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Sustained rapid shrinkage of Yukon glaciers since the 1957–1958 International Geophysical Year

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[1] Glaciers in the Yukon, NW Canada, lost 22% of their surface area during the 50 years following the 1957–58 International Geophysical Year, coincident with increases in average winter and summer air temperatures and decreases in winter precipitation. Scaling these results to ice volume change, we obtain a total mass loss of 406 ± 177 Gt, which accounts for 1.13 ± 0.49 mm of global sea-level rise. Yukon glaciers thinned by 0.78 ± 0.34 m yr^{-1} water equivalent, a regional thinning rate exceeded only by mountain glaciers in Patagonia and Alaska. Our scaling analysis suggests the remaining glaciers have the capacity to contribute a further 5.04 mm to global sea-level rise.
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1. Introduction

[2] The response of glaciers and ice caps (GIC) to climate change is an issue of significant public and scientific concern because of its implications for global sea-level rise (SLR). In addition to ocean thermal expansion, the present day sea-level budget attributes ~half of observed SLR to the ice sheets and ~half to mass losses from GIC [*Cazenave et al.*, 2009]. The GIC contribution to SLR has accelerated over the past decade [*Meier et al.*, 2007], yet the errors associated with estimates of this contribution are often large. Reducing them requires comprehensive studies of regional-scale glacier changes, particularly from undersampled areas that have experienced substantial climate change in recent decades.

[3] Although ~10,000 km^2 of the Yukon, NW Canada, is glacier covered (Figure 1), very little is known about the health of these glaciers due to an absence of field measurements and the difficulty of estimating regional-scale volume changes. NW North America has experienced significant climate change over the past half century, with increases in average winter (October-April, 2.0 ± 0.8°C) and summer (May-September, 1.0 ± 0.4°C) air temperatures and a small increase in precipitation (albeit significant at just 17% of sites) recorded at 67 National Oceanic and Atmospheric Administration (NOAA) and Environment Canada weather stations [*Arendt et al.*, 2009]. Of these stations, the 14 located within the Yukon record similar summer warming (0.99°C), yet a reduction in winter precipitation (on average, −22 mm). Regional climate warming, reduction in winter precipitation and increases in freezing level heights (FLHs) [*Arendt et al.*, 2009] suggest that both the maritime (St. Elias (Figure 1b)) and interior (Mackenzie (Figure 1c)) glacier populations of the Yukon may have experienced large losses during the past 50 years.

[4] Existing measurements of glacier mass loss from the St. Elias mountains are limited either spatially (extrapolation of centreline thinning rates from just three sites, of which only one, Kaskawulsh glacier, is located entirely within the Yukon [*Arendt et al.*, 2002]) or temporally (GRACE satellite gravity solutions from 2003–2007 [*Luthcke et al.*, 2008]). The latter study estimated thinning rates of 0.63 ± 0.09 m yr^{-1} water equivalent (w.e.) during this recent time period. No study to date has measured regional glacier changes in the Mackenzie mountains. Here we present the first comprehensive multi-decadal assessment of Yukon glacier changes (including both St Elias and Mackenzie glacier populations) and their associated contribution to SLR, and evaluate the potential SLR contribution from the remaining glaciers.

2. Methods

2.1. Study Area and Data Sources

[5] We investigated area changes of all 1396 glaciers in the Yukon during the half century between the first International Geophysical Year (IGY1, 1957–58) and the third International Polar Year (IPY3, 2007–09). Our study area comprises the regions between 60–62°N, 135–141°W (St. Elias mountains), and 63–65°N, 130–133°W (Mackenzie mountains) (Figure 1). We delineated glacier boundaries from 802 individual 1:50,000-scale aerial photographs covering every glacier in the Yukon from late summer 1958–60 acquisitions by the Canadian Land Survey, and from 11 Landsat-7 Enhanced Thematic Mapper (ETM+) satellite images acquired in summers 2006–08. Aerial photography prints were digitally scanned at 500 dpi (~2 m ground resolution) and spatially referenced to the orthorectified satellite imagery using >5 ground control points per photograph.

