

Multidecadal Recession of Grinnell and Terra Nivea Ice Caps, Baffin Island, Canada

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ABSTRACT. Multi-temporal satellite imagery and historical aerial photography reveal that two southern Arctic ice caps on Baffin Island have shrunk considerably over the past several decades. Satellite remote sensing shows that over the past three decades, the Grinnell and Terra Nivea ice caps, the southernmost ice caps in the eastern Canadian Arctic, have decreased in area by 18% and 22% respectively, which corresponds to a total area decline of 68 km² since mapping done in the late 1950s. Cumulative ice loss since the mid-1970s has occurred at a rate of -1.69 km²/yr. The Grinnell ice cap has declined in area by -0.57 km²/yr, while the larger Terra Nivea ice cap has lost ice at a rate of -1.1 km²/yr. Interior thinning has led to the exposure of nunataks far from ice margins, and outlet glaciers have retreated substantial distances up-valley. The rapid reduction in ice area is linked directly to increasing summer air temperatures and suggests that these ice caps are in disequilibrium with recent climate conditions. Projections suggest that if the observed ice decline continues to AD 2100, the total area covered by ice at present will be reduced by more than 57%.

Key words: glaciology; glacier change; climate; Grinnell and Terra Nivea ice caps; Baffin Island

RÉSUMÉ. L'imagerie satellitaire multitemporelle et la photographie aérienne historique révèlent que deux calottes glaciaires du sud de l'Arctique, dans l'île de Baffin, ont rétréci considérablement au cours des dernières décennies. La télédétection par satellite montre qu'au cours des trois dernières décennies, l'étendue des calottes glaciaires Grinnell et Terra Nivea, soit les calottes glaciaires les plus au sud de l'Arctique canadien de l'est, a diminué dans une mesure de 18 % et de 22 % respectivement, ce qui correspond à un déclin total de l'étendue de 68 km² depuis que la cartographie a été effectuée vers la fin des années 1950. Depuis le milieu des années 1970, la perte cumulative de glace s'est produite au taux de $-1,69$ km²/an. L'étendue de la calotte glaciaire Grinnell a diminué de $-0,57$ km²/an, tandis que la calotte glaciaire Terra Nivea, dont l'étendue est plus grande, a enregistré une perte de glace de l'ordre de $-1,1$ km²/an. L'amincissement intérieur a donné lieu à l'exposition de nunataks loin des marges glaciaires, et les glaciers émissaires ont reculé sur d'importantes distances en amont de la vallée. La réduction rapide de l'étendue de la glace est directement liée à l'augmentation de la température de l'air d'été, ce qui suggère que ces calottes glaciaires sont en déséquilibre par rapport aux conditions climatiques récentes. Selon les projections, si la réduction observée de la glace se poursuit jusqu'en l'an 2100 A.D., l'étendue totale actuellement couverte par la glace diminuera de plus de 57 %.

Mots clés : glaciologie; changement glaciaire; climat; calottes glaciaires Grinnell et Terra Nivea; île de Baffin

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INTRODUCTION

Over the past century, there has been a near-global retreat of glaciers and ice caps, with ice losses and melt rates increasing in most regions during the last few decades (IPCC, 2013). In the Canadian Arctic, ice losses and melt rates have begun to exceed those recorded over the past several millennia (Anderson et al., 2008; Fisher et al., 2012; Zdanowicz et al., 2012), and some ice caps have receded beyond limits reached during the early Holocene, when insolation was higher (Miller et al., 2013). Evaluating reductions of ice volume in this region has become increasingly important for identifying the various regional contributions to eustatic sea level rise—particularly over the past decade, during which Canadian Arctic contributions have nearly doubled (Gardner et al., 2012). In contrast to the situation in

Greenland and Svalbard, the largest contributing factor to glacier mass/volume changes in the Canadian Arctic is negative surface mass balance rather than outlet glacier calving (Koerner, 2005; Gardner and Sharp, 2007; Sharp et al., 2011; Lenaerts et al., 2013; Van Wychen et al., 2014). The link between ice cap recession and changes in climate is therefore much clearer in this region than for mountain glaciers, the mass balance of which can be strongly influenced by local microclimate and topographic setting (e.g., DeBeer and Sharp, 2009). The recent decline in the area and volume of the Canadian Arctic ice cap has therefore been attributed to the rapid warming in summer observed since 1987 (Gardner et al., 2011).

