Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada

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[1] Climate warming at high latitudes may be contributing to the increase in areal extent of terrain disturbance associated with thawing permafrost. To evaluate change over time we analyzed historical temperature records and mapped retrogressive thaw slumps in the Mackenzie delta region using 1950, 1973 and 2004 aerial photographs. Here we show that rates of retrogressive thaw slump activity from 1973–2004 were significantly greater than during the preceding period (1950–1973) and suggest that these changes have occurred in response to a significant warming of annual and summer air temperatures during the period of record. In rolling, ice-rich terrain, the rate of thaw slump activity can be expected to increase with continued climate warming. The impacts of slumping on landscape evolution and soil and lake chemistry will likely magnify the direct effects of warming on terrestrial and aquatic ecosystems. **Citation:** Lantz, T. C., and S. V. Kokelj (2008), Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada, *Geophys. Res. Lett.*, *35*, L06502, doi:10.1029/2007GL032433.

1. Introduction

[2] Recent temperature increases in the arctic and subarctic have been significantly greater than global averages and the North American western Arctic is one of the most rapidly warming regions on the planet [*Johannessen et al.*, 2004; *Serreze et al.*, 2000]. Permafrost temperatures are rising in response to 20th century climate warming in Alaska and northwestern Canada and the frequency and magnitude of terrain disturbances associated with thawing permafrost, including the degradation of ice wedges and lake shrinkage, is increasing [*Jorgenson et al.*, 2006; *Osterkamp and Romanovsky*, 1999; *Smith et al.*, 2005; *Yoshikawa and Hinzman*, 2003].

[3] Thawing of ice-rich permafrost on sloping terrain can lead to the development of retrogressive thaw slumps [*Burn and Lewkowicz*, 1990]. These conspicuous disturbances common along coastlines and lakeshores in the western arctic initiate when ice-rich soils are exposed and thaw [*Kokelj et al.*, 2005; *Lantuit and Pollard*, 2005; *Mackay*, 1963] (Figure 1). As ground ice ablates, materials turn into a mud slurry and fall to the base of the exposure. If terrain is sufficiently ice-rich and air temperatures are warm, the slump headwall may retreat upslope by several meters in a single summer. Thaw slumps are polycyclic in nature and individual disturbances are often comprised of old, recently stabilized and active scar area, affecting several hectares of terrain (Figure 1) [*Lantuit and Pollard*, 2008]. In addition to the geomorphic significance of thaw slumps [*Lantuit and Pollard*, 2008], these disturbances also affect the chemistry of soils, surface runoff and lake water [*Kokelj et al.*, 2002, 2005], and release organic carbon sequestered in frozen ground [*Lantuit and Pollard*, 2005]. The effect of thaw slumps on terrain stability also makes their activity and distribution relevant in planning linear infrastructure such as oil and gas pipelines.

[4] Accelerated climate warming and the abundance of ice-rich permafrost in the western Arctic raises the possibility that thaw slump activity is increasing. In this paper our objectives are: 1) to examine recent temperature trends (1926–2006) in the Mackenzie Delta region, and 2) to assess changes in the rates of slump growth, and slump headwall retreat.

2. Methods

[5] To examine changes in the annual air temperature in the Mackenzie Delta region we performed regression analyses of historical (1926–2006) temperatures recorded at Inuvik and Aklavik (mean annual, mean summer (June–Sept.), and # days where the maximum temperature >20°C) [*Environment Canada*, 2006; *SAS*, 2004]. Daily temperature data was not recorded in 1936, 1939, 1943, 1944, so these years were omitted from the analysis of the number of days where the maximum temperature exceeded 20°C. To test for first and higher order autocorrelation in the error terms of all time series we calculated the Durbin-Watson statistic using the PROC AUTOREG statement in SAS [*SAS*, 2004].

[6] To calculate the density of thaw slumps in the tundra uplands of the Mackenzie Delta region we identified and recorded the location of all thaw slumps within a 3739 km^2 study corridor using aerial photographs (Figure 2). We also recorded the surficial material associated with each disturbance [*Aylsworth et al.*, 2000]. Rates of thaw slump activity were estimated by randomly choosing 25 aerial photographs of the study area taken in 2004 (Figure 2). We also obtained air photos from 1950 (1:40 000) and 1973 (1:54 000), which correspond to the 25 plot areas in the 2004 images. Each plot used to determine rates of slump activity consists of an entire 1:30 000 aerial photograph and covers approximately 49 km^2. All photos were georeferenced and displayed onscreen in stereo using DVP (DVP-GS, Québec, Canada). Mean standard error associated with the absolute orientation of all photos was 3.0 m and effective pixel sizes of images in each time period were 0.4 m (2004), 1.3 m (1970), and 0.9 m (1950). Since two of these plots fell within the area

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Figure 1. Retrogressive thaw slump adjacent to a tundra lake, Richards Island, Mackenzie Delta region. The arrow at left indicates two field researchers. The areal extent of the entire disturbance is approximately 1ha. Photo: Peter Morse.

burned by an intense 1968 wildfire, which degraded near-surface permafrost [*Heginbottom*, 1972; *Mackay*, 1995], we removed them from the analysis. The 23 photos retained cover approximately 1100 km^2 of terrain.

