Changing River Ice Seasonality and Impacts on Interior Alaskan Communities

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ABSTRACT

Subsistence harvesters in high latitudes rely on frozen rivers for winter access to local resources. During recent decades, interior Alaskan residents have observed changes in river ice regimes that are significant hindrances to travel and subsistence practices. We used remote sensing in combination with local observations to examine changes in seasonality of river breakup and freeze-up and to assess the implications on travel for subsistence harvesters. Spring and autumn air temperatures, respectively, were found to impact timing of breakup (-2.0 days °C^{-1}) and freeze-up ($+2.0$ days °C^{-1}). Spring air temperatures have increased by 0.2°–0.6°C decade^{-1} over the last 62–93 years, depending on study area and time period. Local observations indicate that the breakup season has advanced by about 6 days over the last century. Autumn air temperatures have not changed over the long term, but have been generally warmer over the last 15 years. Over various time periods throughout the last century, we found no change in freeze-up timing for some communities, whereas other communities showed delays of 1.0–2.1 days decade^{-1}. The length of time the river was unsafe for travel during the freeze-up season was 2 to 3 times greater than during breakup. The duration of river ice cover for safe travel has declined over the last century and is expected to decline further as the climate continues to warm, thereby presenting new challenges to accessing subsistence resources and necessitating community adaptation.

1. Introduction

In rural Alaskan communities, many of which are off the road system, people rely on rivers and lakes for travel and access to resources (Johnson et al. 2016). During the summer, people navigate large waterbodies by boat or use all-terrain vehicles on a limited terrestrial trail network. However, the ability to traverse the landscape is greatly enhanced during the winter, when waterbodies, small and large, are firmly frozen and snow covers the landscape, allowing access by snowmobile or dog team (Schneider et al. 2013). During the shoulder seasons of river ice breakup and freeze-up, travel is inhibited by environmental conditions: there may be too much ice to navigate a boat, yet the ice is too thin or discontinuous to travel over by snowmobile, all-terrain

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vehicle, dogsled, or passenger vehicle. Rural harvesters (hunters, fishers, trappers, and gatherers) of subsistence resources have increasingly expressed concern that conditions during breakup and freeze-up have become more dynamic and unpredictable (Brinkman et al. 2016; McNeeley and Shulski 2011). Locals have described many changes in river ice regimes that are likely linked to climate change, including earlier breakup, less "violent" and quieter breakup with fewer ice jams and flooding, delayed freeze-up, longer freeze-up seasons, thinner and more dangerous ice, and more open water during winter (Herman-Mercer et al. 2011; Wilson et al. 2015). Some of these changes have led to travel safety concerns (Brubaker et al. 2011; Clark et al. 2016; Driscoll et al. 2016; Schneider et al. 2013) and reduced access to subsistence harvest areas (Brinkman et al. 2016).

Arctic amplification of climate warming is occurring (Walsh 2014), with the number of days above freezing in interior Alaska increasing over the past century by 40 days (Wendler and Shulski 2009). As a result of rising air temperatures, an advancement in river and lake ice breakup dates and a delay in freeze-up dates have been documented in many regions throughout the circumpolar North (Bieniek et al. 2011; Magnuson et al. 2000; Prowse et al. 2011; Sagarin and Micheli 2001; Šmejkalová et al. 2016). Because frozen waterbodies expand the area of accessible landscape, such a reduction in the duration of ice cover has important implications for rural Alaskans, whose access to subsistence resources could be greatly challenged.

River ice breakup and freeze-up are often defined in scientific literature as single-date events: for example, the date when the river ice begins to flow (Bieniek et al. 2011) or the date when the river has reached complete ice cover (Jeffries et al. 2012). Alternatively, breakup or freeze-up can be viewed as a series of processes that occur over a longer time span (Jeffries et al. 2012). Here, we expand upon the single-date concept to encompass the entirety of the breakup and freeze-up seasons as they relate to safe river navigability. Several studies have shown that the breakup dates of rivers in Alaska have advanced (Bieniek et al. 2011; Sagarin and Micheli 2001), but little has been documented about the remaining breakup season or the temporal patterns regarding the freeze-up season in Alaska. This study takes the novel approach of linking remotely sensed river ice conditions with local observations of travel safety to provide a more complete characterization of how river ice regimes are changing, with attention to potential impacts on people.

This project is part of a larger study conducted in collaboration with nine rural communities throughout interior Alaska. Based on detailed ethnographic, empirical, and anecdotal evidence, we initiated research to quantify changes in river ice regimes to enable preparation for and adaptation to changing river dynamics. We emphasize the direct impacts of changing ice regimes on human safety and access to subsistence resources, though there are many other important physical, hydrologic, and biological consequences of these changes (Jeffries et al. 2012). This project focuses on river ice seasonality around three communities adjacent to major rivers in the Yukon River basin in interior Alaska. We utilized Landsat satellite imagery from 1972 to 2016 to describe the stages of the breakup and freeze-up seasons in terms of areal ice extent, from the onset of ice deterioration to a fully open river, and from initial ice accumulation to a fully ice-covered river. We related the timing of the stages described from remote sensing to 1) local observations of the breakup and freeze-up seasons in order to understand how ice extent relates to river navigability and travel safety and 2) air temperature to understand the hydroclimatic controls of river ice conditions. We assessed the long-term (multidecadal to century scale) changes in river ice seasonality and river navigability using local observations and highlight some of the impacts of these changes on subsistence activities. Our findings characterize changes in river ice breakup and freeze-up that have important consequences for subsistence practices and adaptations of rural subsistence communities as the climate warms.

2. Methods

a. Study area

The Yukon River, ~3200 km in length, flows from northwestern Canada through interior Alaska and into the Bering Sea, draining ~850 000 km^2 (Fig. 1; Brabets et al. 2000). The Tanana River is one of two major tributaries to the Yukon River that is glacier fed. Most streamflow occurs in summer from snowmelt, precipitation, and glacial melt. The Yukon River basin encompasses diverse climatic and physiographic areas with varying permafrost extent, from sporadic to continuous. The basin covers a region that is predominantly composed of boreal forest vegetation and is generally characterized by a cold continental climate with low precipitation. In Fairbanks, Alaska, from 1931 to 2016, mean annual air temperature was $-2.8° \pm 1.3°C$, and mean annual precipitation total was 284 ± 73 mm (ACIS 2017).

Of the nine rural interior Alaskan communities in the Yukon River basin associated with a larger study, three communities representing different regions of the basin were selected as our primary study sites: Beaver, Grayling, and Tok (Fig. 1). A 65-km-diameter buffer

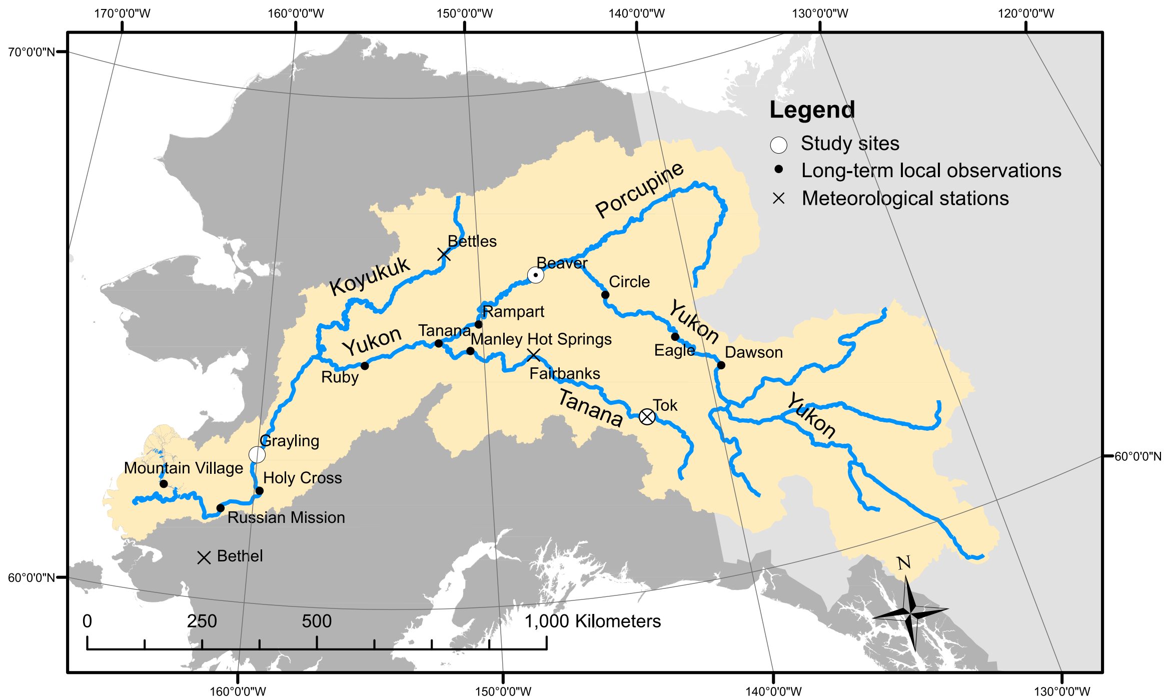

FIG. 1. Map of Yukon River basin (tan) in AK and western Canada showing locations of major rivers, study sites, long-term local observations, and meteorological stations.