Despite considerable efforts to document and monitor ice cap changes in the western, central, and northern Canadian Arctic, glacier change studies in the eastern Canadian

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TABLE 1. General characteristics of satellite images used in this study.

Date	Sensor ¹	Cell size (m)	Data type	Bands
1973.08.15	Landsat 1 MSS	60	Digital Number	4
1974.08.08	Landsat 1 MSS	60	Digital Number	4
1975.08.15	Landsat 1 MSS	60	Digital Number	4
1984.08.11	Landsat 5 TM	30	Surface Reflectance	7
1985.08.21	Landsat 5 TM	30	Surface Reflectance	7
1993.08.11	Landsat 5 TM	30	Surface Reflectance	7
1995.08.10	Landsat 5 TM	30	Surface Reflectance	7
2002.08.12	Landsat 7 ETM Plus	30 (15 pan)	Surface Reflectance	8
2003.08.16	Landsat 5 TM	30	Surface Reflectance	7
2010.09.11	Landsat 5 TM	30	Surface Reflectance	7
2013.09.03	Landsat 8 OLI	30 (15 pan)	Digital Number	8

¹ MSS = Multispectral Scanner, ETM = Enhanced Thematic Mapper, TM = Thematic Mapper, OLI = Operational Land Imager.

Arctic have been limited in spatial and temporal scope. Using satellite data, Gardner et al. (2012) described substantial thinning of glaciers and ice caps on Bylot and Baffin Islands at the regional scale, while local studies have described glacier recession on Bylot Island (Dowdeswell et al., 2007) and eastern Baffin Island (Paul and Kääb, 2005; Paul and Svoboda, 2010) over the past 50 years. Previous work on Baffin Island has particularly focused on the Barnes and Penny ice caps (Sharp et al., 2014) and glaciers around the Cumberland Peninsula (Paul and Kääb, 2005; Paul and Svoboda, 2010). However, the southernmost limits of glacierization in the eastern Canadian Arctic on Baffin Island and in Labrador have not been studied to the same extent as those larger ice caps. This southernmost region contains small mountain glaciers that are rapidly shrinking (Torngat Mountains, Labrador) (Brown et al., 2012; Way et al., 2014) and two small ice caps and numerous glaciers at the southern tip of Baffin Island (Mercer, 1956). Grinnell and Terra Nivea, on Meta Incognita Peninsula, are therefore the southernmost ice caps in the Canadian Arctic. Yet although they are located only ~200 km from a large community (Iqaluit, Nunavut), they have not been comprehensively studied via in situ measurements (Sharp et al., 2014). Both ice caps are positioned on a large coastal plateau at the southern limit of glacierization in the Canadian Arctic archipelago (Fig. 1). Thus, they provide the means to monitor the impacts of climate change on the terrestrial cryosphere in this region (e.g., Bell and Jacobs, 1996). Furthermore, these ice caps have very little debris cover and are subject to minimal topographic shadowing, which makes them well suited for multi-temporal change assessment using moderate-resolution satellite imagery, such as that obtained by the Landsat series of sensors.

This study aims to assess changes in the area of the Grinnell and Terra Nivea ice caps over the past 50 years and to provide insight into the main drivers of recent ice cap changes. Area changes are calculated at a multi-decadal timescale using satellite remote sensing in conjunction with historical data from Canada's National Glacier Atlas (Ommanney, 1980). A particular focus is placed on evaluating ice cap changes over the past decade, a period

during which the eastern Canadian Arctic has experienced rapid regional warming (Comiso and Hall, 2014; Cowtan and Way, 2014a). Results are compared with regional meteorological data to assess the relationship between ice area changes and observed variations in summer air temperature and to evaluate glacier sensitivity to future climate change. This contribution explores the impacts of climate change on the terrestrial cryosphere in an otherwise understudied region and is useful for assessing local ecosystem impacts that could not be evaluated from previous large-scale regional studies.

