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Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon

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Key Points:

- Between 1950 and 2009, total lake area declined, but the total number of lakes increased
- Most of this change was driven by thermokarst lake drainage
- Climatic and thermokarst processes have distinct impacts in lake-rich regions

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Abstract Growing evidence indicates that lake-dominated ecosystems at high latitudes are undergoing significant hydrological changes. Research examining these changes is complicated because both thermokarst and climatic processes likely influence lake dynamics. To examine the relative impacts of these processes in permafrost landscapes, we investigated the dynamics of lake area and number in Old Crow Flats (OCF), Yukon using historical air photos and satellite imagery. Between 1951 and 2007, OCF experienced a decline of ~6000 ha in total lake area but gained 232 lakes. Close to half (49%) of the difference in lake area was driven by the rapid and persistent drainage of 38 large lakes. These catastrophic drainages were associated with new or enlarged outlet channels, resulted in the formation of numerous residual ponds, and were likely driven by thermokarst processes. Our analysis shows that catastrophic lake drainages have become more than 5 times more frequent in recent decades. These changes are likely related to the impacts of increased temperature and precipitation on thermokarst processes. Fifty-nine of the 170 intensively studied lakes showed either large bidirectional fluctuations or gradual cumulative declines. These changes affected a much smaller portion of OCF and were likely driven by interactions between increased precipitation and temperature and individual catchment characteristics. To anticipate landscape-scale changes in these systems, and assess their impact on hydrology, wildlife habitat, and carbon storage, field research is required to better characterize the mechanisms responsible for changes.

1. Introduction

Over the next century, continued increases in temperature and precipitation at high latitudes are anticipated to dramatically alter ecosystems underlain by permafrost [*Avis et al.*, 2011; *Kokelj et al.*, 2013; *Lawrence et al.*, 2012; *Natali et al.*, 2012; *Schuur et al.*, 2011]. Permafrost landscapes rich in ground ice are likely to be particularly sensitive because the degradation of ice-rich permafrost can catalyze thermokarst disturbances with significant ecological and geomorphological impacts [*Kokelj et al.*, 2013; *Kokelj and Jorgenson*, 2013; *Lantz et al.*, 2009]. Widespread thermokarst activity and landscape alteration during warm episodes of Earth history suggest that increasing air temperatures are likely to increase the frequency of these disturbances [*Burn*, 1997; *Jones et al.*, 2011; *Murton*, 1996; *Rampton*, 1988; *Reyes et al.*, 2010]. Recent increases in ground temperature coupled with observations of increased thaw slump activity, degrading ice wedges, and collapsing peat plateaus provide an indication that increases in thermokarst activity are already underway [*Burn and Kokelj*, 2009; *Jorgenson et al.*, 2006; *Kokelj et al.*, 2013; *Lantz and Kokelj*, 2008; *Riordan et al.*, 2006; *Romanovsky et al.*, 2010]. To date, relatively few landscape-scale investigations of thermokarst dynamics have been completed. Additional studies are required to characterize current rates of change and assess the factors influencing susceptibility to thermokarst in both continuous and discontinuous permafrost landscapes.

One of the most dramatic consequences of thermokarst is catastrophic lake drainage. Initiated by a range of processes causing thermomechanical erosion, catastrophic drainage can occur rapidly (hours or days), yielding a drained basin, which persists for millennia [*Hinkel et al.*, 2003; *Mackay*, 1988; *Marsh and Neumann*, 2001]. In areas of discontinuous permafrost where soils have high hydraulic conductivity, internal lake drainage can also be initiated by talik expansion that alters subsurface groundwater connections [*Yoshikawa and Hinzman*, 2003]. In many regions, lake drainage has been occurring since the mid-Holocene [*Hinkel et al.*, 2003; *Mackay*, 1999]. However, recent research using satellite imagery and historical photos indicates that the rate of lake drainage in some regions has changed during recent decades. In areas of discontinuous permafrost, *Smith et al.* [2005] and *Riordan et al.* [2006] have reported reductions in the number of lakes and lake area. In areas of continuous permafrost, recent findings are more variable and include increases in lake area [*Smith et al.*, 2005] and number

