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Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago

Alex S. Gardner[1,2], Geir Moholdt[3,4], Bert Wouters[5], Gabriel J. Wolken[6], David O. Burgess[7], Martin J. Sharp[1], J. Graham Cogley[8], Carsten Braun[9] & Claude Labine[10]

Mountain glaciers and ice caps are contributing significantly to present rates of sea level rise and will continue to do so over the next century and beyond[1–5]. The Canadian Arctic Archipelago, located off the northwestern shore of Greenland, contains one-third of the global volume of land ice outside the ice sheets[6], but its contribution to sea-level change remains largely unknown. Here we show that the Canadian Arctic Archipelago has recently lost 61 ± 7 gigatonnes per year ($\mathrm{Gt\,yr^{-1}}$) of ice, contributing 0.17 ± 0.02 $\mathrm{mm\,yr^{-1}}$ to sea-level rise. Our estimates are of regional mass changes for the ice caps and glaciers of the Canadian Arctic Archipelago referring to the years 2004 to 2009 and are based on three independent approaches: surface mass-budget modelling plus an estimate of ice discharge (SMB+*D*), repeat satellite laser altimetry (ICESat) and repeat satellite gravimetry (GRACE). All three approaches show consistent and large mass-loss estimates. Between the periods 2004–2006 and 2007–2009, the rate of mass loss sharply increased from 31 ± 8 $\mathrm{Gt\,yr^{-1}}$ to 92 ± 12 $\mathrm{Gt\,yr^{-1}}$ in direct response to warmer summer temperatures, to which rates of ice loss are highly sensitive (64 ± 14 $\mathrm{Gt\,yr^{-1}}$ per 1 K increase). The duration of the study is too short to establish a long-term trend, but for 2007–2009, the increase in the rate of mass loss makes the Canadian Arctic Archipelago the single largest contributor to eustatic sea-level rise outside Greenland and Antarctica.

Several long-term records (about 50 years) of the surface mass budget (surface accumulation minus surface ablation) of individual glaciers and ice caps exist for the Canadian Arctic Archipelago (CAA, see Fig. 1)[7,8], but extrapolation of these records to estimate the mass budget of the entire region introduces a large uncertainty. Repeat airborne laser altimetry surveys have been used to estimate that the glaciers of the CAA lost 23 $\mathrm{Gt\,yr^{-1}}$ of ice between spring 1995 and spring 2000 (ref. 9). This represents 0.063 $\mathrm{mm\,yr^{-1}}$ of sea-level rise if we take the global area of the ocean to be $362.5 \times 10^6\,\mathrm{km^2}$ (ref. 10). Since 2000 the CAA has experienced some of the warmest summer temperatures on record, with four of the five warmest years since 1960 occurring after 2004 (Supplementary Information). Between 2005 and 2009 all CAA glaciers with long-term monitoring programmes[7,8] experienced their most negative five-year period of surface mass budget since measurements began in the early 1960s. Here we present three independent estimates of change in total glacier mass between autumn 2003 and autumn 2009 for the northern CAA (Fig. 1; area 106,400 $\mathrm{km^2}$) and two independent estimates for the southern CAA (Fig. 1; area 42,000 $\mathrm{km^2}$).

The first estimate is derived using a numerical model that simulates the regional mass change resulting from the surface mass budget. Ice discharge due to the calving of icebergs from glaciers that terminate in the sea, denoted *D*, is added to the surface mass-budget model results to account for the total regional ice loss (model SMB+*D*) (Supplementary Information). The model is not applied to the southern CAA because there are too few records of glacier mass budget and near-surface temperature with which to calibrate the model. The second estimate derives mass change from the change in land-ice volume measured using repeat laser altimetry from the Ice, Cloud and Land Elevation Satellite (ICESat)[11]. The third estimate is derived using repeat gravity observations collected by the Gravity Recovery and Climate Experiment (GRACE) satellites. The three methods are independent and produce consistent estimates of changes in glacier mass for the years 2004 to 2009 (Fig. 2), where each year refers to the mass-budget year starting in the autumn of the previous calendar year. All estimates are given as the mean $\pm 2\sigma$ (95% confidence interval).

