Extreme melt on Canada's Arctic ice caps in the 21st century

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[1] Canada's Queen Elizabeth Islands contain ~14% of Earth's glacier and ice cap area. Snow accumulation on these glaciers is low and varies little from year to year. Changes in their surface mass balance are driven largely by changes in summer air temperatures, surface melting and runoff. Relative to 2000–2004, strong summer warming since 2005 (1.1 to 1.6°C at 700 hPa) has increased summer mean ice surface temperatures and melt season length on the major ice caps in this region by 0.8 to 2.2°C and 4.7 to 11.9 d respectively. 30–48% of the total mass lost from 4 monitored glaciers since 1963 has occurred since 2005. The mean rate of mass loss from these 4 glaciers between 2005 and 2009 (−493 kg m^{-2} a^{-1}) was nearly 5 times greater than the 1963–2004 average. In 2007 and 2008, it was 7 times greater (−698 kg m^{-2} a^{-1}). These changes are associated with a summer atmospheric circulation configuration that favors strong heat advection into the Queen Elizabeth Islands from the northwest Atlantic, where sea surface temperatures have been anomalously high. **Citation:** Sharp, M., D. O. Burgess, J. G. Cogley, M. Ecclestone, C. Labine, and G. J. Wolken (2011), Extreme melt on Canada's Arctic ice caps in the 21st century, *Geophys. Res. Lett.*, *38*, L11501, doi:10.1029/2011GL047381.

1. Introduction

[2] Wastage of glaciers, ice caps, and ice sheets is the major source of non-steric global sea-level rise. From 2003–2008, glaciers and ice caps accounted for 1.1 ± 0.24 mm a^{-1} of the 1.9 ± 0.1 mm a^{-1} sea level rise due to changes in ocean mass [*Meier et al.*, 2007; *Cazenave et al.*, 2009]. Monitoring glacier and ice cap mass changes thus remains critical to balancing the global sea level budget. Here we show that strong summer warming over Canada's Queen Elizabeth Islands (QEI; Figure 1) since 2005 has resulted in glacier mass balances that are almost five times more negative than the 1963–2004 mean.

[3] Glaciers covered ~104,000 km^2 of the QEI in 2000. Excluding the ice sheets, this is ~26% of the Arctic glacier area and ~14% of the global glacier area. In this region, annual precipitation is <400 mm a^{-1}, and the annual air temperature range is >40°C [*Braithwaite*, 2005]. Surface mass balance of four glaciers (Devon Ice Cap (1699 km^2, northwest sector only), Meighen Ice Cap (75 km^2), Melville South Ice Cap (52 km^2), and White Glacier, Axel Heiberg Island (39 km^2)) has been measured annually for about 50 years [*Cogley et al.*, 1996; *Koerner*, 2005] (Figure 1). Variability in annual mass balance arises largely from changes in summer balance. Winter balances show minimal variability and no trend over the period of record. Annual mass balances were mostly negative from 1960–2003, with a weak trend towards more negative balances over time [*Koerner*, 2005].

2. Summer Warming

[4] Air temperature measurements have been made at Resolute, Eureka and Alert (Figure 1) since the late 1940s. We focus on annual summer mean temperature records from Resolute and Eureka (Figure 2a), which are derived by averaging daily minimum and maximum air temperatures for June to August. These records are well correlated (r = 0.82). Following a warm period between the mid 1950s and early 1960s, mean summer temperatures cooled by 1–2°C to record minima in the late 1960s at Resolute and late 1970s at Eureka. They then increased by 1.0–1.5°C by the late 1990s, and by a further 1.0–1.5°C to a peak in the late 2000s that exceeds that of the 1950s and early 1960s. At Eureka, 2009, 2005, 2007 and 2008 were 4 of the 5 warmest summers since 1948, and 2005–2009 was the warmest pentad (mean 5.2°C). The warmest summer at Resolute was 2007 (4.5°C); 2005–2009 was the warmest pentad (3.4°C).

