and 2015 temperatures were not anomalous relative to the period 1979 – 2015. Combined, 2014-2015 displayed temperature anomalies of up to 0.5°C, which was deemed satisfactory given that future projected changes are in the order of 3-4°C (Extended Data Fig. 5). All spatial layers were reprojected and interpolated to 1 km^2 cells to match the resolution of the Bedmap2 ice thickness layer. The degree day value for day *i* in cell *x* gives a measure of the time spent above freezing (and thus potential for ice melt), calculated as:

(1)

$$DD_{ix} = \frac{1}{n}\sum_{t=1}^{n}\begin{cases} T_{ix}(t), & T_{ix}(t) > 0 \\ 0, & T_{ix}(t) \leq 0 \end{cases}$$

where $T_{ix}(t)$ is the air temperature (°C) at time step *t* on day *i* in cell *x*, and *n* is the total number of time steps per day (here *n* = 8 as the time step is 3h).

Climate model data

Changes in surface air temperature (temperature at 2 m above the surface) and precipitation rate were estimated from climate model output from the most recent phase, phase 5, of the World Climate Research Programme's (WCRP) Coupled Model Inter-comparison Project[58] (CMIP5). The CMIP5 dataset comprises output from approximately 50 different fully coupled climate and earth-system models (or model variants) and was the primary source of climate model data for the analysis included in the IPCC Fifth Assessment Report[34] (AR5). In this study, we use data from two types of simulation: (i) 'historical' simulations for which past known climate forcings such as observed greenhouse gas concentrations are used and (ii) future scenario Representative Concentration Pathway (RCP) simulations for which a number of different possible future outcomes in terms of anthropogenic climate forcing are defined[33]. Here we use a medium forcing scenario (RCP4.5) and the most extreme, high forcing scenario (RCP8.5). For the variables considered in this study, 21st century change is quantified as the difference between time-mean climatologies over the 30-year period 2069-2098 from the RCP simulations and the time-mean climatology over the 30-year period 1970-1999 from the historical simulations. The variables used in this study are surface air temperature (CMIP5 variable name "tas") and total precipitation rate (variable name "pr") for which monthly mean data were evaluated. For these variables, data from 38 of the CMIP5 models was found to have data available for the historical-RCP4.5 scenario pair and 40 models for the RCP8.5-historical scenario pair (listed in Supplementary Table 5).

Climate model subsetting

The key region for change was identified as the Antarctic Peninsula. Many of the CMIP5 climate models are run at rather low atmospheric resolution (see Supplementary Table 5), which affects the representation of the high mountains of the Antarctic Peninsula in these models[59]. In addition, many models exhibit large biases in a main feature of regional circulation, the Amundsen Sea Low (ASL), which exerts a strong influence on Antarctic Peninsula temperature and precipitation[60]. We therefore identified a subset of CMIP5 models taking into account model resolution and fidelity at reproducing observed characteristics of the ASL.

For resolution, the criterion for model subsetting was to select those models with a latitudinal grid spacing of less than the median of 1.9° across the 40 models listed in Supplementary Table 5. After applying this constraint 17 of the 40 models remained. Although higher resolution climate model data than that available from the CMIP5 dataset would be preferable, this procedure identifies a more appropriate subset of the currently-available model output. With regard to the ASL, ref. 60 identified 11 CMIP5 models that most reliably reproduce the observed characteristics of the ASL. Applying a further constraint, whereby only those models identified by ref. 60 were included, left a subset of 9 models: CMCC-CM, CCSM4, CESM1(BGC), CESM1(CAM5), EC-EARTH, MRI-CGCM3, MRI-ESM1, HadGEM2-AO, CNRM-CM5. To avoid duplication of model variants from the same modelling centre the following additional filtering was conducted as follows:
(i) CESM1(CAM5) was chosen instead of CESM1(BGC) due to its smaller bias in ASL representation.
(ii) MRI-CGCM3 was chosen over MRI-ESM1due to its smaller bias in ASL representation.
This resulted in the final subset of 7 models as follows: CMCC-CM, CCSM4, CESM1(CAM5), EC-EARTH, MRI-CGCM3, HadGEM2-AO, and CNRM-CM5.

Sensitivity to using an alternative method that combines the full ensemble of available model data in estimating the mean future projected change (known as ensemble regression (ER)[61] and referred to here as the full-ensemble ER mean) and the above subset (the subset ensemble mean) was evaluated by using both approaches in analysis. Before producing multi-model averages it was necessary to re-grid onto a common atmospheric grid. The HadGEM2-AO atmospheric grid (1.875° longitude x 1.25° latitude) was chosen as the common grid.

Future Degree Days

The projected changes in temperature (ΔT) were added to current temperatures to calculate temperatures at 3-hourly intervals (equation 2) for the year 2098 for RCP4.5 and RCP8.5 emissions scenarios (and RCP2.6 for the full-ensemble ER mean).

(2)

$$T_{fx} = T_{cx} + 0.835\ \Delta T_x$$

Where T_{fx} is future temperature in cell x, T_{cx} is current temperature in cell x using the AMPS 3 hourly air temperature records and ΔT_x is the projected change in air temperature (°C) in cell x for the year 2098, multiplied by 0.835 as the temperature projections were made on a hundred-year timeframe (1998 – 2098), yet current temperatures were averaged for 2014 and 2015, which is only a 83.5-year timeframe (assuming some of the change occurred pre 2014).

Daily degree days for the year 2098, under the two climate change scenarios (RCP4.5, RCP8.5, & RCP2.6 for full-ensemble ER mean projections) were then calculated according to equation (1), using future air temperatures.

Delta Degree Days

The daily difference in degree days (ΔDD) was determined for each RCP scenario by subtracting the current daily degree day values from future daily degree day values. These values were then reprojected to the 1 km^2 Bedmap2 grid.

Radiation

Potential direct solar radiation was calculated daily for 365 days in a year at a 1 km^2 resolution, according to the methods described in ref. 62. This method incorporates radiation corrected for incident angle, diffuse & reflected radiation, insolation, latitude, elevation, slope and aspect and assumes a clear sky (no clouds). Cloud effects have been incorporated into temperature-index models in previous studies, but did not improve model performance[54]. In the absence of any reliable fine-scale projected data, we assume that potential direct solar radiation will be the same in 2014/2015 and 2098.

Melt

In temperature-index models, the melt rate is determined by the 'degree day factor', which represents the amount of melt that will occur under one degree day. When incorporating radiation the commonly used 'degree day factor' is replaced by a 'melt factor', where daily radiation is used to vary the melt rate, making it spatially explicit (eg. north-facing slopes, particularly in coastal Antarctica, will receive more sunlight and consequently melt faster).

Total melt for the years 2014-2098 was calculated for three RCP scenarios as per equation (3).

(3)

$$M_x = \sum_{i=1}^{365} \Delta DD_{ix}\,(MF + aI_{ix})$$

where M_x is the total melt (mm) for cell *x* that has occurred between 2014 and 2098, ΔDD_{ix} is the daily difference in degree days for day *i* in cell *x*, *MF* is the melt factor (mm d^{-1} $°C^{-1}$; Table 3), *a* is the radiation coefficient (m^2 W^{-1} mm d^{-1} $°C^{-1}$; Table 3), and I_{ix} is the daily potential radiation (W m^2) for day *i* and cell *x*.