was used to define the study area around each community. We chose the size of the study area in an effort to both represent core subsistence areas (Johnson et al. 2016) and maximize the sample size of remote sensing observations. Beaver (pop. 84) is located in the Yukon Flats region in the upper Yukon River. Contemporary Beaver is self-reported as 100% Alaska Native. In 2011, residents reported harvesting an estimated 11 718 kg of wild foods, or 163 kg per capita. Grayling (pop. 193) is a Holikachuk Athabascan community located along the lower–middle Yukon River. The community has a mixed-cash economy where residents engage in both cash-earning employment and seasonal subsistence activities. In 2011, Grayling residents harvested an estimated 23 629 kg of wild foods (112 kg per capita). Tok (pop. 1258) is in eastern Alaska near the upper Tanana River. Of the three study communities, Tok has a much different ethnic profile, with only 16% of residents self-reporting as Alaska Native; however, annual per capita levels of wild resource use were only slightly lower than Beaver and Grayling at 92 kg (120 177 kg total community harvest). Unlike Beaver and Grayling, Tok is located along the road network.

b. *Remote sensing data*

Satellite imagery from Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) sensors were acquired from the United States Geological Survey (USGS; USGS 2017). We used scenes during the shoulder seasons from each of the three study areas from 1972 to 2016. The full breakup season was captured using imagery from mid-March through May. Imagery from mid-October through November was used for the freeze-up season. Because of low sun elevation, imagery was generally not available beyond mid-November, limiting our ability to capture the end of the freeze-up season in many years. The repeat orbit cycle for each Landsat satellite is 16 days. However, at the high latitudes of our study areas, there was substantial overlap between passes, allowing for repeat coverage at less than a 16-day cycle. There were some gaps in image availability due to cloud cover and privatization of the Landsat program from 1985 to 1992. In this study, we used historic imagery from 313 dates during the spring breakup period and 120 dates during the fall freeze-up period.

We visually interpreted the satellite imagery to define different stages of the breakup and freeze-up seasons and to determine their timing. Stages of breakup or freeze-up were distinguished from one another on the basis of the spatial extent and patterns of open water or ice cover. Images were displayed as false color composites, with the shortwave infrared (SWIR), near infrared

(NIR), and green bands represented by red, green, and blue. We found that this band combination best enhanced the distinction in reflectance between water and snow. High values in the thermal bands were also sometimes used to differentiate water from other dark surfaces during the freeze-up season. Not all stages were observed each year, and in some years, multiple dates of the same stage were observed. For the analysis of the annual timing of the stages of the breakup and freeze-up seasons, we used the latest date that prebreakup conditions (before significant ice deterioration) or prefreeze-up conditions (before significant ice accumulation) were observed and the earliest date that the rest of the stages were observed.

To test whether our visual interpretations were conducted consistently and reliably, we compared quantitative estimates of the spatial extent of ice deterioration among the different breakup stages in the Beaver study area. This validation was limited to the breakup season because low sun angles and resulting shadows during the freeze-up season inhibited the use of band indices. We mapped open water or deteriorated ice using the normalized difference water index (NDWI; McFeeters 1996), calculated with the digital numbers (DNs) from the green and NIR bands as

$$\mathrm{NDWI} = (\mathrm{green} - \mathrm{NIR})/(\mathrm{green} + \mathrm{NIR}).$$

Landsat surface reflectance products were not used because snow cover and low sun angles reduced the efficacy of atmospheric correction (USGS 2015). The thresholds of NDWI used to delineate water were chosen manually for each image. We excluded all nonriver pixels from the analysis using river channel masks. Channel masks were created using NDWI-based water delineation of snow-free scenes of the river, where water levels (visualized by silt bar exposure) were similar to those of the scenes used in breakup analysis. Because river geomorphology changed over time, four separate channel masks were used. To reduce classification errors resulting from tree shadows, the channel masks also excluded all pixels directly north, northeast, or northwest of land pixels. Cloud masks were manually digitized for each image as necessary, and the values from the NDWI classification were then extracted using the shadow-corrected channel masks. The resulting rasters were maps of water and nonwater pixels in the channel for each date considered. The percentage of the channel area classified as water for each date was used as a quantitative measure of the extent of ice deterioration. We used visually interpreted random locations as reference data in classification accuracy assessments of the NDWI classes. For the accuracy assessments, a stratified random sampling design was used to select a total of 360 points from three classified images spanning the seasonal gradient of ice cover. Geoprocessing was conducted using ArcMap 10 (ESRI, Redlands, California).

c. *Local observations*

We used independent datasets of local observations for several purposes: 1) to validate the remote sensing classifications, 2) to determine when/how the river was used for travel and considered safe or hazardous in relation to the stages of breakup/freeze-up, and 3) to examine long-term trends that could not be assessed with remote sensing data alone.

The Alaska–Pacific River Forecast Center (APRFC) of the National Weather Service maintains databases of local observations of breakup (APRFC 2017a) and freeze-up (APRFC 2017b) for locations throughout the state. These observations were made by ice observers for the National Weather Service, who are either local residents or hydrologists. We used data from Beaver and Grayling to compare with our remote sensing observations and understand seasonal river use in these areas. The data we used for the breakup season included the date of breakup, the date the river ice was considered ‘‘unsafe for person,’’ and the date of the ‘‘first boat’’ use on the river. For the freeze-up season, we used observations of the date the river was considered ‘‘unsafe for boats’’ and the date the river ice was considered ‘‘safe for people.’’ The breakup date was when the main breakup front had moved past a village, but it was subjective, especially in years with a thermal breakup and many small breakup fronts. The date the river was considered ‘‘safe/unsafe for person’’ was generally based on local knowledge and was also inherently subjective. The date the river was considered ‘‘safe/unsafe for person’’ typically applied to the safety of a person traveling on foot, although the dominant means of transportation were usually snowmobile or dogsled. When interpreting results, it is therefore important to note that river ice safety for vehicular use may vary from the dates reported. The databases also included observations of the date the river was considered ‘‘safe/unsafe for vehicle’’; however, since the type of vehicle (e.g., snowmobile or passenger vehicle) was not consistently reported, we did not use those data. Data were available from 1940 to 2016 for Beaver and 1970 to 2011 for Grayling, though there were many years of missing data among the various data categories. There was a long gap in local observations of freeze-up in Beaver from 1983 to 1995. After 1995, the freeze-up dataset from Beaver had inconsistencies and was excluded from analysis.

Table 1. Descriptions of the stages of the breakup and freeze-up seasons, interpreted from satellite imagery. For the breakup stages, the extent of ice deterioration (% river area) derived from NDWI-based classifications of the Beaver study area is also included (mean ± SD).

Stage	Description	Deteriorated ice or open water (% river area)
Breakup		
Ice covered	River is ice covered, except for isolated open water features.	0.3 ± 0.3
Somewhat deteriorated	River is predominantly ice covered, but large open water leads are widespread.	11 ± 7
Severely deteriorated	River has nearly contiguous expanse of ice but is severely deteriorated with large expanses of open water.	46 ± 11
Partially open	Active breakup. River has open stretches, but large expanses remain clogged with ice.	74 ± 6
Mostly open	River is mostly open, but main channel still has floating ice; some sloughs may still have contiguous ice.	86 ± 9
Open	River is clear of ice.	100 ± 0
Freeze-up		
Mostly open	River is mostly open, but initial freezing has begun; some sloughs and tributaries may be ice covered.	
Narrowly open	Sides of main channel are ice covered, leaving a narrow open channel; most sloughs and tributaries are ice covered.	
Mostly ice covered	Some stretches of river are fully ice covered, and some stretches have open water.	
Almost fully ice covered	River is almost fully ice covered but has widespread open water leads.	
Ice covered	River is fully ice covered, except for isolated open water leads.	