[5] Air temperature has been measured at automatic weather stations in the accumulation zones of the Agassiz Ice Cap (1736 m a.s.l.) since 1988 (with data gaps in 1993 and 1995) and Devon Ice Cap (1815 m a.s.l.) since 1997 (Figures 1 and 2a). Temperatures are measured once per minute with a Campbell Scientific Canada model 107F thermistor (accuracy ±0.4°C) housed in a Gill radiation shield maintained at 1.5 to 2 m above the glacier surface, and averaged to hourly or daily values. Measurements were not corrected for sensor height changes. Strong correlations exist between summer mean temperature records from Agassiz and Eureka (r = 0.90, slope = 1.1), and Devon and Resolute (r = 0.79, slope = 0.63). The warmest summers were 2008 (−3.3°C), followed by 2005, 2007 and 2009 at Agassiz, and 2001 (−4.2°C), followed by 2007, 1998, 2005, 2008 and 2009 on Devon. Mean summer temperatures for 2000–2004/2005–2009 (Agassiz, −5.5°C and −4.4°C; Devon −5.9°C and −5.0°C) show strong summer warming since 2005.

[6] Summer mean temperature anomalies (relative to 1948–2008) at 700 hPa geopotential height from the NCEP/NCAR R1 Reanalysis (NNR) [*Kalnay et al.*, 1996] were computed for seven major ice-covered regions: northern

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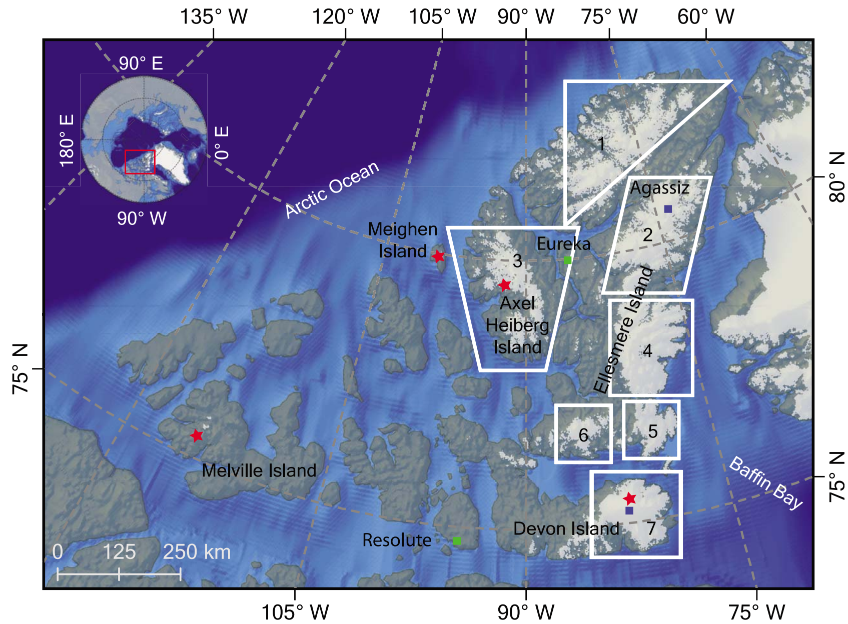

Figure 1. Map of the Queen Elizabeth Islands showing the locations of Environment Canada weather stations (Resolute and Eureka; green), on-ice automatic weather stations (Agassiz and Devon Ice Caps; blue), the four glaciers where annual surface mass balance is measured (Devon Ice Cap, Melville South Ice Cap, Meighen Ice Cap, and White Glacier; red), and seven major glaciated regions for which summer mean land surface and 700 hPa air temperatures were calculated.

Ellesmere Island, Agassiz Ice Cap, Axel Heiberg Island, Prince of Wales Icefield, Manson Icefield, Sydkap, and Devon Ice Cap (Figures 1 and 2b). Summer temperatures in the Agassiz/Devon regions correlate well with local on-ice air temperature records (Agassiz, 1988–2009, r = 0.96, slope = 0.93; Devon, 1997–2009, r = 0.93, slope = 0.87). 2005, 2007, and 2008 are among the ten warmest summers in all regions. 1955–1959 and 2005–2009 are the warmest pentads in the NNR records. Summer temperatures from 2005–2009 exceeded the period mean by 1.3–1.5°C in all regions.