As it was not possible to obtain direct measurements of melt rate on a continental scale, we relied on the literature to estimate the melt rate (Supplementary Tables 6 - 8). There was little information available regarding melt factors (*MF*) directly, therefore the large number of globally recorded degree day factors (*DDF*; Supplementary Table 6) were used to calculate the *MF*, as per equation (4).

(4)

$$MF = DDF - (aI)$$

Where *MF* is the melt factor, *DDF* is the degree day factor (Extended Data Table 5), *a* is the radiation coefficient (Extended Data Table 5) and *I* is the daily radiation, here I = 121.862, which is the mean daily radiation across the Antarctic continent.

Various melt factor and radiation coefficients were utilised to estimate lower and upper bounds for total melt (Extended Data Table 5), which allowed us to incorporate uncertainty in our estimates of melt rate. The lower and upper bounds represent the lowest and highest possible melt we could expect based on a literature review of the melting rates of snow/ice, whilst the mean represents the melt rate that would occur using the mean coefficient values. The three calculated melt factors (lower, upper, mean) reflect the range of degree day factor values in the literature well, if somewhat conservatively (Supplementary Table 6). The lower and upper radiation coefficients (*a*) represent the mean of all values found in the literature for snow and ice respectively (Supplementary Table 8). As there is no measure of the relative amounts of snow and ice cover on a continental scale for Antarctica, it was reasonable to use coefficient values for snow to generate the lower bound and coefficient values for ice to generate the upper bound (ice generally melts at a faster rate than snow due to decreased albedo).

We generated 15 melt scenarios overall (mean, lower and upper bound for each RCP; two RCPs for the subset ensemble approach, and three RCPs for the full-ensemble ER mean approach).

Incorporation of precipitation into melt projections

The precipitation climate model projections were extracted from the CMIP5 dataset as described above. Like ΔT, we multiplied ΔP by 0.835 as the precipitation projections were made on a hundred year timeframe, yet we use a 83.5-year timeframe (beginning 2014/2015). ΔP was then reprojected to the Bedmap2 1 km^2 grid.

We then incorporate precipitation into melt projections by subtracting ΔP from the total melt for each cell, yielding an estimate of melt adjusted for future changes in precipitation As the ensemble regression methodology has not yet been developed for application to precipitation projections, the 9 full-ensemble ER mean scenario projections (Extended Data Table 2 and Extended Data Fig. 3) do not take projected changes in precipitation into account.

Impact of melt on ice-free areas

Bedmap2

To determine how ice melt would impact the physical environment we overlaid the 21 melt scenario layers onto the Bedmap2 ice thickness layer[51]. The 'thin ice' model that was used to generate ice thickness in the absence of direct thickness measurements[51] led to the occasional estimation of zero ice-thickness cells beyond the boundaries of known ice-free areas (ie. cells with an ice-thickness of zero that did not overlap an ice-free area in the ADD medium resolution rock outcrop layer), perhaps an artefact of the gridding algorithm (P. Fretwell, pers comms 2015), and possibly also due to the integer nature of the Bedmap2 layer, where cell values were generated (or rounded) to the nearest metre. These cells with a false zero thickness are likely thin ice, but are not genuinely ice-free according to the ADD rock outcrop layer. To deal with the uncertainty in the true value of these cells, we generated 16 ice-thickness layers, where we applied nominal thickness values increasing at 10 cm intervals from 0.0 m to 1.5 m to all Bedmap2 cells identified with an ice-thickness of zero (all other cell values remained the same). We then generated a 'likelihood' of melt, where we subtracted the melt (m) from each of the 16 ice-thickness layers, summed the number of times the cell became ice-free (ie. reached a thickness of zero) and divided by 16 to give the overall probability of becoming ice-free based on the Bedmap2 ice thickness layer. To generate estimated future ice-free layers for each of the three climate scenarios we used a majority decision rule, where only cells with 50% or greater probability of melting were included in our future ice-free layers. We then used binary rasters as our output to indicate whether or not a cell was ice-free. While this method still has the potential to both underestimate and overestimate the true number of cells that are likely to become ice free, we believe simulating a range of values and using the majority rule represents a realistic yet conservative approach to making these predictions. Increasing the number of direct measurements of ice-thickness around ice-free areas would help to reduce uncertainty in future models of these regions. We were not able to account for glacial retreat or positive feedback cycles in our models, where increasing meltwater can further increase surface melt[63] and retreating glaciers accelerate the retreat of other glaciers[64,65]. These processes all likely accelerate ice melt and therefore reinforce the conservative nature of our estimates of ice-free area expansion.

Future ice-free layers

Cells projected to be ice-free were extracted and all contiguous cells (including cells that touch only diagonally) were assigned to the same 'region group' using ArcMap 10.3. The raster cells were then converted to polygons and dissolved by region group. Each group of contiguous raster cells now represents a single polygon.

As ice melt doesn't follow the strict geometric lines of raster cells, polygon smoothing was necessary to remove the polygon edges remnant of the cells. After multiple trials, Polynomial Approximation with Exponential Kernel (PAEK) smoothing (3 km tolerance; ArcGIS tool) was applied to each new polygon layer. This smoother best fitted the scale of the ADD

Version 7 medium resolution ice-free layer. We then merged these layers with the current ice-free layer to generate the final future ice-free layers. These layers generated using the model subset ensemble mean have been made available through the Australian Antarctic Data Centre (AADC – data.aad.gov.au DOI Pending).

Metrics

To summarise the predictions in a biologically meaningful manner, we used the Antarctic Conservation Biogeographic Regions (ACBRs[16, 26]), which identify biologically distinct regions across the continent, and provide an appropriate scale to develop and apply conservation management. We combined the interspersed ACBR 1 and ACBR 3 to facilitate our analyses of physical changes and connectivity, and hereafter refer to this as ACBR 3a – North Antarctic Peninsula. The ACBRs are a commonly used spatial framework for Antarctic research, management and policy, and have been endorsed by the Antarctic Treaty System (ATS)[16, 18, 66, 67].

Each polygon in the future ice-free layers was assigned to an ACBR via a spatial join with the current ice-free layer. We generated metrics describing the extent and connectivity of ice-free areas, at a continental and bioregional scale (Supplementary Table 9). Metrics were generated using ArcGIS (V10.3).

Statistics

We used one-way analysis of variance (ANOVA) within each ACBR to test for differences in ice-free metrics (Supplementary Table 9) under the different RCP scenarios, using R version 3.2.3[68]. Results presented in the main manuscript refer only to RCP4.5 and RCP8.5 using the model subset ensemble mean. Projected new ice-free area from the full-ensemble ER mean projections are shown in Extended Data Table 2 and Extended Data Fig. 3.

Data Availability

The ice-free layers generated using the model subset ensemble mean have been made available through the Australian Antarctic Data Centre (AADC – data.aad.gov.au - DOI Pending).

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Supplementary Information is available in the online version of the paper.