To examine long-term changes in breakup, we used the date of Yukon River breakup in Dawson, Yukon Territories, Canada, from 1896 to 2016. These data were available through the U.S. Environmental Protection Agency (EPA 2016). Because the freeze-up datasets for communities on the Yukon and Tanana Rivers were incomplete and of shorter durations, we used the date the river ice was considered "safe for people" from all communities with at least 30 total years of records (10 sites; Fig. 1). These data were acquired through APRFC (APRFC 2017b). The local records of freeze-up date were analyzed for relationships with air temperature and trends over various time periods since 1900, spanning 42–108 years.

d. Meteorological data

We assessed relationships of monthly mean air temperature (°C), monthly cumulative thawing degree-days (TDDs), and monthly cumulative freezing degree-days (FDDs) with the timing of the stages of breakup and freeze-up. Daily air temperature data were provided by the Applied Climate Information System (ACIS) via the Alaska Climate Research Center (ACIS 2017). Meteorological data used in this study were from the closest stations to each primary study site (Bettles for Beaver; Bethel for Grayling; Tok for Tok) and from Fairbanks for the 10 sites of local freeze-up observations.

e. Statistical analysis

To investigate relationships between breakup/freeze-up phenology and air temperature, we utilized parametric methods such as simple linear regression and correlation analysis when statistical assumptions were met. Data were tested for normality using the Shapiro–Wilk test and transformed when necessary. When assumptions for parametric testing were not met, nonparametric correlations (Spearman's rho) were used. To test for monotonic trends in the breakup and freeze-up datasets, the nonparametric Mann–Kendall trend test was employed. Trend detection in meteorological time series was conducted using correlation analysis and simple linear regression. Rates of change were assessed using the slopes of simple linear regressions. Model assumptions of normality, independence, and constant variance of residuals were checked with regression diagnostic plots. Additionally, we conducted one-tailed t tests comparing mean autumn air temperatures between two time periods (before and since 2002) to determine whether an apparent recent increase in temperature was statistically significant. Statistical significance was determined at $p < 0.05$. Values presented in the text are means ± standard deviation (SD). Statistical analyses were performed using JMP Pro 13 (SAS Institute Inc., Cary, North Carolina).

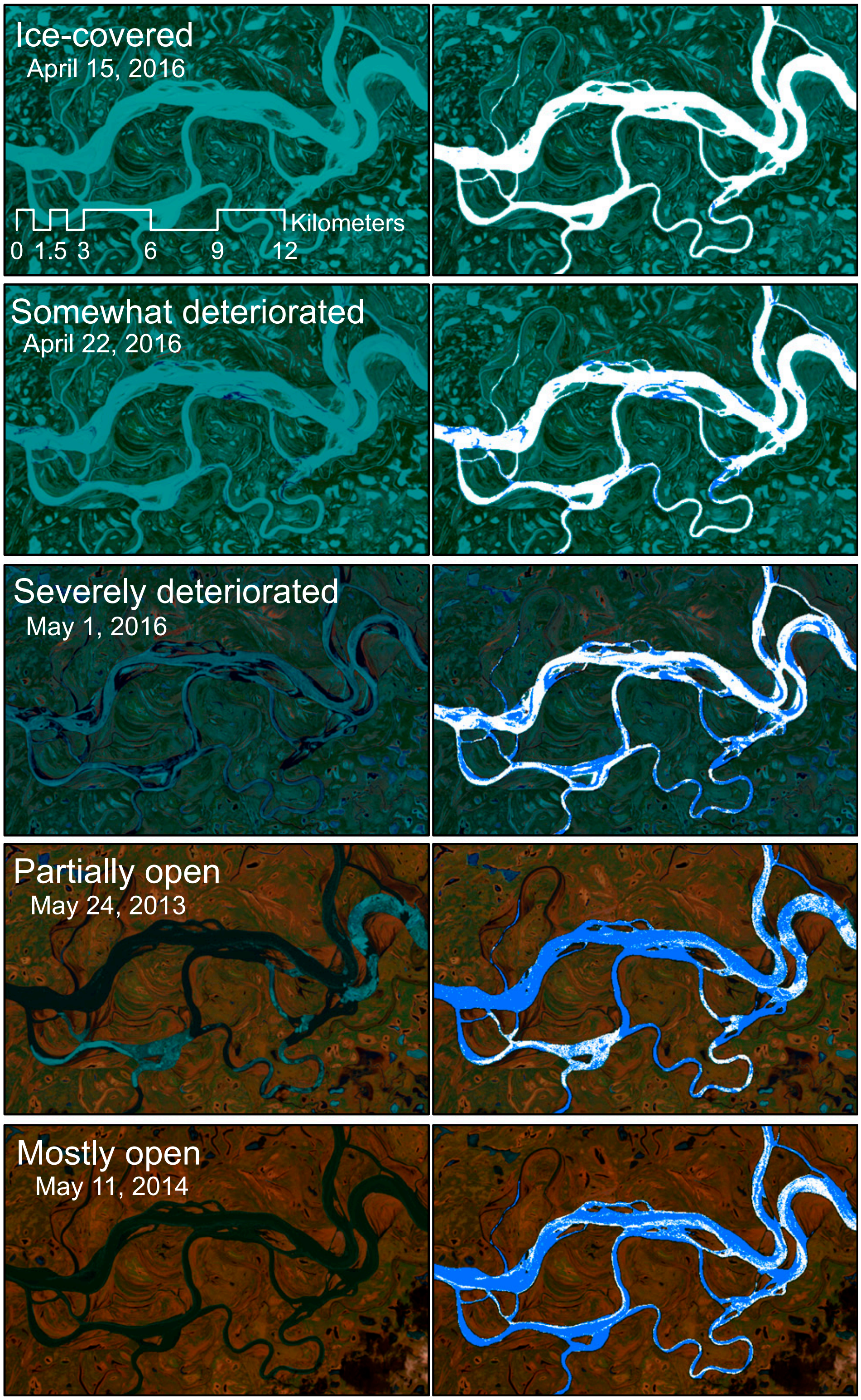

FIG. 2. Examples of breakup stages in the Beaver study area. (left) Landsat imagery as color composites (R: SWIR, G: NIR, B: green), where water appears dark blue and snow/ice appears light blue. (right) Landsat composites overlain with NDWI-derived classifications of the river as snow (white) or water/deteriorated ice (blue).

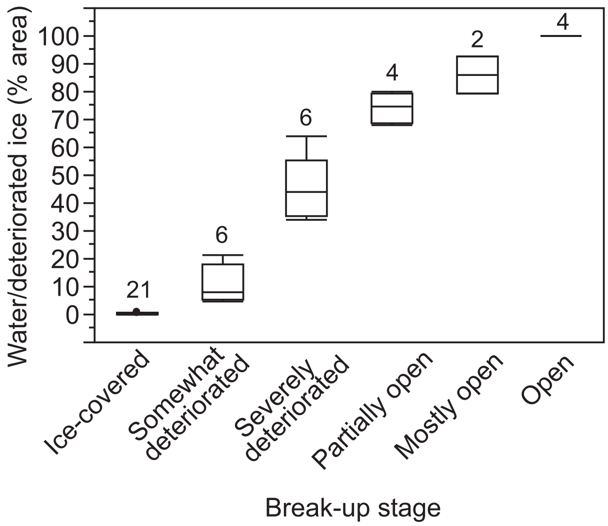

FIG. 3. Box plot showing spatial extent of open water or deteriorated ice (% river area) by breakup stage, calculated from NDWI-based classifications of remotely sensed imagery of the Beaver study area. The boxes represent the median and first and third quartiles, the whiskers represent the range of values, and the points represent outliers. Numbers indicate sample size per stage.

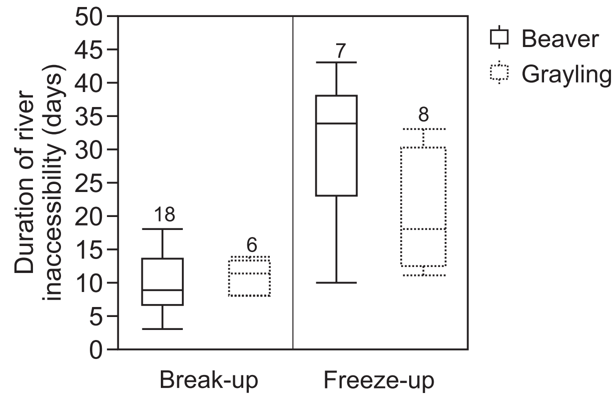

FIG. 4. Duration of river inaccessibility (days) during breakup and freeze-up seasons in Beaver and Grayling, computed from local observations of travel safety by foot and by boat. The boxes show the median and first and third quartiles and the whiskers show the range of values. Numbers depict sample size.