DATA AND METHODS

Ice cap outlines were derived from both satellite imagery and existing historical databases (see Ommanney, 1980) using ESRI ArcGIS 10™. A digital elevation model prepared by the Canada Centre for Mapping and Earth Observation was used to evaluate positions of glacier termini and to visualize satellite imagery in 3D with ESRI ArcScene™. This model (from the Canadian Digital Elevation Dataset [CDED]) was created from stereo photogrammetry of 1959 aerial photography and has a vertical accuracy of ± 9 m and a horizontal accuracy of ± 10 m. Historical ice cap outlines were acquired from the National Topographic Database developed by Natural Resources Canada's Centre for Topographic Information. These outlines were derived from 1958 aerial photography at a 1:250 000 scale and correspond to the same 1958 area values for each ice cap provided by Ommanney (1980) and Sharp et al. (2014).

A total of 11 clear-sky satellite images were acquired by the Landsat series of sensors over the time period 1973–2013 (Table 1). Remotely sensed imagery was acquired in Geotiff format through the United States Geological Survey's Earth Explorer interface. Seven of these images were provided as atmospherically corrected surface reflectance values, and the remaining four were provided as stretched digital numbers without atmospheric correction. Imagery was already georeferenced except imagery from 1973, which was co-registered to 1975 imagery from the same sensor (Landsat 1). Comparisons between

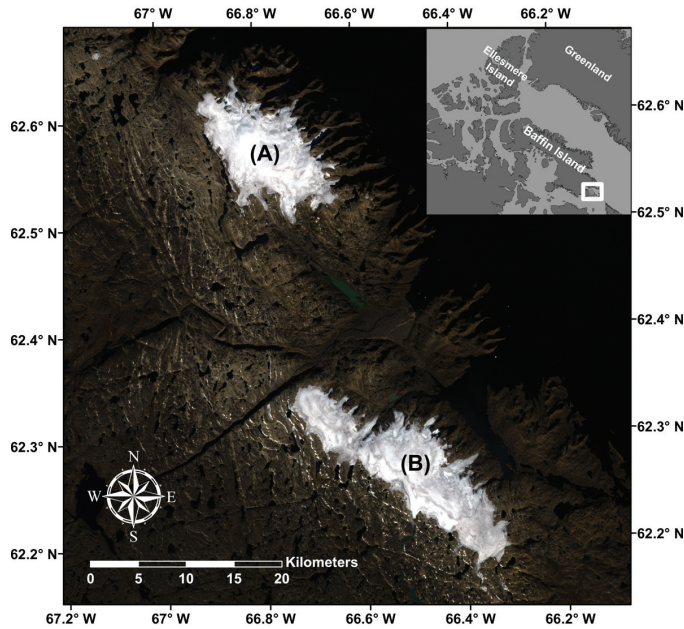


FIG. 1. Satellite image of Grinnell (A) and Terra Nivea (B) ice caps. Satellite image is a late-summer (11 September 2010) true colour composite from Landsat 5 Thematic Mapper.

images and topographic base maps (± 20 m) from the Canadian National Topographic Database show that the original image georeferencing was accurate within one pixel (Landsat TM/ETM/OLI: < 30 m, MSS: < 80 m). Images were clipped and composited in PCI Geomatica™ to cover a smaller area, and principal component analysis (PCA) was performed on each image's bands (e.g., four bands for Landsat 1, seven bands for Landsat 5, 7, and 8) to reduce the dimensionality of the input images while retaining most of their spectral information (e.g., Pope and Rees, 2014). The first three principal components (PCs) accounted for more than 97% of the variance in the input data, and the first PC typically accounted for less than 90% of the total variance.

The first three PCs were extracted and classified using maximum likelihood supervised classification (e.g., Wolken, 2006) from 375 manually collected training areas separating the image into five major classes: bare ground, ice, lake, ocean, and vegetation (75 per class). Each individual training site covered an area of 0.023 km² or ~ 25 pixels, and the cumulative training area for each image was 6.9 km². False and true colour composites were used in conjunction with the first three PCs to visualize and inform ice cap delineation. To guide the delimitation of ice margins, satellite images were draped over the CDED digital elevation model. Misclassified pixels (typically associated with lake ice and seasonal snow cover) were manually corrected using on-screen digitization (e.g., Käab, 2005; Pellikka and Rees, 2009). Manual correction of images was required in areas of poor spectral contrast (typically debris-covered or shadowed portions of outlet glaciers or glacier-fed lakes adjacent to ice margins) (Paul et al., 2013). On some images, late-lying seasonal snow cover made estimating glacier area problematic; therefore, in order to reduce the uncertainties

