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Contemporary (1951–2001) Evolution of Lakes in the Old Crow Basin, Northern Yukon, Canada: Remote Sensing, Numerical Modeling, and Stable Isotope Analysis

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ABSTRACT. This study reports on changes in the distribution, surface area, and modern water balance of lakes and ponds located in the Old Crow Basin, northern Yukon, over a 50-year period (1951–2001), using aerial photographs, satellite imagery, a numerical lake model, and stable O-H isotope analysis. Results from the analysis of historical air photos (1951 and 1972) and a Landsat-7 Enhanced Thematic Mapper (ETM+) image (2001) show an overall decrease (-3.5%) in lake surface area between 1951 and 2001. Large lakes typically decreased in extent over the study period, whereas ponds generally increased. Between 1951 and 1972, approximately 70% of the lakes increased in extent; however, between 1972 and 2001, 45% decreased in extent. These figures are corroborated by a numerical lake water balance simulation (P-E index) and stable O-H isotope analysis indicating that most lakes experienced a water deficit over the period 1988–2001. These observed trends towards a reduction in lake surface area are mainly attributable to a warmer and drier climate. The modern decrease in lake levels corresponds well to changes in regional atmospheric teleconnection patterns (Arctic and Pacific Decadal oscillations). In 1977, the climate in the region switched from a predominantly cool and moist regime, associated with the increase in lake surface area, to a hot and dry one, thus resulting in the observed decrease in lake surface area. Although some lakes may have drained catastrophically by stream erosion or bank overflow, it is not possible to determine with certainty which lakes experienced such catastrophic drainage, since an interval of two decades separates the two air photo mosaics, and the satellite image was obtained almost 30 years after the second mosaic of air photos.

Key words: thaw lakes, lake levels, remote sensing, modeling, stable O-H isotopes, Old Crow, northern Yukon

RÉSUMÉ. La présente étude fait état des changements caractérisant la répartition, l'étendue et le bilan hydrique contemporain des lacs et des étangs situés dans le bassin Old Crow, dans le nord du Yukon, sur une période de 50 ans (1951–2001). L'étude s'est appuyée sur des photographies aériennes, l'imagerie satellitaire, un modèle numérique des lacs et l'analyse des isotopes stables O-H. D'après les résultats de l'analyse des photos aériennes historiques (1951 et 1972) et d'une image par capteur ETM+ (Enhanced Thematic Mapper) de Landsat-7 (2001), il y a eu rétrécissement général (-3,5 %) de la surface des lacs entre 1951 et 2001. D'un point de vue général, l'étendue des grands lacs a diminué au cours de la période visée par l'étude, tandis que celle des étangs a augmenté. Entre 1951 et 1972, l'étendue d'environ 70 % des lacs s'est accrue, mais entre 1972 et 2001, l'étendue de 45 % des lacs a diminué. Ces données ont été corroborées au moyen de la simulation numérique du bilan hydrique des lacs (indice P-E) et de l'analyse des isotopes stables O-H, qui ont laissé entrevoir que la plupart des lacs ont enregistré un déficit en eau au cours de la période allant de 1988 à 2001. Les tendances de réduction de la surface des lacs qui ont été observées sont principalement attribuables à un climat plus chaud et plus sec. La diminution contemporaine du niveau des lacs correspond bien aux changements caractérisant les modèles régionaux de téléconnexion atmosphérique (oscillations décadaires arctiques et pacifiques). En 1977, le climat de la région est passé d'un régime à prédominance fraîche et humide (associé à l'augmentation de la surface des lacs de la région) à un régime chaud et sec, ce qui s'est traduit par la diminution de la surface des lacs qui a été observée. Bien que certains lacs puissent avoir été drainés de manière catastrophique en raison de l'érosion des cours d'eau ou du débordement des rives, il est impossible de déterminer avec certitude quels lacs ont été la cible d'un assèchement si catastrophique puisqu'un intervalle de deux décennies sépare les deux mosaïques de photographies aériennes, et que l'image satellitaire a été obtenue presque une trentaine d'années après la deuxième mosaïque de photo aérienne.

Mots clés : lacs thermokarstiques, niveaux des lacs, télédétection, modélisation, isotopes stables O-H, Old Crow, nord du Yukon

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INTRODUCTION

During the last few decades, the Canadian Arctic has undergone significant hydrological changes. Increasing air temperatures, in both summer and winter, have led to the melting of some small Arctic glaciers (Dowdeswell et al., 1997; Overpeck et al., 1997; Miller et al., 2004), a reduction in sea ice cover (Fisher et al., 2006), an increase in river discharge, and a longer open-water season for rivers and lakes (Peterson et al., 2002; Prowse and Carter, 2002; Duguay et al., 2006). These hydrological changes tend to be in the same direction; however, studies that examined modern changes in the distribution and surface area of lakes in the Arctic have shown that the direction of change is ambiguous (e.g., Frohn et al., 2005; Hinkel et al., 2005, 2007; Smith et al., 2005). Regions located in the discontinuous permafrost zone have shown a substantial decrease in lake surface area (Osterkamp et al., 2000; Yoshikawa and Hinzman, 2003; Christensen et al., 2004; Smith et al., 2005), whereas in regions with continuous permafrost, most studies have found little long-term trend in lake extent (Riordan et al., 2006). For example, Smith et al. (2005) reported an increase in the continuous permafrost of Siberia, but this study was based on only two dates (1973 and 1998) of relatively coarse resolution satellite imagery. The increase in lake surface area could be due to either a wet year in 1973 or a dry year in 1998 in that region. Smol and Douglas (2007) did document substantial lake shrinkage in the High Arctic, and Plug et al. (2008), who discerned no real trend in lake surface area in the Tuktoyaktuk Peninsula, found that lake extent was mostly related to the interannual variability in precipitation. In fact, most of the recent hydrological changes observed at high latitudes correlate better with regional atmospheric pressure differentials (such as the Arctic Oscillation, the North Atlantic Oscillation, the Pacific Decadal Oscillation, and the North Pacific indices) than with air temperature alone (Hurrell, 1995; Thompson and Wallace, 1998; Peterson et al., 2002; Bonsal et al., 2006). The reason is that atmospheric pressure differentials affect air temperatures, regional storm patterns (precipitation), prevailing winds and evaporation—in other words, the regional climate—at various temporal scales.

In the continuous permafrost zone of the western Canadian Arctic, several lacustrine plains host thousands of lakes that provide breeding habitats for aquatic animals, waterfowl, and caribou herds. Three of the largest are the Old Crow, Bluefish, and Bell-Driftwood basins located in the northern Yukon (Fig. 1). Recent aerial and ground reconnaissance surveys of these basins revealed that several large lakes (e.g., Zelma and Netro lakes) are experiencing important declines in water levels. For example, Wolfe and Turner (2008) document the rapid drainage of Zelma Lake in the Old Crow Basin over a three-week period in July 2007. The sudden drainage of the lake (a loss equivalent to 5.8 million m^3, or a 43% loss in lake surface area) was not due to warmer air temperature or increased evaporation, but rather to March–May precipitation much greater than the long-term average, which triggered the erosion of an outlet channel and subsequent drainage of the lake through that channel into the adjacent basin. Given that this reduction in lake surface area contrasts with what has been observed for lakes in other regions of the continuous permafrost zone, it is not known if this event can be extrapolated to the majority of lakes in the region, or if it represents a unique event that happened when a certain set of conditions were met. Field observations of the presence of drained lake basins and abandoned shorelines around some lakes in the Old Crow Basin suggest that lake drainage or a reduction in lake surface area is ongoing in the region. In fact, a paleoecological study by Lauriol et al. (2009) shows that water levels in