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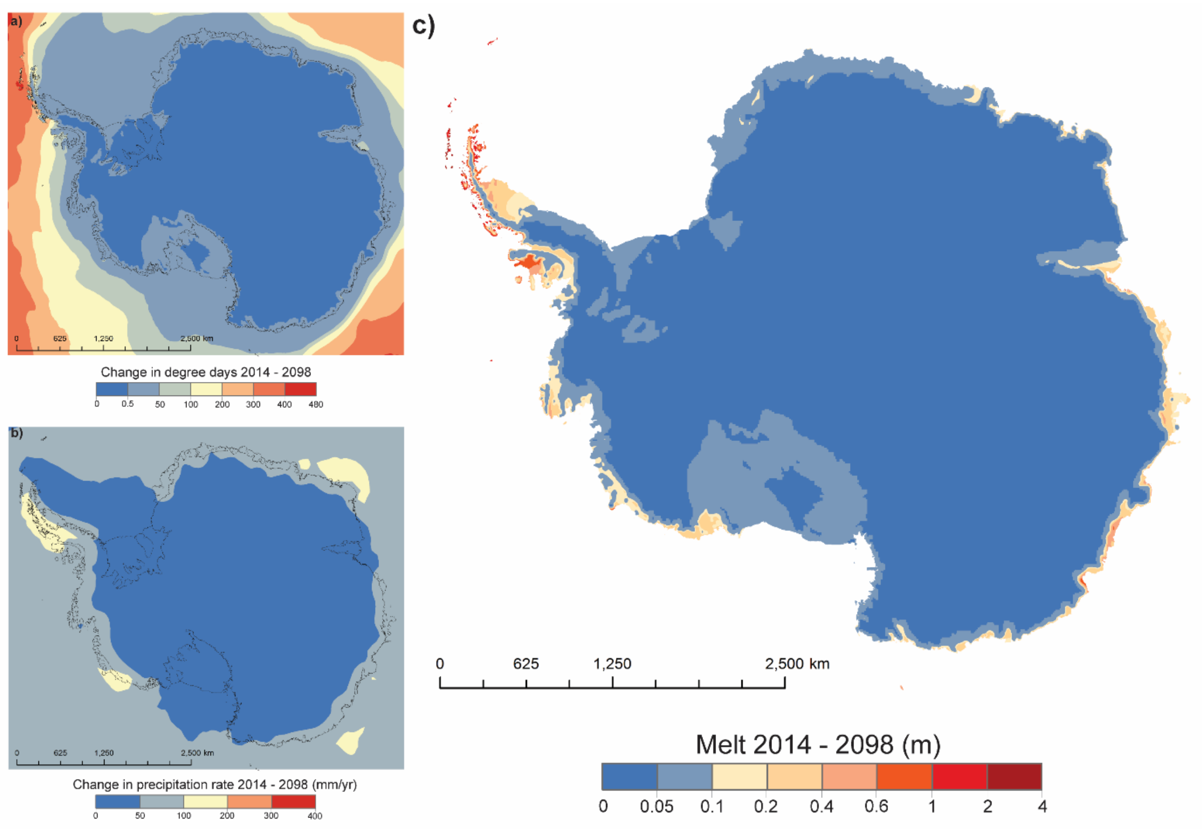
Author Contributions

J.L. and A.T. conceived the idea. T.B. and B.R. generated the climate data. J.L. designed and undertook the melt modelling, analysed the data and led the writing with contributions from all other authors.

Author Information

The future ice-free area layers are available through the Australian Antarctic Data Centre (AADC – data.aad.gov.au DOI Pending). Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to J.L. (jasmine.lee1@uqconnect.edu.au).

Extended Data



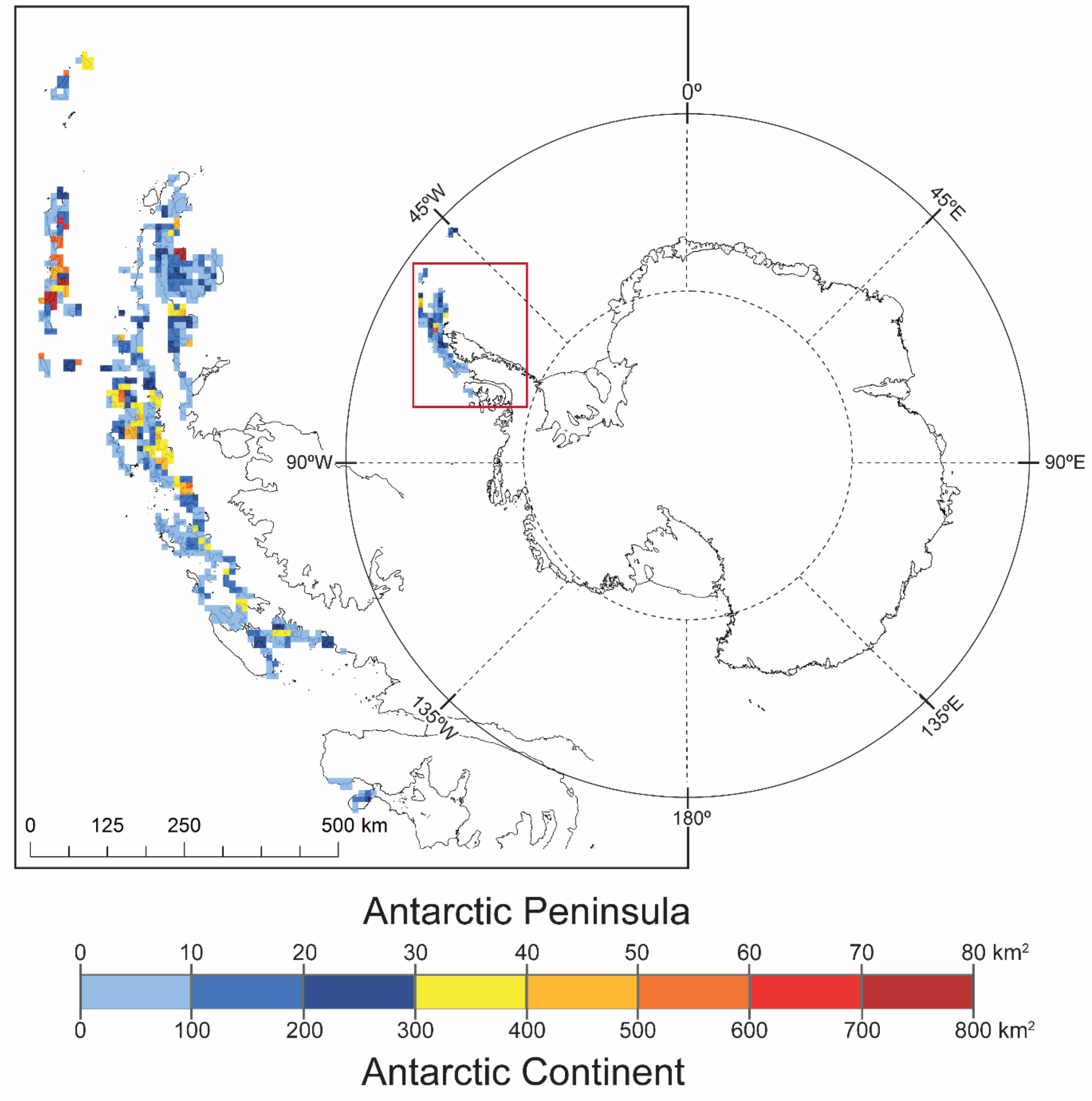
Extended Data Figure 1. Projected 21st century climate change between 2014 and 2098 under RCP4.5, showing ***a)*** the change in degree days, ***b)*** the change in precipitation rate (mm/yr), and ***c)*** projected melt (m) using mean melt coefficients.

