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LETTER

Acceleration of thaw slump activity in glaciated landscapes of the Western Canadian Arctic

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Abstract

Climate change is increasing the frequency and intensity of thermokarst, but the influences of regional climate and physiography remain poorly understood. Retrogressive thaw slumping is one of the most dynamic forms of thermokarst and affects many areas of glaciated terrain across northwestern Canada. In this study, we used airphotos and satellite imagery to investigate the influence of climate and landscape factors on thaw slump dynamics. We assessed slump size, density, and growth rates in four regions of ice-rich terrain with contrasting climate and physiographic conditions: the Jesse Moraine, the Tuktoyaktuk Coastlands, the Bluenose Moraine, and the Peel Plateau. Observed increases in: (1) the area impacted by slumps (+2 to +407%), (2) average slump sizes (+0.31 to +1.82 ha), and (3) slump growth rates (+169 to +465 $m^2 yr^{-1}$) showed that thermokarst activity is rapidly accelerating in ice-rich morainal landscapes in the western Canadian Arctic, where slumping has become a dominant driver of geomorphic change. Differences in slump characteristics among regions indicate that slump development is strongly influenced by topography, ground ice conditions, and Quaternary history. Observed increases in slump activity occurred in conjunction with increases in air temperature and precipitation, but variation in slump activity among the four regions suggests that increased precipitation has been an important driver of change. Our observation that the most rapid intensification of slump activity occurred in the coldest environment (the Jesse Moraine on Banks Island) indicates that ice-cored landscapes in cold permafrost environments are highly vulnerable to climate change.

1. Introduction

Rapid changes in climate at high latitudes have raised significant concerns regarding the stability of landscapes underlain by ice-rich permafrost (Serreze *et al* 2000, ACIA 2005, Jorgenson *et al* 2006, Christensen *et al* 2007, Lantz and Kokelj 2008, Kanevskiy *et al* 2014, Kokelj *et al* 2015). It is known that past periods of warming had significant impacts on the geomorphology of permafrost landscapes in the western Arctic of North America. During the early Holocene climate optimum (Kaufman *et al* 2004, Gajewski 2015), higher summer air temperatures in northwestern North America contributed to increased thaw depths (Burn 1997) and widespread thermokarst causing the initiation of thaw lakes (Rampton 1988, Mackay 1992, Lacelle *et al* 2004, Reyes *et al* 2010) and alluviation of stream valleys (Mann *et al* 2010). Growing evidence suggests that recent climate change is also rapidly increasing the frequency and magnitude of thermokarst disturbance (Jorgenson *et al* 2006, Lantz and Kokelj 2008, Gooseff *et al* 2009, Kokelj *et al* 2013, 2015, Lantz and Turner 2015).

Retrogressive thaw slumping is a dynamic form of thermokarst that impacts sloping terrain underlain by ice-rich permafrost (Burn and Lewkowicz 1990, Robinson 2000, Jorgenson and Osterkamp 2005, Kokelj and Jorgenson 2013). Slumps are common in ice-rich glacial landscapes of the western Canadian Arctic (St-Onge and McMartin 1999, Dyke and