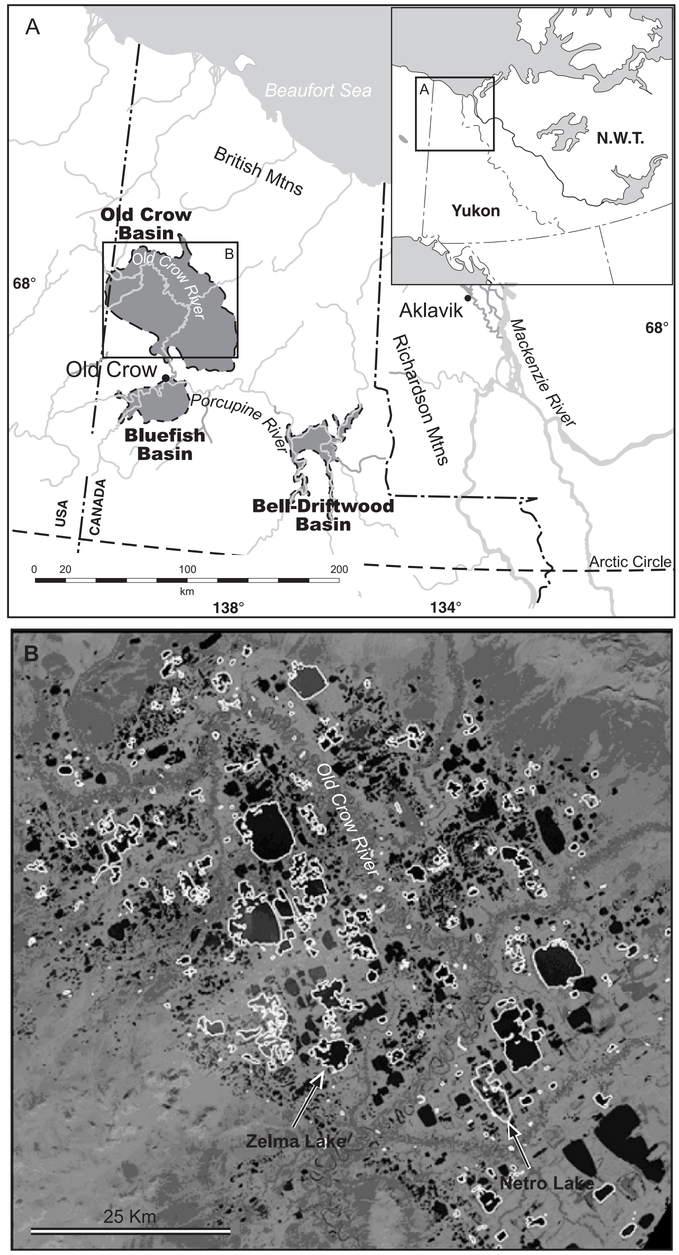

FIG. 1. A) Map of northern Yukon, showing the location of areas referred to in text. B) Landsat ETM+ image of the Old Crow Basin obtained in the summer of 2001. Lakes used in the calculations are outlined in white.

lakes of the nearby Bluefish Basin began to decrease gradually around 3700 yr. BP, which coincided with the arrival of a cold and dry climate. (One lake, however, showed evidence of sudden drainage.)

In this study, we reconstruct the surface area and water balance of lakes in the Old Crow Basin for the modern period 1951–2001 to determine whether the observed trends are related to the ongoing climate change or represent unique events. Changes in lake surface area over this 50-year period are determined by comparing digitally rectified air photographs from 1951 and 1972 and a Landsat 7 Enhanced Thematic Mapper (ETM^+) image acquired in 2001. The modern lake water balance is evaluated using a numerical lake model and stable isotope analysis, and then both the lake surface area and water balance are compared to the local and regional climate records (surface air temperature, precipitation, and regional atmospheric oscillation indices). As most of the lakes are of thermokarstic origin, the potential influence of geomorphologically driven changes on lake extent is also discussed. Overall, the results contribute to a better understanding of the evolution of lakes in a region underlain by thick permafrost in glacio-lacustrine sediments.

STUDY AREA

The Old Crow Basin is located in the northern Yukon, approximately 200 km west of the Mackenzie Delta, within the continuous permafrost zone (Fig. 1). Like the neighboring Bluefish and Bell-Driftwood basins, the Old Crow Basin was formed by the Laramide orogeny during the early Tertiary, with subsequent infilling of late Tertiary and Quaternary clastic sediments originating from the neighboring Old Crow and Keele ranges. Although most of the northern Yukon (including the Old Crow region) remained ice-free during the late Pleistocene (Hughes, 1972), the neighboring Laurentide and Cordilleran ice sheets profoundly affected the region's hydrology (Lemmen et al., 1994). During the last glacial maximum, the Laurentide Ice Sheet blocked the Peel and Porcupine rivers when it reached the eastern edge of the Richardson Mountains at McDougall Pass, creating an extensive lake (glacial Lake Old Crow) in the Old Crow, Bluefish, and Bell-Driftwood basins (Fig. 1). During the presence of glacial Lake Old Crow, more than 7 m of glacio-lacustrine sediments were deposited in the basins. The glacial lake drained by 14–12 000 BP through the Ramparts of the Porcupine, which allowed permafrost to aggrade in the glacio-lacustrine sediments. The warm climatic conditions during the early Holocene and the presence of permafrost allowed for high sub-aerial peat accumulation rates in the basins due to increased primary productivity and low organic matter decomposition (Litchi-Fedorovich, 1974; Ovenden, 1982).

The Old Crow Basin, which covers an area of over 560 000 ha, consists of two physiographic units: the Old Crow Flats and the Old Crow River valley. As a result of

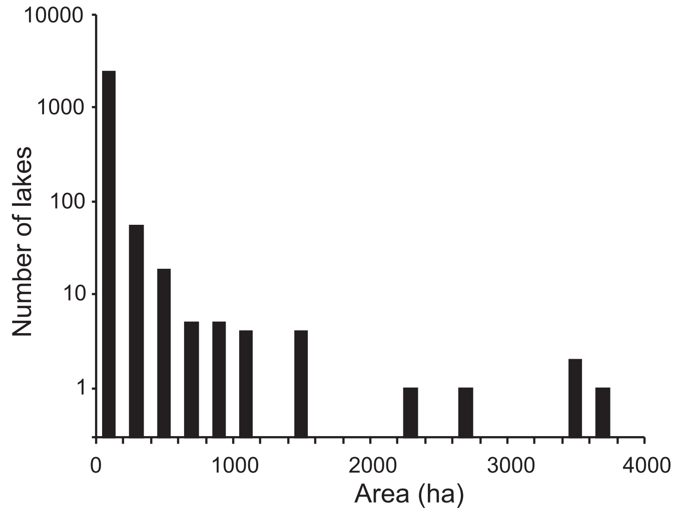

FIG. 2. Bar graph showing the number of lakes of various sizes (area in hectares) in the Old Crow Basin, calculated from 1:250 000 scale maps.

the continuous incision of the Old Crow River following the drainage of glacial Lake Old Crow, the river valley is located 40–50 m lower than the Flats. The analysis of 1:250 000 scale maps (NTS sheet numbers 117A/B, 116N, and 116O) using ArcGIS indicates that the Old Crow Basin contains over 2700 lakes, which average 44 ha in surface area (range = 1–3700 ha). On the Old Crow Flats, 92% of the lakes occupy an area of 100 ha or less, and lake frequency decreases rapidly with increasing size (Fig. 2). The origin of the lakes in the Old Crow Basin is not certain, but most are thought to be of thermokarst origin because they are flat-bottomed, shallow (< 2 m deep) and tend to be elongated essentially at a right angle to the prevailing summer wind direction (NE–SW). However, non-thaw lakes may also be present on the Flats, as well as many oxbow lakes along the Old Crow River valley. Under the deepest lakes (maximum of ca. 4 m), the soil is probably unfrozen (i.e., a thaw bulb is present).

The present-day climate in the Old Crow Basin is characterized by a continental sub-Arctic regime, with long cold winters, short mild summers, and relatively low precipitation. The normal mean annual air temperature (1970–2000) recorded at the Old Crow meteorological station is -9.0˚C (January: -31.1 ± 4.8˚C; July: 14.6 ± 1.4˚C; Environment Canada, 2004). The deviation from the normal mean annual air temperature is shown in Figure 3. Overall, data from Old Crow and nearly meteorological stations (not shown) indicate a slight increase in annual air temperature over the 1951–2001 period, with a climatic regime shift around 1977, where the mean annual air temperatures are warmer for the 1977–2001 period compared to the previous 1951–75 period. Total annual precipitation recorded at the meteorological station averages 265 mm, with approximately half falling in solid form (Environment Canada, 2004). Cyclonic activities are responsible for some of the precipitation, but during the summer months, rainfall frequently results from local convection effects (Wahl et al., 1987). The long-term (1951–2001) total annual precipitation shows an increasing trend (Fig. 3), with lower precipitation during the cooler 1951–75 period. On a seasonal basis, however, summer and winter precipitation both show a significant increasing trend, but there is no significant trend in spring or fall (data not shown). Winds in the area are generally light, and the prevailing wind direction is from the northeast year-round (Wahl et al., 1987). Overall, these climatic conditions ensure the preservation of continuous permafrost in the Old Crow Basin. The depth of the active layer in the basin has been measured at 30 to 60 cm, depending on the characteristics of the surface sediments and vegetation, and the permafrost is ca. 60 m thick (Smith and Burgess, 2002).

