Arctic, Antarctic, and Alpine Research, Vol. 42, No. 1, 2010, pp. 9–18

An Analysis of Past and Future Changes in the Ice Cover of Two High-Arctic Lakes Based on Synthetic Aperture Radar (SAR) and Landsat Imagery

Timothy L. Cook† and*
*Raymond S. Bradley**

*Department of Geosciences, Climate System Research Center, University of Massachusetts, 611 North Pleasant Street, Amherst, Massachusetts 01002, U.S.A.
†Corresponding author: tcook@geo.umass.edu

Abstract

Space-borne remotely sensed data can provide valuable insight into cryospheric processes in remote high-latitude regions for which direct observations are limited. In this study we use synthetic aperture radar (SAR) and Landsat imagery to evaluate recent changes in the ice cover of Upper and Lower Murray Lakes (81°20′N, 69°30′W) on Ellesmere Island, Nunavut, Canada. These data highlight changes in ice conditions that have occurred over the past decade and provide a means for assessing the likely impacts of rising temperatures on future lake-ice conditions. Under current (1997–2007) climatic conditions the Murray Lakes average several weeks of ice-free conditions in August and early September, although in some years a partial ice cover persists throughout the year. The observed relationship between summer temperature and ice melt at Upper and Lower Murray Lakes suggests that recent warming in the High Arctic has forced the lakes near a threshold from a state characterized by perennial ice cover to the current state that includes seasonal melting of lake ice. Projected future warming will significantly increase the duration of ice free conditions on Upper and Lower Murray Lakes, with ice-out predicted to occur 13.5 ± 4.0 and 17.6 ± 5.6 days earlier, respectively, for every 1 °C increase in mean June–July temperature.

DOI: 10.1657/1938-4246-42.1.9

Introduction

The duration of ice cover on lakes is of fundamental importance to physical, chemical, and biological processes in lake systems. Specifically, ice cover limits the exchange of water, nutrients, gases, and light and heat energy between a lake and its surroundings (Adams, 1981). In high-arctic lakes, changes in ice cover are believed to be a dominant factor controlling shifting biological communities (Smol, 1983, 1988; Douglas and Smol, 1999; Keatley et al., 2008), and a number of studies have attributed recent changes in the sedimentary records of high-arctic lakes to changing ice conditions (e.g. Perren et al., 2003; Besonen et al., 2008; Tomkins et al., 2009). On a larger scale, changes in lake-ice duration influence the regional hydrologic cycle and can affect the regional surface energy balance (Jeffries et al., 1999).

The timing of lake-ice formation and breakup are highly sensitive to climatic conditions, with the dominant factor being surface air temperature (Palecki and Barry, 1986; Vavrus et al., 1996; Weyhenmeyer et al., 2004; Bonsal et al., 2006). As a result, records of lake-ice phenology have proven to be a useful indicator of climatic changes (e.g. Assel and Robertson, 1995; Magnuson et al., 2000). In the Arctic, where instrumental climate data are limited, remote sensing of lake-ice conditions can provide valuable insight into climatic conditions and the response of lake systems to climatic change. Observational and proxy climate records indicate that recent temperatures in the Canadian High Arctic are the warmest of the last century (e.g. Kalnay et al., 1996; Rayback and Henry, 2006) and likely the warmest of the past several hundred years (e.g. Overpeck et al., 1997; Cook et al., 2009). Projections of future temperature change in the High Arctic indicate the potential for continued warming in excess of 5 °C by the end of the 21st century (Christensen et al., 2007).

Recent climate warming is likely to have produced significant changes in Arctic lake-ice conditions with even greater changes in lake-ice conditions expected due to future warming. Yet, despite the importance of ice cover to lacustrine environments, our understanding of lake-ice conditions in the High Arctic has been limited by a lack of regular observations. Notable exceptions to this are studies by Heron and Woo (1994), Adams et al. (1989), and Doran et al. (1996). Consequently, this study aimed to improve our understanding of the sensitivity of lake ice cover to both past and future changes in climatic conditions by using remote sensing data to evaluate recent changes in the ice cover of Upper and Lower Murray Lakes in the Canadian High Arctic.

Study Area

Upper and Lower Murray Lakes are long, narrow fjord-like lakes on northeastern Ellesmere Island, Nunavut, Canada (81°20′N, 69°30′W; Figs. 1, 2). Upper Murray Lake (UML) has a surface area of ~7.6 km^2 and a maximum depth of 83 m. Lower Murray Lake (LML) has a surface area of ~5 km^2 and a maximum depth of 46 m. The two lakes occupy a narrow, glacially carved valley with a maximum relief of approximately 1000 m. The Murray Lakes valley trends north-south along the length of the lower lake and northwest-southeast along the length of the upper lake. The surrounding land rises most steeply along the western shore of the lower lake where the slope rises >700 m over a distance ~1 km providing a local horizon ~35° above horizontal. Consequently, significant shading of Lower Murray Lake occurs in the afternoon and early evening when the sun is in the west (Fig. 2). In other directions around the lower lake and around most of the upper lake, the local horizon is generally less

1523-0430/10 $7.00

FIGURE 1. Regional map showing the location of Upper and Lower Murray Lakes as well as other sites mentioned in the text. Also shown is the grid box associated with NCEP/NCAR reanalysis temperature data used in this study.

than 20° and shading is much less of a factor. Climatically, the region is a polar desert with a mean annual temperature around −19 °C, and mean annual precipitation (mostly in the form of snow) <150 mm water equivalent (weq) (Maxwell, 1981). Temperatures above freezing occur only from early June through late August. Maximum daily temperatures during the summer typically range between 0 and 10 °C and occasionally reach as high as 20 °C. The combination of a long, cold winter and a brief summer melt season currently leads to the development of a thick ice cover and limited ice-free conditions. Ice thickness at the start of the melt season in early June 2005 ranged from ~1.5 to 2.2 m.

Data and Methods

Changes in lake-ice coverage were analyzed using space-borne synthetic aperture radar (SAR) data from the Canadian Space Agency (CSA) RADARSAT-1 satellite. The combination of an orbital geometry and beam positions that provide a 1–2 day revisit cycle at high northern latitudes and the ability to return data regardless of sun or cloud conditions make the RADARSAT-1 satellite particularly well suited to monitoring changes in the ice cover of arctic lakes. Archived SAR data for the period 1997 through 2007 were provided by the Alaska Satellite Facility (ASF). A total of 115 images, including RADARSAT-1 fine and standard beam and ScanSAR Wide B images (8, 25, and 100 m resolution, respectively) provided approximately weekly coverage of ice conditions during the melt season of each year in the record.

FIGURE 2. Aerial photograph looking north across Lower Murray Lake in the foreground and Upper Murray Lake which wraps behind the hill to the left in the background. Note the significant shadow across much of Lower Murray Lake which occurs in the afternoon.