In general, the CAA receives low amounts of precipitation (100–300 $\mathrm{kg\,m^{-2}\,yr^{-1}}$) with locally higher rates (300–1,000 $\mathrm{kg\,m^{-2}\,yr^{-1}}$)

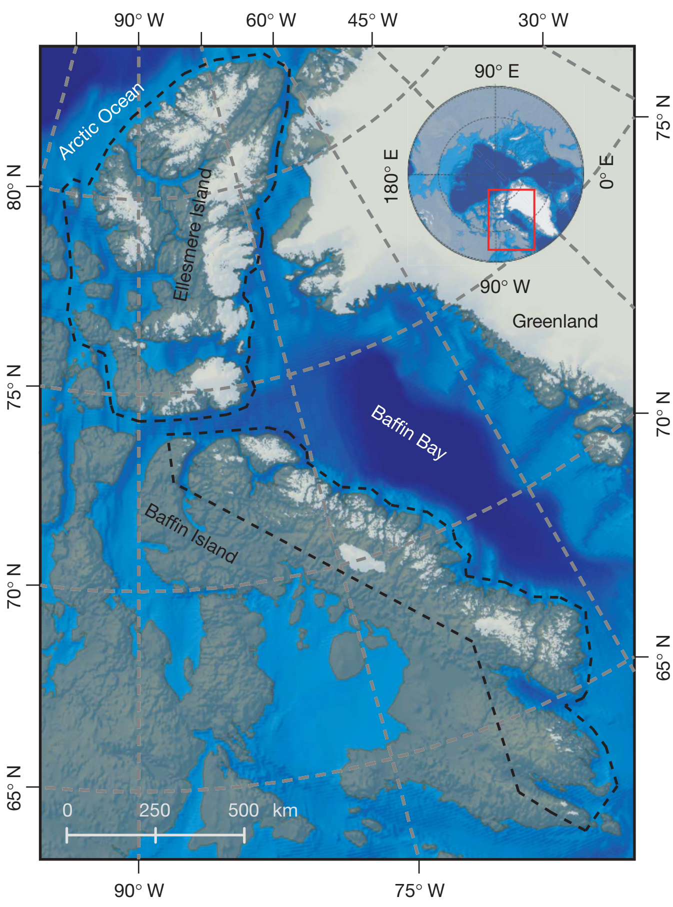

Figure 1 | Glaciers and ice caps of the Canadian Arctic Archipelago. Black dashed lines delineate the northern and southern study regions. The main panel is an enlargement of the red rectangle superimposed on the map of the Arctic (inset).

[1]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, T6G 2E3, Canada. [2]Department of Atmospheric, Oceanic and Space Science, University of Michigan, Ann Arbor, Michigan 48109, USA. [3]Department of Geosciences, University of Oslo, N-0316 Oslo, Norway. [4]Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, La Jolla, California 92093, USA. [5]The Royal Netherlands Meteorological Institute, NL-3730 AE De Bilt, Netherlands. [6]Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources, Fairbanks, Alaska 99709, USA. [7]Geological Survey of Canada, Ottawa, Ontario, K1A 0E8, Canada. [8]Department of Geography, Trent University, Peterborough, Ontario, K9J 7B8, Canada. [9]Department of Geography and Regional Planning, Westfield State University, Westfield, Massachusetts 01086, USA. [10]Campbell Scientific Canada Corp., Edmonton, Alberta, T5M 1W7, Canada.