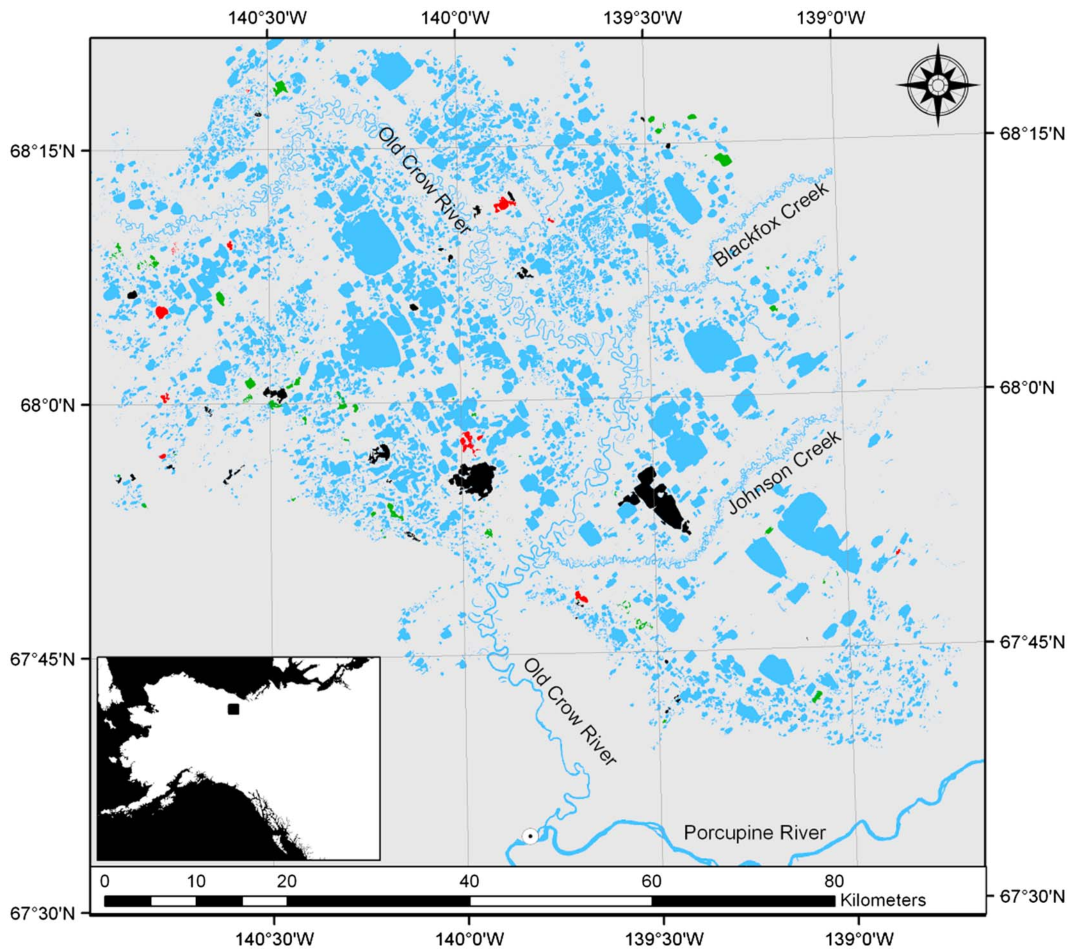

Figure 1. Map of the study area showing the drained lakes assessed in this study. Lakes shown in black exhibited catastrophic drainages (persistent reductions in area greater than 30%). Lakes shown in green exhibited large bidirectional changes in area greater than 30%. Lakes shown in red exhibited a gradual cumulative reduction of 30% in area. The black box in the inset map at the bottom left shows the location of the study area in western North America.

[*Jones et al.*, 2011; *Smith et al.*, 2005], evidence of stability in lake area and number [*Riordan et al.*, 2006; *Rover et al.*, 2012], and decreases in lake area [*Jones et al.*, 2011; *Labrecque et al.*, 2009]. Despite this variation, recent studies have been taken as evidence that the number of thermokarst drainages is increasing in the area of discontinuous permafrost and are stable or increasing in areas of continuous permafrost [*Jones et al.*, 2011].

Recent evidence from across the Canadian North indicates that climatic variation can also alter lake area. In many regions, increases in lake desiccation have been associated with the impacts of elevated air temperature and lengthening ice-free seasons on evaporation [*Bouchard et al.*, 2013; *Carroll et al.*, 2011; *Smol and Douglas*, 2007]. Evaporation is particularly important for lakes that receive less water from snowmelt [*Bouchard et al.*, 2013; *Turner et al.*, 2014]. Since many recent studies on northern lake dynamics identified drained lakes by examining changes between images separated by 15–20 years [*Hinkel et al.*, 2007; *Jones et al.*, 2011; *Labrecque et al.*, 2009], it is unclear if observed changes were mediated by thermokarst processes (resulting in rapid and permanent shifts) or by the impact of climate change on water balance (resulting in gradual changes or large bidirectional fluctuations). To clarify if lake drainage mediated by thermokarst is increasing, case studies that distinguish among hydrological scenarios and processes leading to changes in lake area are required. Such research may also help to clarify the range of processes driving changes in lake area and whether shifts in regional climate are influencing thermokarst-induced lake drainage. In this study we used remotely sensed images to map the number and area of all the lakes in Old Crow Flats, Yukon during four time periods (1951, 1972, 1994, and 2007). To evaluate the processes contributing to changes in lake area and number, we used the nearly annual record of Landsat images after 1973 to

Table 1. Air Photos and Satellite Imagery Used to Study the Lakes of Old Crow Flats

Image Source	Dates	Resolution
Gray-scale air photo	1951–1952	15 m
Gray-scale air photo	1972	15 m
Landsat 1	1973–1977	79 m
Landsat 2	1975–1980	79 m
Landsat 3	1977–1982	79 m
Landsat 4	1983	30 m
Landsat 5	1994; 1984–1999; 2003–2010	30 m
Landsat 7	2000–2002	30 m
SPOT 5	2007	10 m

classify changes in lake area as either (1) catastrophic drainages, (2) large bidirectional fluctuations, or (3) gradual cumulative declines.

2. Methods

2.1. Study Area

This study focuses on the northern portion of the Old Crow Flats Ecoregion (Old Crow Flats). This area is located in northwestern Canada approximately 150 km south of the Beaufort Sea Coast (Figure 1). The regional climate is continental and is characterized by cold winters (mean January temperature = −31.1°C) and warm summers (mean July temperature = 14.6°C). Mean annual precipitation measured at the Old Crow Airport is 266 mm with slightly less than half falling as snowfall [*Turner et al.*, 2010]. The boundaries of Old Crow Flats Ecoregion are defined by the extent of Glacial Lake Old Crow, which occupied the area at the end of the last glaciation (~15,000 years B.P.), and soils are underlain by thick glaciolacustrine silt and clay sediments rich in ground ice [*Roy-Léveillée and Burn*, 2011; *Smith et al.*, 2004; *Zazula et al.*, 2004]. Over 8700 lakes and small ponds occupy roughly 23% of this 5600 km^2 area [*Turner et al.*, 2014] and are perched above the flow of the Old Crow River drainage network that exports water south to the Porcupine River and westward to the Yukon River (Figure 1). This landscape is a mosaic of terrestrial, riparian, and aquatic environments that provide abundant habitat for muskrat, moose, fishes, and migratory birds [*Smith et al.*, 2004].