The difference in the amplitude of the SAR backscatter signal produced by open water and decaying lake ice allows the two features to be distinguished in SAR imagery (Fig. 3). Calm, open water has a low backscatter signal due to a lack of internal

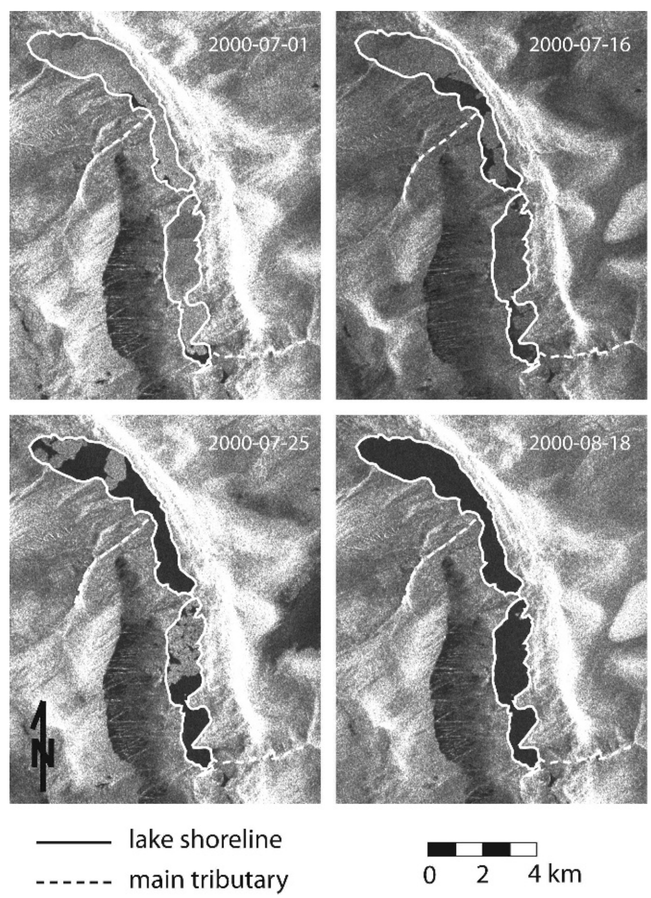

FIGURE 3. Sequence of RADARSAT-1 SAR image sub-scenes showing an increase in the percentage of open water (dark, textureless tone) on Upper and Lower Murray Lakes during the year 2000 melt season. The original RADARSAT-1 data (©Canadian Space Agency—CSA) were provided by the Alaska Satellite Facility (ASF).

reflectors and produces a dark, textureless tone in the SAR imagery. In contrast, decaying ice has a higher backscatter signal and produces a gray, textured tone in the SAR imagery (Jeffries et al., 2005). For example, the increase in the area of the dark, textureless region in the sequence of SAR image sub-scenes in Figure 3 reflects the increase in the area of open water on Upper and Lower Murray Lakes during the year 2000 melt season. Although the first appearance of small areas of open water was more difficult to discern in the lower resolution ScanSAR images, area calculations based on different resolution data acquired as melting commenced were comparable when data was obtained within a span of a few days.

The rate and timing of ice decay was quantified by measuring changes in the area of ice cover recorded in the sequence of SAR images from each melt season. SAR byte-scaled amplitude images were geocoded to an Albers equal area projection and then analyzed using image analysis software. A polygon or series of polygons outlining regions of open water in each image were digitized and then the area of the polygons relative to the total surface area of the lake was used to calculate the percentage of ice cover remaining. The end of ice breakup, or simply ice-out as used herein, was defined as the time when the lake was 100% ice free. The ice-out date was estimated by interpolating between the date of the last SAR image depicting partial ice cover and the date of the first ice-free SAR image based on the trend in the rate of ice cover reduction observed in the preceding images. Because of the low backscatter contrast between open water and newly formed ice, the precise timing of lake freeze-up proved more difficult to identify in the SAR imagery. Consequently, ice formation is not discussed further. However, temperatures at the Murray Lakes typically fall below freezing by the end of August and it can be assumed that ice growth is initiated shortly thereafter.

In addition to the SAR data, 19 Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images were acquired courtesy of the U.S. Geological Survey. GeoTIFF images corresponding to Spectral Bands 1, 2, and 3 were combined into a multichannel Red-Green-Blue (RGB) image. Image channels were adjusted to approximate a natural color appearance and to enhance contrast. Resultant images were converted to grayscale for presentation purposes (Fig. 4). The failure of the Scan Line Corrector onboard Landsat 7 ETM+ on 31 May 2003 resulted in data gaps (diagonal black lines) in subsequent imagery. Due to the missing data coverage in recent Landsat data and the limited number of images available prior to 31 May 2003 (4 images, only 1 of which displayed appreciable melting), the Landsat imagery was not utilized for the lake-ice area calculations. Nonetheless, the Landsat imagery proved valuable for validating the interpretation of the SAR data.

Specifically, meltwater pooling on lake surfaces can present backscatter characteristics similar to those of open water (Hall, 1998) and presents a potential challenge in the delineation of ice and open water in the SAR data. However, in all cases where both SAR and Landsat imagery are available from a similar time period, the Landsat imagery confirms the interpretation of open water areas in the SAR data (cf. Fig. 4). In addition, field observations by the authors indicate that the pooling of water on top of similar lakes on Ellesmere Island is limited to the first few weeks of the melt season. As cracks develop and/or the ice becomes unfrozen from the shoreline, melt water drains from the surface. This draining process appears to occur prior to any appreciable decline in the areal extent of the lake ice. If water resting on ice in the early part of the melt season was being misinterpreted as open water we would anticipate observing a subsequent increase in the area of ice cover once those regions drained. However, this was not observed in the data.

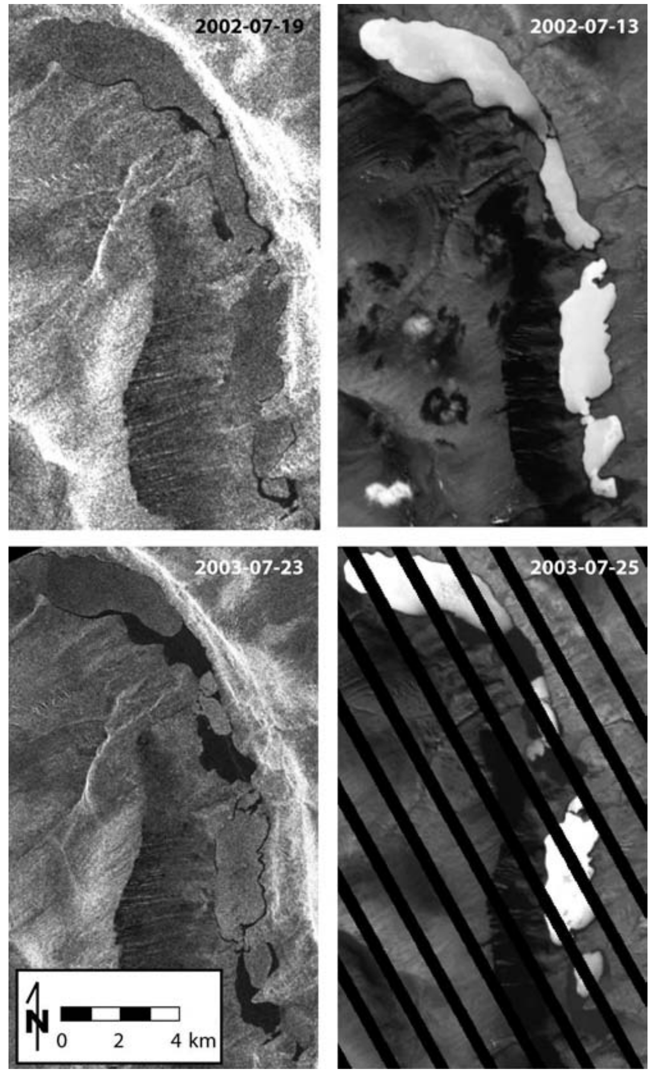

FIGURE 4. Comparison of RADARSAT-1 SAR image sub-scenes (left) with Landsat ETM+ imagery (right). The similar pattern of open water and ice observed in the two data sets helps to validate the interpretation of the SAR imagery in terms of ice extent. The black lines in the 25 July 2003 Landsat image are a consequence of the failure of the Scan Line Corrector onboard Landsat 7 on 31 May 2003. Note that the SAR data has not been terrain corrected, thus the location of high relief features on the landscape may appear out of place. The original RADARSAT-1 data (©Canadian Space Agency—CSA) were provided by the Alaska Satellite Facility (ASF); Landsat images were provided by the U.S. Geological Survey.