associated with calculated area changes, decadal, rather than interannual, estimates of change were determined. Pairs of images from two consecutive years in each decade were used to estimate ice area, and the estimate for each decade was taken as the mean of the areas (ice cap outlines) derived from those two images. The upper and lower uncertainty bounds were taken to be the greater and lesser estimates of ice area, respectively. Because the early 1970s Landsat 1 images have lower spatial and spectral resolution, it is possible that some peripheral seasonal snow cover may have been misclassified as glacier ice. However, according to Global Land Ice Measurements from Space (GLIMS) glacier classification protocols, perennial ice masses connecting to the main glacier body should be included within ice margins (Raup and Khalsa, 2010). Therefore, the early 1970s ice area estimates were based on the classification of the 1975 image (least peripheral snow cover) followed by the manual assessment of three late-season images (from 1973, 1974, and 1975) to ensure that classified ice was perennial rather than seasonal (e.g., Paul et al., 2010).

Historical daily land-only temperature data were acquired for the region (62° – 63° N, 66° – 67° W) from the Berkeley Earth Surface Temperature (BEST) Project's gridded (1°) average temperature product (e.g., Rohde et al., 2013a, b). Data were acquired as temperature anomalies, and daily baseline climatological values corresponding to 1951–80 average values were added to the anomalies to produce absolute monthly air temperatures over the period 1900–2013. The analysis here is restricted to April to September (the months during which positive temperatures are typically observed to occur). The BEST data were preferred over other data sources such as Environment Canada's homogenized station network (Vincent et al., 2012) because of their long record, high spatial and temporal resolution, and automated homogeneity adjustments (see Rohde et al., 2013a). The BEST data compare favorably with the reanalysis datasets that are most accurate in remote Arctic regions (e.g., ERA-Interim, Merra) (Screen et al., 2012; Lindsay et al., 2014; Simmons and Poli, in press) and have been shown by Cowtan and Way (2014b) and Way and Viau (in press) to be reliable when compared to local air temperature data acquired from high-latitude climate stations. To evaluate changes in regional snowfall, we used quality-controlled gridded (1°) cold-season precipitation reanalysis data for the region obtained from the Global Precipitation Climatology Centre (Becker et al., 2013).

RESULTS

Glacier Area Changes

Area estimates derived from satellite imagery ranged from 199.14 km² (1975) to 153.44 km² (2013) for the Terra Nivea ice cap and from 134.29 km² (1975) to 109.14 km² (2013) for the Grinnell ice cap (Fig. 2). The additional ice and perennial snow area (beyond the ice caps) in the region

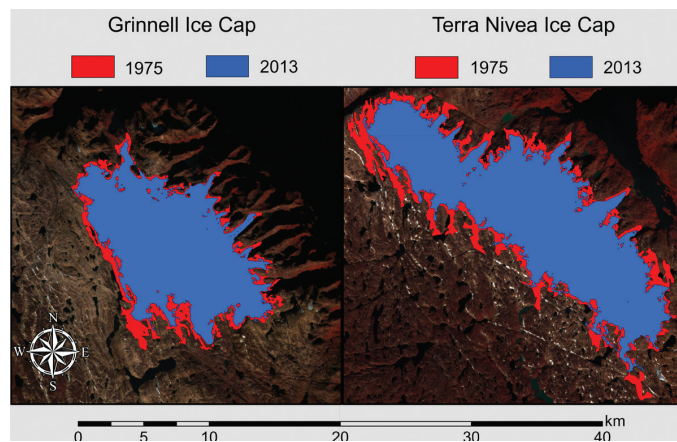


FIG. 2. Multi-temporal ice cap outlines for Grinnell (left) and Terra Nivea (right) corresponding to 1975 (red) and 2013 (blue).

ranged from 44.95 km² (2002) to 8.91 km² (1995), with a median of 17.14 km². On multidecadal timescales, both ice caps retreated in each time interval considered, with an overall area decrease of ~21% over the whole period (Fig. 3). The decadal estimates for the Terra Nivea ice cap area ranged from 199.14 km² (1975) to 154.76 ± 1.32 km² (2010–13), indicating a decline in ice area of 22% over the past four decades. For Grinnell, the corresponding decline in ice area was 18%, from 134.29 km² in 1975 to 110.04 ± 0.90 km² in 2010–13 (Table 2). The surrounding snow-covered area showed greater multidecadal change (~36%) and more inter-decadal variability than the ice cap area because some years had anomalously low or high snow cover and because ice cap recession left remnant peripheral ice masses in some areas.