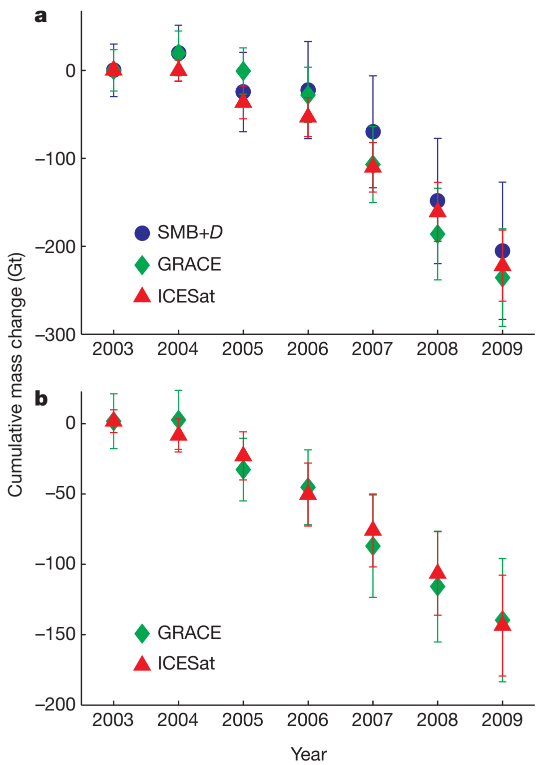

Figure 2 | Cumulative change in glacier mass between autumn 2003 and autumn 2009. Separate estimates are provided for the northern (**a**) and southern (**b**) CAA. Error bars represent the 95% confidence interval.

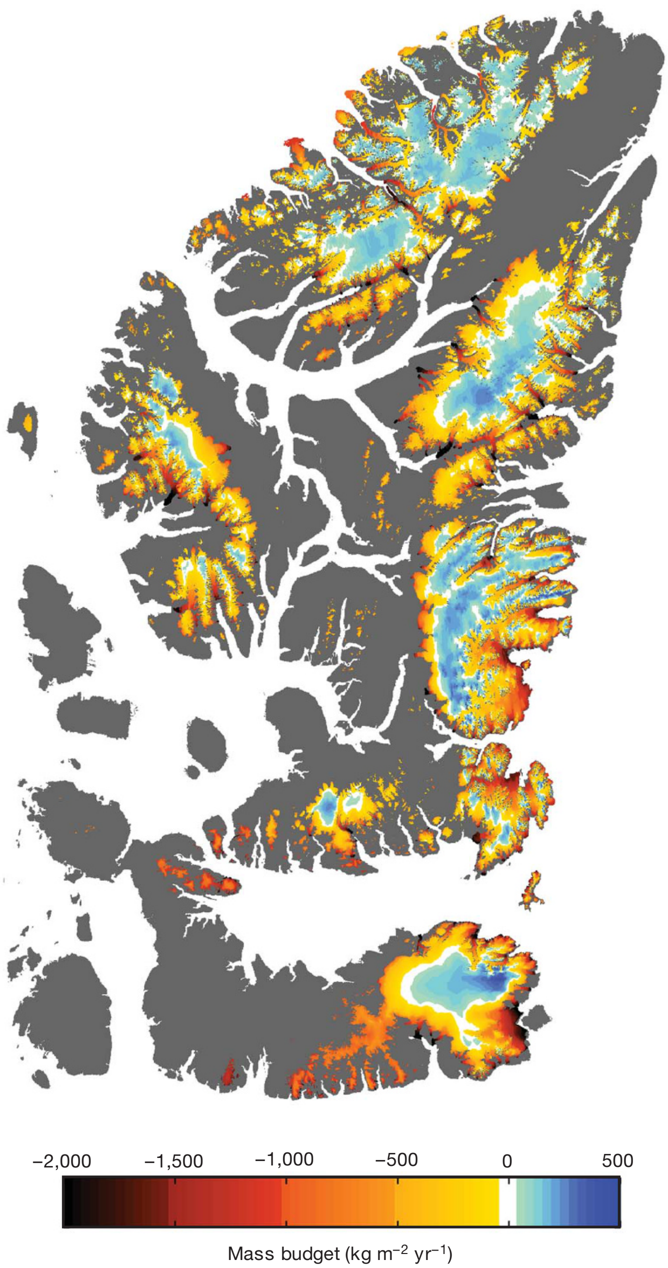

Figure 3 | Modelled surface mass budget of the northern CAA between autumn 2003 and autumn 2009. The model resolution of 0.5 km allows us to resolve the highly negative surface mass budgets of the outlet-glacier tongues.