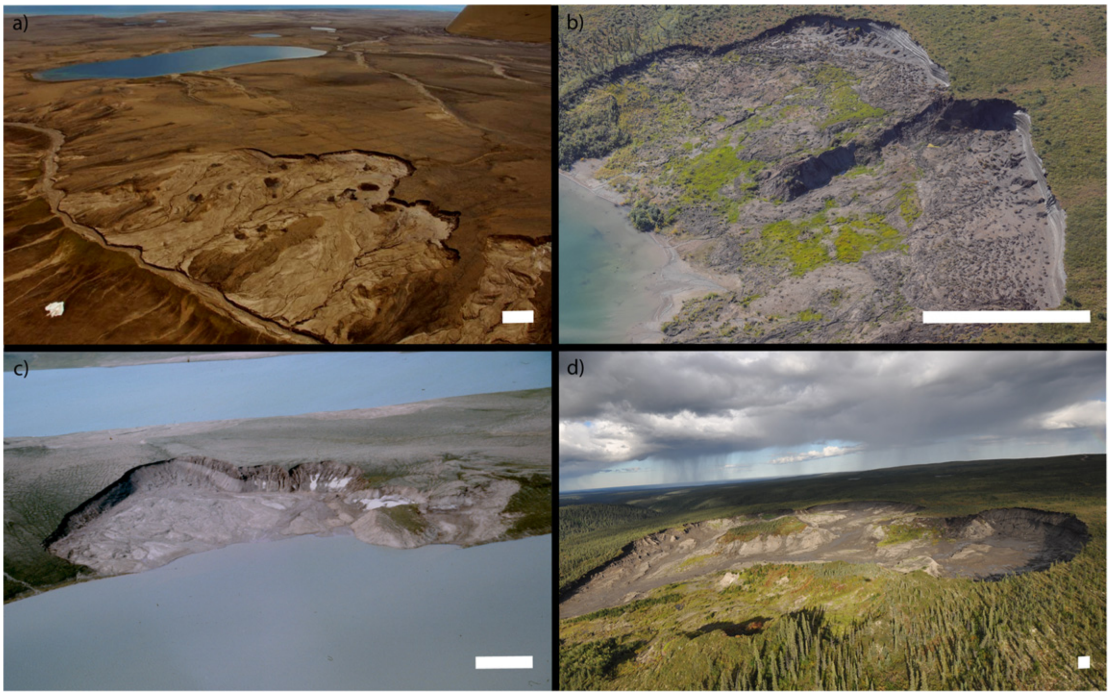

Figure 1. Active retrogressive thaw slumps in the four study regions. (a) Jesse Moriane, eastern Banks Island (2010), (b) the Tuktoyaktuk Coastlands, Mackenzie Delta region (2012), (c) Bluenose Moraine, western Nunavut (1988), and (d) the Peel Plateau, Lower Mackenzie Basin (2010). White bars represent ~45 m. Images from (a) Ecosystem Classification Group (2012), (b) Trevor Lantz, (c) St. Onge and McMartin (1995), and (d) Steven Kokelj.

Savelle 2000, Lantz and Kokelj 2008, Lacelle *et al* 2010), the Alaskan and Brooks Ranges and their glaciated foothills (Jorgenson *et al* 2008, Balser *et al* 2009, Swanson 2012), and across similar landscapes in northwestern Siberia (Astakhov *et al* 1996, Alexanderson *et al* 2002; Leibman *et al* 2014). Thaw slumps couple thermal and geomorphic processes to expose and rapidly thaw thick layers of ground ice, modify slope morphology, and transport large volumes of thawed materials downslope to lakes, valley-bottoms or coastal zones (Lantuit *et al* 2012, Kokelj *et al* 2015). An active thaw slump consists of a headwall of ablating ground ice at the upper boundary of the disturbance, a scar zone, and frequently a debris tongue consisting of a supersaturated slurry that moves downslope by viscous flow (figure 1) (Burn and Lewkowicz 1990, Lantuit and Pollard 2008, Kokelj *et al* 2015). Thaw slumps are initiated through a variety of mechanisms of physical and thermal erosion, and where topographic and ground ice conditions permit, these disturbances can remain active for several decades and impact tens of hectares of terrain (Lacelle *et al* 2015). Slumps can have significant impacts on terrain morphology (Lewkowicz 1987, Kokelj *et al* 2015), downstream sediment and geochemical flux (Bowden *et al* 2008, Kokelj *et al* 2013, Pizano *et al* 2014), and ecological processes (Lantz *et al* 2009, Mesquita *et al* 2010, Thienpont *et al* 2013, Chin *et al* 2016).

Retrogressive thaw slump activity is increasing in the Canadian Arctic (Lantuit and Pollard 2008, Lantz and Kokelj 2008, Kokelj *et al* 2015), but variation in thaw slump characteristics and rates of change across physiographic and climatic regions are not well understood. Slump activity is affected by external factors such as climate (Balser *et al* 2014, Kokelj *et al* 2015), but the landscape response to climate change and the spatial distribution and physical characteristics of thaw slumps also vary with ground ice content, physiography and geomorphic conditions (Lacelle *et al* 2015). In this study we investigated the influence of landscape factors and climate on thaw slump dynamics within the glaciated terrain of western Canadian Arctic in four study areas with contrasting climate and environmental conditions (table 1 and figure 2). These areas include the Jesse Moraine on eastern Banks Island; the Tuktoyaktuk Coastlands east of the Mackenzie Delta; the Bluenose Moraine in western Nunavut; and the Peel Plateau in the lower Mackenzie Valley (figure 2). Digitizing active thaw slumps using historic (1950–1960) and modern (2004–2008) aerial photographs and satellite imagery, in conjunction with regional descriptions of surficial materials, topography, geomorphology, ground temperature and climate, permitted us to test the following research hypotheses: (1) the distribution of hummocky moraine and regional physiography control variation in the size and density of thaw slumps among study areas; (2) in the past 4–5 decades, the terrain impacted by slumping has increased in all regions of the western Arctic; and (3) the rates of change are greatest in the warmest and wettest environment (Peel Plateau, lower Mackenzie valley), and lowest in the coldest and driest environment (Jesse Moraine, Banks Island).

Table 1. Environmental characteristics of the four study areas showing mapped area, dominant surficial unit (the terrain unit that occupied the largest portion of the study area; elevation (range and mean ± 1 SD); mean annual air temperature (MAAT), mean annual precipitation (MAP); temperature change from 1950–2005; precipitation change from 1950 to 2000; and ground temperatures. Regional annual climate data are from WorldClim and the Commission for Environmental Cooperation (Hijmans *et al* 2005, Commission for Environmental Cooperation 2011a, 2011b) and, except where noted, changes in climate variables are from the GHCN v3 model (Hansen *et al* 2010, NASA GISS 2014). Except where noted, surficial geology is from Fulton (1995). Topographic indices were determined from Government of Canada (2000).