Extended Data Table 1. Lower, mean and upper bounds of new ice-free area (km^2) projected under two IPCC climate change scenarios for the Antarctic continent by the year 2098, using subset ensemble mean models. Bounds refer to the lower and upper ice melt coefficients used to derive melt projections for each of the RCPs. Results for full-ensemble ER mean models are available in Extended Data Table 2.

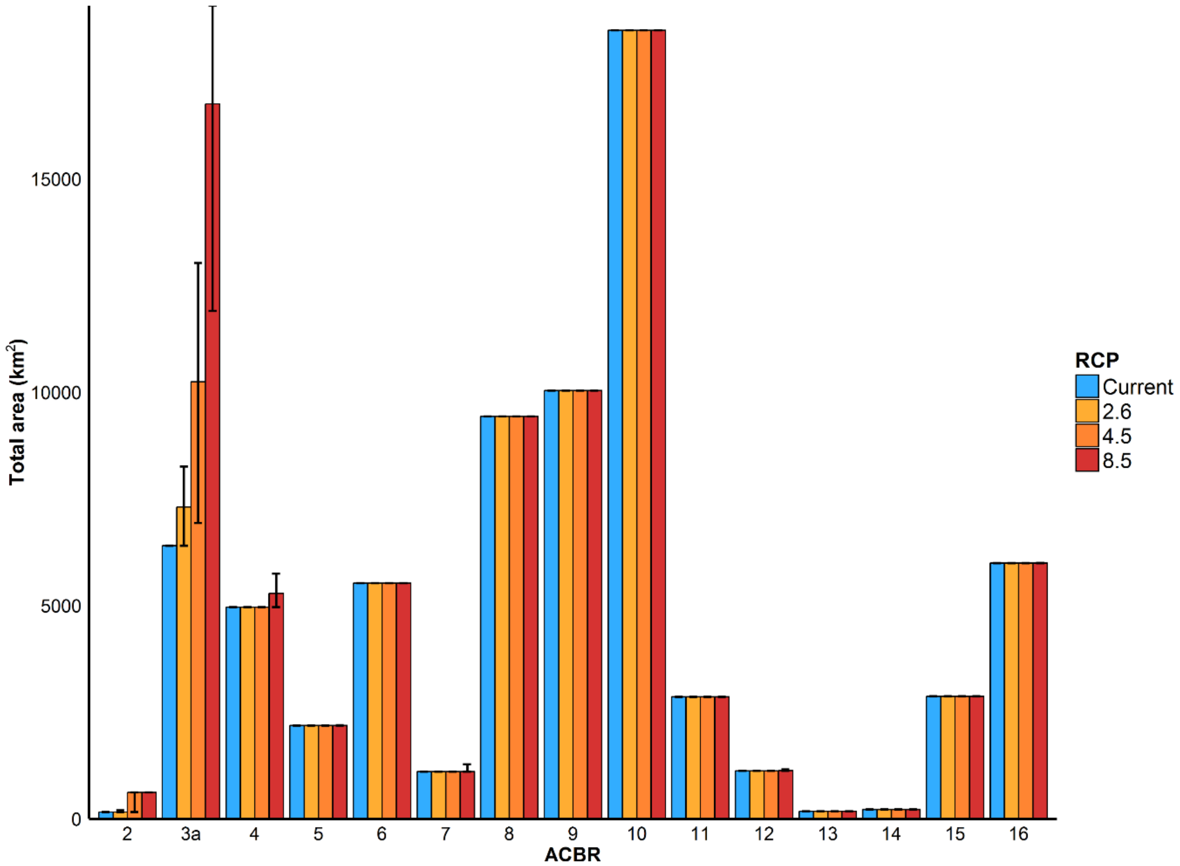
	Lower Bound	**Mean**	**Upper Bound**
RCP4.5	2,100	7,708	10,205
RCP8.5	7,847	14,027	17,267

Extended Data Table 2. Lower, mean and upper bounds of new ice-free area (km^2) projected under two IPCC climate change scenarios for the Antarctic continent by the year 2098, using full-ensemble ER mean models. Bounds refer to the lower and upper ice melt coefficients used to derive melt projections for each of the RCPs.

	Lower Bound	**Mean**	**Upper Bound**
RCP2.6	0	910	1,902
RCP4.5	534	4,305	7,088
RCP8.5	5,971	11143	14,112



Extended Data Figure 2. New Antarctic ice-free area (km^2) predicted to emerge between 2014 and 2098 under the 'mean' melt scenario for RCP4.5. Grid cell resolution is 50 km in the continental map and 10 km in the Antarctic Peninsula inset.



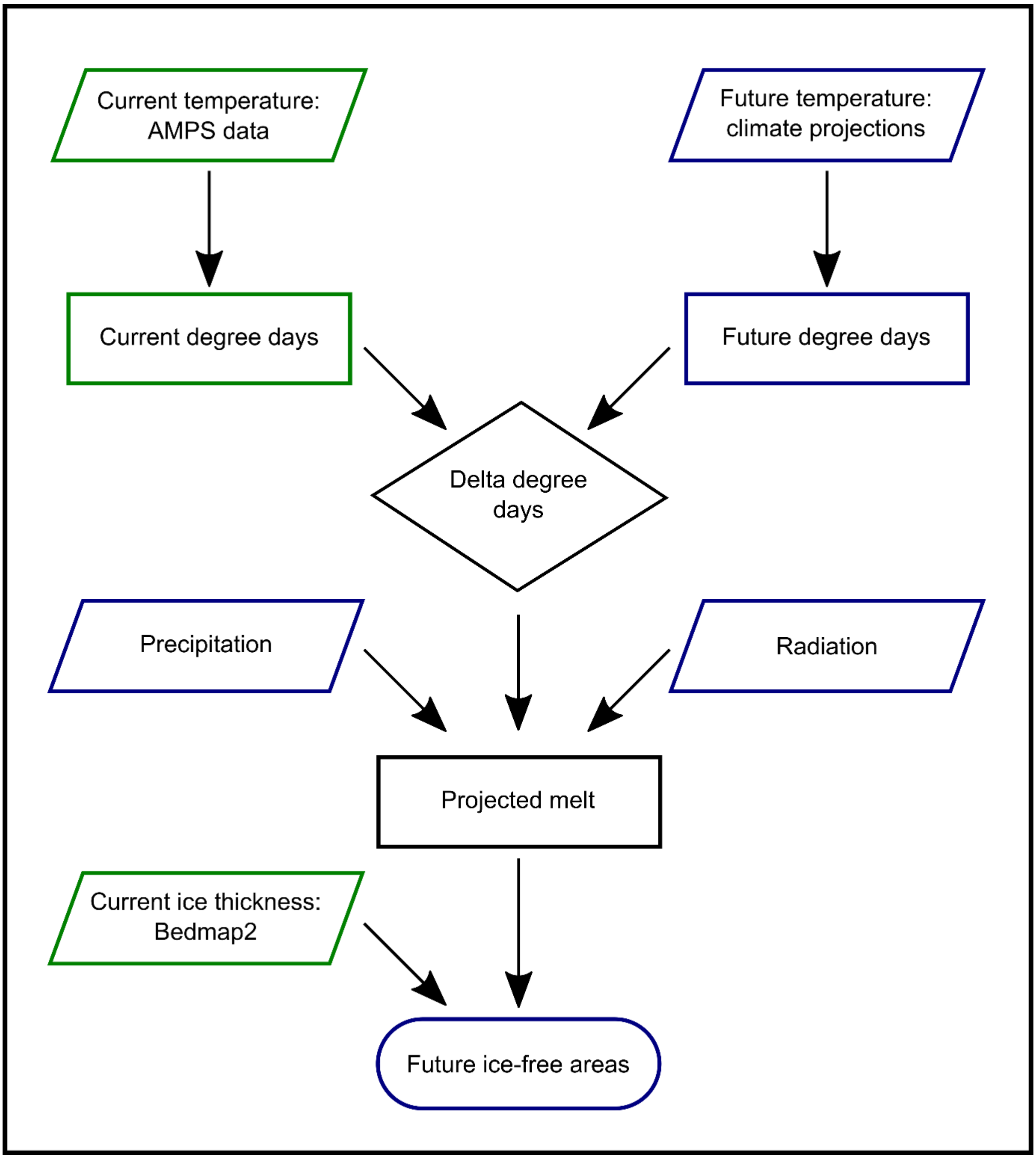
Extended Data Figure 3. Current and future ice-free area (km^2) in each Antarctic Conservation Biogeographic Region, with future estimates given for three different climate change scenarios (RCP2.6, RCP4.5, RCP8.5), using full-ensemble ER mean models. Bars represent total area using the mean ice-melt coefficients, whilst error bars represent the lower and upper bounds respectively (total area using the lowest and highest ice melt coefficients).