Instrumental climate data were obtained from two permanent weather stations operated by Environment Canada that are located at Alert and Eureka, Nunavut (Fig. 1). In addition, reanalysis data were obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; Kalnay et al., 1996). These data provide a daily mean surface air temperature value for a 2.5 × 2.5 degree grid box based on the blending of a combination of a global numerical weather prediction model and observational data. Upper and Lower Murray Lake fall within the grid box centered on 82.5°N, 70°W, but are very near the southern boundary of this box (Fig. 1). Consequently, reanalysis data from the adjacent grid box centered at 80°N, 70°W was also acquired for comparison

TABLE 1

Results of correlation analysis between the mean daily temperature record at the Murray Lakes and the available long-term regional records.

Temperature series	Correlation coefficient (R)	Significance (P value)
Alert	0.752	<0.001
Eureka	0.704	<0.001
Reanalysis (82.5°N, 70°W)	0.770	<0.001
Reanalysis (80°N, 70°W)	0.631	<0.001

purposes. Fourteen months (10 June 2005 through 4 August 2006) of surface air temperature measurements were recorded at the Murray Lakes field site with an Onset Computer Corporation HOBO Pro Temp H08-030-08 temperature logger. According to the manufacturer, the stated accuracy of the logger is better than ±0.5 °C for temperatures between 0 and 40 °C; between 0 and −40 °C accuracy decreases to approximately ±1.25 °C. No additional verification of the accuracy of the temperature loggers was conducted. The temperature logger was placed in a solar radiation shield 2 m above the ground surface and sited on the isthmus between Upper and Lower Murray Lakes at 81.35492°N, 69.53679°W. This site was approximately 50 m north of the Lower Murray Lake shoreline. Temperature was recorded at 1 h intervals from which mean daily temperatures were calculated.

The local observational data were used to evaluate the reliability of the various long-term temperature records in terms of their ability to accurately reflect daily temperatures at the field site. Specifically, we compared the Murray Lake observational data with mean daily temperature records from Alert and Eureka, and the NCEP/NCAR reanalysis data from grid boxes centered on 82.5°N, 70°W and 80°N, 70°W. Prior to comparison, low frequency (seasonal) variability was removed from each record by producing a spline curve that fit the individual record and then calculating residual daily temperatures relative to the spline value. Correlation coefficients were then calculated between each of the regional records and the Murray Lake record using the residual temperature values. Results of the correlation analyses indicate that daily temperatures at Murray Lake are most accurately predicted by the NCEP/NCAR reanalysis data from the grid box centered at 82.5°N, 70°W (R = 0.770; Table 1). However, comparison of the reanalysis data and the Murray Lake data indicates that the reanalysis data systematically underestimates local Murray Lake temperatures during the months of May through September (Fig. 5). This discrepancy may be a consequence of the location of the grid box relative to the Murray Lakes and the large geographic and topographic variability within the grid box which includes much of the upland, glaciated interior of northern Ellesmere Island as well as several hundred square kilometers of the Arctic Ocean.

In order to account for the temperature difference during the months of May through September, a linear regression was calculated between the reanalysis and Murray Lake records using only the data from those months (Fig. 5). The equation of the regression line,

$$\text{Murray Lake Temp} = 3.146 + (0.958 \times \text{Reanalysis Temp})\ (R = 0.922), \quad (1)$$

was then used to adjust the daily reanalysis temperature data from the months of May through September in each year of the record (Fig. 5). This correction also improves the agreement among the reanalysis temperature data and the available observational data from Eureka and Alert. The uncorrected reanalysis data produced a mean June–July–August (JJA) temperature for the 1997–2007 study period of 0.4 °C, considerably below mean JJA temperatures of 4.3 °C and 1.2 °C at Eureka and Alert, respectively. The correction applied to the reanalysis data brings the average reanalysis summer temperature value up to 4.0 °C which is in line with the local observations. Because Alert is located adjacent to the Arctic Ocean along the north coast of Ellesmere Island, it is reasonable that the corrected reanalysis temperatures are in closer agreement with the Eureka temperatures. All further use and discussion of the reanalysis temperature data refers to the adjusted record. To facilitate the comparison of temperature data with ice cover observations, cumulative melting degree days (CMDD) were calculated on an annual basis. CMDD are a running total of mean daily temperatures for each day that temperatures are above 0 °C.

Results and Discussion

ANNUAL ICE BREAKUP

Observations of ice coverage on Upper and Lower Murray Lake during the period 1997 through 2007 show a wide range of

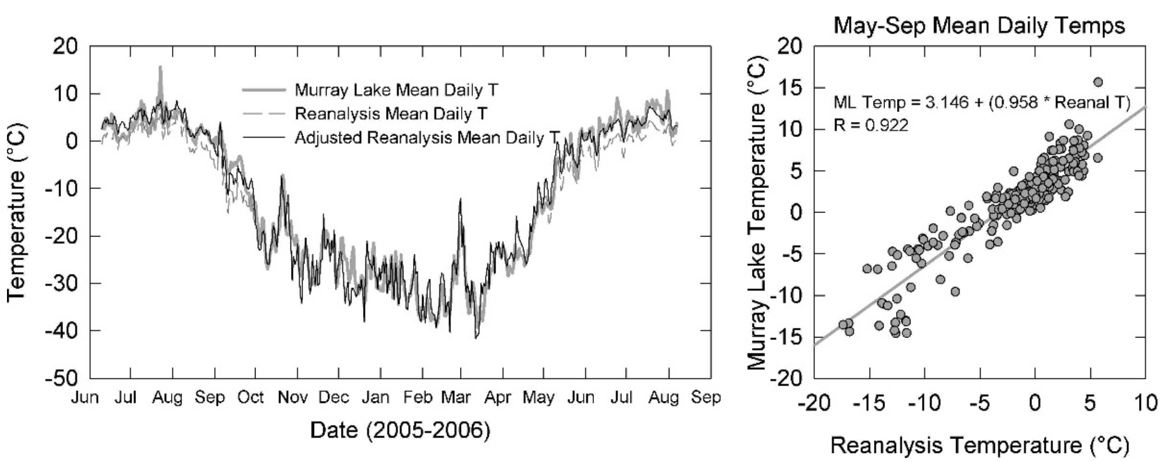

FIGURE 5. (left) Mean daily temperature at the Murray Lakes compared to reanalysis temperature data from a grid box centered on 82.5°N, 70°W. The reanalysis data (dashed gray line) systematically underestimated May–September temperatures at the Murray Lakes. Consequently, the reanalysis temperature record was adjusted based on a linear regression of the May through September temperature data (right). The adjusted reanalysis temperature series (thin black line) shows much better agreement with the local observations (solid gray line).