Region	Map area (km^2)	Dominant surficial unit	Elevation (m)	MAAT (°C)	MAP (mm)	Temperature change (1950–2005) (annual, warm season[a])	Precipitation change (1950–2000) (annual, warm season[a])	Ground temperature (with location, depth, and year)
Jesse Moraine	603	Till blanket (100%)	Range: 255 (0–255) Mean: 125 ± 101	−14.0 ± 0.5	141.6 ± 5.0	+2.3 °C +0.4 °C	+50.9 mm +14.1 mm	<−10 °C from Banks Island (from Smith and Burgess 2000, Golder Associates Ltd. 2012)
Tuktoyaktuk Coastlands	1371	Till blanket (60%)	Range: 245 (0–245) Mean: 58 ± 49	−10.2 ± 0.3	192.6 ± 17.4	+2.4 °C +1.1 °C	+38.8 mm +9.9 mm	−3 to −7 °C ~ in study region (Burn and Kokelj 2009)
Bluenose Moraine	3262	Till blanket (97%)	Range: 500 (203–703) Mean: 538 ± 85	−12.0 ± 0.3	220.5 ± 8.3	+2.3 °C[b] +1.4 °C[c]	+58.5 mm +13.6 mm	−4.4 °C and −7.7 °C ~210 km SE of study region (from Smith and Burgess 2000)
Peel Plateau	1278	Till blanket (80%)	Range: 767 (1–768) Mean: 305 ± 129	−8.7 ± 0.3	305.2 ± 10.7	+1.8 °C +0.8 °C	+48.5 mm +14.8 mm	−1 to −3.0 °C ~ in study region (O'Neill *et al* 2015)

[a] Warm season: May—October.
[b] Kugluktuk homogenized data from ~175 km SE of study region (Environment Canada 2012). $R^2 = 0.29$, $\mathbf{P < 0.01}$, Durbin–Watson = 1.8, $P = 0.22$.
[c] Kugluktuk homogenized data (Environment Canada 2012). $R^2 = 0.10$, $\mathbf{P = 0.017}$, Durbin–Watson = 2.6, $P = 0.99$.

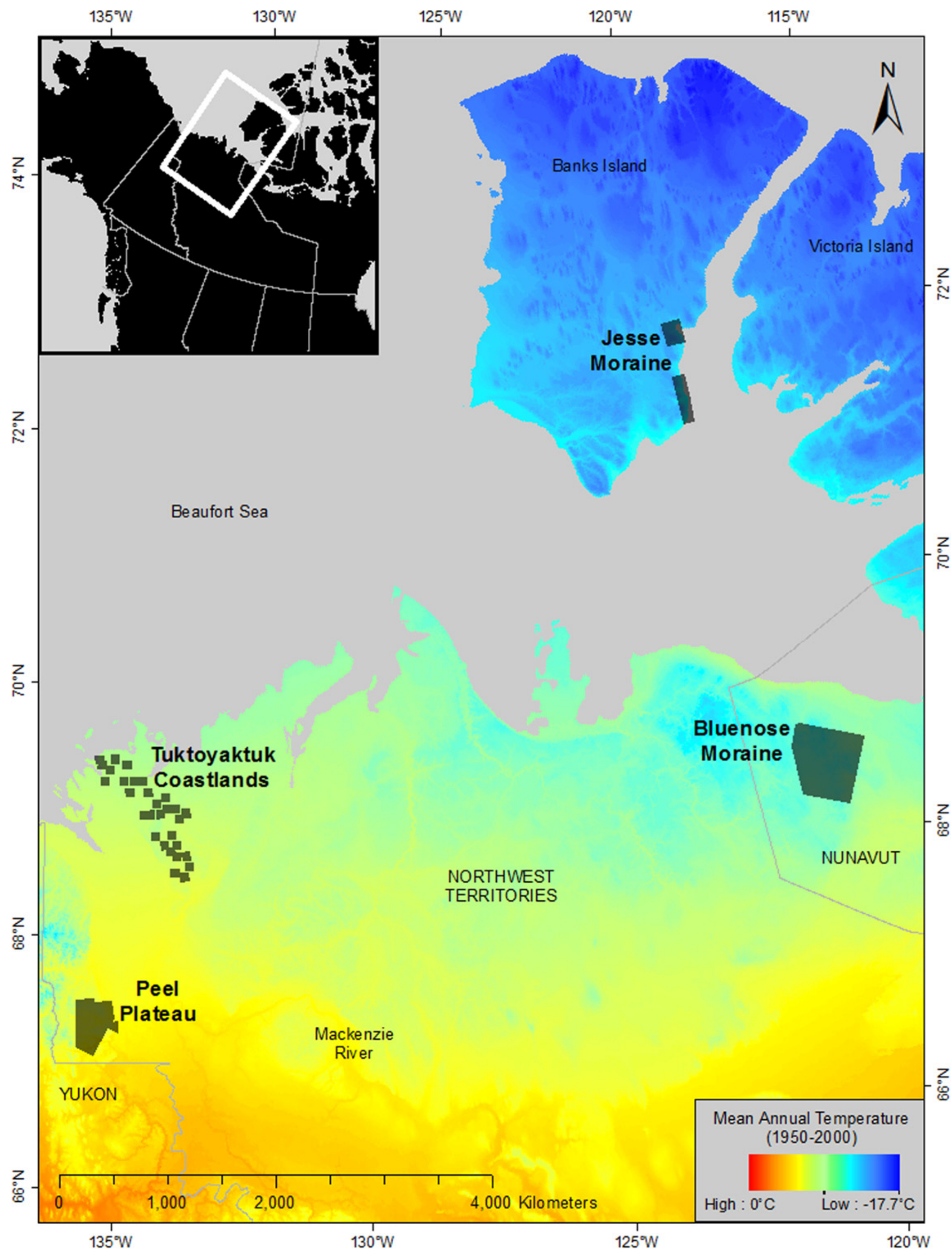

Figure 2. Map showing the four study regions (the Jesse Moraine, the Tuktoyaktuk Coastlands, the Bluenose Moraine, and the Peel Plateau), where retrogressive thaw slumps were mapped in two time periods, using satellite imagery and airphotos. Mean annual air temperature calculated from 1950 to 2000 averages is from Commission for Environmental Cooperation (2011a).