3. Results

a. Breakup season

Six stages of the seasonal progression of river ice breakup were classified through visual interpretation of satellite imagery, and, for the Beaver study area, deteriorated ice or open water extent was mapped using a dynamic NDWI threshold (Table 1, Figs. 2, 3). An assessment of the NDWI classification yielded a high overall accuracy of 94% and a kappa index of 0.87 (Table S1). The extent of deteriorated ice/open water increased with each progressive breakup stage, with little overlap between stages (Fig. 3).

Temporal relationships between our breakup stage classifications and local observations were used to validate the classifications and to interpret how these stages relate to local river usage (Fig. S1). The timing of the "partially open" stage, derived from interpretations of satellite imagery, was in close agreement with local observations of active breakup in Beaver, approximating a 1:1 relationship with a mean difference of 1 ± 2 days. The "mostly open" stage, interpreted from satellite imagery, occurred near the time of the local observation of "last ice," preceding it by 3 ± 1 days in Beaver. The "open" stage occurred after the local assessment of "last ice" by 5 ± 2 days in Beaver and 3 ± 2 days in Grayling.

The timing of the "severely deteriorated" stage corresponded well with the local assessment of "unsafe for person," with a mean difference of 0 ± 2 days in Beaver and −2 ± 3 days in Grayling, though parts of the river were likely unsafe before this point (see Fig. 2; "somewhat deteriorated"). The first boat use on the river was documented 3 ± 3 days after local observations of breakup (Beaver) and 2 ± 2 days before the last ice (Beaver and Grayling). The beginning of boat travel coincided well with the remote classification of the "mostly open" stage of breakup, with a mean difference of 0 ± 2 days (Beaver). The duration of the unnavigable portion of the breakup season (excluding vehicular ice travel) derived from local observations ("first boat" minus "unsafe for person") was 10 ± 5 days in Beaver and 11 ± 3 days in Grayling (Fig. 4).

Interannual variation in the timing of the breakup stages was substantial, averaging 26 days and ranging from 10 to 39 days (Fig. S2). The breakup stages were generally earlier in the Tok study area. Overall, the onset of the "somewhat and severely deteriorated" stages of breakup ranged from April to mid-May (Fig. S2). The "partially open" through "open" stages of breakup typically occurred during May, or April–May in Tok (Fig. S2). Across all communities, earlier breakup stages appeared to be more common after ~2000, though only a few of these stages exhibited statistically significant trends ("severely deteriorated" in Beaver and Tok and "partially open" in Grayling; Fig. 5).

For each of the study areas, the timing of the breakup stages had consistent inverse relationships with local mean air temperature in April, May, or April–May combined (Fig. 6). On average, 59% of the variance in breakup phenology was explained by air temperature. The slopes of the relationships between breakup phenology and monthly mean air temperature averaged −2.0 days °C^{-1}. At each of the meteorological stations, April and May

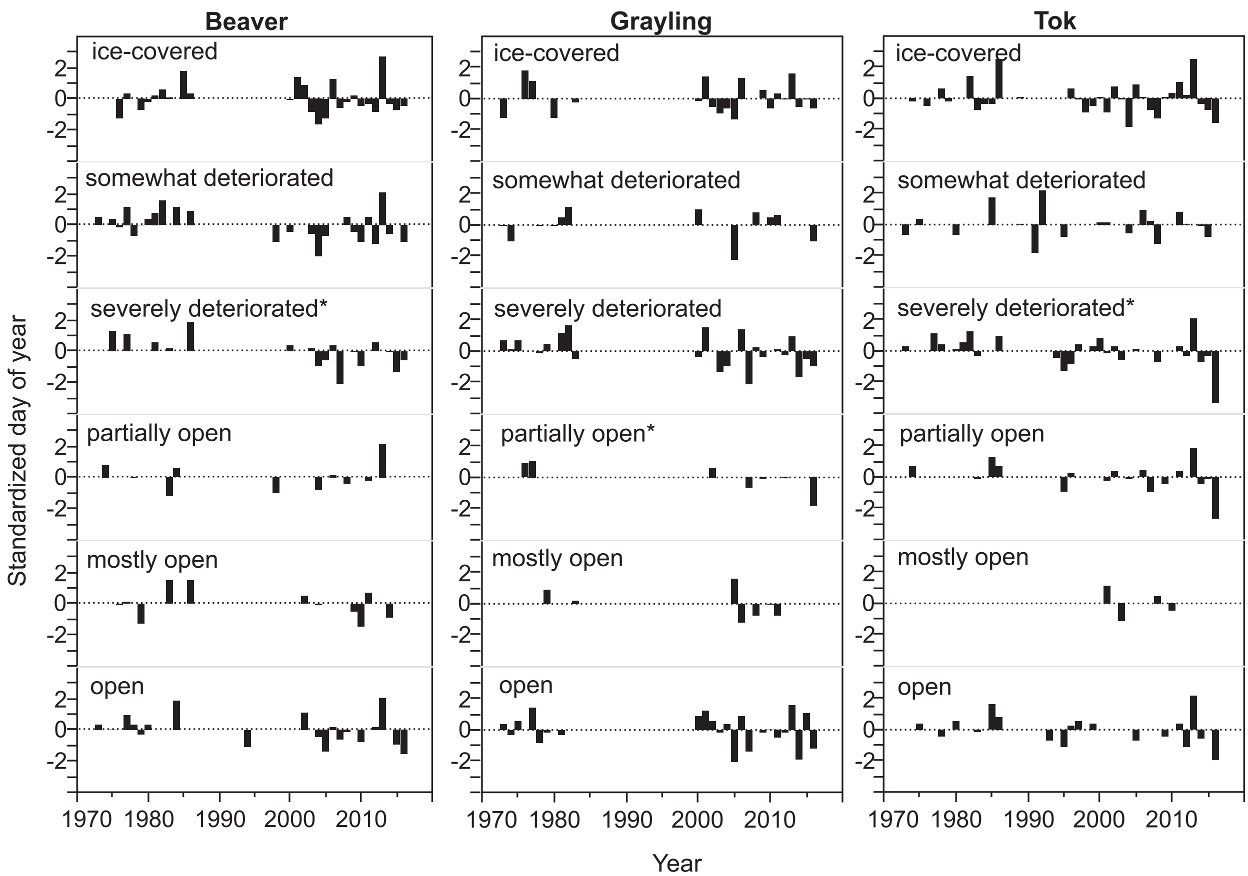

FIG. 5. Variation in timing of breakup stage by year for each study area, based on satellite imagery. Day of year was standardized by subtracting the mean/SD to emphasize departures from the mean. Mann–Kendall trend tests were conducted on original values. Asterisks indicate significant trends.

air temperatures showed significant warming by 0.2°–0.6°C decade^{-1} over the last 62–93 years, except for Bethel (near Grayling) in April (Table S2). The timing of breakup stages was also related to springtime TDD, but the relationships were generally weaker than with monthly mean air temperatures and are not presented here.

The dates of the stages of breakup in Beaver, Grayling, and Tok were strongly correlated with the Yukon River breakup date recorded in Dawson, Yukon Territories (Table S3). Dawson breakup date was inversely related to time ($n = 119$, $t = -0.29$, $p < 0.0001$), with the slope of the linear regression indicating an advance of 6 days century^{-1} (Fig. 7). The earliest breakup date since 1896 occurred in 2016 (Fig. 7).

b. *Freeze-up season*

Five stages of the seasonal progression of freeze-up were identified using satellite imagery (Table 1, Fig. 8). Analysis of local observations showed that the date the river was considered unsafe for travel by boat was frequently within a few days of the first appearance of ice in October, but this difference in timing was highly variable (Beaver: 1 ± 5 days, Grayling: −3 ± 8 days; Fig. S3). For Beaver and Grayling areas, the beginning of the safe ice travel season (determined from local observations) ranged from mid-October through early December and was roughly coincident with the "mostly ice covered" stage of freeze-up (determined from satellite imagery) (Beaver: 1 ± 6 days, Grayling: 2 days; Fig. S3). The mean period of river inaccessibility during the freeze-up season, based on local observations ("safe for people" minus "unsafe for boat"), was 30 ± 11 days for Beaver and 21 ± 9 days for Grayling (Fig. 4).