[7] During the 1950s and 2000s, the summer Atlantic Multi-decadal Oscillation (AMO) index was predominantly positive [*Chylek et al.*, 2009], indicating anomalously warm sea surface temperatures in the Atlantic Ocean from 0–70°N [*Parker et al.*, 2007]. In summers after 2005, a region of anomalously high 700 hPa geopotential heights extended over much of Greenland, the QEI, and the Canada Basin. The associated anti-cyclonic atmospheric circulation anomaly favors transport of warm air from the northwest Atlantic into the Canadian Arctic via Baffin Bay, resulting in positive anomalies in summer mean 700 hPa temperature for 2005–2009 over western and northern Greenland, Baffin Island and the QEI [e.g., *Sharp and Wolken*, 2011].

3. Land Surface Temperature (LST)

[8] Measurements of glacier surface temperature provide direct evidence of changing melt conditions on glaciers. Higher summer mean surface temperatures indicate more prolonged and/or intense melt [*Hall et al.*, 2006]. We analyzed LST data from the MOD11A2 product (based on the MODIS (Moderate Resolution Imaging Spectroradiometer)/Terra LST dataset). Several ground-truthing and validation efforts over a widely distributed set of locations have found the accuracy of these data to be ±1° C [*Wan et al.*, 2002]. We used 8-day composites of daytime clear sky LST data on a global 1 km sinusoidal grid (MODIS subsetted land products, Collection 5 [*Oak Ridge National Laboratory Distributed Active Archive Center*, 2010]). Clear sky data are identified using a cloud mask [*Ackerman et al.*, 1998] that tends to map more clouds than actually exist over snow and ice [*Hall et al.*, 2006]. We averaged 1 km LST data for each 8-day period over 23 by 23 km pure snow/ice boxes centered on the interior regions of the largest ice masses in the seven major glaciated regions of the QEI (Figure 2c), and obtained annual mean summer LSTs for each box by averaging over the period June 2 to September 5 of each year (2000–2009). Mean surface elevations in each box ranged from 850 m (Manson Icefield) to 1868 m (Agassiz Ice Cap), and were >1400 m for five of the seven regions. Boxes cover the higher elevation regions of each ice mass, where LST only rarely reaches the melting point of ice, so the LST data can be used to assess whether or not the NNR data are a reliable indicator of air temperature trends across the QEI.

[9] Mean clear sky LSTs may underestimate true mean LSTs on glaciers because low clouds tend to be associated with warmer surface conditions [*Hall et al.*, 2006], and year-to-year variability in cloud cover may cause variability in measured LSTs that is unrelated to variability in measured air temperatures. To test for this, we correlated each LST record with each of the four station and seven NNR mean summer air temperature records. For each LST record, we obtained correlation coefficients >0.82 with at least one station record and >0.90 with at least one NNR record. This suggests that interannual variability in LST and local air temperatures are well coupled. Mean summer LSTs increased over time in all seven regions (Figure 2c), and were especially high in 2005, 2007, 2008 and 2009. The 2005–2009 mean summer LST exceeded that for 2000–2004 by between 0.8°C (Devon Ice Cap) and 2.2°C (Axel Heiberg Island). The highest LSTs were