concentrated on the east-facing slopes flanking Baffin Bay (Fig. 1). Surface air temperatures over ice masses in the region exceed the freezing point during only two to three months of the year. Because there is generally low interannual variability in precipitation and high variability in melt production, interannual variability in the regional surface mass budget is largely governed by changes in the summer surface energy budget[7]. These are strongly correlated with summer surface air temperatures[12–14], which are, in turn, highly dependent on local synoptic conditions[15,16]. In this study we apply a surface mass-budget model that determines surface melt using the temperature-index method[17,18]. The model is forced with downscaled[19] and bias-corrected temperature and precipitation fields from the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis (Supplementary Information). For the years 2004 to 2009 the modelled mass loss from the surface mass budget (SMB) plus ice discharge (D), where $D = 4.6 \pm 1.9$ Gt yr^{-1} (Supplementary Information), of the northern CAA was 34 ± 13 Gt yr^{-1} (Fig. 3). The average mass loss from the northern CAA was 7 ± 18 Gt yr^{-1} for the years 2004 to 2006, increasing to 61 ± 18 Gt yr^{-1} for the years 2007 to 2009 with a peak loss of 79 ± 30 Gt yr^{-1} in 2008. The difference between the two periods is primarily due to a 42 Gt yr^{-1} increase in melt production, which resulted from regionally warmer summer air temperatures in the lower troposphere. Warmer temperatures also contributed to a 7% decrease in snow fraction. A slight decrease in annual precipitation amount, and changes in the amount of meltwater retained by the annual snowpack, contributed another 12 Gt yr^{-1} to the increased mass loss.

For both the northern and southern CAA, we derived elevation changes from ICESat's Geoscience Laser Altimeter System (GLAS) for the period 2003–2009 (ref. 20). Elevation changes are estimated relative to rectangular planes that are fitted to 700-m-long segments of near-repeat-track data[21]. The planes represent a simplified surface topography such that multi-temporal elevation measurements that are slightly offset in location can be compared. We then extrapolate elevation changes to volume changes and convert them to mass changes using a plausible range of firn and ice densities (Supplementary Information). For the years 2004 to 2009, ICESat results show that the northern CAA lost 37 ± 7 Gt yr^{-1} and that the southern CAA lost 24 ± 6 Gt yr^{-1}. ICESat results show increases in mass loss between 2004–2006 and 2007–2009 of 39 Gt yr^{-1} and 14 Gt yr^{-1} for the northern and southern CAA, respectively. Recent observations in both Alaska[22] and Greenland[23] have found that marine-terminating glaciers are thinning more rapidly than land-terminating glaciers. To assess whether the same phenomenon is occurring in the CAA, we separately determined elevation changes for marine- and land-terminating glacier basins (Supplementary Information). Our results show no difference in the area-averaged rate of elevation change between the two basin types, suggesting that total ice discharge from marine-terminating glaciers has not accelerated in recent years. This gives increased confidence in both the extrapolation of ICESat elevation changes and our estimate of ice discharge.

Lastly, we derived mass changes for both the northern and southern CAA from GRACE gravity measurements. Mass-change estimates from GRACE agree very well with the other two data sets for the northern CAA, with an average mass loss between 2004 and 2009 of $39 \pm 9\,\mathrm{Gt\,yr^{-1}}$. The observations confirm the sharp increase in northern CAA mass loss between 2004–2006 and 2007–2009, with an increase in the average mass loss of $60\,\mathrm{Gt\,yr^{-1}}$. The southern CAA is estimated to have lost ice at an average rate of $24 \pm 7\,\mathrm{Gt\,yr^{-1}}$ over the six-year study period, with a $16\,\mathrm{Gt\,yr^{-1}}$ increase in the rate of loss between the first three and last three years, and is in very good agreement with ICESat. The most likely sources of the disagreement between the three methods are: uncertainties in constraining the terrestrial water storage in the GRACE estimates, the identification of the appropriate end-of-season mass change in the GRACE signal, and fewer ICESat elevation retrievals in 2009 (Supplementary Information).

The error-weighted mean of all mass-change estimates gives a total mass loss for the CAA of 368 ± 41 Gt or 1.01 ± 0.11 mm sea-level rise for the years 2004 to 2009. Most of the mass loss came from the northern CAA, which lost 224 ± 30 Gt, with the remaining 144 ± 28 Gt coming from the southern CAA (see Supplementary Figs 1–3 for a further subdivision of the mass losses within the northern and southern CAA). We estimate that the majority of the mass loss (about 92%) is due to meltwater runoff, with a much smaller contribution coming from ice discharge from marine-terminating glaciers (about 8%). Three-quarters of all mass loss occurred in the last three years of the observation period with an average loss of $92 \pm 12\,\mathrm{Gt\,yr^{-1}}$, or $0.25 \pm 0.03\,\mathrm{mm\,yr^{-1}}$ sea-level rise. This rate is four times greater than the estimated mass loss for CAA over the period 1995 to 2000 (ref. 9).