Old Crow Flats is part of the traditional territory of the Vuntut Gwich'in, who refer to this area in Gwich'in as *Van Tat* (meaning land of many lakes). This ecosystem holds enormous cultural value for the Vuntut Gwich'in, who have used this area for subsistence for thousands of years [*Vuntut Gwitchin First Nation and Smith*, 2009]. Old Crow Flats was designated as a Ramsar wetland of International Importance in 1982. A large portion of Old Crow Flats is included in Vuntut National Park, and the remainder is protected by an agreement between the Vuntut Gwitchin First Nation (VGFN) and the Yukon government [*Parks Canada*, 2010]. Recently, Vuntut Gwich'in land users have become concerned about environmental change in this important ecosystem and have reported an increase in the number of lakes draining and drying in recent years [*Arctic Borderlands Ecological Knowledge Cooperative* (*ABEK Coop*), 2007; *Wolfe et al.*, 2011].

2.2. Classifying Changes in Lake Area

To identify and characterize lake drainages in Old Crow Flats, we assembled a series of remotely sensed images from 1951 to 2010 (Table 1). This included gray-scale air photos from the National Library of Canada (1951, 1952, and 1972), Landsat images (1973–2010), and SPOT 5 imagery acquired in 2007 (Table 1). Landsat images were obtained from the U.S. Geological Survey archive. Orthomosaics prepared by *Labrecque et al.* [2009] were supplemented with additional air photos georeferenced using ArcGIS (version 9.3.1).

In the first part of our analysis, we used panchromatic air photos from 1951, 1952, and 1972 and satellite imagery from 1994 (Landsat 5) and 2007 (SPOT 5) to digitize the extent of the more than 8700 lakes and ponds in the study area (Table 1). The resultant data layers were used to calculate the number and area of lakes in each time period mapped (Table 2). Subsequently, any lake larger than 2 ha ($n = 3312$), which exhibited a change in surface area greater than 5% during any of the 3 time intervals ($n = 170$), was subjected to the more detailed analysis described in the next paragraph.

To examine the changes in area in these lakes, we used the Landsat archive (1973–2010) to quantify the interannual changes in lake area by digitizing the shorelines of all 170 lakes on an annual basis. Cloud-free Landsat images acquired during the snow-free season were available for all years except 1974 and 1998. This allowed us to map the 170 study lakes in 1973, all years from 1975–1997 and 1999–2010. To minimize mapping error, we manually digitized the boundaries of each lake while viewing imagery on screen. Digitization was completed using ArcGIS (version 9.3.1), and lake areas were calculated using Hawths Analysis Tools for ArcGIS (version 3.2.7).

In the first part of the analysis, lakes were digitized using gray-scale air photos and panchromatic satellite images (Table 1). In the second component of the analysis, we delineated the boundaries of each lake using color infrared imagery from Landsat and SPOT. To assess the percent mapping error associated with varying image resolutions and lake sizes, we mapped 12 lakes of varying size using the same image downsampled to the following resolutions: 10 m, 15 m, 30 m, and 79 m. This analysis showed that increased mapping error was associated with decreasing lake size and image resolution. When lakes in all size classes were mapped using imagery with resolutions ≤30 m map, error ranged from 0.2 to 1.3%. Mapping error associated with the coarsest imagery (Landsat Multispectral Scanner (79 m)) varied with lake size and ranged from 1 to 16%. In the first part of our analysis, we used images with resolutions ≤30 m, and we are confident that we could detect changes greater than 5% in all lakes >2 ha. Since the second part of our analysis involved lower-resolution imagery, less well-suited to detect small changes, we opted to use the more conservative threshold of changes described in the next section.

To discriminate between (1) catastrophic drainages, (2) large bidirectional fluctuations, and (3) gradual cumulative changes in lake area, we calculated an index of proportional change in lake area between subsequent years.

$$\Delta \ \mathrm{Area}(\mathrm{Lake}_i) = \frac{\mathrm{Area}_t - \mathrm{Area}_{t+1}}{\mathrm{Area}_{1972}}$$

For complete drainages, this index takes on a value of 1. Lakes that exhibited small changes have values close to zero, and lakes that increased in area over the period of comparison have negative values (negative losses). This index was calculated annually for all 170 lakes. Since image acquisition dates ranged from May to September, this index allowed us to date a change in area within a 16 month window (from May of 1 year and September of the following year). Changes in this index over time were used to classify each of the 170 lakes into the following categories:

1. Catastrophic drainages: Decreases in lake area ≥30% occurring between subsequent images (e.g., 1981–1982), with no increase in area ≥30% over remainder of the data record. We used a threshold of 30% because it was similar to the threshold used by *Hinkel et al.*, 2007 but also enabled us to detect changes in small lakes (2–4 ha) where mapping error was relatively high.
2. Large fluctuations: Increase or decrease in lake area ≥30% occurring between subsequent images (e.g.,1981–1982) followed by a decrease or increase ≥30%, respectively.
3. Gradual-cumulative declines: Decrease in lake area ≥30% over the entire record resulting from cumulative annual losses in area.
4. No threshold change: Lake did not exhibit an increase or decrease in area ≥30% between subsequent images or over the entire period of record.

2.3. Estimating Catchment Area

To estimate the catchment area of each of the 170 lakes, we used a SPOT 5 image acquired in July 2007, Canadian National Topographic Database vector data showing creek locations, and a digital elevation model (30 m horizontal resolution; available from Yukon Geomatics) to manually digitize catchment area in ArcGIS (version 10.1). Portions of catchments within peripheral headwater locations were easily distinguishable as elevation changes and the location of stream networks were visible in the available spatial data. For areas with less relief, SPOT imagery was particularly helpful for estimating the extent of lake catchments. For example, surface flow pathways not often represented in the creek vector spatial data were visible in the SPOT image. Where no hydrological connection was visible between adjacent lakes, a catchment boundary was assumed to bisect the terrestrial area between water bodies. The 2007 SPOT imagery was also used to digitize lake areas, and these values were used to calculate lake area to catchment area ratios for each of the 170 lakes.