During the period of satellite record, the mean rate of ice loss for both ice caps combined was -1.69 km²/yr. However, the Terra Nivea ice cap shrank at a faster rate (-1.1 km²/yr) than the smaller Grinnell ice cap (-0.57 km²/yr) (Fig. 3, Table 2). For both ice caps, area changes occurred along all margins, with the greatest changes observed along the northwestern margin for Terra Nivea and in the southwest for Grinnell (Fig. 2). Although this study does not explicitly examine glacier elevation changes, the lowermost outlet glacier termini of Grinnell and Terra Nivea ice caps changed by +100 m and +80 m, respectively, over the study period. For Grinnell, these changes reflect the transition of two outlet glacier termini from tidewater-terminating to land-terminating, while for Terra Nivea this change follows the recession of outlets to higher elevations (Fig. 4). The largest relative area changes found in the entire record from the two ice caps occurred over the past decade (2002 to 2013), when Grinnell lost 9.5 km² of ice and Terra Nivea lost 15 km².

Ice cap outlines derived from historical aerial photography contained in Canada's Glacier Atlas (Ommanney, 1980) and obtained by E.K. Dowdeswell extend the record back to 1958 (Sharp et al., 2014). These data show negligible changes (> 5 km²) in total ice cap area from 1958 to 1975, when the satellite record began (Fig. 3).

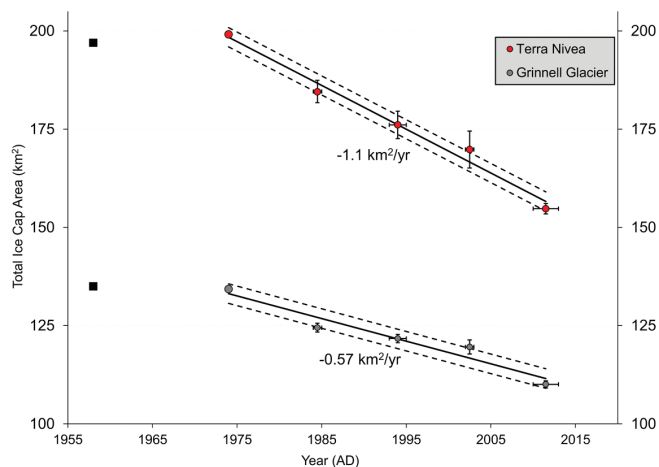


FIG. 3. Time series of multi-decadal area changes from satellite remote sensing for Terra Nivea (red dots) and Grinnell (grey dots). Ice cap areas derived from historical aerial photography (Ommanney, 1980; Sharp et al., 2014) are shown as black squares. Dotted lines depict 95% confidence intervals.

Historical and Recent Climate Change

The long instrumental record of mean summer air temperatures for this region (Rohde et al., 2013a, b) shows an overall warming of ~1.5°C from 1900 to 2013 (Fig. 5A). The historical record of mean summer air temperatures is also characterized by alternating cold periods (1910–30, 1940–50) and warm periods (1930–40, 1950–60) from the late 19th century to the 1970s, followed by an abrupt warming of ~1.5°C over the past three decades. Average daily maximum summer air temperature shows greater warming over the past century (0.4°C/decade) than daily minimum air temperature (0.1°C/decade) (Fig. 5A). In the past 10 years (in contrast to the 20th century), average maximum air temperature has commonly exceeded 10°C. According to the BEST data, the number of days during the melt season (April–September) with average air temperatures above 1°C has not changed substantially over the past century; however, there are clear positive trends towards an increase in the frequency of average air temperatures exceeding 5°C and 10°C (Fig. 5B). As a result, the ratio between warm season thawing and freezing degree-days has approximately doubled from a 20th century average of ~0.90 to ~1.75 over the past decade (Fig. 5C).