2. Methods

2.1. Study areas

To evaluate the influence of climate and landscape factors on the size, distribution and growth dynamics of thaw slumps, we selected four impacted study areas in the western Arctic (figure 1). These regions span 5° of latitude, a gradient of approximately 5 °C in mean annual air temperature (MAAT), a 10 °C range in permafrost temperatures, and a two-fold difference (from ~150 to 300 mm) in total annual precipitation (figure 1 and table 1). The intensively mapped study areas range in size from 600 to 3200 km^2, with study area sizes constrained by the imagery available. The most northerly study area, the Jesse Moraine on Banks Island, is a Low Arctic polar desert with the coldest and driest climate (MAAT = −14 ± 0.5 °C; MAP = 141.6 ± 5.0 mm) and a mean annual ground temperature around −10 to −12 °C (table 1). The Peel Plateau is the southernmost study area and is located in the high subarctic, where precipitation is twice as high (MAP = 305.2 ± 10.7 mm) and mean annual air temperature is 5 °C warmer than Banks Island. The Peel Plateau also has the highest ground temperatures, which range from −1 to about −3.0 °C (table 1). The climates of the Bluenose Moraine and Tuktoyaktuk Coastlands were intermediate with MAAT of between −12 and −10 °C, respectively, and MAP of ~200 mm.

Air temperatures have increased over the past 5 decades in all study areas, with the largest increases occurring in winter (table 1). Rainfall has also increased across all of these study regions, but the greatest relative increase has occurred in the Jesse Moraine on Banks Island (table 1), which in the past has been referred to as a polar desert (Vincent 1982). All study regions were ice-covered during the last glacial maximum and contain thick layers of ice-rich permafrost and local ice-cored terrain, which occurs in association with hummocky moraine (Mackay 1971, St-Onge and McMartin 1999, Lacelle *et al* 2004, Lakeman and England 2012). The relative topographic relief and the density of lakes and streams vary among the four study areas. The Tuktoyaktuk Coastlands and Bluenose Moraine are lake-dominated environments, and the Peel Plateau and Jesse Moraine are fluvially incised landscapes. The Peel Plateau is characterized by the greatest relative relief and the Tuktoyaktuk Coastlands is the most topographically subdued landscape (table 1). Additional background on the study regions is provided in the supplementary materials.

2.2. Thaw slump mapping

To inventory thaw slumps and estimate rates of landscape change, we obtained greyscale airphotos and color satellite imagery from two time periods for each study region. Imagery had the following resolutions: Jesse Moraine (1960 = 2.4–2.5 m; 2004 = 0.6 m); Tuktoyaktuk Coastlands (1950 = 0.9 m; 2004 = 0.5 m); Bluenose Moraine (1952 = 0.9 m; 2006 = 10 m); and Peel Plateau (1950–1954 = 0.8–1.6 m; 2007–2008 = 0.6–10 m) (table S1). Active slumps were identified based on the presence of recently exposed sediments, poorly-developed vegetation, and a well-defined headwall (figure S1). All active slumps in each study area were digitized on-screen by viewing georeferenced imagery in ArcMap (2D; versions 10.0 and 10.1), Summit Evolution (3D; version 6.7), or DVP photogrammetry suite (3D; DVP-GS, Quebec, Canada). The mean annual rate of growth for each mapped slumps was calculated as follows:

$$\text{Rate of slump growth} = \frac{A_2 - A_1}{t},$$

where A_1 is the historical area (m^2), A_2 is the modern area (m^2), and t is the number of years between images. If multiple slumps coalesced into a single disturbance between the two time periods, they were treated as a single entity in first time period (A_1) by summing their areas. To explore the influence of slump size on average growth rate, we also calculated the proportional growth rate relative to modern slump size.

$$\text{Proportional growth rate} = \frac{\frac{(A_2 - A_1)}{A_2}}{t}.$$

Slump areas were delineated using imagery with variable resolutions, but even the coarsest imagery (10 m) was suitable for mapping because the majority of disturbances we mapped were larger than 0.05 ha (figure S1). To account for differences in image resolution among regions we used minimum mapable areas that reflected the quality of imagery used (Lantz and Kokelj 2008). In the Bluenose Moraine and the Peel Plateau, slumps were mapped to the nearest 0.1 ha. In the Tuktoyaktuk Coastlands and the Jesse Moraine, slumps were mapped to the nearest 0.01 ha. To test for differences in slump growth rates among study regions, we used a one way analysis of variance (R, version 3.0.0, 2013-04-03, The R Foundation for Statistical Computing, www.r-project.org).