Interannual variation in the timing of all the freeze-up stages averaged 22 ± 7 days and varied by up to 32 days (Fig. S4). Late freeze-up stages appeared to be more common in the last two decades; however, only a minority of the stages ("narrowly open" in Beaver; "almost fully ice covered" in Grayling) exhibited a statistically significant positive trend (Fig. 9).

The timing of several of the freeze-up stages ("mostly open," "narrowly open," or "ice covered") were

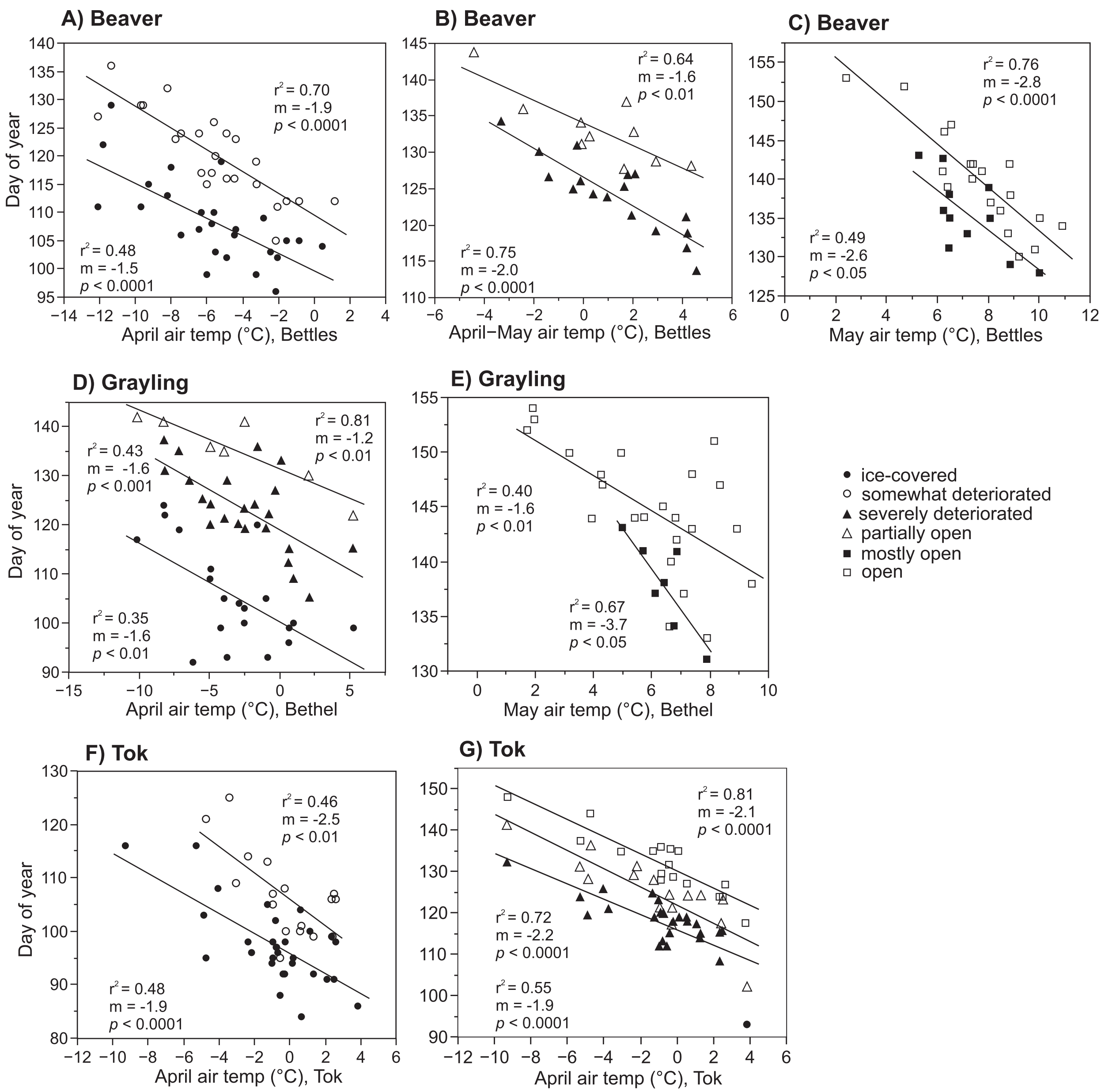

FIG. 6. Timing of breakup stages, based on satellite imagery, in relation to mean spring air temperatures for each study site. Only statistically significant relationships are shown.

directly related to mean air temperatures in October or October–November (Fig. 10). On average, monthly mean air temperature explained 68% of the variance in freeze-up stage timing (Fig. 10). The average slope of these relationships was +2.0 days °C^{-1}. Mean October and November air temperatures showed no long-term (62–93 years) trends (Table S2); however, mean October air temperature was above the long-term average in at least 10–13 of the last 15 years (since 2002) across the four meteorological stations (Fig. 11). To test whether this apparent recent increase in autumn air temperature was statistically significant, we conducted one-tailed *t* tests comparing mean October air temperatures before and since 2002. Mean October air temperature was significantly higher in the latter time period at each of the meteorological stations, with increases ranging from 1.6° to 2.6°C (Fig. 11). Freeze-up stage timing was also related to autumn FDD, but relationships were weaker than with monthly mean air temperatures.

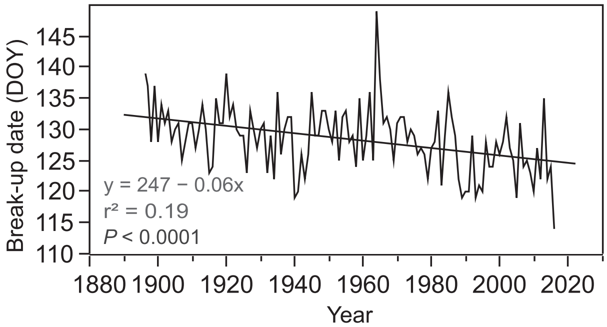

FIG. 7. Long-term trend in Yukon River breakup date, based on local observations at Dawson, Yukon Territories, from 1896 to 2016.

Local records of freeze-up date (when river ice was considered safe for a person on foot) from 10 sites across interior Alaska on the Yukon and Tanana Rivers were analyzed for relationships with air temperature and trends over various time periods since 1900 (Table 2). Freeze-up dates at 80% of the sites were significantly correlated with October air temperature, and 30% were correlated with both October and November air temperature (Table 2). Sixty percent of the sites showed no trend in freeze-up date timing, but 40% of the sites had a significant delay in freeze-up date over time, with the increase ranging from 1.0 to 2.1 days decade^{-1} (Table 2, Fig. 12).

4. Discussion

a. Description of breakup and freeze-up seasons

Through interpretation of satellite imagery, we described several stages of the river breakup season, from before the onset of ice deterioration through the disappearance of ice (Table 1), and related these stages to local observations. Our qualitative classifications of breakup stage were tested and validated by close associations with local observations and by NDWI-based classifications showing consistent spatial cover of open water or deteriorated ice within each stage (Fig. 3). The breakup stage that we classified as ''severely deteriorated'' coincided well with local assessments of unsafe river ice conditions (Fig. S1), though some areas of the river are likely unsafe well before that point (Fig. 2). Local records showed that the first boat use on the river usually occurs before the ''last ice'' has disappeared from the river, corresponding best with our determination of a ''mostly open'' river (Fig. S1). The relationships between local observations and the stages of the shoulder seasons demonstrate that satellite imagery can be reliably utilized to characterize river ice conditions for the breakup season in particular, where the beginning and end of the breakup season are both straightforward to detect.