2.2. Derivation of Area Changes

[6] Glacier margins were manually digitized as polygon shapefiles (surface area = margin minus bedrock, nunataks). Glaciers flowing from drainage divides were digitized separately based on ice-surface contours from Canadian National Topographic Series (NTS) digital maps. Margins of debris-covered glaciers were delineated using map contours and visual interpretation. Polygons were delineated in historical aerial photographs, overlaid onto contemporary satellite imagery and edited where change had occurred. Margins were edited only where change was clearly evident,

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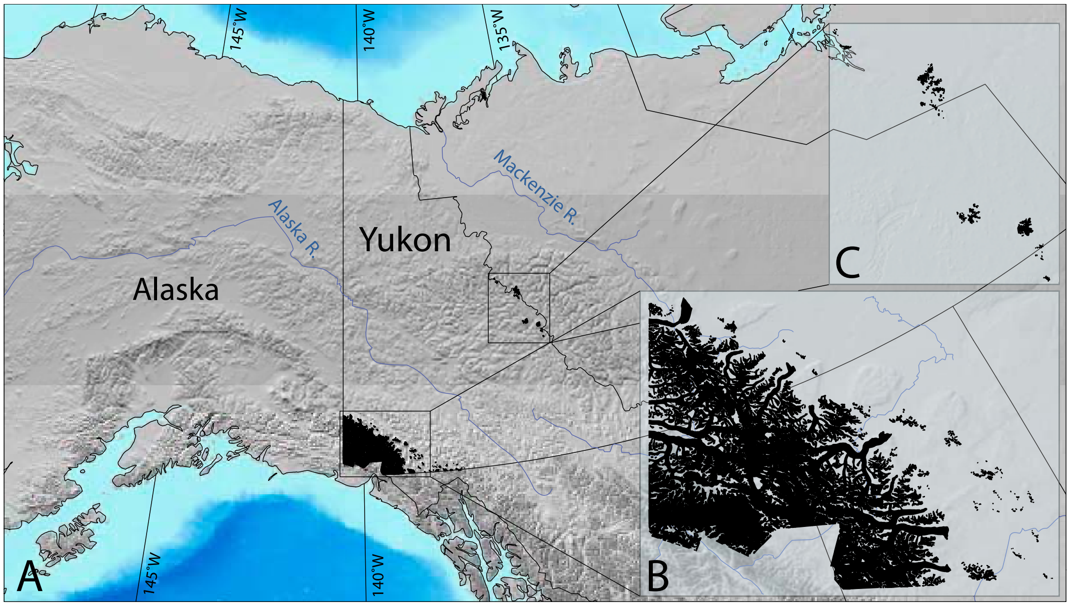

Figure 1. (a) Location map showing the extent of glacial ice (black shading) in the Yukon, NW Canada. Insets display detail of (b) St Elias and (c) Mackenzie Mountain glacier populations. Background image is a shaded relief mosaic derived from GTOPO/SRTM digital elevation data.

an approach which may conservatively estimate retreat at debris-covered glaciers. We included surge-type glaciers in our area calculations, having identified 19 surging glaciers (totaling 924.2 km^2, or 10% of the total area) from morphological evidence and previously published material [e.g., *Clarke and Collins*, 1984; *Clarke et al.*, 1986]. Due to limited photographic coverage glaciers overlying international and provincial borders were cropped along administrative boundary lines. Area change errors were calculated by selecting a random sample of 50 glaciers and deriving an ice-area uncertainty fraction based on the root sum of squares (RSS) of individual error components appropriate to each glacier (±15 m for clear-ice margins, ±45 m for debris/snow-covered margins, ±15 m for image registration uncertainty). The fractions appropriate to each of these 50 glaciers were then averaged and scaled to the entire dataset [e.g., *DeBeer and Sharp*, 2007].

2.3. Volume/Area Scaling

[7] We calculated volumes and volume changes for each individual glacier (excluding surge-type glaciers) by scaling glacier area (A) to ice volume (V) using the power law relation:

$$V = c_a A^{\gamma}$$

[*Chen and Ohmura*, 1990; *Bahr et al.*, 1997], where c_a is equal to 0.28 m$^{(3\text{-}2\gamma)}$, and γ is a scaling exponent equal to 1.375. These coefficients were calibrated from direct measurements of area and volume change of non-tidewater glaciers in the nearby Western Chugach Mountains, Alaska [*Arendt et al.*, 2006], and are therefore the most appropriate available for our (non-tidewater valley glacier) sample. While this approach may generate large errors at the individual glacier scale, it is suitable (errors typically <25%) for large, regional-scale glacier populations [*Meier et al.*, 2007]. Yukon IGY1 and IPY3 glacier inventory data and full area and volume calculations are available for download as auxiliary material.[1]