[7] Slumps visible within the 23 study plots were digitized for all three time periods while being viewed in stereo using DVP (DVP-GS, Québec, Canada). To ensure that our measurements were not biased by differences in effective pixel sizes of photos from different years, we used a minimum mapping area of 10 m^2. The annual rates of slump growth from 1950–1973 and 1973–2004 were obtained by dividing the change in area by the number of years in the period between photos. Thaw slumps that were inactive over the entire period of study were removed from the analyses.

[8] Slumps may grow laterally and upslope, but their development may also be concurrent with lake expansion. Our mapping did not account for disturbed terrain lost to lake expansion, which occurred in approximately ten percent of studied cases. The lake shorelines at the remainder of the disturbances were comparatively stable. Due to terrain loss in association with shoreline retreat, our estimates of slump growth are likely conservative. Thus, in order to provide a second metric of slump activity we measured the changes in slump headwall position along transects established through highly active slumps (1950–2004 growth rates > 70 m^2/year; n = 50) using a minimum mapping distance of 10 m. The annual rates of maximum headwall retreat (1950–1973, 1973–2004) were estimated by dividing the change in headwall position by the number of years in the period between photos. To determine if these rates of slump activity differed between the two time periods, we performed a within-subject *t*-test [*SAS*, 2004]. To meet the assumption of normality, the rates of slump growth and headwall retreat were log-transformed.

3. Results

[9] Air temperatures fluctuated considerably from year to year, but mean annual, mean summer temperature, and the number of days with temperature over 20°C per year show a significant increase from 1926 to 2006 (Figure 3). The linear regression of mean annual temperatures from 1926 to 2006 describes a 1.9°C increase in average annual temperature ($F_{1,79}$ = 22.74, P < 0.001 r^2 = 0.224) (Figure 3a). Similarly, the analysis of summer conditions shows that mean June to September air temperatures have risen by 2.2°C since 1926 ($F_{1,79}$ = 22.0, P < 0.001 r^2 = 0.218) (Figure 3b). Reflecting the increasing mean summer temperatures, the annual total number of days with the maximum temperatures above 20°C have also increased by 14.3 days since 1928 ($F_{1,73}$ = 17.32, P < 0.001 r^2 = 0.192) (Figure 3c). These time series did not exhibit significant first or higher order autocorrelation of error terms. Summer temperatures are cooler at the coast than at inland locations [*Burn*, 1997], but strong correlations in air temperatures between Inuvik, Shingle Point (68°57′N, 133°13′W) and Tuktoyaktuk (69°26′N, 133°00′W) (r^2 > 0.95) indicate that the warming trend observed in the long-term composite record for the central Delta has been a regional phenomena.

[10] A total of 541 areas affected by thaw slumps were mapped along lakeshores in our 3739 km^2 study region (Figure 2). Morainal deposits comprising approximately 55% of the landscape are associated with 70% of the thaw slumps, while the remaining disturbances were distributed approximately proportional to the relative areas occupied by glaciofluvial (22%), lacustrine (17%) and colluvial (1%) deposits. All slumps mapped were associated with tundra lakes and ponds, impacting approximately 8% of the 2880 lakes greater than 1 ha in area.

[11] From 1950 to 1973, the areal extent of all thaw slumps mapped increased by about 15% and by 2004 the total area had grown by approximately 36%. The mean rate of slump growth from 1973 to 2004 was about 1.4 times the rate estimated for the period from 1950 to 1973 (Figure 4a) and the difference in the rates from the two time periods was significantly greater than 0 (t_{110} = 5.19, P < 0.001). The mean rate of slump headwall retreat during the period from 1973 to 2004 was approximately double that estimated for