Extended Data Table 3. Current and future values of bioregional (and continental: C) ice-free area metrics under RCP8.5, mean melt coefficients (mean area of ice-free patches (km^2), total ice-free area (km^2), number of ice-free patches, mean distance to nearest neighbour (m), mean distance to neighbours within 10km (km), mean number of neighbours within 10 km). * denotes significant change between current and scenario values (p-value <0.01, see Supplementary Tables 1 – 4). Metrics for RCP4.5 are shown in Extended Data Table 4.

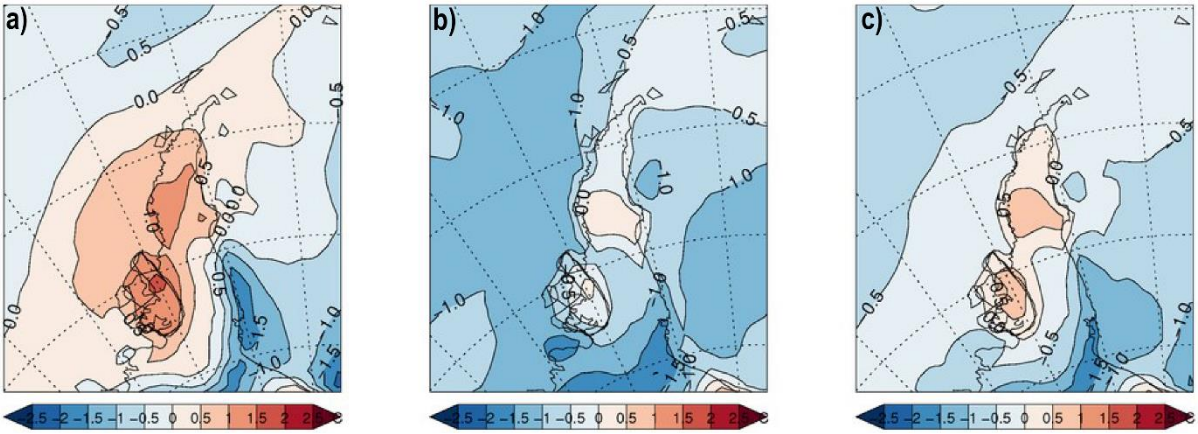
ACBR	**Mean area**		**Total Area**		**No. of IF**		**Mean dist NN**		**Mean dist NN 10 km**		**Mean No. N 10 km**	
	C	**8.5**	**C**	**8.5**	**C**	**8.5**	**C**	**8.5**	**C**	**8.5**	**C**	**8.5**
2	1.5	15.2	160	623	105	41	633	438*	5.5	4.3*	18.7	8.4*
3a	1.2	6.6*	6,398	18,853	5,534	2,872	705	835	5.7	5.4*	29.0	19.6*
4	1.1	1.4	4,962	5,993	4,556	4,327	813	849	5.7	5.8	25.0	24.6
5	2.2	2.2	2,188	2,192	989	987	1,663	1,667	5.1	5.1	10.0	10.0
6	5.3	5.3	5,523	5,523	1,040	1,040	1,972	1,972	5.0	5.0	8.8	8.8
7	3.5	3.4	1,109	1,161	320	341	2,173	2,029	4.9	4.9	21.5	27.0*
8	2.2	2.2	9,431	9,437	4,322	4,322	840	840	5.7	5.7	22.7	22.7
9	12.8	12.8	10,038	10,038	784	784	1,332	1,332	5.1	5.1	9.8	9.8
10	5.5	5.5	18,480	18,480	3,344	3,344	1,199	1,199	5.4	5.4	12.3	12.3
11	5.4	5.4	2,859	2,859	526	526	1,133	1,133	5.5	5.5	14.1	14.1
12	2.4	2.4	1,128	1,136	472	472	2,563	2,604	4.8	4.8	6.3	6.3
13	1.7	1.7	179	179	106	106	4,327	4,327	4.8	4.8	8.2	8.2
14	1.3	1.3	217	219	172	172	3,273	3,268	4.4	4.4	5.5	5.5
15	1.5	1.5	2,875	2,875	1,855	1,855	1,141	1,141	5.7	5.7	19.4	19.4
16	9.2	9.2	5,992	5,995	651	650	2,345	2,346	4.8	4.8	8.4	8.4
C	2.9	3.9	71,537	85,564	24,776	21,839	1,098	1,174	5.5	5.5	20.3	18.0

Extended Data Table 4. Current and future values of bioregional (and continental: C) ice-free area metrics under RCP4.5, mean melt coefficients (mean area of ice-free patches (km^2), total ice-free area (km^2), number of ice-free patches, mean distance to nearest neighbour (m), mean distance to neighbours within 10 km (km), mean number of neighbours within 10 km). * denotes significant change between current and scenario values (p-value <0.01, see Supplementary Tables 1 – 4). Metrics for RCP8.5 are shown in Extended Data Table 3.