In the last decade, air temperatures have increased in all warm-season months (those with temperatures above 0°C). The largest increase has occurred in July, and the smallest in June (although until recently September was the coldest “warm” month). These data suggest that melt season peak intensity and duration have substantially increased, as was similarly observed on the Barnes ice cap from satellite observations (Dupont et al., 2012). In contrast with the large changes observed in summer air temperatures from the 1950s to present, winter precipitation reanalysis data show no monotonic positive or negative trend over the same period (Fig. 5D). Although the nearest meteorological

TABLE 2. Decadal-scale ice area estimates for Terra Nivea and Grinnell ice caps and surrounding regions.

Decade	Terra Nivea	Grinnell	Ice/Snow
1973–75	199.14 km ²	134.29 km ²	N/A
1984–85	184.59 ± 2.97 km ²	124.46 ± 1.52 km ²	24.76 ± 7.45 km ²
1993–95	176.08 ± 3.49 km ²	121.71 ± 1.07 km ²	18.53 ± 9.62 km ²
2002–03	169.83 ± 4.69 km ²	119.55 ± 1.80 km ²	27.31 ± 17.64 km ²
2010–13	154.76 ± 7.45 km ²	110.04 ± 0.90 km ²	15.84 ± 1.14 km ²
Total Change	22.29%	18.06%	36.01%

station is more than 200 km away (in Iqaluit, Nunavut), the regional trends in winter snowfall recorded by Environment Canada across the eastern Canadian Arctic are in agreement with the reanalysis data used in this study, indicating no trend in winter precipitation (Zhang et al., 2011; Sharp et al., 2014).

DISCUSSION AND SUMMARY

Over the past 50 years, the Grinnell and Terra Nivea ice caps have undergone greater proportional reductions in ice area (~21%) than many other glaciers and ice caps in the Canadian Arctic (e.g., Sharp et al., 2014). For example, on Bylot Island, glaciers lost 5.1% of their area between ~1960 and ~2000, while to the northeast of this study's location on Baffin Island, Barnes and Penny ice caps lost only ~2% of their area over the same period (Dowdeswell et al., 2007; Sharp et al., 2014). Similarly, glaciers in the Queen Elizabeth Islands lost on average ~2.7% of their area between ~1960 and ~2000. This average includes the Devon ice cap, which lost ~2.4% of its area (Burgess and Sharp, 2004; Sharp et al., 2014). The glaciers nearest to the ice caps studied, on Cumberland Peninsula to the northeast, lost a total of 12.5% of their area between ~1920 and 2000 (Paul and Kääb, 2005; Paul and Svoboda, 2010; Svoboda and Paul, 2010). While the ice losses from the Grinnell and Terra Nivea ice caps reported in this study are higher than those for larger High Arctic ice caps, they are lower than losses from small plateau ice caps on northern Baffin Island (~55% from 1958 to 2005) reported by Anderson et al. (2008). It is possible that the coastal location of both ice caps may have had moderating impacts on regional melt rates through fog and low-level clouds, which are prevalent in the coastal Arctic during summertime (Mercer, 1956; Maxwell, 1981; Jiskoot et al., 2012). However, the overall results of this study indicate that small low-Arctic plateau ice caps have displayed greater sensitivity to recent climate change, as shown in loss of ice area since the 1950s, than many other Canadian Arctic glaciers and ice caps.

Decades of monitoring ice retreat rates have shown that summer air temperature rather than winter precipitation is the primary control on the mass balance of most ice caps in the Canadian Arctic (Koerner, 2005). Mercer (1956) previously suggested that the Grinnell and Terra Nivea ice caps would be particularly sensitive to changes in summer air temperature (as opposed to winter precipitation)