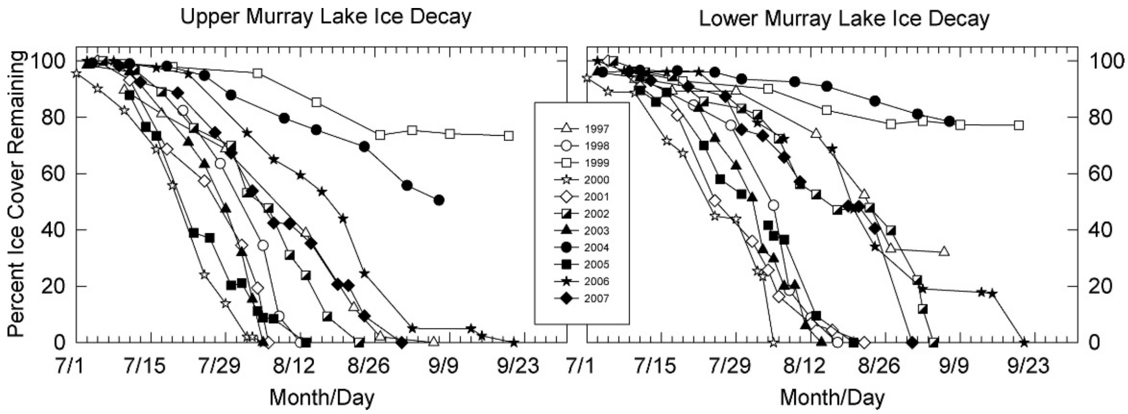

FIGURE 6. Annual record of ice decay on Upper and Lower Murray Lakes showing changes in the area of the lake covered by ice during each summer from 1997 through 2007.

variability in both the rate and timing of ice breakup (Fig. 6). Ice melt likely begins in early June when temperatures start to exceed 0 °C; however, a decrease in total ice surface area was not discernable in the SAR imagery until early July. Ice-out dates typically ranged from early August through early September with the mean date of ice-out 16 August on Upper Murray Lake and 24 August on Lower Murray Lake. However, ~50 to 75% of the ice cover on Upper Murray Lake remained throughout the 1999 and 2004 melt seasons and ~30 to 80% of the ice cover remained on Lower Murray Lake throughout the 1997, 1999, and 2004 melt seasons.

Air temperature during the preceding days, weeks, or months is generally considered the dominant climatic variable affecting the timing of ice breakup (Palecki and Barry, 1986; Vavrus et al., 1996; Weyhenmeyer et al., 2004). The timing and length of the interval over which air temperatures influence ice breakup is highly dependent on the region of interest (Palecki and Barry, 1986). The dominant time period controlling ice breakup at Upper and Lower Murray Lakes was evaluated by calculating Pearson product moment correlations between the Julian dates of ice-out and mean air temperatures over a variety of time periods (Table 2). The highest correlation for a defined calendar interval was associated with mean temperatures during June and July ($R = -0.79$ for UML, and $R = -0.79$ for LML), although June temperatures on their own produce nearly as strong a correlation.

TABLE 2

Pearson product moment correlation results between the timing of ice-out on Upper (UML) and Lower (LML) Murray Lakes mean temperatures over various time intervals. Significant correlations are in bold. *The term "melt period" is defined herein as the interval between the first day of above-freezing temperatures and the ice-out date.

	Correlation coefficient (R)		Significance (P value)	
Temperature variable	UML	LML	UML	LML
Mean June temp	**−0.716**	**−0.777**	**0.030**	**0.0233**
Mean July temp	−0.501	−0.426	0.170	0.293
Mean August temp	−0.152	0.196	0.697	0.641
Mean annual temp (Sep–Aug)	−0.499	−0.425	0.172	0.294
Mean winter temp (Sep–May)	−0.418	−0.332	0.263	0.422
Mean June and July temp	**−0.786**	**−0.791**	**0.012**	**0.0193**
Mean June, July, August temp	−0.612	−0.586	0.080	0.127
Mean "melt period" temp*	**−0.842**	**−0.937**	**0.004**	**<0.001**

The negative coefficient indicates that higher mean temperatures in June and July correspond to earlier ice breakup.

An even stronger correlation is obtained if the timing of ice-out is compared to the average temperature of the "melt period" defined herein as the period of time starting on the first day of above freezing temperatures and ending on the date of complete ice-out. The average length of the melt periods for Upper and Lower Murray Lakes are 74 and 81 days, respectively. The correlation coefficients determined between the ice-out dates and melt period temperature for Upper and Lower Murray Lake were $R = -0.84$ and $R = -0.94$, respectively. These results are to be expected as the timing of ice-out is more likely to reflect the temperature conditions during the specific period of time that melting is taking place rather than a predefined calendar interval that may or may not coincide with the timing of most active melting.

Despite the general relationship between the timing of ice-out and mean June and July temperatures, deviations from this pattern are observed (Fig. 7). These discrepancies reflect two main sources of uncertainty in this analysis. The first relates to differences between the local temperature conditions at the Murray Lakes and the reanalysis temperature record used in this study. Another source of uncertainty stems from the complexity of the processes influencing ice formation, growth, and decay throughout a given year. The melting of ice occurs at a rate controlled by the energy balance of the ice sheet (e.g. Ashton,

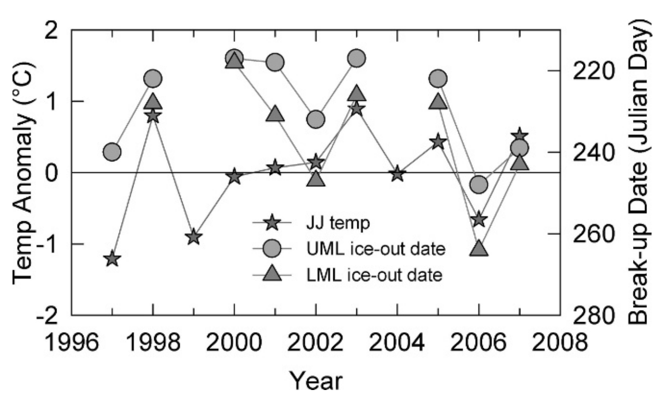

FIGURE 7. Mean June and July temperatures anomalies (relative to 1997–2007 mean) and ice-out dates for the each year of the record. Note that the ice-out date scale has been reversed in order to emphasis the relationship between summer temperatures and the timing of ice-out. Missing data points reflect those years in which complete ice-out did not occur.