ACBR	**Mean area**		**Total Area**		**No. of IF**		**Mean dist NN**		**Mean dist NN 10 km**		**Mean No. N 10 km**	
	C	**4.5**	**C**	**4.5**	**C**	**4.5**	**C**	**4.5**	**C**	**4.5**	**C**	**4.5**
2	1.5	15.2	160	623	105	41	633	438*	5.5	4.3*	18.7	8.4*
3a	1.2	3.2*	6,398	13,575	5,534	4,232	705	722*	5.7	5.6*	29.0	27.3*
4	1.1	1.1	4,962	5,030	4,556	4,537	813	813	5.7	5.7	25.0	25.0
5	2.2	2.2	2,188	2,188	989	989	1,663	1,663	5.1	5.1	10.0	10.0
6	5.3	5.3	5,523	5,523	1,040	1,040	1,972	1,972	5.0	5.0	8.8	8.8
7	3.5	3.5	1,109	1,109	320	320	2,173	2,173	4.9	4.9	21.5	21.5
8	2.2	2.2	9,431	9,431	4,322	4,322	840	840	5.7	5.7	22.7	22.7
9	12.8	12.8	10,038	10,038	784	784	1,332	1,332	5.1	5.1	9.8	9.8
10	5.5	5.5	18,480	18,480	3,344	3,344	1,199	1,199	5.4	5.4	12.3	12.3
11	5.4	5.4	2,859	2,859	526	526	1,133	1,133	5.5	5.5	14.1	14.1
12	2.4	2.4	1,128	1,128	472	472	2,563	2,563	4.8	4.8	6.3	6.3
13	1.7	1.7	179	179	106	106	4,327	4,327	4.8	4.8	8.2	8.2
14	1.3	1.3	217	217	172	172	3,273	3,273	4.4	4.4	5.5	5.5
15	1.5	1.5	2,875	2,875	1,855	1,855	1,141	1,141	5.7	5.7	19.4	19.4
16	9.2	9.2	5,992	5,992	651	651	2,345	2,345	4.8	4.8	8.4	8.4
C	2.9	3.4	71,537	79,245	24,776	23,391	1,098	1,125	5.5	5.5	20.3	19.5



Extended Data Figure 4. Simple overview of the methods used to model changes in distribution and size of Antarctic ice-free areas at the end of the 21st century.



Extended Data Figure 5. Annual mean surface air temperature (at 2 metres) anomalies for **a)** 2014, **b)** 2015 and **c)** 2014-2015. The anomalies are relative to the period 1979 through 2015. The source of data is the ECMWF ERA-interim re-analysis (Dee et al. 2011).

Extended Data Table 5. Coefficients used in melt calculations and the method by which they were calculated. Where *a* is the radiation coefficient, *DDF* is the degree day factor and *MF* is the melt factor.

Bound	***a*** **(m^2 W^{-1} mm d^{-1} °C^{-1})**	**Method coefficient calculated**	***DDF*** **(mm d^{-1} °C^{-1})**	**Method coefficient calculated**	***MF*** **(mm d^{-1} °C^{-1})**	**Method coefficient calculated**
Lower Bound	0.0158	(mean of all literature ***a*** values for snow)	2.87	(mean of all literature ***DDF*** values for snow minus STD)	0.94	MF = 2.87 - (0.0158 * 121.862)
Upper Bound	0.0223	(mean of all literature ***a*** values for ice)	14.19	(mean of all literature ***DDF*** values for ice plus STD)	11.47	MF = 14.19 - (0.0223 * 121.862)
Medium (best guess)	0.019	(mean of upper and lower bound)	8.53	(mean of upper and lower bound)	6.21	MF = 8.53 - (0.019 * 121.862)

*Due to the large variation in recorded DDF's (Supplementary Table 6) STD was used for calculating the DDF for lower and upper bounds in order to give robust estimates of melt rates.

Supplementary Material

Supplementary Table 1. ANOVA analysis of log-transformed “total ice-free area” for subset ensemble mean models, mean melt coefficients.

ACBR	F-statistic	P value (Current – RCP4.5)	P value (Current – RCP8.5)
2	$F_{2,185} = 0.12$	0.696	0.696
3a	$F_{2,12635} = 41.68$	<0.001	<0.001
4	$F_{2,13417} = 0.004$	0.954	0.977
5	$F_{2,2962} = 0.001$	1.0	0.972
6	$F_{2,3117} = <0.001$	1.0	1.0
7	$F_{2,978} = 2.225$	1.0	0.07
8	$F_{2,12963} = <0.001$	1.0	1.0
9	$F_{2,2349} = <0.001$	1.0	1.0
10	$F_{2,10029} = <0.001$	1.0	1.0
11	$F_{2,1575}= <0.001$	1.0	1.0
12	$F_{2,1413} = 0.005$	1.0	0.933
13	$F_{2,315} = <0.001$	1.0	1.0
14	$F_{2,513} = 0.008$	1.0	0.911
15	$F_{2,5562} = <0.001$	1.0	1.0
16	$F_{2,1949} = 0.006$	1.0	0.927

Supplementary Table 2. ANOVA analysis of log-transformed “mean distance to nearest neighbour” for subset ensemble mean models, mean melt coefficients.

ACBR	F-statistic	P value (Current – RCP4.5)	P value (Current – RCP8.5)
2	$F_{2,184} = 6.697$	<0.005	<0.005
3a	$F_{2,12635} = 3.849$	0.006	0.159
4	$F_{2,13417} = 0.035$	0.964	0.805
5	$F_{2,2962} = 0.004$	1.0	0.935
6	$F_{2,3117} = <0.001$	1.0	1.0
7	$F_{2,978} = 1.164$	1.0	0.189
8	$F_{2,12963} = <0.001$	1.0	1.0
9	$F_{2,2349} = <0.001$	1.0	1.0
10	$F_{2,10029} = <0.001$	1.0	1.0
11	$F_{2,1575} = <0.001$	1.0	1.0
12	$F_{2,1413} = 0.002$	1.0	0.961
13	$F_{2,315} = <0.001$	1.0	1.0
14	$F_{2,513} = <0.001$	1.0	0.992
15	$F_{2,5562} = <0.001$	1.0	1.0
16	$F_{2,1949} = 0.003$	1.0	0.944

Supplementary Table 3. ANOVA analysis of “mean distance to neighbours within 10km” for subset ensemble mean models, mean melt coefficients.

ACBR	F-statistic	P value (Current – RCP4.5)	P value (Current – RCP8.5)
2	$F_{2,184} = 14.41$	<0.001	<0.001
3a	$F_{2,12591} = 75.41$	0.008	<0.001
4	$F_{2,13373} = 0.032$	0.979	0.818
5	$F_{2,2911} = <0.001$	1.0	0.978
6	$F_{2,3012} = <0.001$	1.0	1.0
7	$F_{2,957} = 0.008$	1.0	0.911
8	$F_{2,12933} = <0.001$	1.0	1.0
9	$F_{2,2337} = <0.001$	1.0	1.0
10	$F_{2,9975} = <0.001$	1.0	1.0
11	$F_{2,1572} = <0.001$	1.0	1.0
12	$F_{2,1331} = <0.001$	1.0	0.992
13	$F_{2,291} = <0.001$	1.0	1.0
14	$F_{2,480} = <0.001$	1.0	0.986
15	$F_{2,5511} = <0.001$	1.0	1.0
16	$F_{2,1862} = <0.001$	1.0	0.99

Supplementary Table 4. ANOVA analysis of “mean number of neighbours within 10km” for subset ensemble mean models, mean melt coefficients.