Parameters that describe regional environmental conditions were used as a basis to interpret differences in slump characteristics and their changes over time in the four study areas (table 1). We used Fulton's (1995) national-scale compilation to characterize the dominant surficial unit in each study area. Topographic characteristics (mean, standard deviation and range of elevations) were derived from digital elevation models published in the Canadian Digital Elevation Data resource (Government of Canada 2000). MAAT and mean annual precipitation (MAP) for each region were estimated data from WorldClim and the Commission for Environmental Cooperation (Hijmans *et al* 2005, Commission for Environmental Cooperation 2011a, 2011b). This dataset is a grid (resolution = 1 km^2) of average monthly temperature and precipitation interpolated from weather station data (1950–2000). Changes in annual (November–October) and growing season (May–October) air temperatures between 1950 and 2005 were derived from NASA GISS maps of temperature change. These maps show gridded estimates of linear changes in temperature which are based on the least squares regression of temperatures from the GHCN v3 model (Hansen *et al* 2010, NASA GISS 2014). Data from the Bluenose Moraine area was not available from this model, so we used homogenized data from Environment Canada (2012) that combined temperature observations from two stations at Kugluktuk, NWT (~175 km SE of the study region). We used least squares regression of annual and growing season temperatures from this dataset to estimate change between 1950 and 2005. To check for autocorrelation in this data we calculated the Durbin–Watson statistic. Changes in annual (November–October) and growing season (May–October) precipitation between 1950 and 2000 were derived from NASA GISS maps of changes in precipitation. These maps show gridded estimates of linear change based on least squares regression of precipitation data from the CRU TS 2.0 model (Mitchell *et al* 2004, NASA GISS 2014). Map outputs from NASS GISS do not provide significance tests for the trends reported.

Permafrost temperatures in each study area were estimated using the minimum reported ground temperatures from the closest available boreholes, or from regional compilations, which exist for the Tuktoyaktuk Coastlands (Burn and Kokelj 2009) and for the Peel Plateau (O'Neill *et al* 2015). Ground temperatures for the Jesse and Bluenose Moraines (Banks Island and mainland western Nunavut) were based on sparse data from a northern Canada ground temperature map reported in Smith and Burgess (2000) and for data from Johnson Point on Banks Island (Golder Associates 2012) (locations are noted in table 1).

3. Results

Slump activity over the last 50 years increased in all of the study areas (figure 3), but there were notable differences in slump size, density and growth rates among regions (table 2 and figure 3). The Jesse Moraine study region had the highest modern density of thaw slumps (50.1 slumps/100 km^2) and greatest proportional area impacted by disturbance (49.0 ha/100 km^2) (figure 3(C) and table 2). Disturbance density in 1960 was already high in comparison with other regions, but active disturbances were small and the total disturbed area was relatively low (table 2). Between 1960 and 2004, this area experienced a 247% increase in the number of active slumps, a 46% increase in mean slump area, and a 407% increase in total active slump area (table 2 and figure 3(C)). The majority of slumps on the Jesse Moraine were associated with fluvial environments. To our knowledge, the Jesse Moraine study area is one of the most intensely impacted thermokarst landscapes in the Canadian Arctic (table 2 and figure 3).

The Tuktoyaktuk Coastlands had the third highest thaw slump density (5.2 slumps/100 km^2), but since active disturbances were relatively small, the proportion of slump-impacted terrain was lower than the other study regions (11.0 ha/100 km^2) (table 2(B) and figure 3). Thaw slumps in this lake-rich environment were associated entirely with lake shores. The region experienced only a marginal (2%) increase in active slump area between 1950 and 2004 (table 2) and there was a significant decline in the total number of contemporary active slumps. This decline was due to the growth and coalescence of disturbances, which resulted in a 67% increase in average slump size (table 2). Unlike the growth rate calculations done by Lantz and Kokelj (2008), which included all identifiable active and inactive slump surfaces from 1950 to 2004, we only included slumps that could be identified as active on both the early and late imagery.

Recent imagery shows that the Bluenose Moraine had the lowest slump density (2.5 slumps/100 km^2), but highest proportion of medium and large slumps (figure 3(A)). Thaw slumps in this region developed primarily along lakeshores (94%) and their mean area in 2006 was 5.3 ± 6.4 ha. In 2006, the proportional area of impacted terrain in the Bluenose Moraine (13.3 ha slump/100 km^2 study region) was lower than the Jesse Moraine and the Peel Plateau, but greater than the Tuktoyaktuk Coastlands (table 2 and figure 3(A)). In the Bluenose Moraine, between 1952 and 2006, there was a 55% increase in the number of disturbances and an 83% increase in total area impacted (table 2 and figure 3(A)).

The largest slumps (>5 ha) observed in this study developed on the fluvially-incised Peel Plateau (figure 3(D)) (Brooker *et al* 2014, Kokelj *et al* 2015, Lacelle *et al* 2015). Slump density in Peel Plateau was similar to the Tuktoyaktuk Coastlands, but the proportional area impacted in 2007–2008 (24.2 ha/100 km^2) was high due to the abundance of very large disturbances. The number of slumps we mapped did not increase in the Peel Plateau, but total disturbance area increased by 64%. The Peel Plateau also showed the largest increase in mean slump size (2.30 ha to 7.81 ha) over time (table 2).