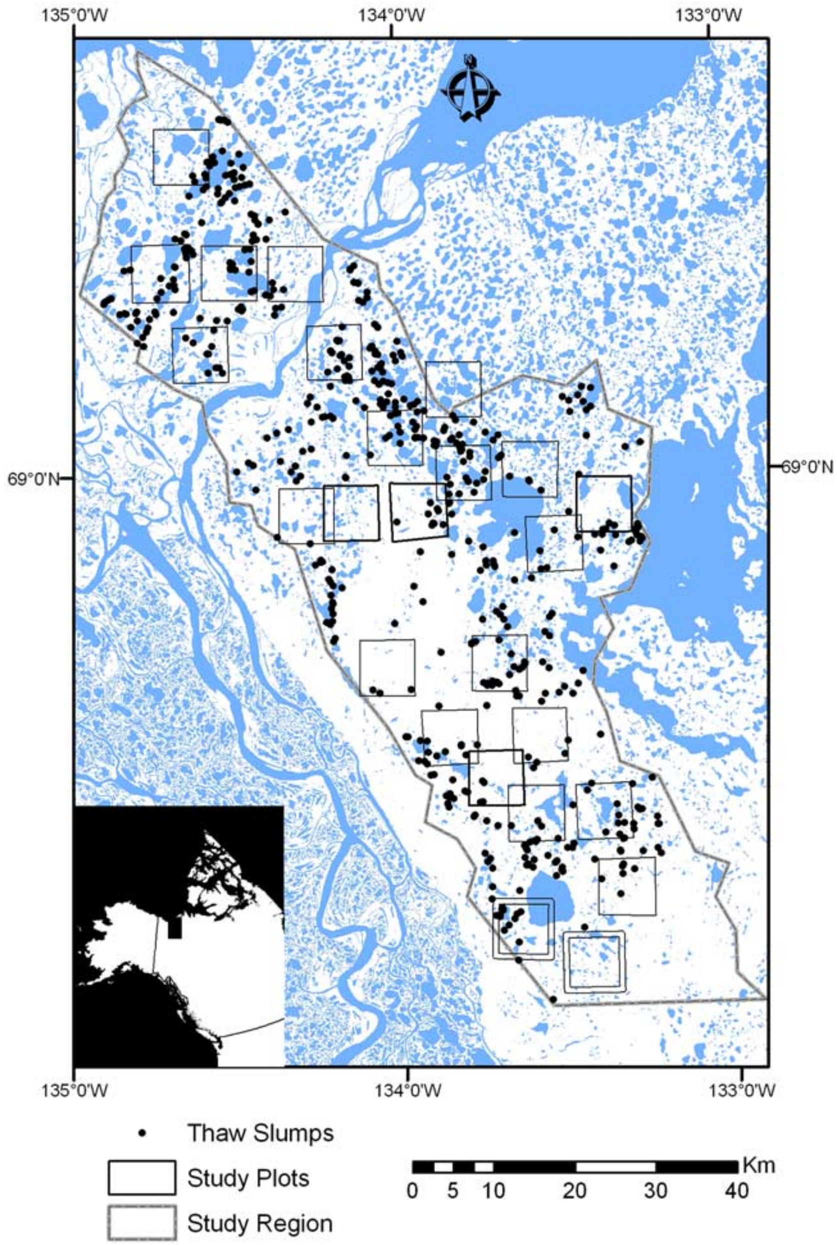

Figure 2. Map of the retrogressive thaw slumps in the upland tundra study region east of the Mackenzie River Delta. Areas bounded by a single line represent study plots where disturbances were mapped on aerial photographs taken in 1950, 1973 and 2004. The study plots affected by the 1968 fire are marked by a border of two solid lines.

the period from 1950 to 1973 and the difference was significantly greater than 0 (Figure 4b; t_{49} = 3.86, P < 0.001). In 1950, 1973, and 2004 mean slump sizes were 1.02, 1.15, and 1.34 ha respectively.

4. Discussion

[12] Long term activity of thaw slumps is determined by the frequency of slump reactivation and the rates and extent of headwall retreat. The growth of an active slump is related to the ice content of the thawing terrain, slump aspect, and morphology [*Lewkowicz*, 1986, 1987] Within this context of site specific conditions, slump growth will occur in response to the ablation of ground ice during the thaw season [*Lewkowicz*, 1986]. Our observation that a random sample of active slumps exhibited significantly higher growth rates from 1973–2004 than from 1950–1973 suggests that a regional driver of slump growth has subsumed site specific controls. Process studies have shown that a model including net radiation, temperature, vapor pressure and wind speed best describe ground ice ablation in slumps, although air temperature alone can also explain a significant proportion of the short-term variability of ground ice ablation (r^2 = 0.39) [*Lewkowicz*, 1986]. At longer time scales, models that only employ air temperature successfully explain rates of ablation (r^2 = 0.98) and headwall retreat (r^2 = 0.68–0.97) [*Kerfoot*, 1969; *Robinson*, 2000].