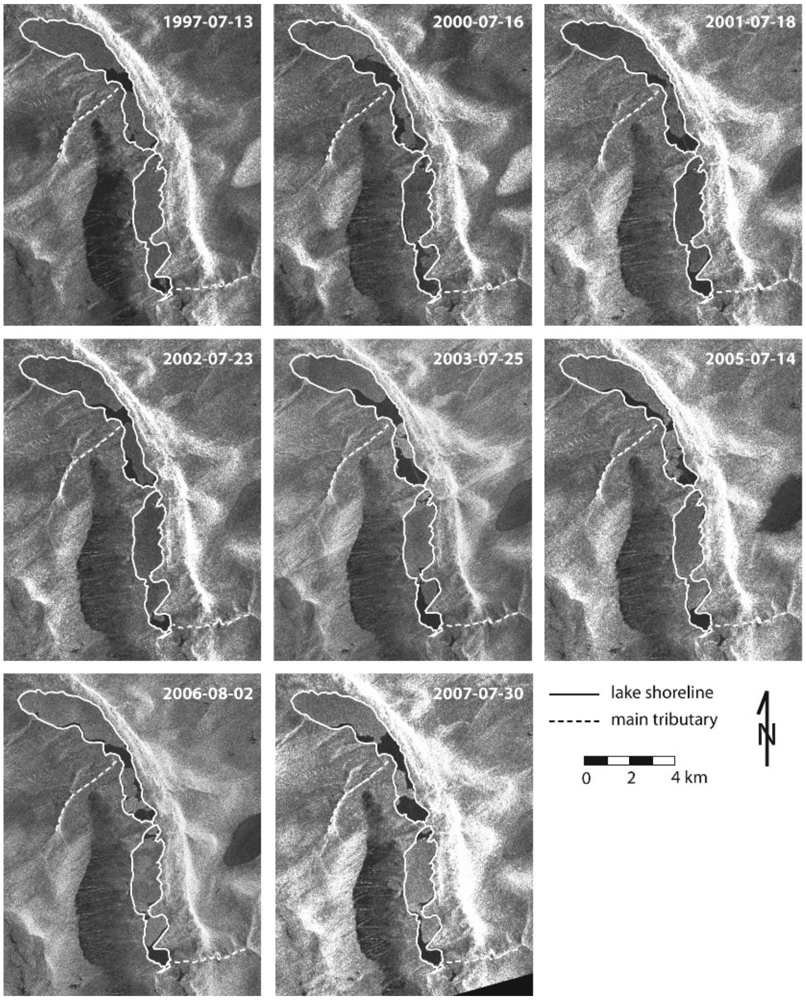

FIGURE 8. RADARSAT-1 SAR image sub-scenes showing initial ice breakup on Upper and Lower Murray Lakes. Note the consistent pattern of open water first occurring near the center of Upper Murray Lake and the south end of Lower Murray Lake. The original RADARSAT-1 data (©Canadian Space Agency—CSA) were provided by the Alaska Satellite Facility (ASF).

1983; Heron and Woo, 1994; Liston and Hall, 1995; Duguay et al., 2003) with the rate of ice breakup further influenced by dynamic processes related to wind and water currents (Ashton, 1980). If the rate of melting and ice breakup remains constant, the timing of ice-out will vary according to ice thickness at the start of the melt season which in turn varies in response to winter temperature and snow conditions.

Snow accumulation interacts with the underlying ice sheet in a complex, nonlinear manner which can both increase the overall ice thickness and/or slow its growth and decay (Vavrus et al., 1996). Specifically, the accumulation of snow can lead to the formation of superimposed snow-ice when the ice sheet gets depressed below the hydrostatic water level and the snow cover becomes water saturated and then freezes (Adams and Roulet, 1980; Duguay et al., 2003). On the other hand, snow cover insulates the underlying ice sheet, limiting conductive heat loss from the lake to the atmosphere in autumn and reducing warming in spring. As a result, lakes with a thicker snow cover will tend to have thinner ice and an earlier breakup date relative to similar lakes that have less snow cover (Vincent et al., 2008). Field observations by the authors of completely clear ice (i.e. lacking a layer of superimposed snow-ice) on the Murray Lakes in 2005 and other Ellesmere Island lakes including Lake Tuborg, South Sawtooth Lake, and Lakes C1, C2, and C3 on several occasions over the past decade suggest that the formation of snow-ice may not be a significant process on these large, high-arctic lakes, although variations from this pattern should be expected and additional observations are needed. Limited snow-ice formation may reflect low winter snow accumulation, which is typically less than 150 mm weq, relative to the thick (~2 m) ice cover on these lakes. However, without measurements of annual snow accumulation and ice thickness, our ability to fully evaluate the role of snow accumulation on the timing of ice breakup is limited.

Physical processes related to wind and water currents play a significant role in delaying the onset of ice formation during autumn and enhancing ice breakup during spring, with the influence of wind generally being more pronounced on lakes with a larger surface area (Ashton, 1980). Comparison of SAR images corresponding to the initial breakup period on the Murray Lakes highlights the role of dynamic processes in ice breakup. Observations of the initial breakup of ice cover in mid to late July of each year for which data are available reveal a consistent pattern of ice breakup, with open water initially forming in the center of Upper Murray Lake and in the south end of Lower Murray Lake (Fig. 8). This pattern of ice breakup was observed in the field during August 2006 and is consistent with Landsat images acquired on 13 July 2002, 23 July 2003, 21 July 2005, and 25 July 2007 (cf. Figure 4). Landsat data from the initial breakup period during other years were not available. These regions correspond to the locations of the inlets of the main tributaries draining into each of the lakes, and likely reflect the influence of warmer inflowing water and/or the physical breakup of the ice sheet by water currents. Consequently, some of the variability in the timing of ice breakup in the Murray Lakes likely results from mechanical processes not directly associated with air temperatures.

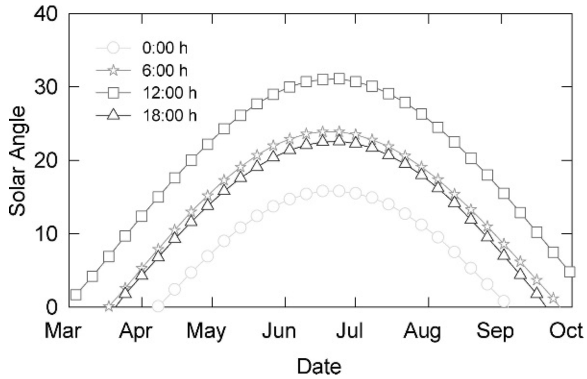

FIGURE 9. Seasonal variations in the angle of the sun above the horizon for different times of day at the Murray Lakes field site.

An interesting feature of the Murray Lakes ice decay record is the consistent delay in the timing of ice-out on Lower Murray Lake relative to Upper Murray Lake. On average, Lower Murray Lake ice-out occurs ~7 days after ice-out on Upper Murray Lake. Because the two lakes are essentially responding to the same climatic forcings, other factors must be responsible for the difference in the timing of ice-out. All other factors being similar, ice-out on deeper lakes typically occurs later as some of the energy that would go to melting ice is lost to the heating of the underlying water column (Vincent et al., 2008). However, Upper Murray Lake is considerably deeper than Lower Murray Lake (83 m versus 46 m maximum depth), so lake depth cannot be the controlling factor. Instead, it seems likely that the significant afternoon shading which occurs on Lower Murray Lake (cf. Fig. 2) reduces surface air temperatures over the lake and limits the absorption of solar radiation, which in turn reduces the rate of ice decay. Astronomical tables can be used to determine the angle of the sun above the horizon at different times of day at the Murray Lakes field site (Fig. 9; http://aa.usno.navy.mil/data/docs/AltAz.php; last accessed 31 December 2008). As the local horizon to the west of Lower Murray Lake is ~35° above horizontal, the sun would be below the local horizon for much of the afternoon and evening, whereas the much lower local horizon around the upper lake indicates that shading is much less of a factor on Upper Murray Lake. Differences in the surface area of the two lakes may play an additional role as the larger surface of the upper lake provides a larger fetch and increases the potential for physical breakdown of ice by wind and wave action. Consequently, the combination of reduced sunlight and limited wind action likely delays the rate of ice breakup on Lower Murray Lake. Furthermore, it is possible that differences in ice growth on the two lakes, which is also influenced by lake volume, surface area, and shading, leads to different initial ice conditions at the onset of melting in the spring. Consequently, changes in the relative importance of these different factors add additional uncertainty to the relationship between air temperature and ice decay.