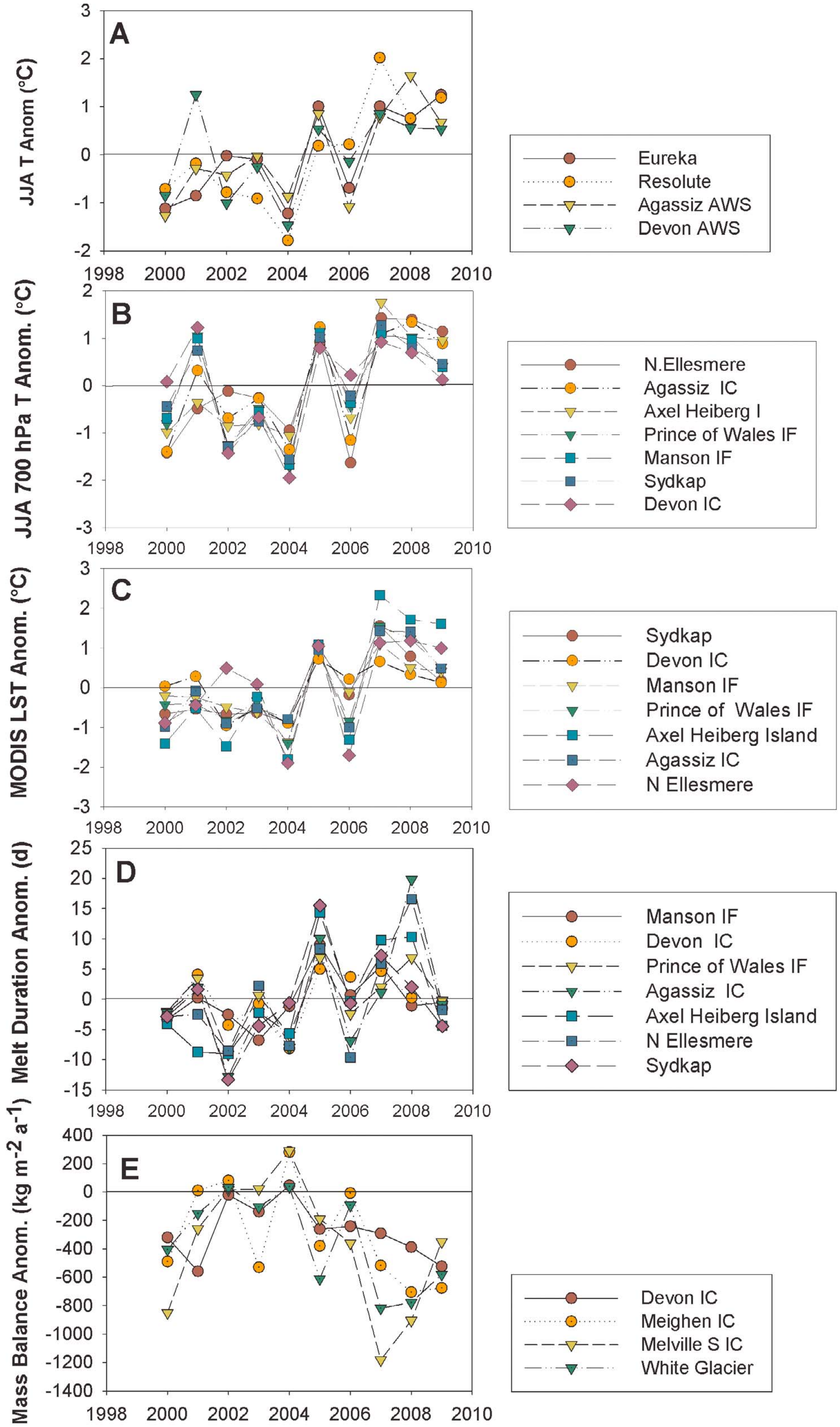

Figure 2. Annual anomalies (relative to the 2000–2009 mean) in (a) mean summer (June–August) air temperature at Resolute, Eureka, the Agassiz Ice Cap and the Devon Ice Cap; (b) mean summer 700 hPa air temperature over seven glaciated regions of the Canadian Arctic from the NCEP/NCAR R1 Reanalysis (see Figure 1); (c) mean summer MODIS land surface temperature in seven glaciated regions of the Canadian Arctic (see Figure 1); (d) summer melt duration for seven glaciated regions of the Canadian Arctic (see Figure 1); and (e) annual surface mass balance for Devon Ice Cap, Melville South Ice Cap, Meighen Ice Cap, and White Glacier.

recorded in 2005 in the southeast of the region (Devon Ice Cap, Manson Icefield, Sydkap), and in 2007 or 2008 in the north and west of the region.