[13] Over the two time periods (1950–1973 and 1973–2004) that the rate of slump growth has increased, the mean summer air temperatures at Inuvik have risen by 1.3°C and

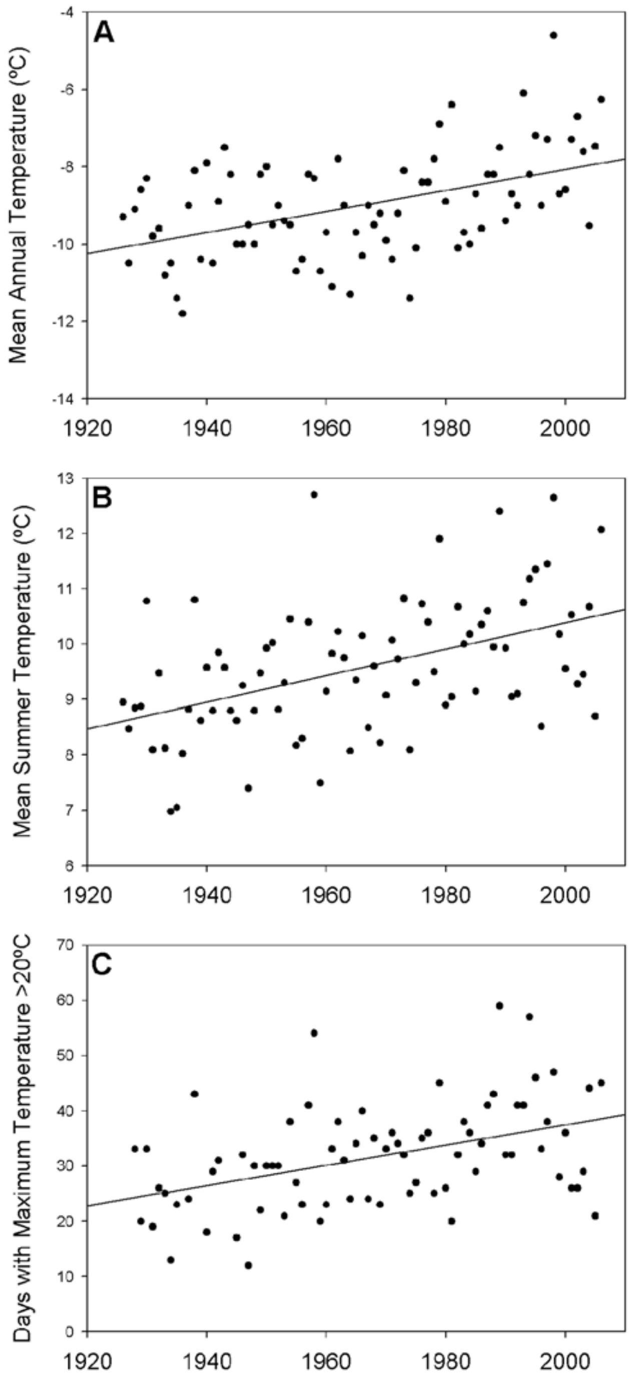

Figure 3. Air temperature time series for the central Mackenzie Delta region from 1926 to 2006. Series plotted include: (a) mean annual, (b) mean summer (June–September), and (c) number of days where the maximum temperature exceeded 20°C (1928–2006). The solid lines represent the least squares regressions.

the annual total of days with air temperature exceeding 20°C have increased by 9.9 days (Figures 3 and 4). Summer warming and increased ground ice ablation is the most plausible explanation for the regional increase in rates of slump headwall retreat and overall slump growth rates. Increases in the number of thaw slumps west of the Mackenzie Delta have also been observed over a similar time period [*Lantuit and Pollard*, 2008; *Wolfe et al.*, 2001].

[14] The rates of slump activity that we describe here are considerably lower than those, which have been reported in other areas [*Kerfoot*, 1969; *Lantuit and Pollard*, 2005, 2008; *Wolfe et al.*, 2001] largely due to the decadal time periods for which our growth rates have been estimated. It is likely that growth of even the most active slumps has been punctuated by periods of stability [*Lantuit and Pollard*, 2008; *Robinson*, 2000; *Wolfe et al.*, 2001]. Given the polycyclic nature of slumps, a regional increase in slump area suggests that frequency of reactivation may also be increasing. Thermal-erosion is well-established as a trigger mechanism for thaw slumps at the coastline or along rivers [*Lantuit and Pollard*, 2008], but initiating factors in upland settings around small lakes, including active layer deepening, warming permafrost, wave action, and gullying by surface runoff, remain poorly understood.