The current pattern of ice cover on Upper and Lower Murray lakes, characterized by a very brief period of open water and the occasional occurrence of ice cover throughout the year, suggests that the Murray Lakes are presently in a marginal climatic setting where slightly colder climatic conditions could lead to the establishment of a perennial ice cover. Perennial (multiyear) ice covers have been observed at several other locations in the High Arctic and also in parts of Antarctica. In particular, Lakes A, B, C1, C2, and C3 along the northern coast of Ellesmere Island have typically maintained year-round ice covers in the past (Belzile et al., 2001; Lenormand et al., 2002; Jeffries et al., 2005), and Colour Lake on Axel Heiberg Island has occasionally maintained an ice cover through the summer, although not in consecutive years (Adams et al., 1989; Doran et al., 1996). Doran et al., (1996) suggested that an ice cover that lasted through the summer at Colour Lake effectively trapped water that had been warmed during that summer and led to elevated water temperatures the following spring, limiting the tendency of a multiyear ice cover to persist. This interpretation is consistent with observations at Upper Murray Lake which show early ice-out dates in 2000 and 2005, the two years following residual ice years. Ice-out in 2000 (on 4 August) was the earliest observed in the record and occurred during a year characterized by abnormally low ice-cover on other northern Ellesmere Island lakes (Jeffries et al., 2005), suggesting that changes in the ice cover on the Murray Lakes are consistent with regional conditions.

PAST ICE CONDITIONS

Observational and proxy climate records indicate that recent temperatures in the Canadian High Arctic are the warmest of the last century (e.g. Kalnay et al., 1996; Rayback and Henry, 2006) and likely the warmest of the past several hundred years (e.g. Overpeck et al., 1997; Cook et al., 2009). The impact of recent warming on the ice cover of the Murray Lakes was evaluated based on the relationship between the area of ice cover remaining and the cumulative melting degree days (CMDD) at that time (Fig. 10). Figure 10 includes all of the ice cover data points from Figure 5 plotted as a function of CMDD instead of time. As melting degree days accumulate, there is a clear decreasing trend in the area of ice cover remaining. During the period 1997–2007 a minimum of 286 and a mean of 325 CMDD were required to reach complete ice-out on Upper Murray Lake and a minimum of 294 and a mean of 353 CMDD were required to reach complete ice-out on Lower Murray Lake (Table 3).

Cumulative melting degree days provide a reasonable approximation of the energy available for melt processes (Bilello, 1980). As ice decay evolves and ice becomes weakened and is able to move about the lake surface, dynamic processes become increasingly important to ice breakup (Michel et al., 1986). Thus, the increased scatter in measurements of ice extent as CMDD increase likely reflects the increasing importance of dynamic processes to ice breakup as well as annual variations in initial ice conditions resulting from differences in winter ice growth. Nonetheless, the trend of the ice cover–CMDD relationship can be used to evaluate the influence of changing climatic conditions on ice decay, and the envelope of values provides an indication of the range of internal variability within the system.

A mean cumulative melting degree day curve was determined from mean daily temperatures during the period 1997–2007 (Fig. 10). Also determined were CMDD curves calculated based on 0.5, 1.0, and 1.5 °C reductions in mean daily temperatures, which result in 295, 257, and 221 total CMDD, respectively (Fig. 10). The total CMDD based on mean 1997–2007 temperatures (336 CMDD) is only slightly above the mean number of CMDD needed to reach ice-out on Upper Murray Lake (325 CMDD) and below the mean number of CMDD needed to reach ice-out on Lower Murray Lake (353 CMDD) during the observation period. Consequently, a temperature reduction of less than 1.0 °C, relative to the 1997–2007 mean, would produce a CMDD total well below the minimum value required for ice-out on either Upper or Lower Murray Lakes during the period of record.

These results suggest that only a minor decrease in mean temperature would be required to shift the Murray Lakes between

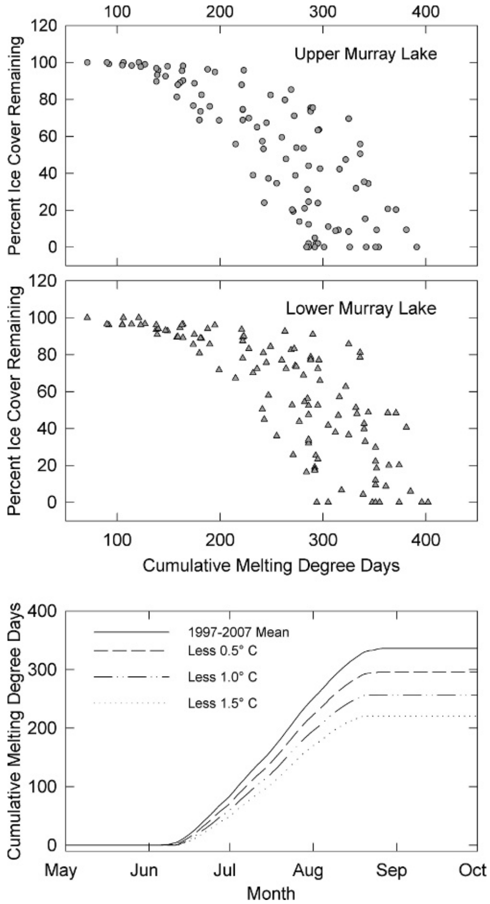

FIGURE 10. (top) Percent ice cover remaining on Upper and Lower Murray Lakes plotted as a function of cumulative melting degree days (CMDD). Plots include all data from 1997 to 2007, with each data point reflecting the percentage of ice cover remaining and the total CMDD on the date the SAR image was acquired. (bottom) Cumulative melting degree days calculated based on mean daily temperatures during 1997–2007 and 0.5, 1.0, and 1.5 °C reductions from this mean. Comparison of the top and bottom panels indicate that complete melting of Upper and Lower Murray Lakes is unlikely to occur if temperatures are reduced by 1.0 °C, resulting in an end of melt-season total of only ~250 CMDD.

TABLE 3

Ice-out dates and the total cumulative melting degree days (CMDD) required to reach ice-out on Upper and Lower Murray Lakes during each year of the record. Missing values indicate complete ice-out did not occur.

	Upper Murray Lake		Lower Murray Lake	
Time period	Ice-out date	CMDD to ice-out	Ice-out date	CMDD to ice-out
1997	240	286	—	—
1998	222	354	228	374
1999	—	—	—	—
2000	217	301	218	305
2001	218	284	231	348
2002	232	326	247	351
2003	217	351	226	402
2004	—	—	—	—
2005	222	342	228	355
2006	248	292	264	294
2007	239	391	243	396
1997–2007 mean	228	325	236	353

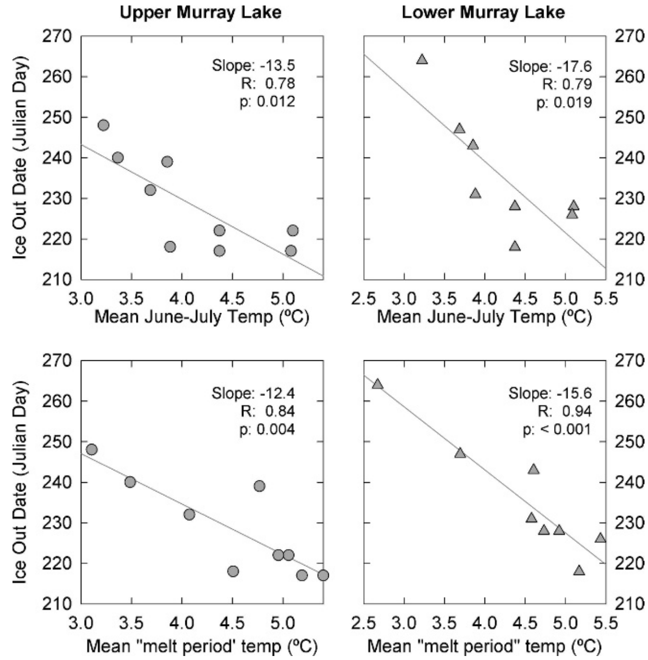

FIGURE 11. The relationship between the timing of ice-out and mean June and July (top) and "melt period" (bottom) surface air temperatures. Linear regression lines indicated that ice-out on the Murray Lakes is likely to occur ~12 to 18 days earlier per °C temperature increase. Years during which complete ice-out did not occur are not plotted.