Long-term slump growth rates differed among the four study regions and co-varied with slump size. On the Bluenose Moraine and Peel Plateau, where slumps are particularly large, the growth rates were more than double those in the Tuktoyaktuk Coastlands and the Jesse Moraine (460 ± 123 m^2 yr^{-1} and 465 ± 222 m^2 yr^{-1} versus 169 ± 54 m^2 yr^{-1} and 194 ± 24 m^2 yr^{-1}, respectively; $F_{3,526} = 12.7$, $P < 0.01$; figure 3 and table 2). Regressing slump growth rates against slump area showed a positive relationship between these two variables (figure 4 and table S2). When normalized by area, slump growth rates did not show significant differences among regions (table S2).

4. Discussion

4.1. Slump impacted terrain

Our mapping shows that retrogressive thaw slumping is an important driver of geomorphic change in environments in the western Canadian Arctic that are dominated by ice-rich morainal deposits (figures 1–3). In accordance with our first hypothesis, the variation in slump size, density, and growth among our study regions was related to landscape factors including surficial geology, topography, ground-ice distribution and geomorphic setting. For example, the Jesse Moraine on Banks Island had the greatest number of slumps and the largest total slump area impacted, making it one of the most intensively impacted

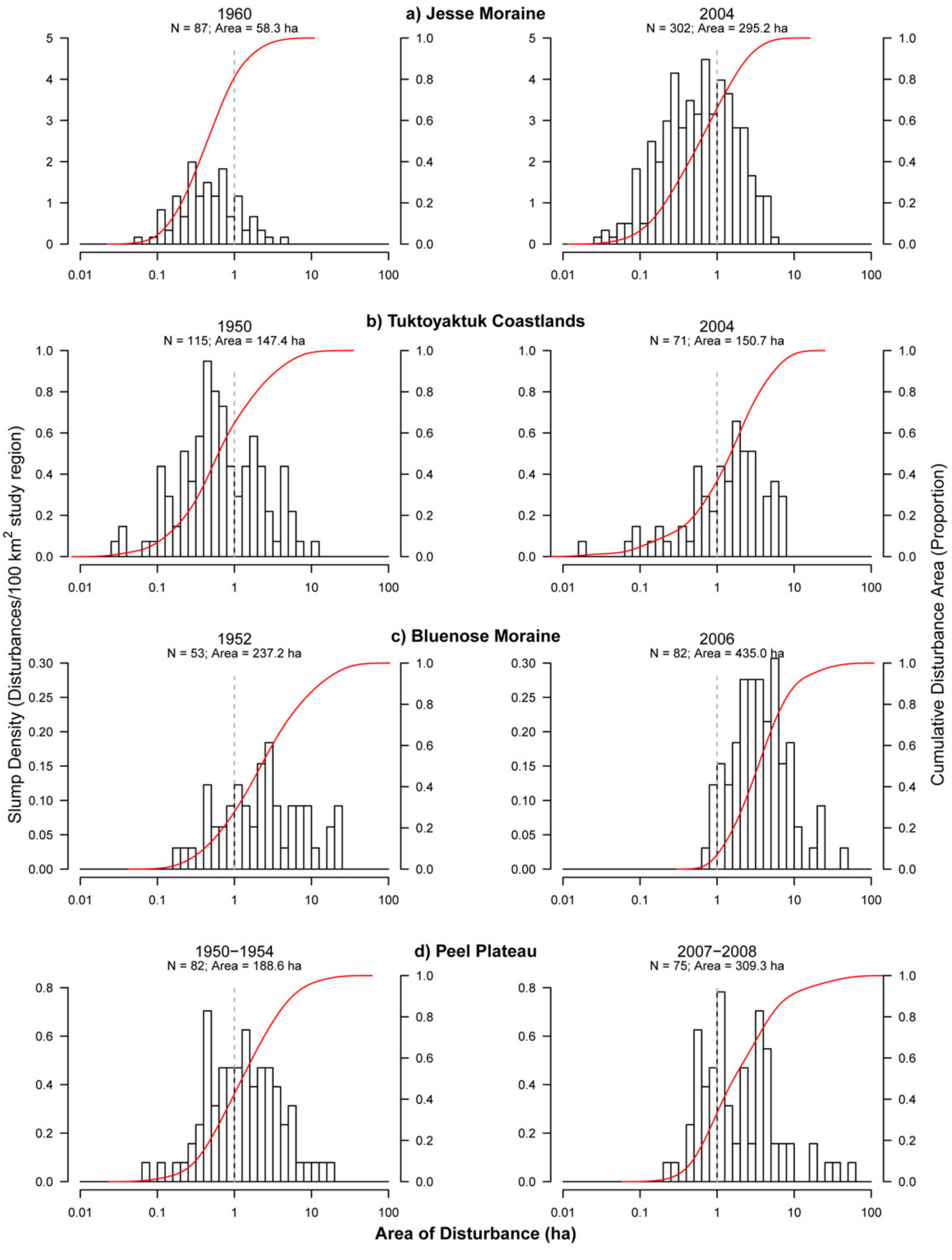

Figure 3. Histograms of slump area distributions mapped on historical (left) and modern (right) imagery in each region. Bars represent the number of slumps of different sizes standardized by study region (disturbances/100 km^2 study region). The red curve represents the cumulative disturbance area as a proportion. (a) The Jesse Moraine, (b) the Tuktoyaktuk Coastlands, (c) the Bluenose Moriane, and (d) the Peel Plateau. Note that *y*-axes differ among regions.

landscapes in the Canadian Arctic. The sensitivity of the ice-cored moraine on eastern Banks Island to thaw slumps is related to the widespread distribution of buried glacier ice in this area (Lakeman and England 2012), veneered by a thin till-layer, which can be less than 1 m thick.