[8] To give an idea of the sensitivity of volume estimates to the choice of scaling coefficients we calculated a range of estimates using coefficients derived from glaciers in the Alps, Cascades and similar regions [*Chen and Ohmura*, 1990], the Canadian Cordillera (south of our study area [*DeBeer and Sharp*, 2007]), and from solely physical considerations [*Bahr et al.*, 1997] (see Table 1). While individual volume estimates based on Chugach coefficients are preferred, use of other coefficients gives a range of values. As uncertainty in volume changes from the choice of scaling coefficients is typically an order of magnitude greater than those due to area measurement errors, we consider volume uncertainty due to area change errors as negligible. Instead we calculate the uncertainty of scaled volume changes as the maximum difference between estimates using Chugach coefficients and those using the different coefficients provided in Table 1.

[9] We acknowledge an additional uncertainty resulting from areas cropped along administrative boundary lines. Of the 1396 glaciers in our inventory, 52 were cropped at the Yukon-Alaska boundary. In 20–25 cases the cropping took place along a drainage divide (digitized separately, see above). While it is difficult to accurately assess the uncertainty of scaled volumes for the remaining cropped glaciers, it is likely that these volumes will be underestimated. As the number of glaciers affected by this issue is small (2% of the total sample size) we consider this uncertainty to be insignificant compared to scaling coefficient errors.

[10] We converted volume changes to mass changes by assuming a constant density-depth profile [*Bader*, 1954] (that is, considering volume losses to consist of glacier ice

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/gl/2009gl042030.

Table 1. Sensitivity of Yukon Glacier Mass Loss Estimates to Published Scaling Coefficients c_a and γ in the Power Law Relation, $V = c_a A^{\gamma}$

c_a/γ	Coefficient Source	Mass Loss (Gt, 1958–60–2006–08)	Difference From[a] (Gt)
0.280 $m^{(3-2\gamma)}$/1.375	*Arendt et al.* [2006]	406[a]	
0.206 $m^{(3-2\gamma)}$/1.360	*Chen and Ohmura* [1990]	229	177 (−44%)
0.013 $m^{(3-2\gamma)}$/1.520	*Chen and Ohmura* [1990]	256	150 (−37%)
0.115 $m^{(3-2\gamma)}$/1.405	*Chen and Ohmura* [1990]	285	121 (−30%)
0.210 $m^{(3-2\gamma)}$/1.360	*DeBeer and Sharp* [2007]	233	173 (−43%)
0.191 $m^{(3-2\gamma)}$/1.375	*Bahr et al.* [1997]	277	129 (−32%)

[a]Yukon mass loss estimate calculated using scaling coefficients calibrated from glaciers in the nearby Western Chugach Mountains [*Arendt et al.*, 2006]. The fourth column provides total and percentage differences from this value, as calculated using five different sets of scaling coefficients.

only) and multiplying by the ratio of the density of ice to water (d_i/d_w = 0.917 [e.g., *Paterson*, 1994]). Thickness change rates were calculated by dividing mass changes by the average of the old and new glacier areas [e.g., *Echelmeyer et al.*, 1996; *Arendt et al.*, 2002].

3. Results

[11] During the 50 years between IGY1 and IPY3, total ice area in the Yukon shrank from 11,622 km^2 in 1958–60 to 9,081 km^2 in 2006–08, a loss of 2,541 ± 189 km^2. This represents a 22% loss of glacier area over the course of 50 years. None of the surge-type glaciers we identified advanced during this time period. Viewing glacier area change (as a percentage of initial area) against initial area (1958–60) showed that glaciers of all sizes experienced substantial losses (Figure 2). In ten cases, glaciers >50 km^2 lost ≥20% of their 1958–60 area.

[12] Applying the volume/area scaling approach we calculated a total (w.e.) mass of Yukon glaciers during IGY1 (1958–60) as 2218 Gt. The equivalent mass in IPY3 (2006–08) was 1812 Gt. Our measured volume changes equate to mass losses in the range 155 ± 68 Gt (assuming all mass lost is old snow (d_i/d_w = 0.35)) to 406 ± 177 Gt (assuming all mass lost is glacier ice). Given that most of the losses result from glacier melt and occurred at low elevations on the glacier, a value towards the upper limit of this range seems likely. Assuming all mass lost is glacier ice, we calculate an annual loss rate of 8.12 ± 3.54 Gt yr^{-1}. Averaging this mass loss over the area of the Earth's oceans (3.61 × 10^{14} m^2 [e.g., *Bindoff et al.*, 2007]), we find that loss of Yukon glaciers contributed a total of 1.13 ± 0.49 mm to global SLR between IGY1 and IPY3. This corresponds to an annual SLR contribution of 0.02 ± 0.009 mm yr^{-1} between 1958–60 and 2006–08. Our scaling approach suggests that the remaining mass of glacier ice in the Yukon is equivalent to a global SLR contribution of 5.04 mm.