4. Melt Season Duration

[10] Melt season duration is correlated with the annual positive degree-day total [*Wang et al.*, 2005], which is used to calculate summer melt amounts in temperature index mass balance models. Inter-annual variability in snow accumulation on QEI glaciers is minimal, so glacier ice (with a low albedo and high degree-day factor) is probably exposed for longer periods in their ablation zones during longer melt seasons. Both effects are likely to increase rates of mass loss from glaciers in longer melt seasons. *Wang et al.* [2005] used enhanced resolution (2.225 km^2 pixel spacing) Version 1 evening overpass data products from the Ku-band SeaWinds scatterometer on QuikSCAT [*Long and Hicks*, 2005] to monitor melt season duration in the seven major glaciated regions of the QEI from 2000–2004. The seasonal onset of surface melt is defined by the abrupt reduction in the normalized radar cross-section, σ^o, that occurs when liquid water first appears on the glacier surface. Return to winter conditions is marked by an increase in σ^o. Melt season duration was calculated as the number of days between the dates of melt onset and return to winter conditions, minus the duration of any within-summer periods of freezing conditions. The estimated uncertainty of the melt duration was 10.1 d [*Wang et al.*, 2005].

[11] We extended the melt season duration record to the end of QuikSCAT observations in 2009. Changes in the processing of raw QuikSCAT data in July 2006 led to a second version of the enhanced resolution products. As the two versions produce identical σ^o values for evening satellite overpasses in overlapping years throughout the study area, we used Version 1 data for 2000–2004 [*Wang et al.*, 2005] and Version 2 data for 2005–2009 [*Wolken et al.*, 2009]. We determined melt durations for each year for each glaciated cell in each region, and calculated annual mean melt durations for each region.

[12] Annual melt duration anomalies (relative to the 2000–2009 mean) were positive in five or more regions in 2001, 2005, 2007 and 2008 (Figure 2d). This is consistent with LST and air temperature data that show these summers were unusually warm. Anomalies were negative everywhere in 2000, 2002, 2004 and 2009, and in five regions in 2003 and 2006. Averaging across all regions, the longest melt seasons were 2005 and 2007 and the shortest were 2002 and 2004. The mean melt duration for 2005–2009 exceeded that for 2000–2004 in all regions. The magnitudes of the changes in melt duration, LST, and NNR 700 hPa mean summer temperature between 2000–2004 and 2005–2009 all increased from the southeast (+4.7 d, +0.8°C, +1.1°C on Devon Ice Cap) to the northwest of the region (+11.9 d, +2.2°C, +1.6°C on Axel Heiberg Island). Correlations between melt duration and NNR 700 hPa mean summer temperatures were statistically significant ($r > 0.7$, $p < 0.05$) for all glacierized regions except Manson Icefield, and always greater than correlations with the Resolute and Eureka records. For northern Ellesmere Island and Agassiz Ice Cap, melt duration was correlated more strongly with summer mean temperatures at the Agassiz ice cap automatic weather station ($r = 0.93$ and 0.85 respectively) than with the NNR data. There is a clear coupling between melt season duration and summer mean air temperatures over the QEI glaciers.