The end of the safe boating season often coincided with the appearance of ''first ice'' (Fig. S3), but the high variance in the mean difference in timing suggests factors other than freezing (e.g., low water levels) also can mark the end of the safe boating season. The end of the safe boating season typically occurred before we detected any significant ice formation with satellite imagery. Winter travel on ice begins before the river is fully ice covered and corresponded most closely with the stage we described as ''mostly ice covered'' (Fig. S3). Though correlated, the areal extent of river ice during freeze-up is not necessarily indicative of safe conditions, since river

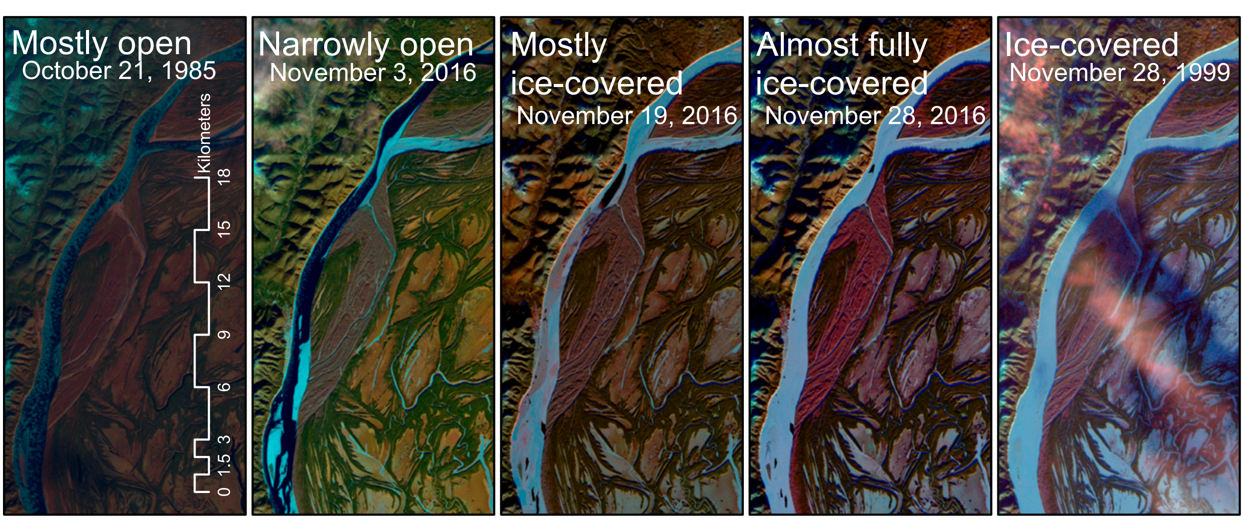

FIG. 8. Examples of freeze-up stages in the Grayling study area. Landsat images are displayed as color composites (R: SWIR, G: NIR, B: green), where water appears dark blue and snow/ice appears light blue.

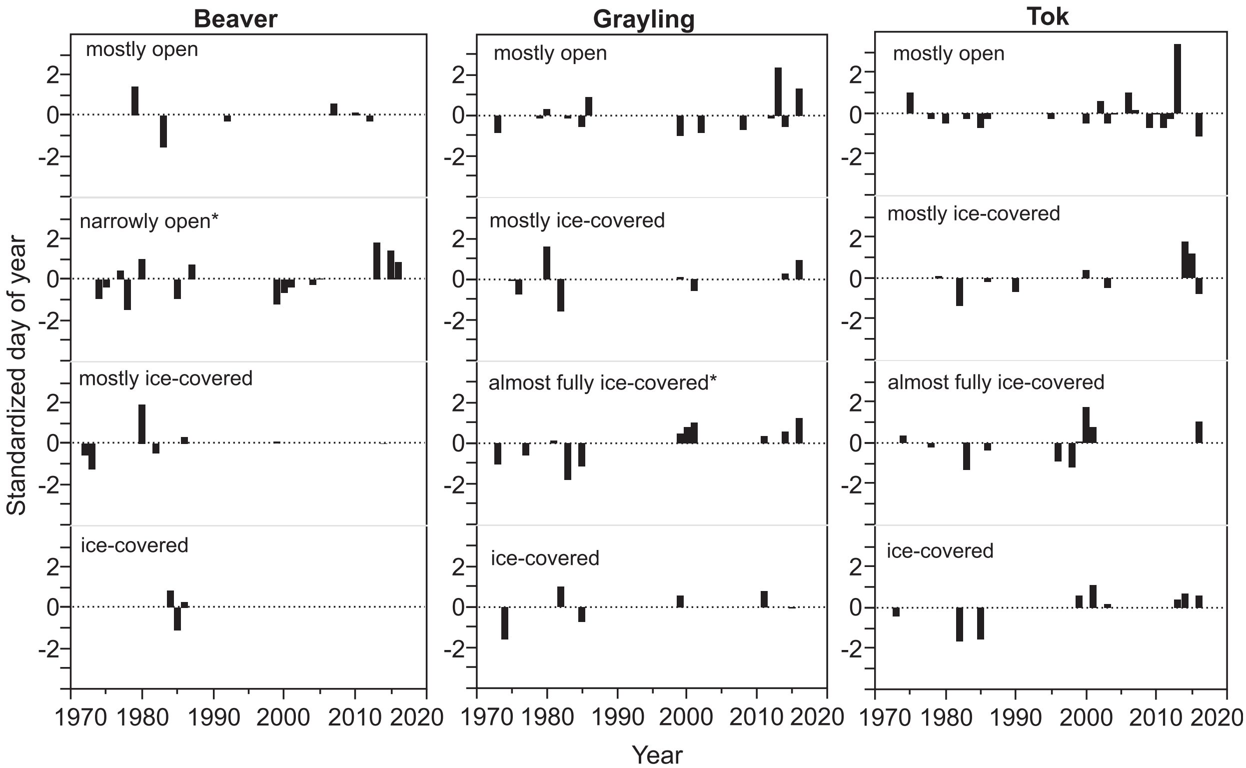

FIG. 9. Variation in timing of freeze-up stages by year for each study area, based on satellite imagery. Day of year was standardized by subtracting the mean/SD to emphasize departures from the mean. Mann–Kendall trend tests were conducted on original values. Asterisks indicate significant trends.

ice gradually thickens throughout winter (Bilello and Lunardini 1996); thus, there are limitations in inferring river ice safety during freeze-up. Safe river ice navigability also likely varied across the study areas at the different stages of freeze-up due to local variation in river morphology (Beltaos 1995; Gerard 1990; Lindenschmidt and Chun 2014). For example, the sinuosity of the Yukon River near Beaver, with many back sloughs with shallower water, allows the majority of the area to become accessible for winter travel even if the main channel cannot be crossed (Fig. 2). By contrast, the Yukon near Grayling is more uniformly wide, with few shallow back sloughs to freeze up early, likely restricting travel until the main channel is sufficiently frozen (Fig. 8).

Using local assessments of river navigability, we quantified the duration of river inaccessibility during the shoulder seasons, though we lacked enough historic data to characterize changes in shoulder season duration over time. We found that the river was considered unnavigable by foot or boat for an average of 10–11 days in the breakup season at two of our study communities (though this would be longer when considering vehicular use; Fig. 4). During the freeze-up season, the period of river inaccessibility was double to triple the length of the period of inaccessibility in the breakup season, averaging 21–30 days (Fig. 4).

b. *Hydroclimatic drivers of river ice regimes and long-term changes*

Multiple climatic, hydrologic, and local factors influence river ice phenology, but air temperature often explains much of the variation in breakup and freeze-up timing (Jeffries et al. 2012). Breakup timing is primarily controlled directly by springtime air temperatures and indirectly by increased discharge from snowmelt (Bieniek et al. 2011). Studies examining breakup dates have found strong relationships with spring air temperature in the North American boreal region (Bieniek et al. 2011; Lacroix et al. 2005; Sagarin and Micheli 2001) and more broadly throughout the Northern Hemisphere (Magnuson et al. 2000; Prowse et al. 2007). Throughout interior Alaska, we found that each of the seasonal stages of river breakup was closely related to local springtime (April, May, or April–May) air temperature, with an increase in monthly mean air temperature of 1°C yielding an average advancement of spring ice deterioration by 2.0 days (Fig. 6). Spring air temperature thus strongly influences both the date that