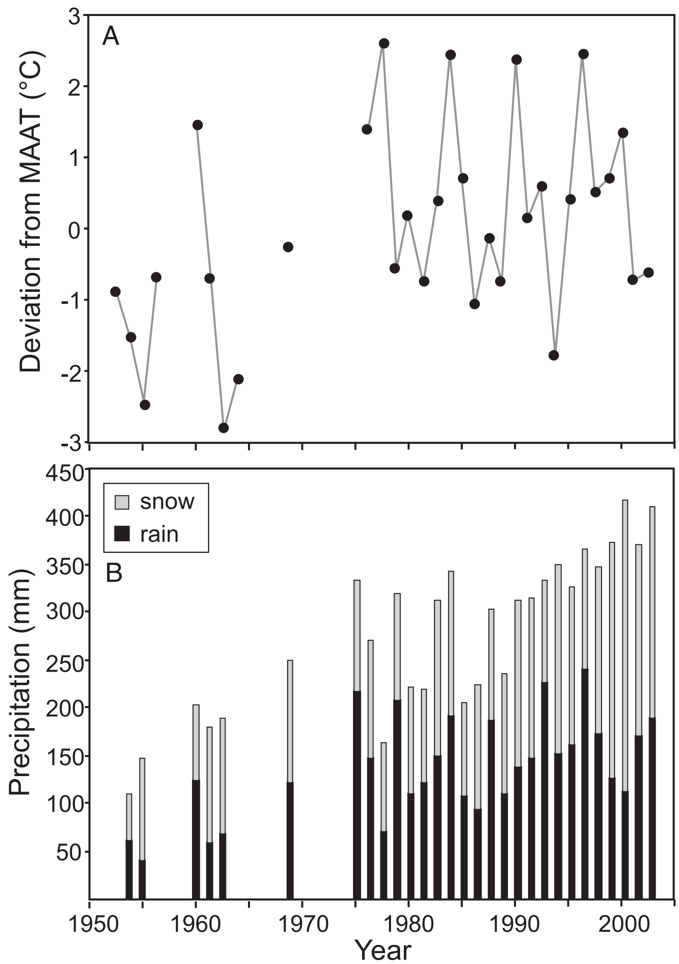

FIG. 3. A) Deviation of temperature recorded at the Old Crow meteorological station from long-term average (1951–2003). B) Amount of rainfall and snowfall recorded at the Old Crow meteorological station. Data from Environment Canada (2004).

MATERIAL AND METHODS

Data Sources for Spatio-Temporal Analysis

Because the Old Crow Basin is a large and isolated wetland, the method chosen for assessing the hydrological changes that occurred there was remote sensing. Hence, two mosaics of aerial photographs (from 1951 and 1972) and one Landsat-7 ETM+ image (2001) were used to quantify changes in lake surface area over the last five decades of the 20th century.

The historical aerial photographs (scale 1:54 000) were acquired from the National Air Photo Library (Ottawa, Canada). For the mosaic of 1951, the majority of the air photographs were taken on 13–15 July. The exceptions were two narrow strips, one covering the eastern end of the mosaic and the other one crossing it roughly in the middle, that were acquired on 7 and 28 August 1952, respectively. All air photographs from 1972 were taken on 8 or 9 July, except those for a strip on the western end of the Old Crow Basin, which were taken on 31 July. In total, 191 aerial photographs (89 from 1951–52; 102 from 1972) were scanned at a resolution of 600 dpi and saved in TIF format. The air photos were then combined into a mosaic by means of Geomatica's OrthoEngine™ software module, using 792 control points for the 1951 mosaic and about 900 points for the 1972 mosaic.

The Landsat-7 ETM$^+$ panchromatic image was acquired on 30 August 2001 under mostly cloud-free conditions. The Landsat ETM$^+$ image, sensitive to the 0.5–0.9 µm wavelength range, had a spatial resolution of 15 m. The image was corrected geometrically to a 1:50 000 topographic map, using 33 ground control points in a quadratic polynomial transformation (root-mean-square error of 0.31 pixel [x] and 0.43 pixel [y]), and reprojected into the Albers Conical Equal-Area system. A cubic convolution method was used for image resampling to make the process of lake delineation easier. The two air photo mosaics were then registered onto the corrected Landsat ETM$^+$ image at the same spatial resolution (15 m).

Since the study area contains over two thousand lakes, it was deemed unrealistic to digitize every lake in the three images manually. Instead, a sample of 300 lakes was selected from a set of random geographic coordinates generated in MS-Excel. The coordinates were then transferred and overlaid on the georeferenced images. No discrimination was made as to the origin of the lakes, so the subset includes thaw lakes and non-thaw lakes. For each year (1951, 1972, and 2001), polygons were traced around the perimeter of the lakes using Geomatica's Vector Editor in the ImageWorks™ module. For cases when islands were found in a lake, polygons were also traced around the islands, and their area was later subtracted from the total lake polygon area. In cases in which a lake had segmented into different portions, or several lakes had coalesced, the largest body of water was taken as the reference. Four lakes represented by open polygons (because of user error) and six small bodies of water showing obvious distortions along the edge of the mosaics were excluded from the analysis. The surface area of the digitized lakes (polygons) was then determined for each year.

TABLE 1. Total lake surface area estimated in the Old Crow Basin in 1951, 1972, and 2001.

Type of Lake	Size (ha)	1951 Number of Lakes	1951 Total Area (ha)	1972 Number of Lakes	1972 Total Area (ha)	2001 Number of Lakes	2001 Total Area (ha)
Ponds	0.025 to 5	86	179.4	85	191.8	84	175.5
Small lakes	5 to 25	73	881.7	75	972.3	76	962.2
Medium lakes	25 to 100	69	3561.1	69	3829.6	68	3643.5
Large lakes	100 to 400	43	7999.4	43	8392.1	42	7669.4
Very large lakes	> 400	19	25043.8	18	24892.2	20	23913.6
All lakes combined		290	37665.4	290	38278.0	290	36364.2

Modern Water Balance

Since no data currently exist on lake water balance in the Old Crow Basin, the modern water balance of a hypothetical 2 m deep lake in the Old Crow Basin was estimated using daily precipitation recorded at the Old Crow meteorological station and a numerical model that simulated daily evaporation rates during the open-water season. Unfortunately, meteorological data were too sparse prior to 1988 to extend the simulation over the years when the air photos were acquired. Consequently, the numerical model simulations cover only the period 1988–2001. The evaporation rate was computed using the following bulk aerodynamic formula:

$$E = \rho_a C_T u_a (q_{sat}-q_a) \quad [1]$$

where ρ_a is the air density (kg m^{-3}), C_T is a stability-dependent transfer coefficient (a decreasing function of increasing atmospheric stability, following Louis, 1979), u_a is the wind speed (m s^{-1}), q_{sat} is the saturation-specific humidity at surface temperature, and q_a is the specific humidity of the air. The resulting units are in kg m^{-2} s^{-1} or mm s^{-1} (given that the density of water = 1000 kg m^{-3}), which are translated to mm d^{-1} by multiplying by the number of seconds in a day (i.e., 86400), and then summed over all days during the open-water season (mm yr^{-1}) to give the annual evaporation rates. The open-water season was calculated using a one-dimensional thermodynamic lake model (see Duguay et al., 2003 for details). This model has been used successfully to simulate ice phenology (ice-on/ice-off dates and duration), as well as ice thickness for lakes of various sizes in Alaska and northern Canada (e.g., Ménard et al., 2002; Duguay et al., 2003; Ménard and Duguay, 2004; Jeffries et al., 2005). During the open-water season, the model calculates evaporation rates using Eq. 1, which is similar in form to the equation proposed by Oswald and Rouse (2004). Tests of this model indicated that it successfully estimated evaporation from small lakes in the Mackenzie River Basin.

RESULTS AND INTERPRETATION

Spatio-Temporal Variations in Lake Surface Area (1951–2001)

The lakes in the Old Crow Basin were arbitrarily subdivided by size into five categories: ponds, small lakes, medium lakes, large lakes, and very large lakes (Table 1). Ponds occupy an area ranging between 0.0225 and 5 ha and constitute about 30% of the 290 lakes considered in the study, but only 0.5% of the total surface area of all lakes combined. Approximately 21% of the lakes sampled exceed 100 ha in area (large and very large lakes), accounting for 87% of the total lake surface area sampled. Only 19 lakes have an area greater than 400 ha, and the maximum size is 3411 ha.

Figure 4 shows the percentage of lakes from each category that underwent a change in surface area. Over the entire 1951–2001 study period, the majority (more than 60%) of the lakes surveyed increased in surface area, which is consistent with the trend of lakes in other regions underlain by continuous permafrost (Smith et al., 2005; Jorgenson et al., 2006). From 1951 to 1972, more than 70% of the lakes surveyed increased in surface area. From 1972 to 2001, the majority of the lakes still showed an increase in surface area; however, 45% of the lakes showed a decrease in their surface area. Only the pond and small lake categories had a greater number of lakes decreasing than increasing their surface area.

Even though the number of lakes showing an increase in lake surface area is greater than those showing a decrease over the 50-year observation period (Fig. 4), these numbers do not translate into an actual increase in total lake surface area. In fact, the results show that the total surface area of all lake categories combined actually decreased (-3.5% or -1301 ha) over the 50-year observation period (Table 2). This reduction in lake surface area can be attributed to the large and very large lakes that underwent a significant reduction in surface area (-1130 ha) over the 1951–2001 period while the small and medium-sized lakes generally increased their extent. We also examined surface area by time periods. Between 1951 and 1972, surface area increased in lakes of all categories (except very large), and the largest increases (up to 10% or 91 ha) occurred in small and medium lakes. In fact, this is the period when most lakes increased in surface area. Between 1972 and 2001, however, surface area decreased in all lake categories, and the most dramatic reductions occurred in ponds (-8.5% or -16 ha) and large lakes (-8.6% or -723 ha). Spatially, no specific region of the Old Crow Basin showed predominant lake expansion or shrinkage events.