ACBR	F-statistic	P value (Current – RCP4.5)	P value (Current – RCP8.5)
2	$F_{2,184} = 70.74$	<0.001	<0.001
3a	$F_{2,12635} = 428.2$	<0.005	<0.001
4	$F_{2,13417} = 0.966$	0.995	0.228
5	$F_{2,2962} = 0.001$	1.0	0.975
6	$F_{2,3117} = <0.001$	1.0	1.0
7	$F_{2,978} = 10.8$	1.0	<0.001
8	$F_{2,12963} = <0.001$	1.0	1.0
9	$F_{2,2349} = <0.001$	1.0	1.0
10	$F_{2,10029} = <0.001$	1.0	1.0
11	$F_{2,1575} = <0.001$	1.0	1.0
12	$F_{2,1413} = 0.001$	1.0	0.976
13	$F_{2,315} = <0.001$	1.0	1.0
14	$F_{2,513} = <0.001$	1.0	1.0
15	$F_{2,5562} = <0.001$	1.0	1.0
16	$F_{2,1949} = 0.001$	1.0	0.972

Supplementary Table 5. List of CMIP5 models used in this study.

Model name	Latitude grid spacing (°)	RCP4.5	RCP8.5
ACCESS1.0	1.3	x	x
ACCESS1.3	1.3	x	x
BCC-CSM1.1	2.8	x	x
BCC-CSM1.1(m)	1.1	x	x
BNU-ESM	2.8	x	x
CanESM2	2.8	x	x
CCSM4	0.9	x	x
CESM1(BGC)	0.9	x	x
CESM1(CAM5)	0.9	x	x
CESM1(WACCM)	1.9	x	x
CMCC-CESM	3.4		x
CMCC-CM	0.7	x	x
CMCC-CMS	1.9	x	x
CNRM-CM5	1.4	x	x
CSIRO-Mk3.6.0	1.9	x	x
EC-EARTH	1.1	x	x
FGOALS-g2	2.8	x	x
FIO-ESM	2.8	x	x
GFDL-CM3	2	x	x
GFDL-ESM2G	2	x	x
GFDL-ESM2M	2	x	x
GISS-E2-H	2	x	x
GISS-E2-H-CC	2	x	x
GISS-E2-R	2	x	x
GISS-E2-R-CC	2	x	x
HadGEM2-AO	1.3	x	x
HadGEM2-CC	1.3	x	x
HadGEM2-ES	1.3	x	x
INM-CM4	1.5	x	x
IPSL-CM5A-LR	1.9	x	x
IPSL-CM5A-MR	1.3	x	x
IPSL-CM5B-LR	1.9	x	x
MIROC-ESM-CHEM	2.8	x	x
MIROC5	1.4	x	x
MPI-ESM-LR	1.9	x	x
MPI-ESM-MR	1.9	x	x
MRI-CGCM3	1.1	x	x
MRI-ESM1	1.1		x
NorESM1-M	1.9	x	x
NorESM1-ME	1.9	x	x

867 **Supplementary Table 6.** Degree day factor (DDF) values obtained from the literature.

868 (to be included as an excel file)

Measurement Type	Value (mm d-1 °C-1)	Paper	Site	Country	Was the value cited from another paper?	Other paper (if required)
Ice	5.4	Hock 1999	Storglaciaren	Sweden	N	
Ice	5.5	Braithwaite 1995	Norway	Norway	Y	Braithwaite 1977
Ice	5.5	Braithwaite 1995	Nigardsbreen	Norway	Y	Laumman & Reeh 1993
Ice	5.5	Braithwaite 1995	Hellstugubreen	Norway	Y	Laumman & Reeh 1993
Ice	5.5	Hock 2003	John Evans Glacier	Canada	Y	Arendt & Sharp (1999)
Ice	5.5	Vaughn 2006		Antarctic Penisula	Y/N	
Ice	5.9	Hock 2003	Hans Tausen Ice Cap	Greenland	Y	Braithwaite et al. 1998
Ice	6.0	Hock 1999	Storglaciaren	Sweden	N	
Ice	6.0	Braithwaite 1995	Swiss glaciers	Switzerland	Y	Kasser 1959
Ice	6.0	Braithwaite 1995	Franz Josef Glacier	New Zealand	Y	Woo & Fitzharris 1992
Ice	6.0	Braithwaite 1995	Alfotbreen	Norway	Y	Laumman & Reeh 1993
Ice	6.2	Braithwaite & Zhang 2000	Glacier de Sarennes	France	Y	Vincent & Vallon 1997
Ice	6.3	Hock 1999	Storglaciaren	Sweden	N	
Ice	6.3	Braithwaite 1995	Store Supphellebre	Norway	Y	Orheim 1970
Ice	6.3	Braithwaite 1995	Artic Canada	Canada	Y	Braithwaite 1981
Ice	6.4	Hock 1999	Storglaciaren	Sweden	N	
Ice	6.4	Braithwaite 1995	Nigardsbreen	Norway	Y	Johannesson et al. 1993; 1995
Ice	6.6	Hock 2003	Rakhiot Glacier	Himalayas	Y	Kayastha et al. 2000
Ice	6.9	Braithwaite & Zhang 2000		Patagonia	Y	Takeuchi et al. 1996
Ice	7.0	Fausto et al. 2009; Greve 2005	Greenland Ice Sheet	Greenland	N	
Ice	7.0	Hock 2003	Thule Ramp	Greenland	Y	Schytt 1955
Ice	7.1	Hock 2003	Morenoglacier	Argentina	Y	Takeuchi et al. 1996
Ice	7.1	Hock 2003	John Evans Glacier	Canada	Y	Arendt & Sharp (1999)
Ice	7.3	Hock 2003	Qamanarssup sermia (West Greenland)	Greenland	Y	Johannesson et al. 1995

Ice	7.4	Hock 2003	Dokriani Glacier	Himalayas	Y	Singh et al. 2000
Ice	7.5	Braithwaite 1995	Nordbogletscher (West Greenland)	Greenland	N	
Ice	7.6	Hock 2003	John Evans Glacier	Canada	Y	Arendt & Sharp (1999)
Ice	7.7	Braithwaite 1995	Satujokull	Iceland	Y	Johannesson et al. 1993; 1995
Ice	8.0	Lefebre et al. 2002		West Greenland	N	
Ice	8.1	Hock 2003	Glacier AX010	Himalayas	Y	Kayastha et al. 2000
Ice	8.2	Braithwaite 1995	Qamanarssup sermia (West Greenland)	Greenland	N	
Ice	8.7	Hock 2003	GIMEX profile	Greenland	Y	Van de Wal 1992
Ice	8.8	Hock 2003	Glacier AX010	Himalayas	Y	Kayastha et al. 2000
Ice	8.9	Braithwaite & Zhang 2000	Griesgletscher	Switzerland	N	
Ice	9.2	Hock 2003	GIMEX profile	Greenland	Y	Van de Wal 1992
Ice	9.3	Hock 2003	Yala Glacier	Himalayas	Y	Kayastha 2001
Ice	9.8	Hock 2003	Kronprins Christian Land	Greenland	Y	Braithwaite et al. 1998
Ice	10.1	Hock 2003	Yala Glacier	Himalayas	Y	Kayastha 2001
Ice	10.8	Pellicciotti et al. 2005	Haut Glacier	Switzerland	N	
Ice	11.7	Hock 2003	Aletschgletscher	Switzerland	Y	Lang 1986
Ice	12.0	Hock 2003	Thule Ramp	Greenland	Y	Schytt 1955
Ice	13.8	Braithwaite 1995	Vestfonna (Spistbergen)	Norway	Y	Schytt 1964
Ice	15.0	Fausto et al. 2009; Greve 2005	Greenland Ice Sheet	Greenland	N	
Ice	16.9	Hock 2003	Khumbu Glacier	Himalayas	Y	Kayastha et al. 2000
Ice	17.5	Lefebre et al. 2002	ETH Camp	West Greenland	N	
Ice	18.6	Hock 2003	Camp IV-EGIG	Greenland	Y	Ambach 1988
Ice	20.0	Hock 2003	GIMEX profile	Greenland	Y	Van de Wal 1992
Ice	33.0	Moris 1999	Moraine Corrie Glacier; Antarctic Peninsula	Antarctica	N	
Snow	2.17	Smith et al. 1998	Rothera Point	Antarctic Penisula	N	
Snow	2.70	Hock 2003	John Evans Glacier	Canada	Y	Arendt & Sharp 1999
Snow	2.80	Braithwaite & Zhang 2000	Qamanarssup sermia	West Greenland	Y	Johannesson et al. 1993 (Hock