2.4. Climate Data and Statistical Analysis

To explore changes in regional climate from 1953 to 2010, we used the meteorological data from the Old Crow Airport to calculate average annual temperature and total precipitation [*Environment Canada*, 2010]. Climate indices were calculated for September 1 to August 31 of each year since any climate-driven changes in lake area (detected between May of 1 year and September of the following year) were likely associated

Table 2. The Area and Number of Lakes in Old Crow Flats During Each Time Period

Year	Area (ha)	Total	<1 ha	1–10 ha	10–50 ha	50–500 ha	>500 ha
1951	121,981	8787	4445	2910	1011	389	32
1972	121,601	8821	4472	2912	1018	388	31
1994	117,304	8929	4512	2981	1032	375	29
2007	115,701	9019	4563	3032	1024	372	28

with this interval. Data recorded at three other stations within 230 km of the OCF were used to compliment the Old Crow Airport record. Stations with the longest records were located north and east of Old Crow (Komakuk Beach, Aklavik, and Fort McPherson). The Mann-Kendall test was used to examine trends in temperature and precipitation for data from each station over the period of record. This approach has been widely used for trend analysis [e.g., *Zhang et al.*, 2000] since it is robust against nonnormality and missing values in data records [*Helsel and Hirsch*, 2002; *Hirsch and Slack*, 1984]. Years omitted from the Old Crow record include 1955–1970, 1972–1980, 2003, and 2006. Trend analysis values were calculated using the water quality (wq) package (version 0.4–1) in *R* (version 3.0.3; 24 December 2014, The R Foundation for Statistical Computing, www.r-project.org). Output included the test statistic *S*, which measures the monotonic dependence of climate variables on time and two measures of significance (*P* value and *Z* score). Trend lines were fit to each station's data using the Theil-Sen slope [*Helsel and Hirsch*, 2002], output from the wq package, and the estimated intercept calculated using the following equation from *Conover* [1980]:

$$b = Y_{\text{median}} - m \times X_{\text{median}}$$

where b is the estimated intercept, Y_{median} is the median value (temperature or precipitation), m is the estimated slope, and X_{median} is the median year of the years with adequate data (<15 days missing).

3. Results

The total surface area of all lakes and ponds in Old Crow Flats decreased by 6280 ha between 1951 and 2007. The 380 ha decline that occurred between 1951 and 1972 was modest compared with the changes in area that took place between 1972 and 1994 and 1994 and 2007. During these periods, lake area dropped by 4297 ha and 1603 ha, respectively (Table 2). Over the same time period, the total number of lakes and ponds in Old Crow Flats increased from 8787 to 9019. The increase in total lake number was driven by the formation of small lakes and ponds after 1972 (Table 2). Larger lakes showed modest decreases in number over the period of record (Table 2).

A total of 170 lakes in Old Crow Flats showed a change in area greater than 5% between 1951/1952 and 1972, 1972 and 1994, or 1994 and 2007. Of these lakes, 38 (~20%) exhibited a catastrophic drainage (Table 3). These permanent decreases in area ranged from 30 to 100%, but the majority of drainages were partial (Figure 2). Prior to their drainage, these 38 lakes ranged in size from 2 to 1602 ha (mean area = 120 ha). In 2010, they were made up of 122 residual water bodies that ranged in size from 0.0002 to 474 ha with a mean of 13 ha. On average, these lakes had low lake area to catchment ratios (0.058; Table 3). The majority of lakes in this category showed clear evidence of new, or significantly enlarged, outlet channels following drainage (Figures 2e and 2f). One of the largest drainage events was directly observed in the spring of 2007, when the water level of Zelma Lake exceeded maximum capacity and an alternate outflow gulley to an adjacent creek was formed that drained over 80% of the lake water volume within a few weeks (Figure 2e) [*Turner et al.*, 2010].

Table 3. Classification of Changes in Lake Area (1951–2010) of 170 Study Lakes in the Old Crow Flats

Lake Class	No. of Lakes (1951–1972)	No. of Lakes (1972–2010)	Mean Lake Area (ha)	Lake Area: Catchment Area
Catastrophic drainage	4	34	123	0.058 (0.089)
Large bidirectional fluctuation	NA (not applicable)	47	35	0.047 (0.072)
Gradual cumulative decline	NA	12	67	0.144 (0.094)
No threshold change	NA	73		0.161 (0.165)