These results may seem surprising considering that studies conducted in other regions of the continuous permafrost zone are showing an increase in surface area for most lakes

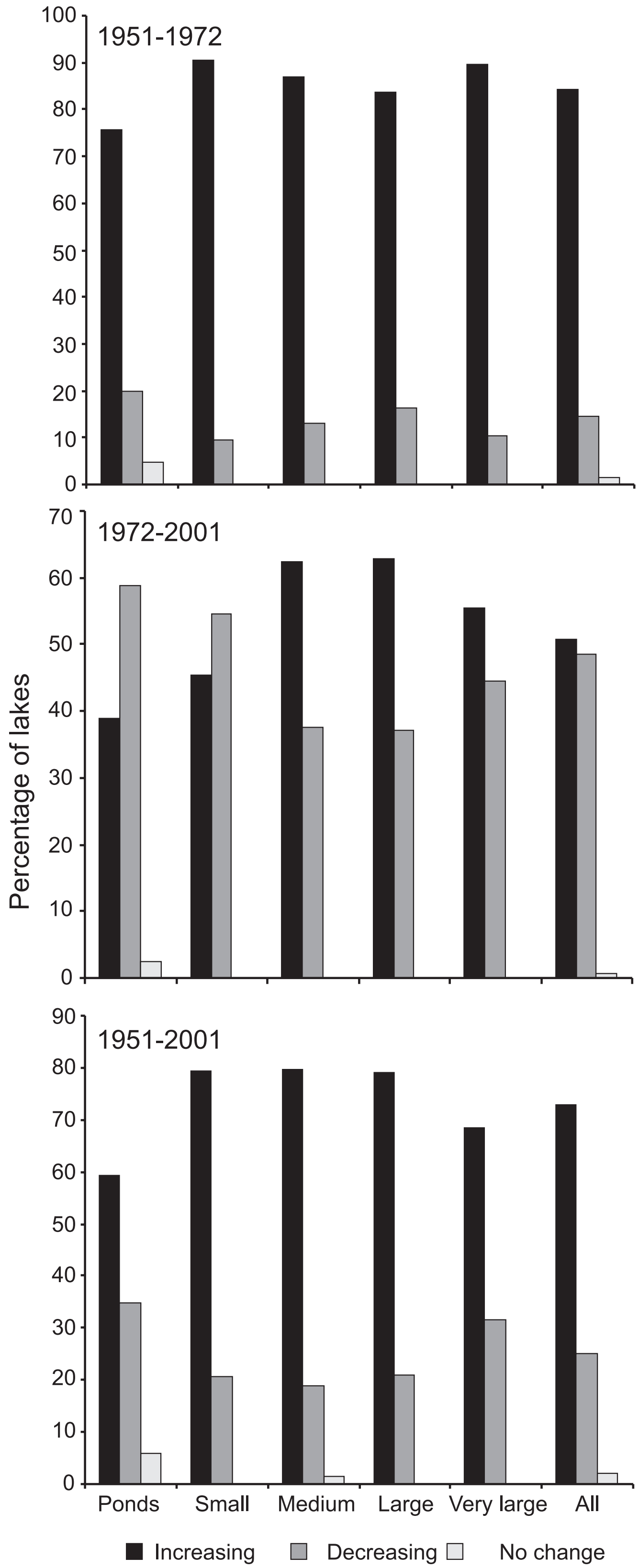

FIG. 4. Percentage of lakes in each size category that experienced a change in surface area during the first two decades, the last three decades, or the entire study period (1951–2001).

(Osterkamp et al., 2000; Christensen et al., 2004; Smith et al., 2005). However, Plug et al. (2008) also observed a general decrease in lake surface area from 1992 to 2001 in a nearby region (Tuktoyaktuk Peninsula). An alternative explanation for the decrease in total lake surface area could be the sudden drainage of lakes. For example, Wolfe and Turner (2008) documented a 43% reduction of Zelma Lake in the Old Crow Basin over a three-week period in 2007. Another such example is Netro Lake, which decreased in area by as much as 1051 ha between 1972 and 2001 (Fig. 5). A large decrease in lake surface area can often be triggered by a catastrophic drainage event (e.g., Zelma and Netro lakes), and such phenomena can have an important impact on the quantified change in lake surface area. However, given that catastrophic drainage occurs over a very short time period (hours to days), it is difficult on the basis of spaceborne technology alone to assess changes in lake surface area related to such events. Therefore, although it is likely that some of the sampled lakes used in the analysis may have experienced a sudden drainage, it is impossible, using only images acquired at 20- or 30-year intervals, to determine whether they did.

Modern Water Balance (1988–2001)

The modern water balance of lakes in the Old Crow Basin during the ice-free period was computed for 1988–2001. The lake breakup dates fluctuate between 20 May and 6 June (Fig. 6), dates which are within the range of ice breakup on the Old Crow River near the confluence with the Porcupine River (ABEK Co-op, 2008). Lake breakup dates have been shown to be reliable indicators of change and variability in climate (e.g., Duguay et al., 2006). Even though the modeled lake breakup dates do not show a trend toward an earlier spring breakup, they are negatively correlated with the spring air temperature (-r = 0.30; $p < 0.20$; n = 14), as would be expected under warmer spring conditions. However, ice breakup dates have been shown to be better correlated with the spring 0˚C isotherm than with spring air temperatures (Bonsal and Prowse, 2003). The fall freeze-up dates show a greater variability, fluctuating between 19 September and 15 October (Fig. 6), dates which are also within the range of ice formation on the Old Crow River (ABEK Co-op, 2008). The modeled freeze-up dates show a slight trend towards later ice formation that is positively correlated with the fall air temperature (r = 0.38; $p < 0.10$; n = 14). Similar results regarding lake freeze-up were obtained by Duguay et al. (2006), who showed from a sample of lakes in northern Canada that ice formation had no statistically significant trend over the last 30 years of the 20th century.

The simulated daily evaporation rates for the open-water season, which is typically from late May to early October, show great variation (Fig. 7). The daily evaporation rates rapidly increase after spring breakup, peak in July, and then decline steadily until fall freeze-up. The annual evaporation rate, which was obtained by summing the daily amounts of evaporation during the ice-free period for a given year, shows great variability, with a minimum of 320 mm yr^{-1} in

TABLE 2. Absolute changes (ha) and relative changes (%) in lake surface area in the Old Crow Basin over the study period.

Type of Lake	1951–72		1972–2001		1951–2001	
	hectares	percent	hectares	percent	hectares	percent
Ponds	12.4	6.9	-16.3	-8.5	-3.9	-2.2
Small lakes	90.6	10.3	-10.1	-1.0	80.5	9.1
Medium lakes	268.5	7.5	-186.1	-4.9	82.4	2.3
Large lakes	392.7	4.9	-722.7	-8.6	-330.0	-4.1
Very large lakes	-151.6	-0.6	-978.6	-3.9	-1130.2	-4.5
All lakes combined	612.6	1.6	-1913.8	-5.0	-1301.2	-3.5

FIG. 5. Images of Netro Lake, an example of a lake that underwent a significant decrease in surface area between 1972 and 2001.

2000 and a maximum of 460 mm yr[1] in 1995 (Fig. 8). Since the annual evaporation rate is based on the ice-free period,

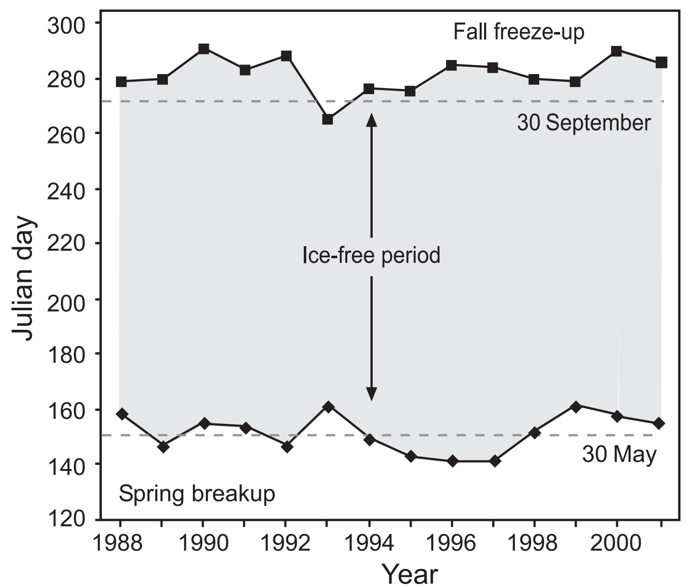

FIG. 6. Simulated ice-on and ice-off dates for lakes in the Old Crow region, northern Yukon, 1988–2001.

it closely follows the duration of that period. The seasonal heat budget of Arctic lakes is controlled by the duration of the open-water season, which in turn determines the magnitude of annual evaporation from these lakes.