						2003 has recorded this as: Johannesson et al. 1995)
Snow	2.90	Braithwaite 1995	Nordbogletscher (West Greenland)	Greenland	N	
Snow	2.96	Huss & Bauder 2009	Silvrettagletsche r	Switzerland	N	
Snow	3.00	Fausto et al. 2009; Greve 2005	Greenland Ice Sheet			
Snow	3.00	Braithwaite et al. 1995	Franz Josef Glacier	New Zealand	Y	Woo & Fitzharris 1992
Snow	3.00	Lefebre et al. 2003		West Greenland	N	
Snow	3.20	Hock et al. 1999	Storglaciaren	Sweden	N	
Snow	3.49	Braithwaite et al. 2006	Global – 180 glaciers		N	
Snow	3.50	Braithwaite et al. 1995	Hellstugubreen	Norway	Y	Laumann & Reeh 1993
Snow	3.70	Braithwaite 1995	Qamanarssup sermia (West Greenland)	Greenland	N	
Snow	3.73	Huss & Bauder 2009	Clarindenfirn	Switzerland	N	
Snow	3.80	Braithwaite & Zhang 2000	Glacier de Sarennes	France	Y	Vincent & Vallon 1997
Snow	3.90	Hock 2003	John Evans Glacier	Canada	Y	Arendt & Sharp 1999
Snow	3.93	Huss & Bauder 2009	Clarindenfirn	Switzerland	N	
Snow	3.96	Braithwaite et al. 2006	Global – 180 glaciers		N	
Snow	3.97	Huss & Bauder 2009	Gr. Aletshgletscher	Switzerland	N	
Snow	4.00	Braithwaite et al. 1995	Nigardsbreen	Norway	Y	Laumann & Reeh 1993
Snow	4.10	Hock 2003	John Evans Glacier	Canada	Y	Arendt & Sharp 1999
Snow	4.40	Hock 1999	Storglaciaren	Sweden	N	
Snow	4.40	Braithwaite et al. 2006	Global – 180 glaciers		N	
Snow	4.40	Braithwaite et al. 1995	Nigardsbreen	Norway	Y	Johannesson et al. 1993 (Hock 2003 has recorded this as: Johannesson et al. 1995)
Snow	4.50	Braithwaite et al. 1995	Alfotbreen	Norway	Y	Laumann & Reeh 1993
Snow	4.50	Braithwaite & Zhang 2000	5 Swiss Glaciers	Switzerland		

Snow	4.50	Braithwaite & Zhang 2000	Weissflujoch	Switzerland	Y	Zingg 1951
Snow	4.50	Braithwaite & Zhang 2000	Weissflujoch	Switzerland	Y	De Quervain 1979
Snow	5.40	Braithwaite et al. 1995	Gr. Aletshgletscher	Switzerland	Y	Lang et al. 1976 (Hock 2003 records this as: Lang et al. 1986)
Snow	5.48	Lefebre et al. 2002	ETH Camp	West Greenland	N	
Snow	5.50	Vaughn 2006	Antarctic Peninsula	Antarctica	Y/N	
Snow	5.50	Hock 2003	John Evans Glacier	Canada	Y	Arendt & Sharp 1999
Snow	5.70	Braithwaite et al. 1995	Satujokull	Iceland	Y	Johannesson et al. 1993 (Hock 2003 has recorded this as: Johannesson et al. 1995)
Snow	5.70	Hock 2003	Dokriani Glacier	Himalyas	Y	Singh et al. 2000
Snow	5.90	Hock 2003	Dokriani Glacier	Himalyas	Y	Singh & Kumar 1996
Snow	6.00	Smith et al. 1998	Spartan Glacier	Antarctic Penisula	Y	Jamieson & Wager 1983
Snow	6.30	Smith et al. 1999	White & Sverdrup Glaciers	Arctic Canada	Y	Braithwaite 1981
Snow	6.50	Szafraniec 2002	Hansbreen	Svalbard	N	
Snow	7.30	Hock 2003	Glacier AX010	Himalyas	Y	Kayastha et al. 2000
Snow	7.68	Pellicciotti et al. 2005	Haut Glacier, Switzerland			
Snow	8.70	Hock 2003	Glacier AX010	Himalyas	Y	Kayastha et al. 2000
Snow	11.60	Hock 2003	Glacier AX010	Himalyas	Y	Kayastha et al. 2000

Supplementary Table 7. Melt factor (MF) values obtained from the literature.

Value (mm d^{-1} °C^{-1})	Paper	Site	Country
1.8	Hock et al. 1999	Storglaciaren	Sweden
1.97	Pellicciotti et al. 2005	Haut Glacier	Switzerland
0.49	Huss et al. 2009	Clariden Upper	European Alps
0.52	Huss et al. 2009	Clariden Lower	European Alps
0.5	Huss et al. 2009	Aletsch	European Alps
0.43	Huss et al. 2009	Silvretta	European Alps

Supplementary Table 8. Radiation coefficient (a) values obtained from the literature.

Measurement Type	Value (m^2 W^{-1} mm d^{-1} °C^{-1})	Paper	Site	Country
Ice	0.0192	Hock et al. 1999	Storglaciaren	Sweden
Ice	0.0254	Pellicciotti et al. 2005	Haut Glacier	Switzerland
Snow	0.0144	Hock et al. 1999	Storglaciaren	Sweden
Snow	0.0125	Pellicciotti et al. 2005	Haut Glacier	Switzerland
Snow	0.0172	Huss et al. 2009	Clariden Upper	European Alps
Snow	0.0181	Huss et al. 2009	Clariden Lower	European Alps
Snow	0.0175	Huss et al. 2009	Aletsch	European Alps
Snow	0.0151	Huss et al. 2009	Silvretta	European Alps

Supplementary Table 9. Metrics describing current and future ice-free areas within Antarctic Conservation Biogeographic Regions

Metric Name	Description
Mean area	Mean area of individual ice-free patches
Total area	Total area of all ice-free patches
No. of IF	Number of ice-free patches
Mean dist NN	Mean distance to nearest neighbour
Mean dist NN 10 km	Mean distance to neighbours that fall within 10 km
Mean No. N 10 km	Mean number of neighbours that fall within 10 km