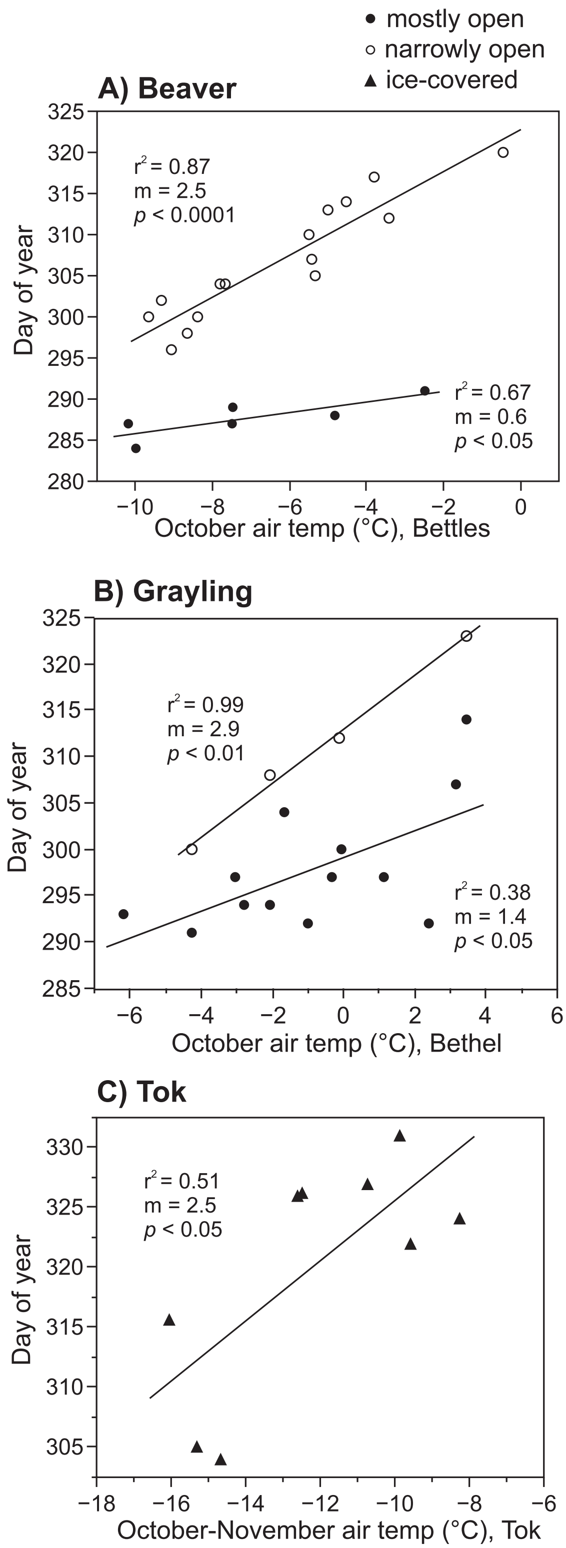

FIG. 10. Timing of freeze-up stages, based on satellite imagery, in relation to mean autumn air temperatures for each study site. Only statistically significant relationships are shown.

the river becomes unsafe for ice travel and the date it becomes navigable for boat travel. Similarly, the timing of several of the stages of freeze-up was closely related to mean air temperature in late fall (October or October–November). Each 1°C increase in monthly mean air temperature was associated with an average delay of freeze-up by 2.0 days (Fig. 10). Long-term changes in spring and fall air temperatures would thus be expected to strongly impact the timing of the breakup and freeze-up seasons.

Century-scale changes in monthly mean air temperature in interior Alaska (1906–2006) have varied seasonally, with the largest increase occurring in the month of April (>3.0°C), likely related to early snowmelt causing a reduction in surface albedo (Wendler and Shulski 2009). Similarly, we found an increase in springtime air temperatures (April and/or May) in all of our study areas by 0.2°–0.6°C decade^{-1} (Table S2). Likewise, Yukon River breakup date at Dawson has advanced by 6 days over the last century (Fig. 7), comparable to the average rate of change of 6.5 days century^{-1} reported for the Northern Hemisphere as a whole (Magnuson et al. 2000). This rate of change is also consistent with our finding of breakup advancement by 2.0 days °C^{-1} (Fig. 6), given an increase in April air temperature of ~3.0°C century^{-1} (Wendler and Shulski 2009). The warmest years on record, however, have occurred during the last quarter-century, so the century-scale linear regression may not capture the accelerated rate of recent change. A similar magnitude of change has likely occurred in both the onset and the completion of ice deterioration in interior Alaska, shortening the duration of the winter ice travel season and advancing the start of the boating season.

Long-term changes in the freeze-up season were less consistent than the breakup season. Of the 10 interior Alaskan communities we examined for trends in freeze-up timing over various time periods since 1900 (spanning 42–108 years), 60% showed no trend, and 40% showed positive trends ranging from delays of 1.0–2.1 days decade^{-1} (Table 2, Fig. 12). Over the last ~40 years, delays in the timing of a couple of the freeze-up stages from the remote sensing analysis were also found (Fig. 9). Over the long term (62–93 years), there was no evidence of an increase in autumn air temperature (Table S2), consistent with climatological studies of this region (Bieniek et al. 2014; Wendler and Shulski 2009). In the 15 years since 2002, however, October air temperatures have generally been elevated throughout the region (Fig. 11). Recent increases and anomalies in October/November air temperature in subarctic Alaska have also been noted in other studies (Bieniek et al. 2014; Walsh 2014; Walsh et al. 2017).

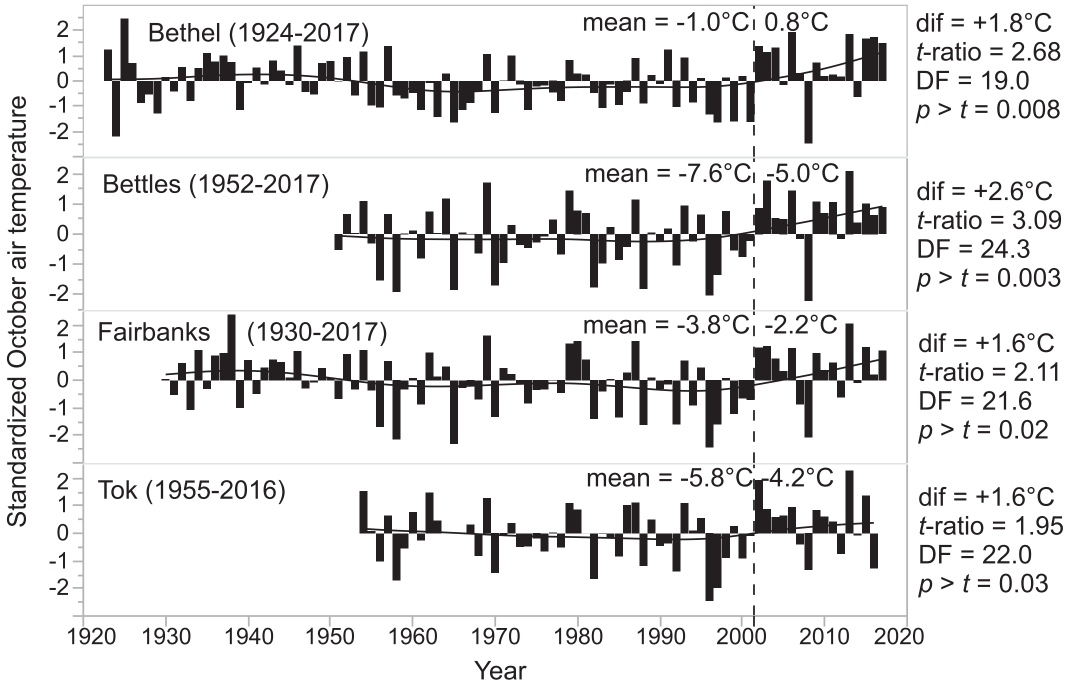

FIG. 11. Variation in October air temperatures over time at four meteorological stations. Values shown were standardized by subtracting the mean/SD. Cubic splines were fit using a lambda of 0.05 and standardized *X* values. The standardized time series show an apparent increase in October air temperatures after the year 2001 (dashed vertical reference line). One-tailed *t* tests were conducted to determine if mean October air temperatures were greater during the latter time period. Mean October air temperature for each time period and results of *t* tests are displayed.

Multiyear to multidecadal fluctuations in the air temperature time series render trend detection sensitive to the particular years and time period analyzed (Bieniek et al. 2014) and could help explain the variation in trends found across the communities. Whether the recent increase in October air temperature in interior Alaska reflects short-term variability or a new normal related to climate warming is uncertain. However, the dramatic decline in Arctic sea ice extent in recent decades has contributed to a substantial increase in autumn air temperature in the arctic region of Alaska and could also be contributing to the recent increase in autumn air temperature observed in the subarctic interior region (Bieniek et al. 2014; Walsh 2014; Walsh et al. 2017; Wendler et al. 2014). The recent warming in October air temperatures likely explains the widespread perception among rural Alaskan communities that freeze-up now tends to occur later than it did two or three decades ago (Carothers et al. 2014).

c. *Impacts of changing ice regimes on communities*

Changes in river ice regimes impact access to fish and game subsistence resources and can adversely affect travel safety. The reduction in the duration of river ice cover represents a shorter season for safely traversing the wider landscape over frozen water bodies. For example, Carothers et al. (2014) analyzed local observations of environmental change in nine interior and northwest Alaska communities and found that in most of these communities, unpredictable ice conditions hindered travel now more than it did 20–30 years ago. Using cultural consensus analysis, they quantified levels of agreement across these communities about specific observations. There was consensus that breakup was occurring earlier than before (Andersen et al. 2013; Carothers et al. 2014). Additionally, in those studies, 85% of respondents noted that river ice is thinner, and as a result, big breakups do not happen as often. Finally, 81% agreed that fall freeze-up occurs later now than it did 20–30 years ago. That such agreement existed between distant communities (e.g., Fort Yukon and Grayling) that access to riverine resources has changed suggests that ‘‘similar phenomena are being observed in many specific locales, despite some vast distances between them’’ (Carothers et al. 2014). The long duration and high variability of the freeze-up season may present particular challenges for subsistence harvesters. Late freeze-up on the Yukon River delays subsistence

TABLE 2. Correlations of freeze-up date with monthly mean air temperatures and trends in freeze-up date over time at communities on the Tanana and Yukon Rivers. Freeze-up date represents the date river ice was considered safe for a person to traverse. Mean October and November air temperatures (1930–2016) were from Fairbanks, AK. Spearman's rho (ρ) is reported for the sites with nonnormal data distributions (‡); otherwise, the correlation coefficient (r) is reported. Kendall's tau (t) from the Mann–Kendall test is reported for trend detection. For sites with significant trends, slopes of the regression between freeze-up date and year are reported.