The bulk aerodynamic model provides information about the amount of water lost by evaporation, but not about the water balance of the lakes. We therefore subtracted the cumulated evaporation values for the ice-free period from the total precipitation recorded at the Old Crow meteorological station during that period, to produce an index of water level (the P-E index). Figure 9 shows that the lakes in the Old Crow Basin have a water deficit (negative P-E index) throughout the simulation period (1988–2001). For a typical 2 m deep lake, the P-E index translates into an average water loss of 11.9 ± 2.8% yr[1]. No systematic monitoring of lake-level fluctuation exists to provide data for comparison to the results of our numerical lake model. However, the negative water balance obtained by the simulation is corroborated by the observations of residents of the hamlet of Old Crow and by the remote sensing analysis, which shows a reduction in lake surface area during the last 20 years of the study period (Table 2) that could be attributed in part to a decrease in lake water level.

Stable O-H isotope results from 10 lakes sampled in the Old Crow Basin during the summers of 1998 and 1999 are

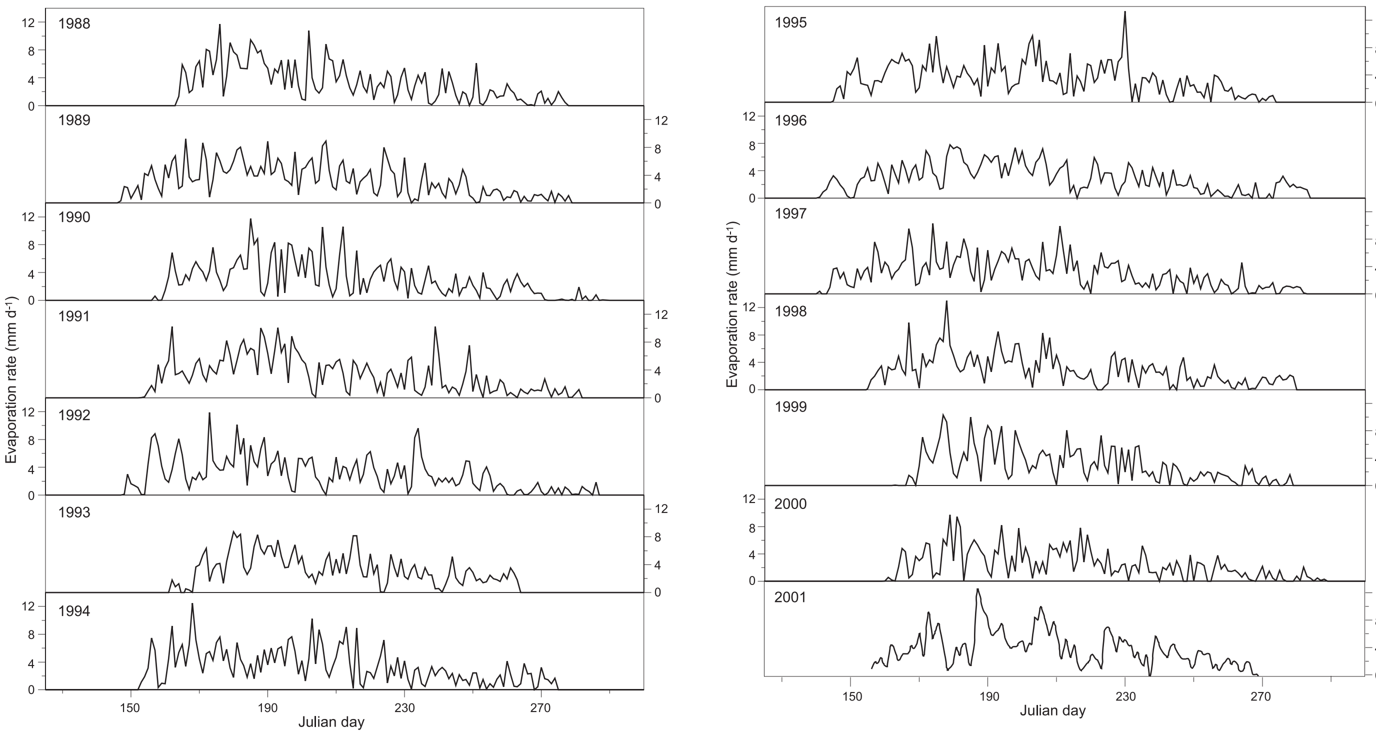

FIG. 7. Simulated daily evaporation rates during the ice-free period for a typical 2 m deep lake in the Old Crow region, northern Yukon, 1988–2001.

consistent with an evaporative effect on the water balance of lakes (Lacelle, 2002). The $\delta^{18}O$ composition of the lakes increases from -18.7‰ in early June to -11.2‰ in late July, which suggests an evaporative enrichment (Table 3). In fact, the isotopic data of the lakes deviate from the local meteoric water line (LMWL) ($\delta D = 6.9\ \delta^{18}O - 20$; IAEA, 2004), which is defined by the isotopic composition of precipitation in the area, and plot along a line with a much lower slope ($\delta D = 5.4\ \delta^{18}O - 53$). This deviation of the lakes' isotopic data from the LMWL reflects the evaporative loss of water from the lakes (Gonfiantini, 1986), thus supporting the numerical lake model results.

DISCUSSION

Results of this study indicate that even though a greater number of lakes are showing an increase in lake surface area, the overall loss of lake surface area was more important, causing a general decrease in lake surface area in the Old Crow Basin. These opposing observations could be attributed in part to the effects of climate change and catastrophic drainage of thaw lakes.

Climate Influence on the Spatio-Temporal Evolution of Lakes

The greater number of lakes showing an increase in surface area in the Old Crow Basin (Fig. 4) could be attributed to the ongoing climate change in the area, which is resulting in increases to both year-round temperatures and precipitation. The higher year-round temperatures are currently leading (or will lead) to earlier snowpack melt, thinner lake ice, a longer open-water season, and a deeper active layer. Consequently, many new ponds and lakes could form or expand as the ground surface thaws and subsides. This observation is not unique to the Old Crow Basin, as other regions in continuous permafrost have also experienced an increase in the number of lakes over the last few years (Smith et al., 2005; Jorgenson et al., 2006).

Although more lakes are showing an increase in surface area, the results from the numerical lake model (P-E index) indicate that during 1988–2001, the lakes in the Old Crow region had a negative water balance (Fig. 9), which is corroborated by the stable O-H isotope analysis of lakes and local observations. Both of these opposing observations (increase in surface area and negative water balance) could be attributed to climate warming. An increase in air temperature leads to the formation or expansion of lakes through thawing and subsidence of the ground surface, and also to increased evaporation. If water loss through evaporation is not compensated by higher precipitation, the water balance may be altered, and the water levels in these lakes will decrease (Marsh, 1986; Woo, 1992). A comparison with the climate record (temperature and precipitation) will shed some light on potential causes for the observed reduction in lake water in the Old Crow Basin. Unfortunately, the climate data for the region are too sparse to compare with the change in total lake surface area over the 1951–2001 period, as there is no climate record for the years of air photo acquisition (1951 and 1972).

Figure 10 (a, b, c) compares the P-E index to summer air temperature, rainfall, and total precipitation. The recent

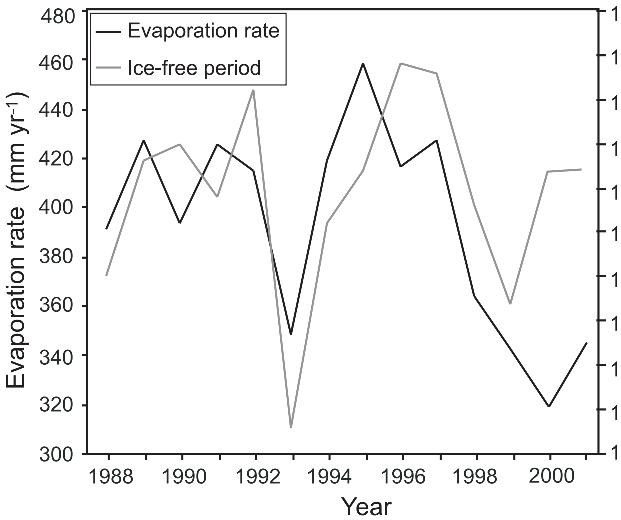

FIG. 8. Simulated annual rates of evaporation during the ice-free period for a typical 2 m deep lake in the Old Crow region, northern Yukon, for the years 1988–2001.