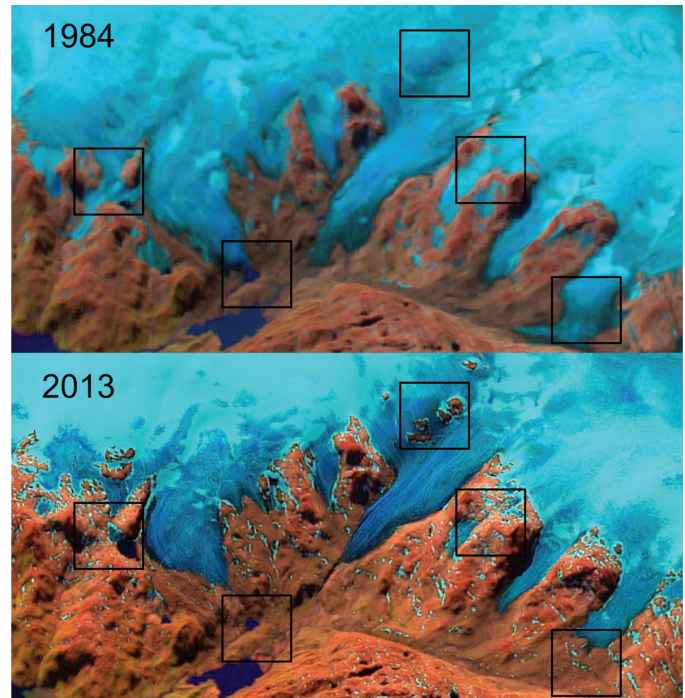


FIG. 4. Three-dimensional oblique of Terra Nivea's northeastern ice margins for 1984 (top panel) and 2013 (bottom panel). Obliques were derived by draping 7-4-2 false colour composite satellite images over a digital elevation model. Areas of significant ice decline are delimited by black rectangles.

because of their geographic location and relatively thin ice cover. The historical air temperature record for the region supports the ice area histories reported in this study and the interpretations of Mercer (1956) and Koerner (2005). Qualitatively, the records of summer air temperature and ice cap area show agreement in that the relative stability in air temperatures between 1958 and 1973–75 is consistent with the negligible changes in the area of both ice caps over the same period. Similarly, the near-linear increase in summer air temperature in the four decades since the 1970s is clearly reflected in the ice area records, which show a rapid linear decrease in ice area over that time period (e.g., Figs. 3, 5A). Analysis of daily air temperature changes presented in this study suggests that the increased frequency of warm (> 5°C) and very warm (> 10°C) days has substantially increased melt season intensity, particularly over the past decade. The suspected cause of the recent regional warming is above-average sea surface temperatures in the North Atlantic coupled with changes in the position and strength of the July circumpolar vortex and reductions in local albedo (Gardner and Sharp, 2007; Wolken et al., 2008; Screen et al., 2012; Sharp et al., 2014). Direct observations of surface thinning at high elevations and the recent emergence of nunataks in the interior of both ice caps indicate that large parts of these ice caps are in disequilibrium with current air temperatures (Fig. 4). Furthermore, the lack of identifiable trends in regional cold-season precipitation data over the study period suggests that changes in snowfall are not a major driver of recent decline in ice area (Fig. 5D).