their current states characterized by seasonal melting and states in which a residual ice cover remains throughout the melt season. Analysis of 20th century observations of summer temperature changes (e.g. Kalnay et al., 1996; Rayback and Henry, 2006) suggests that 20th century warming in excess of 1.0 °C may have indeed forced Upper Murray Lake across a threshold leading away from a state of perennial ice cover. A similar transition has been observed at other lakes along the north coast of Ellesmere Island (Lakes A, B, C1, C2, and C3) which have traditionally been covered by a perennial ice cover (Belzile et al., 2001; Lenormand et al., 2002; Jeffries et al., 2005), but have recently been experiencing ice free conditions during the summer (D. Mueller, personal communication). Transitions in ice cover of this nature are consistent with paleolimnological observations from other high-arctic lakes in which recent, unprecedented shifts in biological communities have been attributed to changes in the duration and extent of summer ice cover (e.g. Perren et al., 2003; Smol et al., 2005). In fact, analysis of a 1000 year sedimentary record from Lower Murray Lake identified the first appearance of diatoms in the lake as recently as 1998 (Besonen et al., 2008), supporting our interpretation that significant changes in the lake system have occurred in recent years.

FUTURE ICE CONDITIONS

Projections of future temperature change in the High Arctic indicate the potential for mean annual temperatures to increase by as much as 5 °C by the end of the 21st century (Christensen et al., 2007). Although warming is expected to be highest in winter (>7 °C), summer warming is likely to exceed 2 °C (Christensen et al., 2007). The relationship between ice-out dates and mean June and July temperatures was used to evaluate the impact of future warming on the ice cover of Upper and Lower Murray Lakes (Fig. 11). As noted previously, the timing of ice-out displayed the strongest correlation with surface air temperatures during a defined calendar time interval spanning June and July (cf. Table 2). A linear regression between mean June and July temperatures and ice-out dates indicates that for each 1.0 °C increase in temperature the timing of ice-out will occur 13.5 ± 4.0 days earlier for Upper Murray Lake and 17.6 ± 5.6 days earlier for Lower Murray Lake. Calculating the regression using the better correlated "melt period" temperature instead of mean June–July temperatures indicates a 12.4 ± 3.0 days per °C relationship for Upper Murray Lake and a 15.6 ± 2.4 days per °C relationship for Lower Murray Lake. Based on either estimate, the results indicate that future warming in the High Arctic will result in significantly longer periods of ice free conditions on these lakes. However, it is important to note the large degree of uncertainty in these estimates, which reflect both the limited data set and the influence of non-temperature-related processes on ice decay.

Recent work has suggested that the timing of ice-out may not respond linearly to changes in temperature (Weyhenmeyer et al., 2004), thus the 12.4 to 17.6 day per °C relationships determined in this study may change as temperatures shift beyond the range of observations. By comparison, historical trends in the ice cover of lower latitude lakes have shown a mean shift in the timing of ice-out by ~5 days per 1.0 °C temperature change (e.g. Assel and Robertson, 1995; Magnuson et al., 2000). In a comprehensive study of past ice conditions on Swedish lakes, Weyhenmeyer et al. (2004) observed ice breakup dates that were 4 to 17 days earlier following a mean annual temperature increase of 0.8 °C. The largest changes were observed in the warmest locations, thus Weyhenmeyer et al. (2004) concluded that future changes in ice conditions due to increased warming are likely to be less drastic in colder regions, which is counter to the large temperature dependence of ice-out identified in this study. However, the coldest site examined by Weyhenmeyer et al. (2004) had a mean annual air temperature near −1.0 °C, whereas mean annual temperature at Upper Murray Lake is −19 °C. Weyhenmeyer et al. (2004) also based their conclusions on an analysis of changes in mean annual temperature, whereas the current study relates the timing of ice-out only to melt season temperatures. Consequently the results of the two studies are not entirely comparable.

It is possible that the climatic conditions at the Murray Lakes, near the threshold necessary for perennial ice cover, lead to an amplified change in the timing of ice-out for a given change in temperature. Quantitative relationships between air temperature and ice breakup are applicable only within specific geographic and climatic settings (e.g. Palecki and Barry, 1986; Weyhenmeyer et al., 2004). In addition, morphometric characteristics of individual water bodies (i.e. depth, surface area) further influence ice decay (Stewart and Haugen, 1990; this study). Consequently, caution must be used when applying the results of this study to other lakes. Nonetheless, the magnitude of the ice-out response to temperature changes as reported here highlights the impacts of future warming on high-arctic lake systems and emphasizes the need for continued study of ongoing environmental changes in the Arctic.

Conclusions

Space-borne synthetic aperture radar data have provided a valuable tool for interpreting the climatic sensitivity of the ice cover on remote high-arctic lakes. Comparison with reanalysis air temperature records allowed for quantification of the relationship between ice cover and climatic conditions. The summer temperature conditions necessary for the complete melting of the ice covers on Upper and Lower Murray Lakes are very near current mean climatic conditions, suggesting that the two lakes are at or near a threshold between a state of perennial ice cover and regular seasonal melting of their ice covers. Recent (20th century) warming has likely forced the Murray Lakes across this threshold, and projected future warming due to anthropogenic causes will further increase the duration of ice free conditions on these lakes. Although the exact response of lake ice to temperature changes will vary according to the local geographic and climatic setting as well as the characteristics of the individual lake, the results presented here indicate that profound changes in the ice cover of high-arctic lakes have recently occurred and that even greater changes should be expected in the future. Given the significance of the timing of ice-out and the length of open water conditions to so many physical, chemical, and biological processes acting both within and beyond the lake, future changes in lake ice cover are likely to have a significant impact on high-arctic environments.

Acknowledgments

This work was made possible by a Massachusetts Space Grant summer fellowship to T. Cook and National Science Foundation Grant No. ATM-0402421. We thank D. Mueller for help with SAR data and F. Keimig for processing the reanalysis temperature data. RADARSAT-1 SAR data were provided by the Alaska Satellite Facility at the University of Alaska Fairbanks. Landsat imagery were provided by the U.S. Geological Survey.

References Cited

Adams, W. P., 1981: Snow and ice on lakes. *In* Gray, D. M., and Male, D. H. (eds.), *Handbook of Snow: Principles, Processes, Management and Use*. Toronto: Pergamon, 437–474.

Adams, W. P., and Roulet, N. T., 1980: Illustration of the roles of snow in the evolution of the winter cover of a lake. *Arctic*, 33: 100–116.

Adams, W. P., Doran, P. T., Ecclestone, M., Kingsbury, C. M., and Allan, C. J., 1989: A rare second year—Lake ice cover in the Canadian High Arctic. *Arctic*, 42: 299–306.

Ashton, G. D., 1980: Freshwater ice growth, motion, and decay. *In* Colbeck, S. C. (ed.), *Dynamics of Snow and Ice Masses*. New York: Academic Press, 261–304.

Ashton, G. D., 1983: Lake ice decay. *Cold Regions Science and Technology*, 8: 83–86.