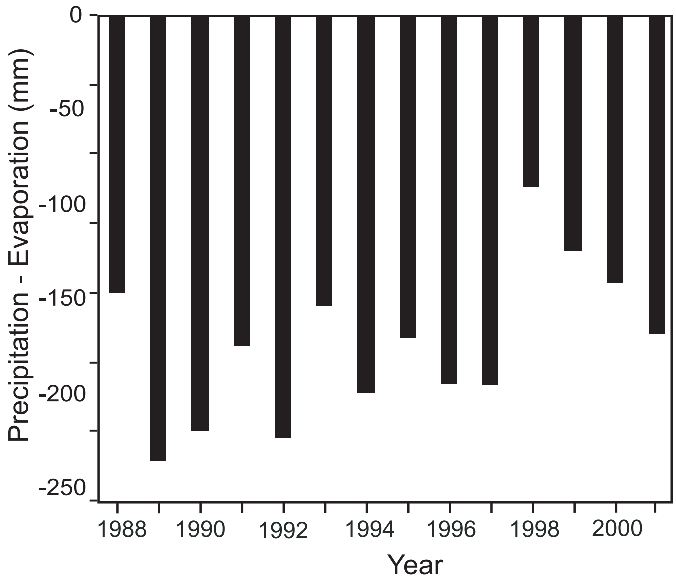

FIG. 9. Lake water balance (precipitation minus modeled evaporation, or P-E index) during the ice-free period, 1988–2001.

increase in summer air temperature (calculated for the ice-free period) cannot explain the drying trend observed in the Old Crow Basin since it is weakly correlated with the P-E index ($r^2 = 0.019$; Fig. 10). However, the rainfall and total precipitation records have a much better correlation with the P-E index ($r^2 = 0.443$ and 0.540, respectively). Plug et al. (2008) also found lake surface area in the nearby Tuktoyaktuk Peninsula to be strongly correlated with precipitation from the previous 12 months. These strong relations are not surprising, considering that the precipitation record comprises half of the P-E index, but they do suggest that atmospheric and pressure systems can affect the spatio-temporal variation of lakes in the region. Such a relation was also observed in the late Pleistocene-Holocene variations of lake water levels: the melting of the Laurentide ice sheet and subsequent rise in sea level reconfigured the regional atmospheric circulation patterns (Lauriol et al., 2009). A comparison of the P-E index and lake surface area variations with atmospheric oscillations affecting the northern Yukon can help to determine whether the observed spatio-temporal variations are affected by these natural oscillations.

The present-day climate in the northern Yukon is influenced by maritime polar air masses originating over the northeastern Pacific and the Beaufort Sea (Hare and Hay, 1974). The interactions between these systems are controlled in part by regional atmospheric circulation patterns, namely the Pacific Decadal Oscillation (PDO), the North Pacific (NP) index, and the Arctic Oscillation (AO) index. The PDO is the primary determinant of sea-surface temperature variability in the North Pacific (Mantua et al., 1997). During positive phases of the PDO, the sea surface along the west coast of North America has warmer-than-normal temperatures, which lead to more humid conditions inland. The NP index describes the intensity of the Aleutian Low pressure system over the Gulf of Alaska and is determined

TABLE 3. Stable O-H isotope composition of lake waters in the Old Crow Basin (data from Lacelle, 2002).

Date	δD (‰)	δ^{18}O (‰)
25/07/1999	-118.2	-11.2
13/07/1999	-119.9	-12.3
07/07/1999	-117.9	-12.4
07/07/1999	-119.1	-12.6
02/07/1999	-122.5	-13.3
02/07/1999	-133.2	-14.4
10/06/1998	-140.8	-16.3
10/06/1998	-142.7	-16.5
14/06/1998	-140.6	-15.6
03/06/1998	-154.7	-18.7
Average	-131.0	-14.3
Standard Deviation	13.2	2.4

by the mean sea-level pressure over the 30˚ N to 65˚ N and 160˚ E to 140˚ W region (Trenberth and Hurrell, 1994). Negative phases of NP are associated with a low-pressure system, allowing warm Pacific moisture inland, while positive phases are associated with a high-pressure system, leading to cooler and dryer conditions over the northern Yukon. The AO is a large-scale atmospheric phenomenon determined by the altitude of the 50 kPa atmosphere pressure level; it causes a redistribution of air masses between polar latitudes and latitudes as far south as 20˚ N (Thompson and Wallace, 1998, 2001). During positive phases of the AO, sea level pressure is reduced at polar latitudes, and high-pressure systems strengthen at mid latitudes. During negative phases of the AO, the pattern is reversed.

Analyses of the correlation between the temporal anomalies of the P-E index and the PDO, NP, and AO indices (June to October teleconnection values) for 1988–2001 are shown in Figure 10 (d, e, and f). The figure shows a moderate correspondence between the P-E index and the PDO ($r^2= 0.132$) and AO ($r^2 = 0.176$) indices, but a weaker one with the NP index ($r^2 = 0.076$). These findings are logical, since positive

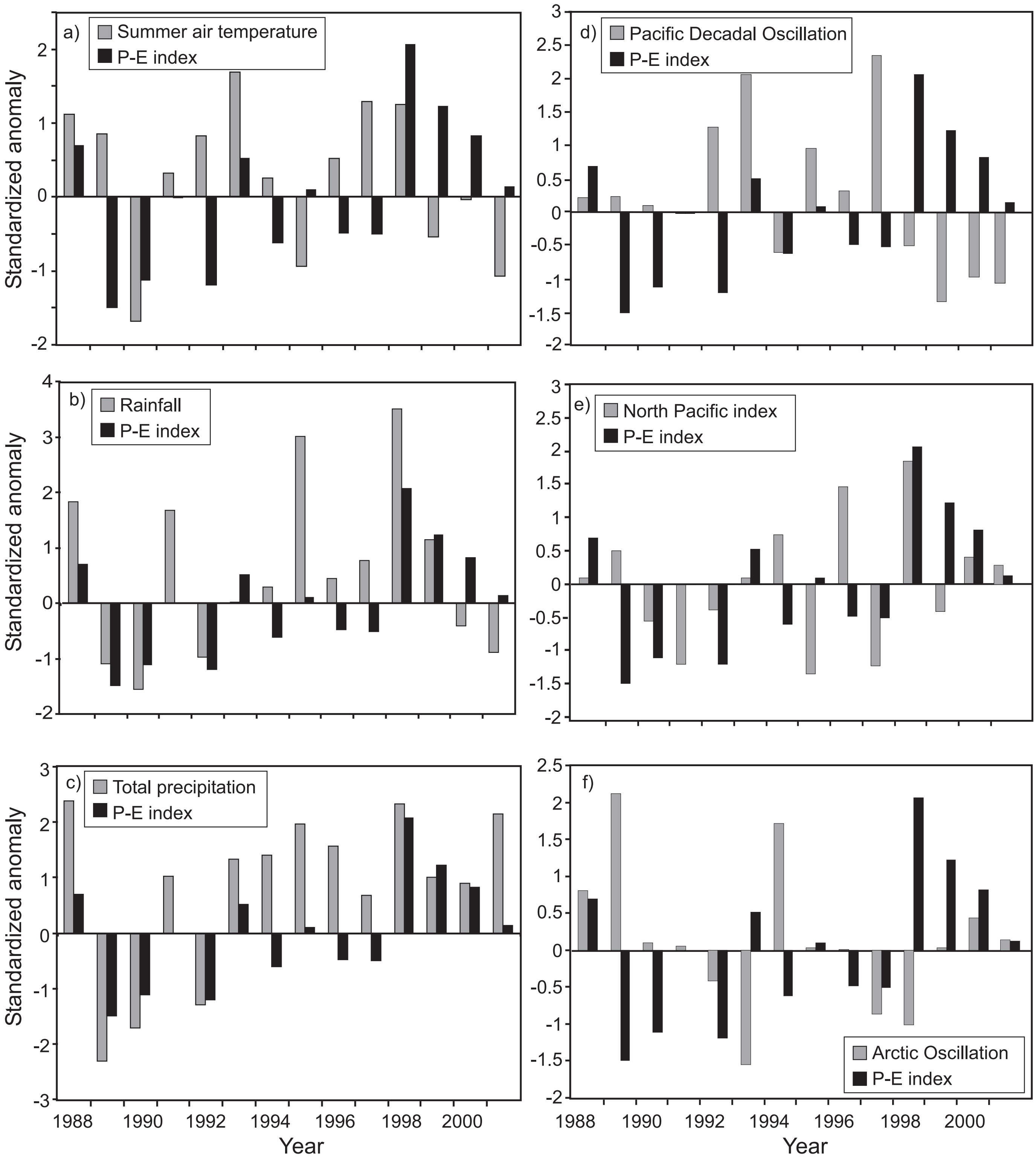

FIG. 10. Standardized anomalies for the P-E index (1988–2001) compared to summer air temperatures, rainfall, total precipitation and to the June-to-October teleconnections of the Pacific Decadal Oscillation, the North Pacific index, and the Arctic Oscillation index. Data sources for the three indices are ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest (PDO), http://www.cgd.ucar.edu/cas/catalog/climind/np.html (NP), and http://www.cdc.noaa.gov/Correlation/ao.data (AO).