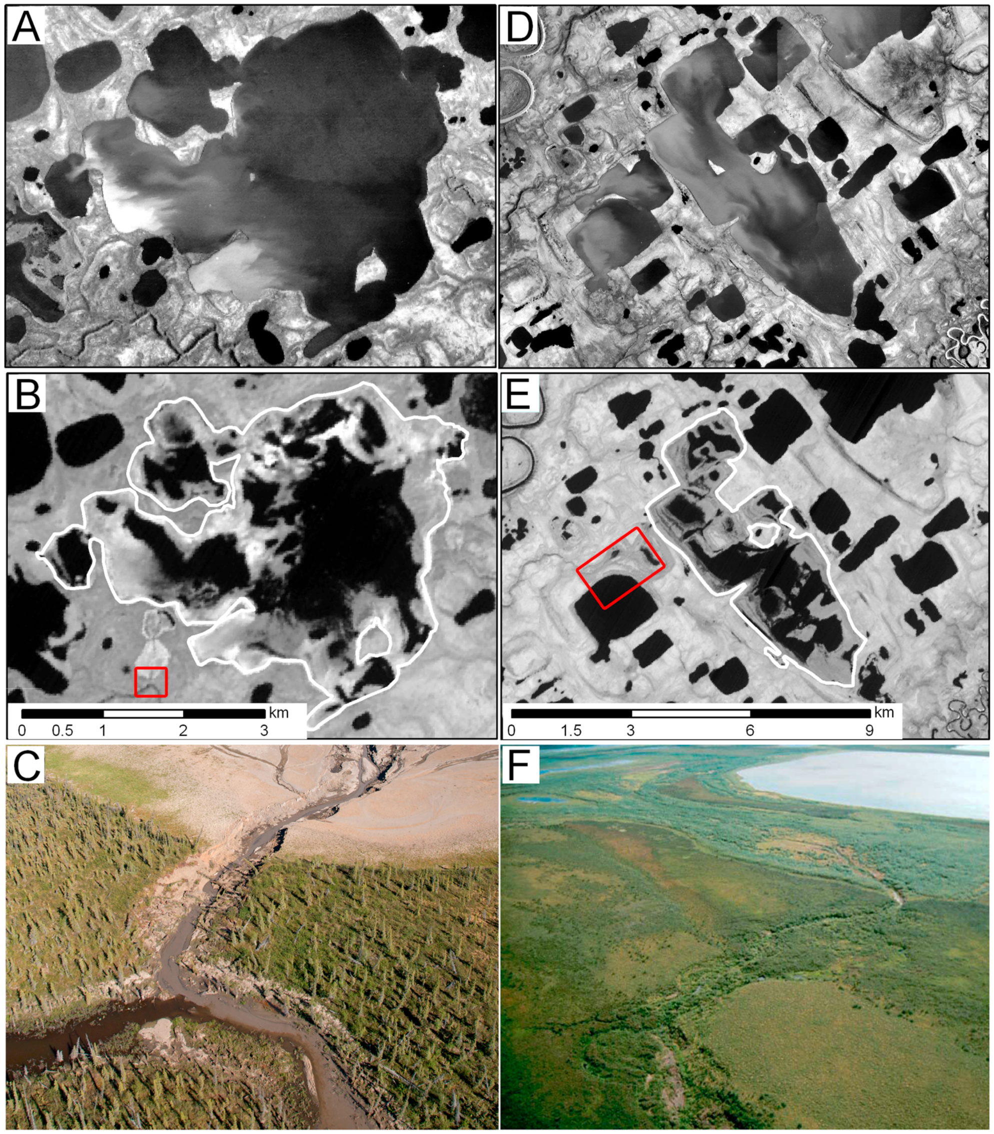

Figure 2. Images showing examples of two large catastrophic drainages in Old Crow Flats: (a) Zelma lake prior to drainage in 1972; (b) Zelma lake following catastrophic drainage in 2007; (c) oblique photo showing the new outlet where Zelma lake drained into the Old Crow River; (d) Netro Lake in 1972 prior to drainage; (e) Netro lake in 2007, 24 years following catastrophic drainage; and (F) oblique photo showing the outlet where Netro lake drained into the Old Crow River in 1983. The approximate area of the oblique photos is shown by the red boxes in Figures 2b and 2d.

A comparison of the frequency of these events in three time periods shows that catastrophic drainages have increased considerably in recent decades (Figure 3). The annual rates of catastrophic drainage from 1972 to 1990 and 1991 to 2009 were 0.94 and 1.05, respectively. This is 4–5 times greater that the annual rate from 1951 to 1972 (Figure 3). Thermokarst processes have also been shown to drive shoreline recession in some parts of Old Crow Flats [*Roy-Léveillée and Burn*, 2011], but it is likely that our approach was too coarse to detect increases in surface area, resulting from shoreline recession rates between 0.1 and 2 m/yr [*Roy-Léveillée*, 2014].

Forty-seven of the lakes we examined in detail were classified as large bidirectional changes (Figure 4). These lakes were characterized by a reduction in area ≥30% between 1972 and 2009, followed by a reversal of the observed change (Table 2). Typically, an increase in area occurred within 1–3 years of the reduction in area but sometimes took more than 5 years. In some cases, sequential "draining" and "filling" occurred up to 6 times within the 37 year record. Lakes exhibiting large bidirectional changes were smaller than lakes

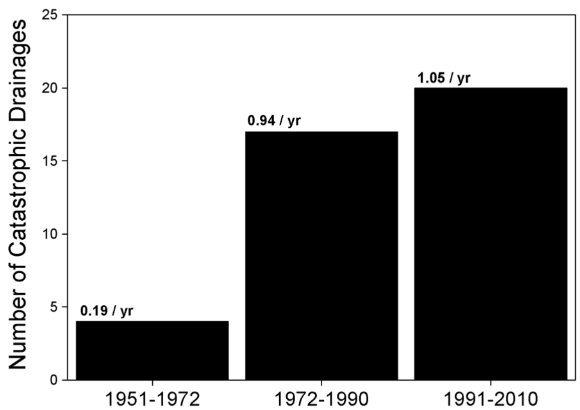

Figure 3. The number of catastrophic lake drainages in Old Crow Flats between 1951–1972, 1972–1990, and 1991–2010. The number above each bar shows the annual rate of catastrophic drainage for each time period.

exhibiting catastrophic drainages (1.5–179 ha with a mean area = 35 ha) and had low lake area to catchment ratios (0.047; Table 3). Although our results show that bidirectional changes are common in Old Crow Flats, it is likely that our change detection approach, which focused on interannual variation in lakes that exhibited a 5% change in area between 1951–1972, 1972–1994, and 1994–2007, underestimated the overall number of bidirectional fluctuations.

Twelve of the lakes we examined showed gradual cumulative declines that exceeded the 30% threshold (Table 2). These lakes ranged in size from 7 to 187 ha (mean = 67 ha) and had a mean lake area to catchment area ratio 3 times higher than other lakes exhibiting ≥30% changes in area. We did not observe any gradual cumulative increases in area exceeding 30%. Our classification of changes in lake area indicates that most of the reductions in the total lake area in Old Crow Flats were driven by the rapid catastrophic drainages of larger lakes, which exposed a total of 2896 ha of lake bottom. Lakes showing gradual cumulative declines and large bidirectional changes of ≥30% affected a much smaller portion of Old Crow Flats: 311 ha and 848 ha, respectively.