4. Discussion

[13] The use of a volume/area scaling-based approach was necessary due to a lack of accurate topographic data from which to make direct measurements of volume change. Our findings may be considered regionally representative as we measured area changes of every glacier in the Yukon, inclusive of both the St Elias (Figure 1b) and Mackenzie Mountain ranges (Figure 1c). While we are confident that our choice of scaling coefficients was appropriate, a sensitivity analysis showed that the maximum difference between mass changes derived from Chugach mountain scaling coefficients and those derived from previously published coefficients (based on physical considerations and empirical findings at glacier populations elsewhere) was ~±40% (Table 1). In the absence of independent validation data, we consider this value to represent a conservative estimate of measurement uncertainty.

[14] While an error bound of ~±40% was appropriate for our regional-scale volume changes, we were able to compare scaling results with direct measurements at a single site in the Yukon; Kaskawulsh glacier (~60°40′N, 138°50′W). Airborne laser altimetry data show that the glacier lost an average of 0.40 Gt yr^{-1} from 1977–2005 (A. Arendt, personal communication, 2009). Our volume/area scaling results suggest that Kaskawulsh lost 0.61 Gt yr^{-1} between IGY1 (1958–60) and IPY3 (2006–08). Although our mass loss is more negative than that derived from direct measurements, the similarity between these two values is encouraging, particularly given the different time interval, the lack of errors in the altimetry estimate, and the uncertainties of assuming all volume losses to consist of glacier ice and from interpreting volume scaling results from individual glaciers.

[15] We have shown that substantial changes in Yukon glacier area between IGY1 and IPY3 were coincident with a period of general summer warming and reduction in winter precipitation recorded at 14 Environment Canada weather stations. We also examined interannual temperature variability in the Yukon, from National Centre for Environ-

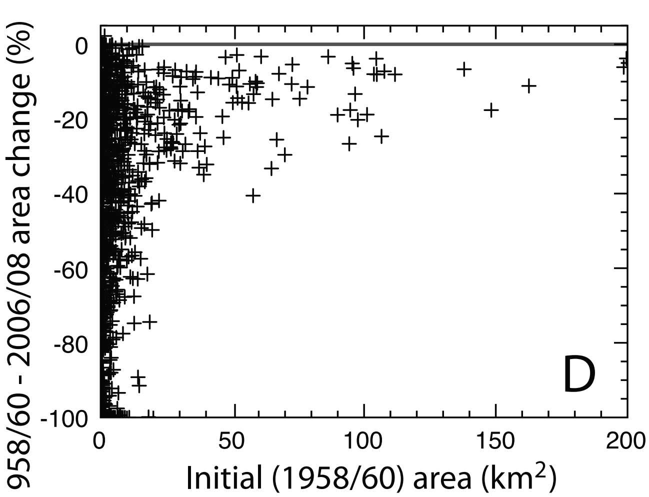

Figure 2. Plot of percentage glacier area change 1958–60–2006–08 as a function of initial (1958–60) glacier area. Nine glaciers larger than 200 km^2 are not shown.