AO and PDO phases are associated with cool and dry climate conditions over the northern Yukon. The influence of atmospheric circulation is also visible in the record of lake surface area variations over the 50-year study period. All lake categories showed a reduction in lake surface area from 1972 to 2001 (Table 2), which is consistent with the modeled

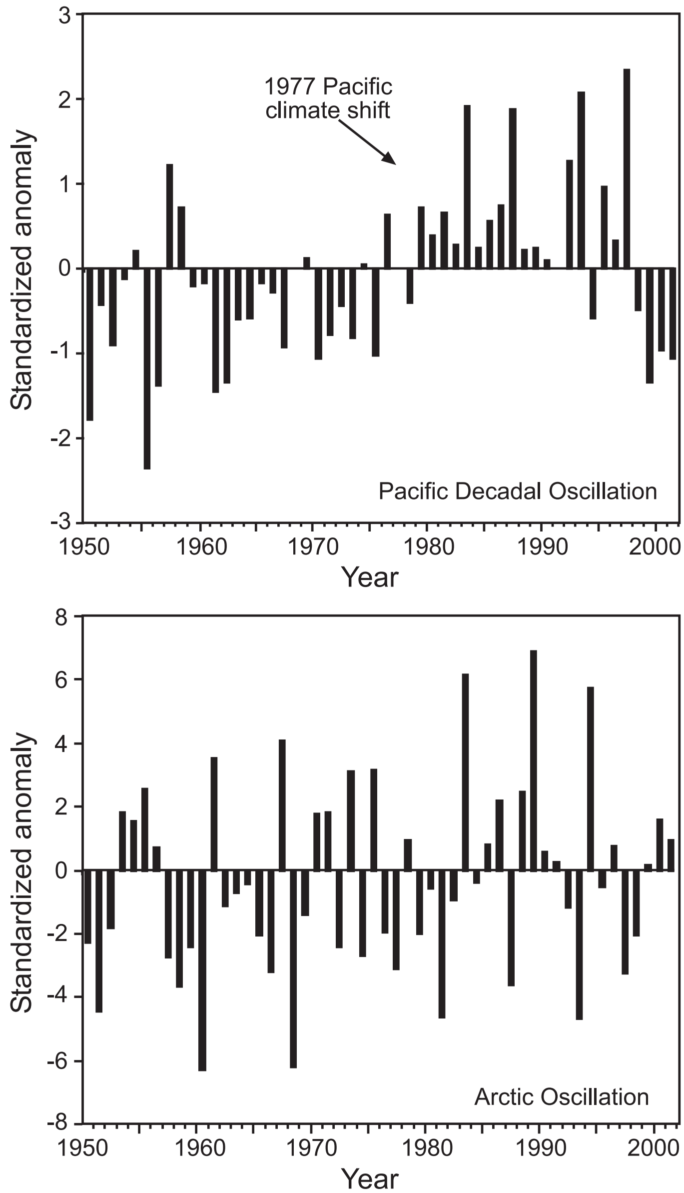

FIG. 11. Standardized anomalies for the June-to-October teleconnection values of the Pacific Decadal Oscillation and the Arctic Oscillation index (1950–2001). Data sources are the same as in Figure 10.

lake water level over the last 14-year period. From 1951 to 1972, however, surface area increased in all lake categories (except the very large lakes; Table 2). This increase corresponds to a period when the PDO and AO indices were in a negative phase, resulting in more precipitation inland (Fig. 11). The period 1951–72 was also cooler, and consequently, there would have been less evaporation. Although the relation cannot be quantified, the switch from a predominantly cool and moist climate regime to a hot and dry one after a Pacific-wide regime shift in 1977 (Mantua et al., 1997; Hartmann and Wendler, 2005) apparently had some influence on the spatio-temporal variations in lake surface area over the 50-year observation period. Overall, these results suggest that regional atmospheric pressure differentials, which affect precipitation, evaporation, and prevailing winds, are also influencing the water balance of lakes in the northern Yukon, which would largely explain the water deficit observed in some northern Yukon lakes during the last decade. This positive relation between atmospheric circulation patterns and lake water balance is not unique to the northern Yukon. In recent studies, Anderson et al. (2005a, b) and Riordan et al. (2006) also demonstrated that changes in the water balance of lakes in the southern Yukon and Alaska were correlated to changes in the regional atmospheric circulation patterns, whereas Bonsal et al. (2006) demonstrated the impact of these atmospheric patterns on ice breakup and freeze-up dates.

Non-Climatic Effects on the Spatio-Temporal Evolution of Lakes

The spatio-temporal evolution of lakes observed in the Old Crow Basin cannot be explained solely as a climate-induced effect, as discussed in the previous section, since climate does not explain the variations observed in some of the lakes (e.g., Zelma and Netro lakes). Even if a greater number of lakes showed an increase in surface area between 1951 and 2001 (Fig. 4), the sudden drainage of at least two of the very large lakes—Sandwich Lake (unofficial name) and Netro Lake—had an important influence on the overall change in the areal extent of water in the Old Crow Flats calculated for the study period. These two lakes contributed to a decrease of 1708 ha in lake surface area for the 1972–2001 period.

Catastrophic lake drainage is a common phenomenon in thermokarst landscapes, and many mechanisms have been proposed (Britton, 1957; Carson, 1968; Everett, 1980; Jorgenson and Shur, 2007). For example, thaw lakes can drain completely or partially in response to bank overflow caused by an increase in precipitation (e.g., Zelma Lake; Wolfe and Turner, 2008), thermal erosion along ice wedge troughs, or headward erosion by streams. Although these processes can be triggered by a climate-related mechanism, most are ongoing erosional processes; thus, it is difficult to predict where or when a lake will drain. In addition, it is difficult using remote sensing imagery alone to assess changes in lake surface area related to catastrophic drainage events given that such events happen over a very short time period (hours to days). Therefore, it is likely that some surveyed lakes may have experienced a sudden drainage, but without images acquired daily, it is impossible to determine whether they did.

Other potential explanations for the observed reduction in lake surface area could be related to the deepening of the active layer and increased precipitation, as the latter would likely result in the drawdown of water tables and the formation of new drainage channels. However, depending on the relative magnitude of these changes, a decrease or increase in lakes might be observed. Internal drainage through taliks connecting newly thawed zones under some large thaw lakes has recently been advanced to explain the reduction in lake surface area in the discontinuous and sporadic permafrost zones of Alaska (Yoshikawa and Hinzman, 2003). In the Old Crow Basin, however, the thick glacio-lacustrine sediments beneath the lakes would restrict groundwater circulation even if permafrost were to disappear. Thaw development may also be accelerated by anthropogenic terrain disturbances. For example, using the narrow ridges between lakes as snowmobile trails damages the sensible surficial permafrost and helps in the breakthrough drainage.

CONCLUSIONS

To quantify the drying-up trend that has been noted in lakes of the Old Crow Basin, northern Yukon, between 1951 and 2001, changes in surface area of a subset of the lakes were estimated from two digitized historical air photograph mosaics and one Landsat ETM+ panchromatic image. The analysis indicated an increase of 1.6% in lake surface area between 1951 and 1972, while an overall decrease of 5% was observed for the 1972–2001 period. The latter figure is corroborated by a numerical lake water balance simulation (P-E index) and stable O-H isotope analysis, which indicate that most lakes experienced a water deficit over the period 1988–2001. The interannual variations in the water balance of the lakes were related to the duration of the open-water season and seemed to reflect climate variations caused by changes in regional atmospheric pressure differentials (mainly the Pacific Decadal and Arctic oscillations). In 1977, the climate in the region switched from a predominantly cool and moist regime, associated with the increase in lake surface area, to a hot and dry one, thus resulting in the observed decrease in lake surface area. However, the variations in lake surface area and water levels are not associated solely with the changing climatic conditions. Numerous geomorphological factors could also have contributed to the decrease or increase in lake surface area. For example, thermokarsting along lake banks would lead to increased lake extent, until eventually erosion could lead to catastrophic drainage. In fact, the drainage of two large lakes in the Old Crow basin was attributed to capture by headward erosion of streams. Internal drainage through taliks has also been advanced to explain shrinkage in lake surface area in the discontinuous permafrost zone of Alaska; however, this process seems unlikely to operate in the Old Crow Basin given that the lakes are underlain by glacio-lacustrine clays, which would restrict groundwater circulation even if permafrost were to degrade significantly.

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REFERENCES

ABEK Co-op. (Arctic Borderlands Ecological Knowledge Co-op). 2008. Old Crow River ice-free period. Whitehorse, Yukon: ABEK Co-op. http://www.taiga.net/coop/indics/ocice.html.

Anderson, L., Abbott, M.B., Finney, B.P., and Burns, S.J. 2005a. Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada. Quaternary Research 64:21–35.

Anderson, L., Abbott, M.B., Finney, B.P., and Edwards, M.E. 2005b. Paleohydrology of the southwest Yukon Territory, Canada based on multiproxy analyses of lakes sediment cores from a depth transect. The Holocene 15:1172–1183.

Bonsal, B.R., and Prowse, T.D. 2003. Trends and variability in spring and autumn 0˚C isotherm dates over Canada. Climatic Change 57:341–358.

Bonsal, B.R., Prowse, T.D., Duguay, C.R., and Lacroix, M.P. 2006. Impacts of large-scale teleconnections on freshwater-ice break/freeze-up dates over Canada. Journal of Hydrology 330:340–353.

Britton, M.E. 1957. Vegetation of the Arctic tundra. In: Hansen, H.P., ed. Arctic Biology, 18th Biology Colloquium. Corvallis: Oregon State University Press. 67–113.

Carson, C.E. 1968. Radiocarbon dating of lacustrine strands in Arctic Alaska. Arctic 21:12–26.

Christensen, T.R., Johansson, T., Åkerman, H.J., Mastepanov, M., Malner, N., Friborg, T., Crill, P., and Svensson, B.H. 2004. Thawing sub-Arctic permafrost: Effects on vegetation and methane emissions. Geophysical Research Letters 31, L04501, doi:10.1029/2003GL018680.