5. Glacier Mass Balance

[13] *Cogley et al.* [1996] and *Koerner and Lundgaard* [1995] described the glacier surface mass balance measurement methods used in the QEI. Uncertainties of annual surface balance estimates are ±~200 kg m^{-2} a^{-1} [*Kaser et al.*, 2006]. Mass balance records from Meighen Ice Cap and White Glacier are well correlated ($r = 0.73$). Correlation coefficients for all other pairs of records are <0.6, however, suggesting that Devon and Melville South Ice Caps are located in different climatic regimes from the other two glaciers. Correlations with Resolute and Eureka summer air temperatures are similar (−0.59 to −0.64) for all records except Melville South Ice Cap, which correlates more strongly ($r = -0.59$) with Resolute. Correlations between the Devon, Meighen and White Glacier records and NNR 700 hPa summer mean air temperature data are statistically significant at $p < 0.05$, and slightly stronger than those with station data (White and Meighen with the northern Ellesmere NNR region ($r = -0.67$ and −0.63 respectively), and Devon with the Devon, Manson, and Prince of Wales NNR regions ($r = -0.73$ to −0.74)). This confirms the relationship between mass balance and summer air temperatures noted by *Koerner* [2005]. Some mass balance records are significantly correlated with melt season duration ($p < 0.05$; Meighen Ice Cap with northern Ellesmere Island melt duration ($r = -0.78$); White Glacier with northern Ellesmere Island ($r = -0.83$), Axel Heiberg Island ($r = -0.80$), and Agassiz Ice Cap ($r = -0.77$) melt durations).

[14] *Koerner* [2005] described trends in surface mass balance up to 2003. 2004 is the only positive balance year since 2003 (Figure 2e). Averaging the data for the 4 glaciers, without weighting by their areas, 2007 is the most negative balance year on record (−702 kg m^{-2} a^{-1}), followed by 2008 (−694 kg m^{-2} a^{-1}) and 2009 (−533 kg m^{-2} a^{-1}). 2005 is ranked 7th (−361 kg m^{-2} a^{-1}) and 2006 17th (−175 kg m^{-2} a^{-1}). The 2005-2009 pentad had the most negative balances since 1960 for all four glaciers. The change in mean annual mass balance between 2000–2004 and 2005–2009 ranged from −143 kg m^{-2} a^{-1} on Devon Ice Cap to −457 kg m^{-2} a^{-1} on White Glacier. This suggests a south-east to north-west increase in the magnitude of mass balance changes between the first and second pentads of the 2000s that is consistent with observed patterns of change in mean summer 700 hPa temperature, LST, and melt season duration.

[15] Between 38% (Melville) and 58% (Devon) of the mass loss from the four glaciers since 1963 occurred between 2000 and 2009. Between 30% (Melville) and 48% (Meighen) occurred between 2005 and 2009. The mean surface mass balance for 2005–2009 was more negative than the 1960–2009 mean by between 235 (Devon Ice Cap) and 402 kg m^{-2} a^{-1} (White Glacier).

[16] New geodetically-based estimates of the regional mass balance of glaciers and ice caps in the QEI [*Gardner et al.*, 2011] confirm the broader significance of the changes described here. These authors report measurements with the Geoscience Laser Altimeter on ICESat that yield a mean mass loss rate of −37 ± 7 Gt a^{-1} for the period 2004–2009, with significantly higher losses (−56.3 Gt a^{-1}) in the period 2007–2009 than in the period 2004–2006 (−17.6 Gt a^{-1}).

Measurements with the GRACE satellites give estimates of -39 ± 9 Gt a^{-1} for 2004–2009, -9.3 Gt a^{-1} for 2004–2006, and -69 Gt a^{-1} for 2007–2009. By way of comparison, the only previous regional mass balance assessment for the QEI, which was based on airborne laser altimetry measurements made in 1995 and 2000, gave a value of -12.6 Gt a^{-1}, with no reported uncertainty [*Abdalati et al.*, 2004].

6. Conclusions

[17] Strong summer warming has occurred over the QEI in the 21st century. Mean summer air temperatures since 2005 have been higher than at any previous time in the last 60 years. Summer warming is linked with an atmospheric circulation anomaly that favors heat transport from the northwest Atlantic, where sea surface temperatures have been anomalously high, into western Greenland and the QEI. The recent succession of warm summers has resulted in higher surface temperatures on glaciers and ice caps, longer melt seasons, and a sharp decrease in glacier surface mass balances. 30–48% of the mass loss from monitored glaciers since 1963 post-dates 2005.

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