Our data also show that ice-rich areas of greater relief promote the development of the large slumps. In the regions with greater relief (the Bluenose Moraine and Peel Plateau), topography promoted the downslope evacuation of thawed materials from the scar zone and the development of tall headwalls (Kokelj *et al* 2015) and perpetuated development of the largest disturbances. The Tuktoyaktuk Coastlands were characterized by relatively small lakeside slumps and the lowest proportional area impacted by disturbance.

Table 2. Mean slump size, slump density, and proportional area impacted in two time periods, showing both net and percent changes.

Study region	Year	Mean slump size ± SD (ha)	Slump density (#/100 km^2)	Proportional impact (ha slump/100 km^2 size of region)
Jesse Moraine	1960	0.67 ± 0.70	14.42	9.7
	2004	0.98 ± 1.02	50.06	49.0
	Difference (% change)	0.31 (+46%)	35.64 (+247%)	39.3 (+407%)
Tuktoyaktuk Coastlands	1950	1.27 ± 1.68	8.39	10.8
	2004	2.12 ± 1.93	5.18	11.0
	Difference (% change)	0.85 (+67%)	−3.21 (−38%)	0.2 (+2%)
Bluenose Moraine	1952	4.48 ± 5.67	1.62	7.3
	2006	5.30 ± 6.42	2.51	13.3
	Difference (% Change)	0.83 (+19%)	0.89 (+55%)	6.0 (+83%)
Peel Plateau	1950–1954	2.30 ± 2.99	6.42	14.8
	2007–2008	4.12 ± 7.81	5.87	24.2
	Difference (% change)	1.82 (+79%)	−0.55 (−9%)	9.4 (+64%)

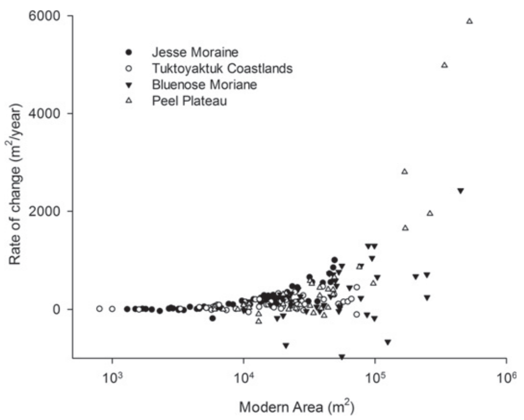

Figure 4. Retrogressive thaw slump growth rates versus modern slump size in the Jesse Moraine, Tuktoyaktuk Coastlands, Bluenose Moraine and Peel Plateau. Results of the least squares regressions for each study region are shown in table S2.

Slump sizes and densities in this region are partly limited by low relief and a greater proportion of lacustrine terrain that is not susceptible to thaw slumping (table 1).

Thaw slump development can have significant geomorphic and ecological impacts because this process rapidly degrades large volumes of ice-rich permafrost and effectively transports sediments and solutes from slopes to downstream environments (Lantuit *et al* 2012, Kokelj *et al* 2013, 2015). Increased slump activity in several of the regions we studied has been shown to exert major geomorphic and ecological impacts (Kokelj *et al* 2009a, 2013, 2015, Lantz *et al* 2009, Malone *et al* 2013, Thienpont *et al* 2013, Chin *et al* 2016). These impacts are likely to continue to intensify because sediment and solute yields increase nonlinearly as slumps enlarge, and once critical size thresholds are reached, several feedbacks intensify downslope sediment transfer and decrease the likelihood of rapid stabilization (Kokelj *et al* 2015, Lacelle *et al* 2015).

4.2. Slump intensification

The observation that thaw slump activity is intensifying across the range of climates in the four study regions is consistent with our second hypothesis and indicates that this form of permafrost degradation is emerging as the dominant driver of geomorphic change in areas of ice-rich moraine in the western Canadian Arctic (figures 1–3). There have been increases in the total number of slumps, mean area of slumps, and the proportion of terrain disturbed since the 1950s in all four of the regions we studied (table 2 and figure 3). This acceleration of thermokarst activity has occurred in conjunction with rising temperatures and increased snow and rainfall, suggesting that climatic factors are important influences. Significant winter warming has caused an increase in MAGT (Smith *et al* 2005) and an extension of the thaw season, which have likely both favoured thermokarst activity. Higher summer air temperatures can increase active-layer thickness (Zhang *et al* 1997, Hinkel *et al* 2001) and thaw near-surface ground ice, which leads to terrain instability. Warmer summer temperatures and radiative inputs are also correlated with ground ice ablation and variation in the rates of headwall retreat (Lewkowicz 1986), and previous observations of increased slump growth have been attributed to rising thaw season temperatures (Lantz and Kokelj 2008). However, our observation that long-term slump growth rates across the four study areas were strongly correlated with disturbance size, and not summer climate (figure 4) suggests that increasing temperatures are not the only driver of increased slump activity. The Jesse Moraine was characterized by the coldest air and permafrost temperatures as well as the lowest rate of summer warming; however, this region experienced the most dramatic intensification of slump activity (figure 3). Furthermore, when multi-decadal growth rates were normalized by slump size, there were no differences among regions with dramatically different summer climates (figure 4 and table S3). Climate trends also indicated that the increase in thaw season air temperatures have been substantially lower than winter warming (table 1). Although there is evidence that increasing permafrost temperatures, driven by rising air temperatures, can alter talik configuration and cause slump initiation along lakeshores (Kokelj *et al* 2009b), the rapidly warming, lake-rich Tuktoyaktuk Coastlands showed the lowest relative geomorphic change of all four regions studied. Taken together, this suggests that increasing air and permafrost temperatures were not the only drivers of the decadal-scale acceleration of thaw slump activity in the western Arctic.