Dowdeswell, J.A., Hagen, J.O., Björnsson, H., Glazovsky, A.F., Harrison, W.D., Holmlund, P., Jania, J., et al. 1997. The mass balance of circum-Arctic glaciers and recent climate change. Quaternary Research 48:1–14, doi:10.1006/qres.1997.1900.

Duguay, C.R., Flato, G.M., Jeffries, M.O., Ménard, P., Morris, K., and Rouse, W.R. 2003. Ice cover variability on shallow lakes at high latitudes: Model simulations and observations. Hydrological Processes 17:3465–3483.

Duguay, C.R., Prowse, T.D., Bonsal, B.R., Brown, R.D., Lacroix, M.P., and Ménard, P. 2006. Recent trends in Canadian lake ice covers. Hydrological Processes 20:781–801.

Environment Canada. 2004. Canadian climate normals or averages 1971–2000: Old Crow A, Yukon Territory. http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html.

Everett, K.R. 1980. Landforms. In: Walker, D.A., ed. Geobotanical atlas of the Prudhoe Bay region, Alaska. CRREL Report 80-14. Hanover, New Hampshire: U.S. Army Cold Regions Research and Engineering Laboratory. 14–19.

Fisher, D., Dyke, A., Koerner, R., Bourgeois, J., Kinnard, C., Zdanowicz, C., De Vernal, A., Hillaire-Marcel, C., Savelle, J., and Rochon, A. 2006. Natural variability of Arctic sea ice over the Holocene. Eos, Transactions, American Geophysical Union 87:273–275.

Frohn, R.C., Hinkel, K.M., and Eisner, W.R. 2005. Satellite remote sensing classification of thaw lakes and drained thaw lake basins on the North Slope of Alaska. Remote Sensing of Environment 97:116–126.

Gonfiantini, R. 1986. Environmental isotopes in lake studies. In: Fritz, P., and de Fontes, J.C., eds. Handbook of environmental isotope geochemistry, Vol. 2: The terrestrial environment. Amsterdam: Elsevier. 113–168.

Hare, F.K., and Hay, J.E. 1974. The climate of Canada and Alaska. In: Landsberg, H.E., ed. Climate of North America, World Survey of Climatology, Vol. II. New York: Elsevier. 49–129.

Hartmann, B., and Wendler, G. 2005. The significance of the 1976 Pacific climate shift in the climatology of Alaska. Journal of Climate 18:4824–4838.

Hinkel, K.M., Frohn, R.C., Nelson, F.E., Eisner, W.R., and Beck, R.A. 2005. Morphometric and spatial analysis of thaw lakes and drained thaw lake basins in the western Arctic Coastal Plain, Alaska. Permafrost and Periglacial Processes 16: 327–341, doi:10.1002/ppp.532.

Hinkel, K.M., Jones, B.M., Eisner, W.R., Cuomo, C.J., Beck, R.A., and Frohn, R. 2007. Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic coastal plain of northern Alaska. Journal of Geophysical Research 112, F02S16, doi:10.1029/2006JF000584.

Hughes, O. 1972. Surficial geology of northern Yukon Territory and northwestern District of Mackenzie, Northwest Territories. Geological Survey of Canada, Paper 96-36.

Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. Science 269:676–679.

Jeffries, M.O., Morris, K., and Duguay, C.R. 2005. Lake ice growth and decay in central Alaska, USA: Observations and computer simulations compared. Annals of Glaciology 40:195–199.

Jorgensen, M.T., and Shur, Y. 2007. Evolution of lakes and basins in northern Alaska and discussion of the thaw lake cycle. Journal of Geophysical Research 112, F02S17, doi:10.1029/2006JF000531.

Jorgenson, M.T., Shur, Y.L., and Pullman, E.R. 2006. Abrupt increase in permafrost degradation in Arctic Alaska. Geophysical Research Letters 33, L02503, doi:10.1029/2005GL024960.

Lacelle, D. 2002. Ground ice investigation in the far northwest Canada. MSc thesis, University of Ottawa, Ottawa, Ontario.

Lauriol, B., Lacelle, D., Labrecque, S., Duguay, C.R., and Telka, A. 2009. Holocene evolution of lakes in the Bluefish Basin, northern Yukon, Canada. Arctic 62:212–224.

Lemmen, D.S., Duk-Rodkin, A., and Bednarski, J.M. 1994. Late Glacial drainage systems along the northwestern margin of the Laurentide Ice Sheet. Quaternary Science Reviews 13: 805–828.

Litchi-Fedorovich, S. 1974. Palynology of two sections of late Quaternary sediments from the Porcupine River, Yukon Territory. Geological Survey of Canada, Paper 74-23.

Louis, J-F. 1979. A parameteric model of vertical eddy fluxes in the atmosphere. Boundary Layer Meteorology 17:187–202.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069–1079.

Marsh, P. 1986. Modelling water levels for a lake in the Mackenzie Delta. In: Proceedings of the Cold Regions Hydrology Symposium, University of Alaska-Fairbanks, Fairbanks, Alaska. Bethesda Maryland: American Water Resources Association. 23–29.

Ménard, P., and Duguay, C.R. 2004. Thermal modelling of ice growth in support of GSC Mackenzie Delta research. Unpubl. report available at the Geological Survey of Canada, Atlantic Region, Bedford Institute of Oceanography, Dartmouth, Nova Scotia B2Y 4A2. 24 p.

Ménard, P., Duguay, C.R., Flato, G.M., and Rouse, W.R. 2002. Simulation of ice phenology on Great Slave Lake, Northwest Territories, Canada. Hydrological Processes 16:3691–3706.

Miller, G., Briner, J., and DeVogel, S. 2004. The rapidly disappearing plateau ice caps of central Baffin Island: Where will it all end? 34th International Arctic Workshop, Programs and Abstracts, 11–13 March 2004, Institute of Arctic and Alpine Research, Boulder, Colorado. 120.

Osterkamp, T.E.L., Viereck, L., Shur, Y., Jorgenson, M.T., Racine, C., Doyle, A., and Boone, R.D. 2000. Observations of thermokarst and its impact on boreal forests in Alaska, U.S.A. Arctic, Antarctic and Alpine Research 32:303–315.

Oswald, C.J., and Rouse, W.R. 2004. Thermal characteristics and energy balance of various-size Canadian Shield lakes in the Mackenzie River Basin. Journal of Hydrometeorology 5: 129–144.

Ovenden, L. 1982. Vegetation history of a polygonal peatland, northern Yukon. Boreas 11:209–224.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., et al. 1997. Arctic environmental change during the last four centuries. Science 278:1251–1256.

Peterson, B.J., Holmes, R.M., McClelland, J.W., Vörösmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., and Rahmstorf, S. 2002. Increasing river discharge to the Arctic Ocean. Science 298:2171–2173.

Plug, L.J., Walls, C., and Scott, B.M. 2008. Tundra lake changes from 1978 to 2001 on the Tuktoyaktuk Peninsula, western Canadian Arctic. Geophysical Research Letters 35, L03502, doi:10.1029/2007GL032303.

Prowse, T.D., and Carter, T. 2002. Significance of ice-induced hydraulic storage to spring runoff: A case study of the Mackenzie River. Hydrological Processes 16:779–788.

Riordan, B., Verbyla, D., and McGuire, A.D. 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. Journal of Geophysical Research 111, G04002, doi:10.1029/2005JG000150.

Smith, L.C., Sheng, Y., MacDonald, G.M., and Hinzman, L.D. 2005. Disappearing Arctic lakes. Science 308:1429, doi:10.1126/science.1108142.

Smith, S.L., and Burgess, M. 2002. Permafrost thickness database for northern Canada. Geological Survey of Canada, Open File 4173.

Smol, J.P., and Douglas, M.S.V. 2007. Crossing the final ecological threshold in high Arctic ponds. Proceedings of the National Academy of Sciences of the United States of America 104:12395–12397, doi: 10.1073/pnas.0702777104.

Thompson, D.W.J., and Wallace, J.M. 1998. The Arctic oscillation signature in the wintertime geopotential height and temperature fields. Geophysical Research Letters 25:1297–1300.

———. 2001. Regional climate impacts of the Northern Hemisphere annular mode. Science 293:85–89.

Trenberth, K.E., and Hurrell, J.W. 1994. Decadal atmosphere-ocean variations in the Pacific. Climate Dynamics 9:303–319.

Wahl, H.E., Fraser, D.B., Harvey, R.C., and Maxwell, J.B. 1987. Climate of Yukon. Climatological Studies No. 40. Ottawa: Atmospheric Environment Service, Environment Canada. 323 p.

Wolfe, B.B., and Turner, K.W. 2008. Near-record precipitation causes rapid drainage of Zelma Lake, Old Crow Flats, northern Yukon Territory. Meridian:7–12.

Woo, M.-K. 1992. Impacts of climate variability and change on Canadian wetlands. Canadian Water Resources Journal 17:63–69.

Yoshikawa, K., and Hinzman, L.D. 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinous permafrost near Council, Alaska. Permafrost and Periglacial Processes 14:151–160.