This increase in mass loss is in direct response to warmer surface air temperatures in summer, to which the glaciers of the CAA have a high sensitivity. Over the six-year period of our study an additional $64 \pm 14\,\mathrm{Gt\,yr^{-1}}$ of ice was lost to the oceans for every 1 K rise in mean summer surface air temperature. Dividing by the total glacier area gives an area-averaged temperature sensitivity of $-430 \pm 90\,\mathrm{kg\,m^{-2}\,yr^{-1}\,K^{-1}}$, which is two times larger than estimated from glacier surface mass-budget records[2,24,25] and is close to sensitivities estimated from regional climatology[2]. The sensitivity to precipitation is much smaller; a 10% increase in precipitation would result in a mass gain of only about $5\,\mathrm{Gt\,yr^{-1}}$. Such a low sensitivity to precipitation is in contrast to glaciers located in wet maritime regions. For example a 10% increase in precipitation over the Patagonia icefields, which have a combined ice area that is one-tenth the size of the CAA, would result in a $12\,\mathrm{Gt\,yr^{-1}}$ gain of mass[26].

To put the mass losses occurring in the CAA into a global perspective, the Patagonia icefields lost ice at an average rate of $28 \pm 11\,\mathrm{Gt\,yr^{-1}}$ between April 2002 and December 2006 (ref. 27) with little change in the ice-loss trend for the years 2007 to 2009 (J. Chen, personal communication). The glaciers of the Gulf of Alaska lost mass at an average rate of $88 \pm 15\,\mathrm{Gt\,yr^{-1}}$ for the years 2004 to 2006, slowing to $70 \pm 11\,\mathrm{Gt\,yr^{-1}}$ for the years 2007 to 2009 (update to ref. 28). The sharp increase in mass loss from the CAA and the slowdown in loss from the Gulf of Alaska makes the CAA the largest contributor to eustatic sea level rise outside Greenland and Antarctica for the years 2007–2009. Because of the high sensitivity to temperature and low sensitivity to precipitation, the CAA is expected to continue to be one of the largest contributing regions to eustatic sea level rise well into the next century and beyond[5].

METHODS SUMMARY

The surface mass-budget model was run at a resolution of 500 m by 500 m for the period 1949 to 2009 (Supplementary Information). Model results are validated against observations and agree well with *in situ* point surface mass-budget measurements (Supplementary Fig. 4: $r = 0.86$, $N = 3{,}717$, standard error $= 350\,\mathrm{kg\,m^{-2}}$). For the four regions with well-established surface mass-budget measurement programmes (Agassiz Ice Cap, north-western Devon Ice Cap, Meighen Ice Cap and White Glacier[7,8]) the model has a very low bias ($-18\,\mathrm{kg\,m^{-2}\,yr^{-1}}$) in the glacier-averaged surface mass budget (Supplementary Information). To be consistent with the other data sets presented in this study, we discuss only mass changes modelled over the ICESat and GRACE operational period between autumn 2003 and autumn 2009.

To recover mass changes from the GRACE measurements we use forward modelling of mass changes in predefined basins, minimizing the least-squares difference between GRACE observations and the forward model in an iterative method (Supplementary Information and refs 29 and 30). To avoid biases from surrounding areas (Supplementary Fig. 1) as a result of the limited spatial resolution and integral character of the GRACE observations, mass changes are modelled for the Greenland Ice Sheet and other areas surrounding the CAA. GRACE measurements were made available by the Center for Space Research (CSR version RL04) and were downloaded from http://podaac.jpl.nasa.gov/DATA_CATALOG/graceinfo.html.

More details about the data and methods can be found in the Supplementary Information.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions A.S.G. developed the study and wrote the paper. A.S.G, G.M. and B.W. all contributed equally to the analysis, using SMB+*D,* ICESat and GRACE, respectively. G.J.W. provided ice and basin outlines, model topography and created Fig. 1. The remaining authors provided *in situ* measurements. All authors discussed and commented on the manuscript at all stages.

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