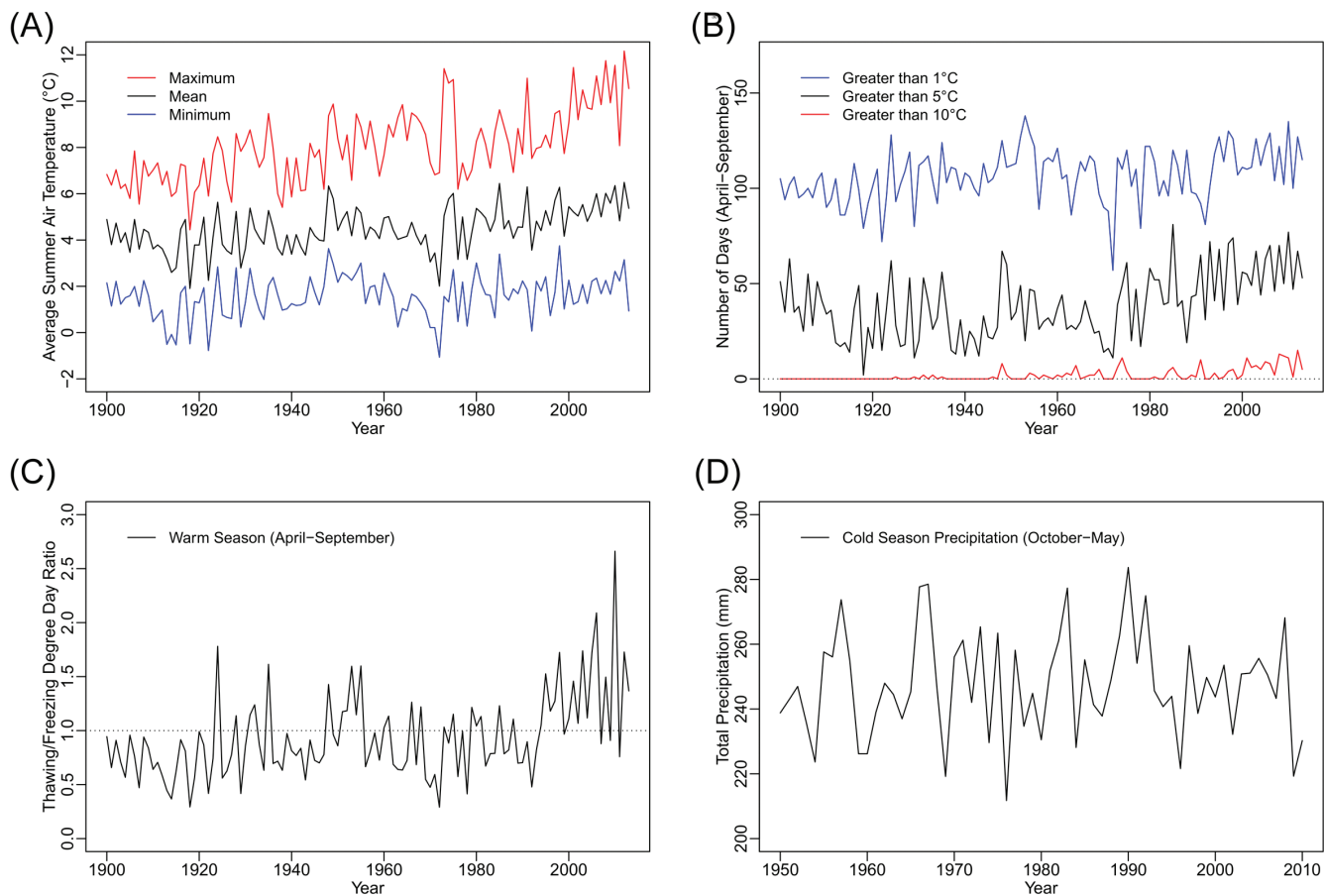


FIG. 5. (A) Minimum (blue line), mean (black line) and maximum (red line) average summer air temperatures, 1900–2013; (B) Cumulative number of warm season (April–September) days with average temperatures exceeding 1°C (blue line), 5°C (black line) and 10°C (red line), 1900–2013; (C) Warm-season (April–September) thawing/freezing degree-days ratios, 1900–2013; (D) Total cold-season precipitation (October–May), 1950–2010.

On the basis of ground photography taken by Porter (1898), Mercer (1956) described some thinning of Boas Glacier, a large north-facing tidewater outlet of the Grinnell ice cap, over the preceding 50 years. The observed increase in summer air temperatures over the past century is consistent with this observation and suggests that these ice caps have been decreasing in area since reaching their maximum extents during the Little Ice Age in the late 1800s (Muller, 1980; Dowdeswell, 1984). Mercer also noted that many of Grinnell's outlets were tidewater glaciers, whereas in recent years, only one east-facing outlet has reached tidewater. An interesting observation is that Grinnell and Terra Nivea, although they have similar elevations and geographic settings, have shown contrasting degrees of ice retreat (Fig. 3). The primary cause of these differential ice loss rates is not investigated in this study, but they could be linked to differences in ice cap hypsometry and thickness or to local meteorological conditions such as coastal fog.

The results of this study suggest that if the rate of ice losses observed over the past four decades were to continue until AD 2100, total ice area relative to 2010–13 would reduce by 57%; Grinnell would lose 46% of its ice area, while Terra Nivea would lose 62%. Enhanced regional warming and changes in ice cap thickness and hypsometry

would likely increase these rates of decline although projections of changes in regional precipitation could potentially offset some future ice losses (Lenaerts et al., 2013). Therefore, in order to partition the regional ice volume contributions to global sea level rise, improved monitoring of the numerous small ice caps in the Canadian Arctic should be a priority.

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