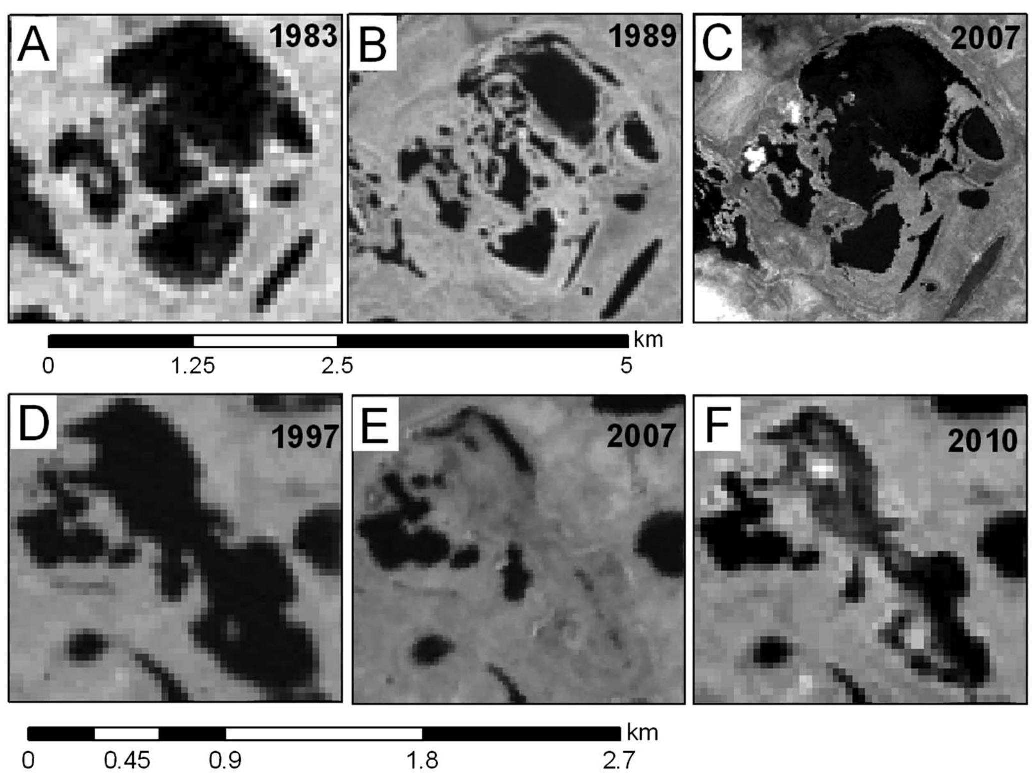

Figure 4. Examples of large bidirectional fluctuations in lake area in Old Crow Flats. (a–c) Lake 8240, which exhibited decreases exceeding 30% followed by increases of equal magnitude 2 times between 1973 and 2010. (d–f) Lake 14451, which exhibited decreases exceeding 30% followed increases of equal magnitude 4 times between 1973 and 2010.

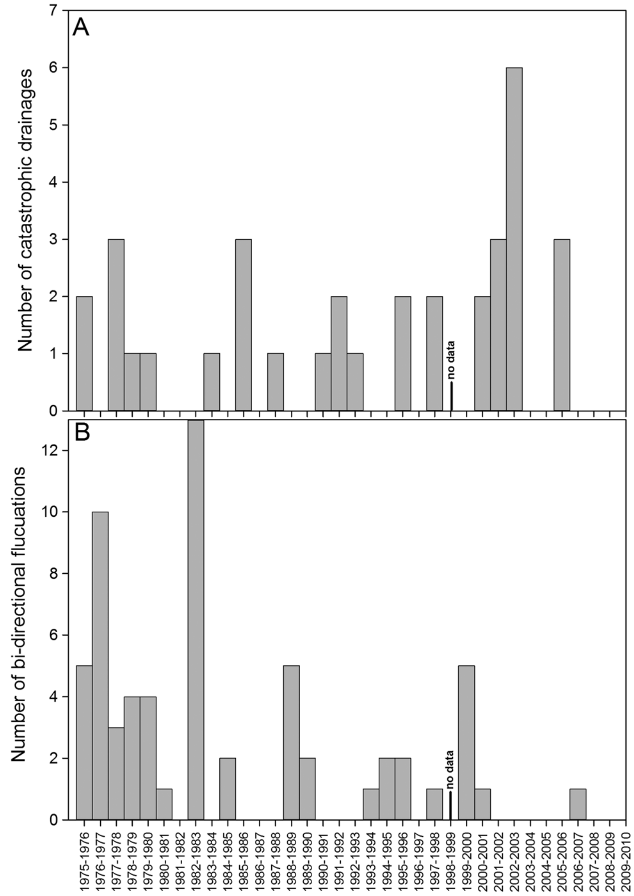

Figure 5. The frequency of catastrophic drainages and bidirectional fluctuations in Old Crow Flats between 1976 and 2010. Catastrophic drainages (Figure 4a) are lakes that exhibited reductions in area exceeding 30% that remained stable over the period of record. Bidirectional fluctuations (Figure 4b) are lakes that showed rapid reductions in area that did not persist over time but were followed by large increases within 1–5 years.

Using the Landsat archive, we were able to isolate the date of each event within a 16 month window. Figure 5a shows the timing of catastrophic drainages over the period of record. This graph indicates that catastrophic drainages have been relatively common in Old Crow Flats in the last three decades, typically occurring every 1 or 2 years, with only a few gaps of more than 2 years. Although they were more frequent overall, large bidirectional fluctuations showed the opposite pattern, with years of drainage clustered together in time, frequently separated by gaps of 3 or more years (Figure 5b).