[15] Thaw slumps are widespread across the tundra landscape (Figure 2) and the aerial extent of disturbance is growing. Since slumping results in the degradation of near-surface permafrost [*Burn*, 2000], this process is also likely to release carbon stored in soils [*Lantuit and Pollard*,

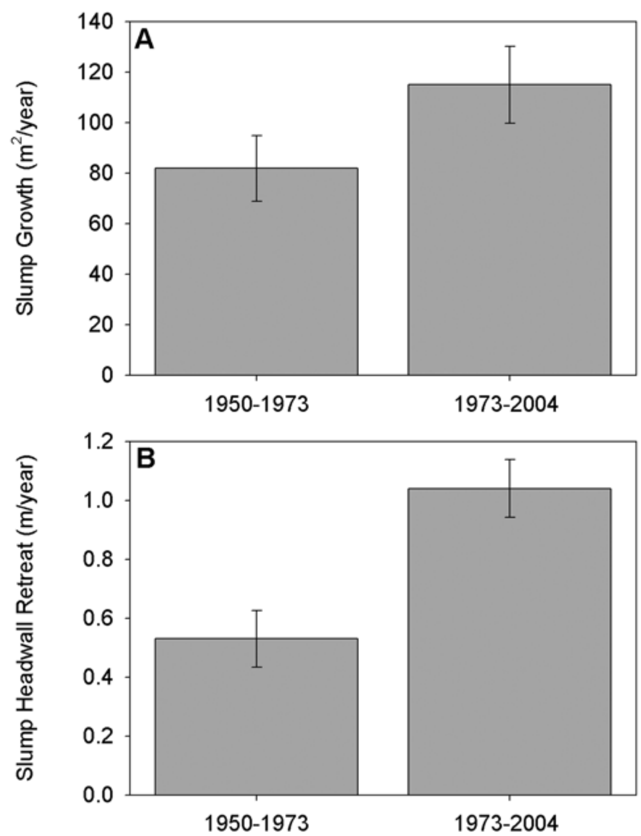

Figure 4. Mean rates of slump growth in the Mackenzie Delta region. (a) Average annual rates of slump growth estimated from the change in areal extent of disturbance from 1950 to 1973 (n = 110) and from 1973 to 2004 (n = 110) for all active slumps mapped on the 23 study plots; and (b) average annual rates of headwall retreat from 1950 to 1973 (n = 50) and 1973 to 2004 (n = 50). Error bars represent ±SE of the mean.

2005; *Zimov et al.*, 2006]. Areas affected by thaw slumping are characterized by ion-rich mineral substrates [*Kokelj et al.*, 2002] and an ameliorated microclimate with respect to the undisturbed terrain [*Burn*, 2000]. Since barriers to establishment constrain the effects of climate warming on vegetation, [*Hurtt et al.*, 1998; *Walther et al.*, 2002] disturbances such as slumps represent localized areas where vegetation may show rapid responses to recent temperature increases [*Forbes et al.*, 2001]. The development of unique plant communities on recent and stabilized slumps (Figure 1), in conjunction with our frequent observation of large and small mammals and songbirds, suggest that slumps are ecologically important islands within the tundra environment.

[16] Thaw slumps have discernable effects on lake-water chemistry even where disturbances occupy only a small percentage of the catchment area. Degrading permafrost releases soluble materials, which are transported by surface runoff from ion-rich slump soils into adjacent aquatic systems, elevating ionic concentrations in lake water [*Kokelj et al.*, 2005]. A positive association between solute concentrations and the proportion of catchment area influenced by thaw slumping [*Kokelj and Burn*, 2005] suggests that permafrost disturbance will be an important factor influencing the chemistry of thousands of lakes in a warming western Arctic.

[17] Overall we draw the following conclusions:

[18] 1. In the central Mackenzie Delta region since 1926, mean annual air temperatures, mean summer air temperatures, and the number of days with maximum air temperatures greater than 20°C have increased by 1.9°C, 2.2°C and 14.3 days, respectively.

[19] 2. Rates of slump growth from 1973 to 2004 were 1.4 times greater than rates from 1950–1973 and rates of headwall retreat increased approximately twofold. Slumps enlarge in summer due to ablation of ground ice, which is driven by net radiation and air temperature. The regional acceleration in slump activity between 1950–1973 and 1973–2004 is likely occurring in response to warming air temperatures.

[20] 3. In ice-rich terrain, the rates and areal extent of thaw slumping can be expected to increase with future warming.

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