Assel, R. A., and Robertson, D. M., 1995: Changes in winter air temperatures near Lake Michigan, 1851–1993, as determined from regional lake-ice records. *Limnology and Oceanography*, 40: 165–176.

Belzile, C., Vincent, W. F., Gibson, J. A. E., and Van Hove, P., 2001: Bio-optical characteristics of the snow, ice, and water column of a perennially ice-covered lake in the High Arctic. *Canadian Journal of Fisheries and Aquatic Science*, 58: 2405–2418.

Besonen, M. B., Patridge, W., Bradley, R. S., Francus, P., Stoner, J. S., and Abbott, M. B., 2008: A record of climate over the last millennium based on varved lake sediments from the Canadian High Arctic. *Holocene*, 18: 169–180.

Bilello, M. A., 1980: *Maximum Thickness and Subsequent Decay of Lake, River, and Fast Sea Ice in Canada and Alaska*. Hanover, New Hampshire: U.S. Army Cold Regions Research and Engineering Laboratory, Report 80-6: 160 pp.

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.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C. G., Räisänen, J., Rinke, A., Sarr, A., and Whetton, P., 2007: Regional Climate

Projections. *In* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L. (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge/New York: Cambridge University Press, 848–940.

Cook, T. L., Bradley, R. S., Stoner, J. S., and Francus, P., 2009: Five thousand years of sediment transfer in a High Arctic watershed recorded in annually laminated sediments from Lower Murray Lake, Ellesmere Island, Nunavut, Canada. *Journal of Paleolimnology*, 41(1): 77–94.

Doran, P. T., McKay, C. P., Adams, W. P., English, M. C., Wharton, R. A., Jr., and Meyer, M. A., 1996: Climate forcing and thermal feedback of residual lake-ice covers in the High Arctic. *Limnology and Oceanography*, 41: 839–848.

Douglas, M. S. V., and Smol, J. P., 1999: Freshwater diatoms as indicators of environmental change in the High Arctic. *In* Stoermer, E. F., and Smol, J. P. (eds.), *The Diatoms: Applications for the Environmental and Earth Sciences*. Cambridge: Cambridge University Press, 227–244.

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

Hall, D. K., 1998: Remote sensing of snow and ice using imaging radar. *In* Henderson, F. M., and Lewis, A. J. (eds.), *Principles and Applications of Imaging Radar*. New York: John Wiley and Sons, Inc., 677–698.

Heron, R., and Woo, M.-K., 1994: Decay of a High Arctic lake-ice cover: observations and modeling. *Journal of Glaciology*, 40: 283–292.

Jeffries, M. O., Zhang, T., Frey, K., and Kozlenko, N., 1999: Estimating late winter heat flow to the atmosphere from the lake-dominated Alaskan North Slope. *Journal of Glaciology*, 45: 315–324.

Jeffries, M. O., Morris, K., and Kozlenko, N., 2005: Ice characteristics and processes, and remote sensing of frozen rivers and lakes. *In* Duguay, C. R., and Pietroniro, A. (eds.), *Remote Sensing in Northern Hydrology: Measuring Environmental Change*. Washington: American Geophysical Union, 63–90.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D., 1996: The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, 77: 437–470.

Keatley, B. E., Douglas, M. S. V., and Smol, J. P., 2008: Prolonged ice cover dampens diatom community responses to recent climatic change in high arctic lakes. *Arctic, Antarctic, and Alpine Research*, 40: 364–372.

Lenormand, F., Duguay, C. R., and Gauthier, R., 2002: Development of a historical ice database for the study of climate change in Canada. *Hydrological Processes*, 16: 3707–3722.

Liston, G. E., and Hall, D. K., 1995: An energy-balance model of lake-ice evolution. *Journal of Glaciology*, 41: 373–382.

Magnuson, J. J., Robertson, D. M., Benson, B. J., Wynne, R. H., Livingstone, D. M., Arai, T., Assel, R. A., Barry, R. G., Card, V., Kuusisto, E., Granin, N. G., Prowse, T. D., Stewart, K. M., and Vuglinski, V. S., 2000: Historical trends in lake and river ice cover in the northern hemisphere. *Science*, 289: 1743–1745.

Maxwell, J. B., 1981: Climatic regions of the Canadian arctic islands. *Arctic*, 34: 225–240.

Michel, B., Ashton, G., Beltaos, S., Davar, K., Frederking, R., Gerard, L., Pratte, B., Tsang, G., and Williams, G., 1986: Hydraulics. *In* Ashton, G. (ed.), *River and Lake Ice Engineering*. Littleton, Colorado: Water Resources Publications, 261–371.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., and Zielinski, G., 1997: Arctic environmental change of the last four centuries. *Science*, 278: 1251–1256.

Palecki, M. A., and Barry, R. G., 1986: Freeze-up and breakup of lakes as an index of temperature changes during the transition seasons: a case study for Finland. *Journal of Climate and Applied Meteorology*, 25: 893–902.

Perren, B. B., Bradley, R. S., and Francus, P., 2003: Rapid lacustrine response to recent High Arctic warming: a diatom record from Sawtooth Lake, Ellesmere Island, Nunavut. *Arctic, Antarctic, and Alpine Research*, 35: 271–278.

Rayback, S. A., and Henry, G. H. R., 2006: Reconstruction of summer temperature for a Canadian High Arctic site from retrospective analysis of the dwarf shrub, *Cassiope tetragona*. *Arctic, Antarctic, and Alpine Research*, 38: 228–238.

Smol, J. P., 1983: Paleophycology of a high arctic lake, Cape Herschel, Ellesmere Island. *Canadian Journal of Botany*, 61: 2195–2204.

Smol, J. P., 1988: Paleoclimate proxy data from freshwater arctic diatoms. *Verhandlungen—Internationale Vereinigung für theoretische und angewandte Limnologie*, 23: 837–844.

Smol, J. P., Wolfe, A. P., Birks, H. J. B., Douglas, M. S. V., Jones, V. J., Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D., Brooks, S. J., Fallu, M.-A., Hughes, M., Keatley, B. E., Laing, T. E., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A. M., Perren, B., Quinlan, R., Rautio, M., Saulnier-Talbot, E., Siitonen, S., Solovieva, N., and Weckström, J., 2005: Climate-driven regime shifts in the biological communities of arctic lakes. *Proceedings of the National Academy of Sciences of the United States of America*, 102: 4397–4402.

Stewart, K. M., and Haugen, R. K., 1990: Influence of lake morphometry on ice dates. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*, 24: 122–127.

Tomkins, J. D., Lamoureux, S. F., Antoniades, D., and Vincent, W. F., 2009: Sedimentary pellets as an ice cover proxy in a High Arctic ice-covered lake. *Journal of Paleolimnology*, 41: 225–242.

Vavrus, S. J., Wynne, R. H., and Foley, J. A., 1996: Measuring the sensitivity of southern Wisconsin lake ice to climate variations and lake depth using a numerical model. *Limnology and Oceanography*, 41: 822–831.

Vincent, W. F., MacIntyre, S., Spige, R. H., and Laurion, I., 2008: The physical limnology of high-latitude lakes. *In* Vincent, W. F., and Laybourn-Parry, J. (eds.), *Polar Lakes and Rivers: Limnology of Arctic and Antarctic Aquatic Ecosystems*. Oxford: Oxford University Press, 65–81.

Weyhenmeyer, G. A., Meili, M., and Livingstone, D. M., 2004: Nonlinear temperature response of lake ice breakup. *Geophysical Research Letters*, 31: article L07203, doi:10.1029/2004GL019530.

MS accepted September 2009