Mann-Kendall trend analysis showed a significant (~2.5°C) increase in average annual temperature in Old Crow between 1953 and 2010 (Figure 6a and Table 4). Total annual precipitation in Old Crow also increased significantly over the period of record (Figure 6b and Table 4). Increases in temperature were also significant at Komatuk Beach and Aklavik, and precipitation increases were significant at Komakuk Beach (Figure 6; Table 4). Temperature and precipitation at Fort McPherson did not exhibit significant trends over time (Figure 6). It should be noted that most of the climate records prior to 1980 are missing from the Old Crow record. Hence, it is possible that the increasing trend for Old Crow may more subtle and similar to the other locations. However, these positive trends are consistent with tree ring records for Old Crow Flats [*Porter and Pisaric*, 2011] and a range of analyses in the western Arctic reporting significant increases in mean annual temperature and total precipitation [*Bonsal and Kochtubajda*, 2009; *Saito et al.*, 2013; *Stafford et al.*, 2000; *Zhang et al.*, 2000].

4. Discussion

Our analysis of historical imagery demonstrates that the landscape evolution of Old Crow Flats is strongly influenced by catastrophic lake drainage. Between 1952 and 2010, 38 lakes showed a single and persistent reduction in lake area that exceeded 30% of the lakes original size. The fact that these events occurred within a relatively short window (12–18 months) and were associated with the presence of new or enlarged outlets (Figure 2) strongly indicates that they were driven by thermomechanical erosion. In ice-rich permafrost environments like Old Crow Flats [*Roy-Léveillée and Burn*, 2011], both thermal and mechanical erosion can facilitate the development of new outlets causing rapid and irreversible lake drainage [*Hinkel et al.*, 2007; *Jorgenson et al.*, 2006; *Mackay*, 1988]. Between 1952 and 2010, 38 lakes drained in the OCF in this manner, increasing the terrestrial surface of the Flats by 2896 ha, accounting for close to half of the overall decline in lake area between 1972 and 2007. Since the majority of these changes were partial and left numerous residual water bodies (Figure 2), these events also explain our observation that the decrease in the total area of lakes in the OCF was accompanied by an increase in the number of small lakes and ponds, similar to what *Jones et al.* [2011] described for thermokarst lake dynamics on the northern Seward Peninsula in Alaska.

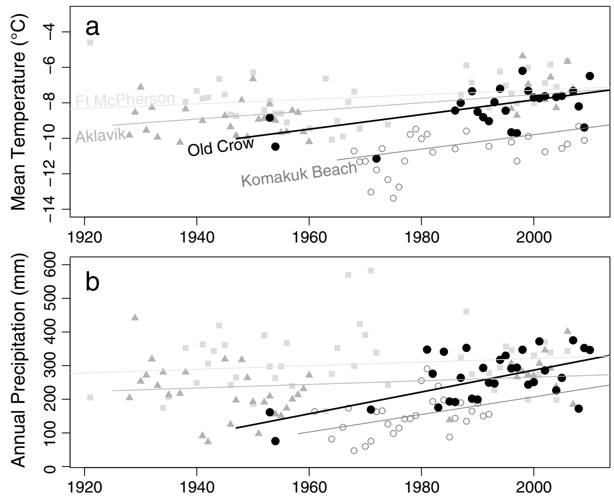

Figure 6. Climate records from four stations in the western Arctic. (a) Average temperature and (b) total precipitation recorded at the Old Crow Airport (1953–2010), Komakuk Beach (1961–2010), Yukon, Aklavik, Northwest Territories (1928–2010), and Fort McPherson, Northwest Territories (1921–2010). Theil-Sen lines illustrate temporal trends in climate values. Increases in temperature were significant at Old Crow, Komatuk Beach, and Aklavik, and precipitation increases were significant at Old Crow and Komakuk Beach (Table 4).

Our observation that the frequency of catastrophic drainage in Old Crow Flats has increased in recent decades is consistent with local perceptions that lakes in the Flats are showing declining water levels [*ABEK Coop*, 2007]. However, compared to other locations within the continuous permafrost zone, the rapid shift in the rate of catastrophic drainage is unusual. On the coastal plain of Alaska *Hinkel et al.* [2007] observed a drainage rate of 0.57 lakes/yr/10,000 km^2 between 1974 and 2001. In the Tuktoyaktuk coastlands, *Mackay* [1988] estimated a drainage rate of 2.31 lakes/yr/10,000 km^2. Recent analysis in both these regions suggests that the rate of catastrophic drainage is stable or declining, respectively [*Hinkel et al.*, 2007; *Marsh et al.*, 2009]. In Old Crow Flats, an increase in the rate of catastrophic drainage from 0.36 to 2.02 (lakes/yr /10,000 km^2) between 1950 and 2009 has significantly altered the nature of the landscape. An increase in catastrophic lake drainage in the OCF also emphasizes that regions within the continuous permafrost zone are undergoing differential responses to changing climatic conditions. The dynamics of catastrophic lake drainage and other thermokarst processes likely depend on a range of factors including ground ice content, surficial materials, topography, hydrology, and changes in regional climate.

It is likely that the changes we observed in Old Crow Flats were associated with recent changes in regional climate. Although the nature of the climate record at all stations (missing and incomplete years) precluded a robust analysis of the correlation between climate and drainage frequency, the nature of the processes involved suggests that recent increases in temperature and precipitation have facilitated the observed changes. Catastrophic lake drainage in ice-rich permafrost environments often follows thermomechanical erosion and lake expansion. Specific mechanisms include headward erosion by stream networks [*Hinkel et al.*, 2007; *Jones et al.*, 2011], thermo-erosion of ground ice [*Hinkel et al.*, 2007; *Mackay*, 1988, 1999], and bank overflow during the periods of high precipitation, rapid snowmelt, snow damming of the lake outlet [*Hinkel et al.*, 2007; *Jones et al.*, 2011; *Mackay*, 1988], lake expansion toward an existing drainage network [*Jones et al.*, 2011], and coastal erosion [*Hinkel et al.*, 2003; *Mackay*, 1988; *Mars and Houseknecht*, 2007]. These threshold processes are episodic and site specific [*Hinkel et al.*, 2003; *Mackay*, 1988], but all of them would be facilitated by the increases in air temperature and precipitation that have been observed

Table 4. Summary Statistics From the Mann-Kendall Analysis of Climate Parameters[a]