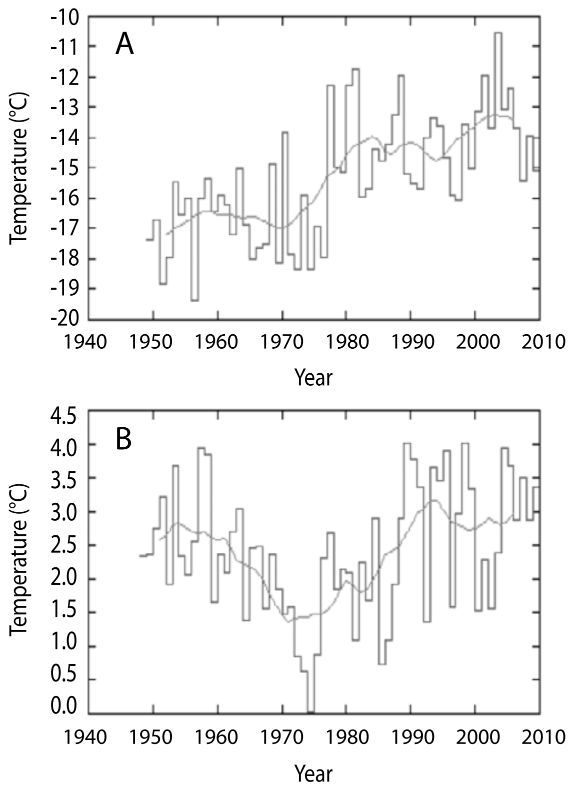

Figure 3. Half yearly averaged 2 m air temperatures in the Yukon, NW Canada, (a) winter, October–March; (b) summer, April–September, from NCEP/NCAR reanalysis model output.

mental Prediction (NCEP)/National Centre for Atmospheric Research (NCAR) reanalysis model output [*Kalnay et al.*, 1996]. NCEP/NCAR temperatures are based strongly on observations and thus fall within the most reliable class of all NCEP variables. Mean air temperatures in the Yukon between 1950 and the present (2010) show a general winter warming trend since 1950 (Figure 3a), and summer warming since ~1970 (Figure 3b). Reduction in precipitation and summer warming result in increasingly negative glacier mass balances as a result of decreases in winter accumulation and increases in summer melting. Winter warming however, may also be important for glaciers in this region. Previous research has shown that (lower elevation maritime) glaciers in the St. Elias mountains have winter FLHs above 6–27% of their ablation areas [*Arendt et al.*, 2009], meaning that they melt during both summer and winter seasons. Rising winter temperatures will increase FLHs, exposing more glacier area to above freezing temperatures and increasing the proportion of winter precipitation that falls as rain. The magnitude of this effect will depend on both the amount of shift in FLH and the glacier's area-altitude distribution [*Arendt et al.*, 2009].

[16] The area-averaged thinning rate of Yukon glaciers between IGY1 and IPY3 was 0.78 ± 0.34 m yr^{-1} w.e. This value is in agreement with an entirely independent estimate of St. Elias mass balance between April 2003 and March 2007 from GRACE satellite gravimetry (mascon region 7, 0.63 ± 0.09 m yr^{-1} w.e. [*Luthcke et al.*, 2008]). The similarity of these two results indicates that recent rapid thinning may have been sustained for much longer than previously assumed. As this value is area-averaged it is possible to compare it with published estimates of regional thinning rates for GIC populations elsewhere in the world. Our thinning rate for Yukon glaciers is larger (although within errors) than the 0.52 m yr^{-1} loss of Gulf of Alaskan glaciers between the mid 1950s and mid 1990s, yet smaller than the 1.80 m yr^{-1} thinning between the mid 1990s and early 2000s [*Arendt et al.*, 2002]. The discrepancy between these two values is likely a result of dynamic thinning of large tidewater glaciers in the Gulf of Alaska (none of which are present within the neighbouring Yukon). Our thinning rate is less than those of the Patagonian icefields [*Rignot et al.*, 2003; *Chen et al.*, 2007] (and mid 1990s-mid 2000s Alaska), yet greater than regional loss rates reported throughout the Canadian [*Abdalati et al.*, 2004] and Norwegian [*Bamber et al.*, 2005; *Nuth et al.*, 2010] Arctic archipelagos.

5. Conclusions

[17] Our calculation of mass loss (comprising measurements from every glacier) provides the first comprehensive multi-decadal estimate of the SLR contribution from Yukon glaciers and will help to reduce the uncertainty of GIC contributions to global SLR. Outside the ice sheets, the regional thinning rate we report here is exceeded only by Patagonian glaciers and by glaciers in Alaska during the period from the mid 1990s to the mid 2000s. Our findings indicate that Yukon glaciers are sensitive to climate perturbations and have experienced significant losses in response to local climate forcing. Our scaling analysis suggests that the remaining glacial ice in the Yukon would contribute a further 5.04 mm to global SLR were it to melt completely.

[18] **Acknowledgments.** Canadian Land Survey aerial photographs were made available from the archive of the National Hydrological Research Institute, Saskatoon, SK, and Landsat 7 ETM+ scenes were obtained from the United States Geological Survey (http://landsat.usgs.gov). This work was funded by grants from the Canadian Federal International Polar Year program and the Natural Sciences and Engineering Research Council. We thank Patrick O'Callaghan for digitizing assistance and Anthony Arendt, Nancy Baron, Alberto Reyes, and two anonymous reviewers for comments which improved the manuscript.

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