Recent field studies in several parts of the Western Arctic indicate that increased rainfall is an important driver of the slump intensification we observed. Increased rainfall can make slopes unstable and increase landslides, gullying, and bank erosion (Cogley and McCann 1976, Lamoureux and Lafrenière 2009, Swanson 2012, Leibman *et al* 2014), all of which can increase the potential of thaw slump activity. The recent acceleration of slump activity on the Peel Plateau has been driven by a significant increase in the intensity of summer precipitation (Kokelj *et al* 2015). Investigation of sequential Landsat imagery and analysis detailed time series of slump sediment flux showed that rainfall events increased sediment removal from the slump scar zone and were an important driver of downslope debris tongue enlargement and slump perpetuation (Kokelj *et al* 2015). Summer season precipitation has increased substantially across all study regions, but the relative increase in rainfall has been greatest on Banks Island where the intensification of slumping has been most pronounced (table 1 and figure 3). The trend in increasing rainfall in this polar desert is supported by observations of recent gullying around the community of Sachs Harbor and the occurrence of thunderstorms and intense rainfall events previously unknown to Inuvialuit observers (Berkes and Jolly 2001, Jolly *et al* 2002). Our data suggest that rainfall-induced increases in slump activity are having profound geomorphic impacts on this fluvially-dominated, ice-cored polar desert landscape, despite the presence of cold, continuous permafrost. Additionally, the largest slumps, displacing the greatest volumes of sediment, were observed on the Peel Plateau, the wettest study area (figure 3 and table 1). Ultimately, it is likely that increased precipitation and air temperature are acting synergistically to intensify slump activity in the western Arctic. Increased rainfall can remove materials from the slump scar zone and perpetuate slump growth, while a longer thaw season and warmer temperatures can accelerate ablation and headwall retreat, and warmer winters may inhibit refreezing of scar zone materials.

4.3. Landscape factors affecting slump changes

Our analysis also shows that the response of permafrost landscapes to changing climate is strongly influenced by geomorphic setting, ground ice conditions, and paleogeography (Kokelj and Jorgenson 2013). Contrary to our third hypothesis, the ice-rich Jesse Moraine, with the coldest air and permafrost temperatures, experienced the greatest intensification of slump activity over the past 30 years; whereas, one of the warmest study areas, the Tuktoyaktuk Coastlands region, experienced the least amount of change (table 2 and figure 3). Several factors likely contribute to the sensitivity of the Jesse Moraine and the comparative stability of the Tuktoyaktuk Coastlands, including the lower proportion of terrain comprized of ice-rich moraine, and the lower topographic gradients in a lake-dominated environment. Because there are few streams, the potential for rainfall-induced fluvial erosion is minimal in the Tuktoyaktuk Coastlands. Furthermore, the massive ground ice deposits on the Tuktoyaktuk Coastlands are typically truncated 2–3 m below the terrain surface by a prominent thaw unconformity that developed during the Holocene thermal maximum (Burn 1997), which likely provides a thick protective layer. During this warm period, the Arctic coastline was up to 150 km north of its present location and the Laurentide Ice sheet had retreated several hundreds of kilometers eastward. The warm climate conditions in this region allowed colonization by spruce forest (Ritchie *et al* 1983), and likely the occurrence of forest fire that can result in deeper thaw (Mackay 1995), truncation of the near-surface massive ice, and widespread thermokarst activity (Rampton 1988, Murton 2001). The paleogeographic and terrain factors that characterize the Tuktoyaktuk Coastlands have made it more resilient to contemporary climate-driven thermokarst than the other areas examined in this study. The Jesse Moraine on Banks Island is extremely susceptible to slump intensification because extensive deposits of massive ground ice, likely consisting largely of buried glacier ice, are covered by a thin overburden of till (Lakeman and England 2012). The high density of smaller slumps that we mapped on Jesse Moraine, many of which were initiated recently, demonstrates that this region has emerged as one of the most dynamic thermokarst environments on the planet (figure 3 and table 2).

5. Conclusions

(1) Thaw slump activity is accelerating in ice-rich morainal landscapes of the western Canadian Arctic, where it is emerging as a dominant driver of geomorphic change.

(2) In conjunction with warming air and permafrost temperatures, increased precipitation is an important driver of thaw slump intensification in the western Canadian Arctic.

(3) Landscape factors including topographic relief, ground ice conditions, and Quaternary history strongly influence slump development, including the magnitudes and rates of geomorphic change.

(4) Ice-cored landscapes in cold permafrost environments are highly vulnerable to thaw slump intensification.

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