Parameter	Location	*S* Statistic	*Z* Statistic	*P* Value
Temperature	**Komakuk Beach**	**123**	**2.689**	**0.007**
	Fort McPherson	97	1.207	0.227
	Aklavik	**165**	**2.431**	**0.015**
	Old Crow	**96**	**2.219**	**0.027**
Precipitation	**Komakuk Beach**	**106**	**2.074**	**0.038**
	Fort McPherson	82	0.819	0.413
	Aklavik	92	1.022	0.307
	Old Crow	**147**	**2.481**	**0.013**

[a]The *S* statistic measures the monotonic dependence of climate variables on time, and the Z statistic and the *P* value are measures of significance. Trends with *P* values ≤0.05 are shown in bold.

in Old Crow Flats. Warming air and ground temperatures have likely increased thaw depth and ground subsidence of ice-rich soils, which may have increased lake expansion and the development of new outlets. Our observation that the year with largest number of catastrophic drainages (2002–2003) was preceded by one of the wettest years on record (Figures 5 and 6) also suggests that recent shifts in precipitation have also catalyzed observed landscape changes.

Recent research in Old Crow Flats shows that lake hydrology is strongly influenced by interactions between cumulative precipitation and catchment characteristics, which together are likely to drive multiple response trajectories for individual lakes [*Turner et al.*, 2014]. Our analysis showing several distinct response classes among our study lakes is consistent with these predictions. In addition to the 38 lakes that exhibited catastrophic drainage in Old Crow Flats, 59 of the lakes we studied showed large changes in area that were either nonpermanent or occurred gradually. The fact that these changes in lake size were reversible, or occurred gradually, suggests that climatic variation, and not thermokarst processes, was the key driver of these changes. Our observation that some lakes exhibited gradual cumulative decreases and others showed bidirectional fluctuations is also consistent with the hypothesis that lakes will respond differently to shifts in precipitation and temperature depending on their catchment characteristics. Small lakes within small catchments tended to show gradual cumulative declines in area, suggesting that hydrologic inputs for these lakes are insufficient to offset the effects of evaporation in dry years [*Marsh and Bigras*, 1988; *Turner et al.*, 2014]. Air temperature increases in OCF over recent decades [*Porter and Pisaric*, 2011] are likely playing a key role in the susceptibility of these small-catchment lakes to evaporation and potential desiccation during dry years [*Bouchard et al.*, 2013].

Large bidirectional fluctuations in lake area tended to be clustered in time (mid-1970s to early 1980s; Figure 5b) and included lakes with large terrestrial catchments located in more peripheral areas of OCF. The fact that the year with the largest number of bidirectional fluctuations (1982–1983) was preceded by a year of extreme precipitation (Figures 5 and 6) suggests that these changes were strongly influenced by variation in precipitation. While experiencing lower water levels during dry years, the relatively large catchments of these lakes likely generated adequate runoff to refill them during wetter years. Reduced frequency of bidirectional fluctuations may be linked with changes in land cover (e.g., expansion of shrub coverage [*Lantz et al.*, 2013; *Myers-Smith et al.*, 2011]) since subsequent increases in snowpack and runoff may offset evaporation during dry years [*Turner et al.*, 2014]. However, further investigation is required to evaluate rates and spatial variation in vegetation change in OCF and its influence on lake water balances. A recent study of lakes on the Alaskan Coastal Plain showing that the duration of evaporative loss is greater in shallower lakes that experience earlier ice off conditions [*Arp et al.*, 2011] also raises the possibility that the bidirectional fluctuations we observed were driven by feedback between lake depth, the timing of ice off, and the duration of evaporative loss.

5. Conclusions and Implications

Our observations in Old Crow Flats show that thermokarst and climatic processes drive different responses in lake systems impacted by increasing temperature and precipitation. This is significant because it shows that our ability to predict landscape level dynamics is contingent on our ability to distinguish which lake types (and landscapes) are susceptible to these processes. A number of recent studies have used measurements of total lake area and number derived from aerial and satellite images to investigate the effects of climate on lake-rich northern environments. While these studies have demonstrated lake surface area reductions across vast regions of Alaska, Siberia, and Canada [*Carroll et al.*, 2011; *Jones et al.*, 2011; *Labrecque et al.*, 2009; *Riordan et al.*, 2006; *Smith et al.*, 2005], it is unclear if these changes are linked directly to climatic controls of lake water balance or have been driven by thermokarst processes [*Jones et al.*, 2011; *Plug et al.*, 2008]. Our observation that catastrophic drainage (permanent, rapid declines in lake area >30%) in the OCF accounted for nearly half the decline in lake area between 1951 and 2007 suggests that thermokarst processes are a key driver of the changes occurring in this landscape. Our results also show that shallow lakes strongly influenced by more prominent evaporation are likely to respond differently depending on the landscape context. The hydrological complexities of this landscape and differential lake responses over time warrant continued research focusing on the drivers of major hydrological events such as catastrophic lake drainage and evaporative loss.

Permanent reductions in lake area will have significant implications for local wildlife, vegetation dynamics, and carbon storage. In Old Crow Flats, vegetation succession on drained lake basins increases habitat heterogeneity. Following drainage, lake basins quickly become dominated by canopy-forming willow communities similar to those found adjacent to rivers and streams [*Marsh et al.*, 2009]. Residual ponds in these basins also frequently support an abundance of aquatic macrophytes. These environments likely provide high-quality habitat for moose [*Bowyer et al.*, 1999; *Collins and Helm*, 1997]. In fact, field observations and satellite collar data collected during the International Polar Year show significant use of these areas by moose. In Arctic environments, lake drainage is typically followed by permafrost aggradation and peatland development [*Mackay and Burn*, 2002]. Recent studies of drained lakes in Alaska suggest that an increase in the frequency of lake drainage may increase regional soil carbon storage, potentially offsetting the effects of other forms of thermokarst on soil carbon loss [*Jones et al.*, 2011].

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