		Correlation analysis			Trend analysis		
			Air temperature				
			Oct	Nov			
Site	Range of years	n	r/ρ	r/ρ	n	t	Slope
Tanana River at Manley Hot Springs	1911–2011	39	0.33*	0.05	42	0.30**	0.21
Yukon River at Beaver	1940–82	30	0.24	0.30	30	0.06	
Yukon River at Circle	1901–2009	27	0.07	0.11	39	0.37***	0.21
Yukon River at Eagle	1968–2012	38	0.39*	0.58***	38	−0.16	
Yukon River at Holy Cross	1901–81	42	0.49***	0.30†	61	0.17†	
Yukon River at Mountain Village‡	1937–2001	33	0.77****	0.38*	33	−0.10	
Yukon River at Rampart	1901–81	26	0.55**	0.35	51	0.09	
Yukon River at Ruby‡	1911–2011	46	0.48***	0.22	48	0.15	
Yukon River at Russian Mission	1928–2000	36	0.34*	0.27	37	0.25*	0.20
Yukon River at Tanana	1901–99	49	0.48***	0.29*	73	0.19*	0.10

† $p < 0.10$
* $p < 0.05$
** $p < 0.01$
*** $p < 0$ 0.00
**** $p < 0.0001$

activities that typically begin in early winter, such as trapping of furbearing mammals and harvesting of some fish species (Van Lanen et al. 2012). Early breakup may result in restricted access to traditional hunting areas, in some regions impacting the springtime caribou hunt (Van Lanen et al. 2012). Related concerns include observations of thinner ice and open leads throughout winter (Herman-Mercer et al. 2011; Wilson et al. 2015); however, further research is needed on midwinter conditions that may impede travel. Many of the changes in the timing and nature of freeze-up and breakup have been detrimental to resource access and safety (Brinkman et al. 2016; Brubaker et al. 2011; Clark et al. 2016; Driscoll et al. 2016; Schneider et al. 2013); however, it is also important to note that some changes have been positive. For example, boat travel has been extended because of early breakup, and rural residents have, in some cases, been able to adapt by altering their mode of travel or behavior (Brinkman et al. 2016). The impacts of changing river ice conditions are complex and variable, but are consistently necessitating adaptation by rural residents that rely on either open or sufficiently frozen water bodies to facilitate travel.

5. Conclusions

This study confirms the widespread concerns of interior Alaskan residents that the timing of breakup and freeze-up is changing, resulting in a shorter season for safely accessing subsistence resources via river ice travel. The timing of the breakup season was closely related to spring air temperature, which has increased by about 3°C over the last century (Wendler and Shulski 2009). As a result, the season for winter ice travel ends earlier, and the boating season begins sooner in the year. The timing of the freeze-up season was related to autumn air temperature, and delays in river ice freeze-up have been documented in some communities. Although autumn air temperatures have not changed over the long term, the last 15 years were characterized by warmer-than-average autumn air temperatures throughout the region. If this recent autumn warming is indicative of a climatic shift, the long duration of river inaccessibility during the freeze-up season will remain a significant limitation on resource access. With projected increases in air temperature in this region (Romero-Lankao et al. 2014), the duration of river ice cover will continue to decline. These changes to river ice regimes present challenges to accessing subsistence resources at traditional times of the year.

This study provides novel quantitative information on river ice breakup and freeze-up of direct relevance to rural communities dependent on local ecosystem services. With regards to the impact of a changing cryosphere on human community health and livelihoods, most research has focused on coastal sea ice (Huntington et al. 2016; Krupnik et al. 2010; Laidler et al. 2009; Lovecraft and Eicken 2011). Our research

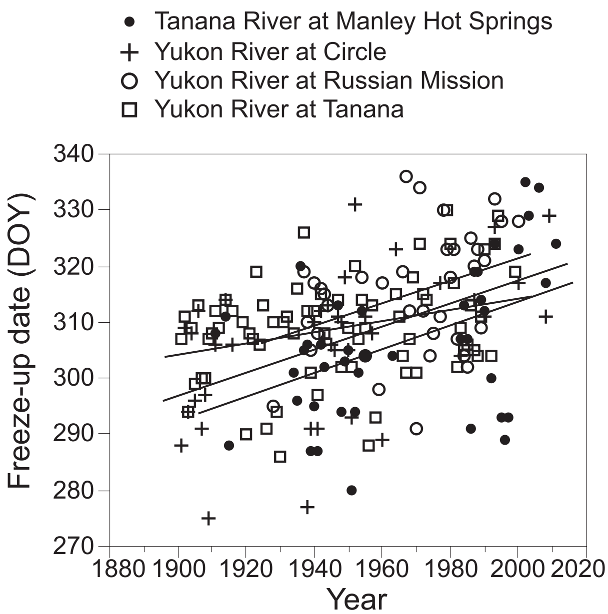

FIG. 12. Freeze-up date (i.e., date river ice considered safe for travel) by year, based on local observations at four communities along the Tanana and Yukon Rivers. Significant positive trends in freeze-up date were detected for these communities using the Mann–Kendall trend test. Simple linear regression lines for each site are shown.

complements rapidly expanding qualitative information on the importance of reliable and stable river ice for subsistence and health (Brinkman et al. 2016; Brubaker et al. 2011; Clark et al. 2016; Driscoll et al. 2016). This research revealed that the time period that river ice corridors are inaccessible to those that depend on them is dynamic (Figs. 4, S2) and shifting with a warming climate (Fig. 7). Further, we demonstrate how remote sensing data and local observations can be used complementarily to form a more complete characterization of river ice conditions and facilitate an assessment of local travel and subsistence opportunities.

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REFERENCES

ACIS, 2017: ACIS [Applied Climate Information System] Daily Data Browser, Alaska Climate Research Center, accessed 19 February 2017, https://climate.gi.alaska.edu/acis_data.

Andersen, D. B., B. Retherford, and C. Brown, 2013: Climate change and impacts on subsistence fisheries in the Yukon River drainage, Alaska. U.S. Fish and Wildlife Service Office of Subsistence Management Fisheries Resource Monitoring Program Final Project Rep. 10-250, 131 pp.

APRFC, 2017a: Break up database. Alaska–Pacific River Forecast Center, National Weather Service, accessed 22 February 2017, https://www.weather.gov/aprfc/breakupDB.

——, 2017b: Freeze up data. Alaska–Pacific River Forecast Center, National Weather Service, accessed 4 April 2017, https://www.weather.gov/aprfc/freezeUp.

Beltaos, S., 1995: Ice jam processes. *River Ice Jams*, S. Beltaos, Ed., Water Resources Publications, LLC, 71–104.

Bieniek, P. A., U. S. Bhatt, L. A. Rundquist, S. D. Lindsey, X. Zhang, and R. L. Thoman, 2011: Large-scale climate controls of interior Alaska river ice breakup. *J. Climate*, **24**, 286–297, https://doi.org/10.1175/2010JCLI3809.1.

——, J. E. Walsh, R. L. Thoman, and U. S. Bhatt, 2014: Using climate divisions to analyze variations and trends in Alaska temperature and precipitation. *J. Climate*, **27**, 2800–2818, https://doi.org/10.1175/JCLI-D-13-00342.1.

Bilello, M., and V. Lunardini, 1996: Ice thickness observations. North American Arctic and subarctic, 1974–75, 1975–76 and 1976–77, Part 9. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, 224 pp.

Brabets, T. P., B. Wang, and R. H. Meade, 2000: Environmental and hydrologic overview of the Yukon River basin, Alaska and Canada. USGS Water-Resources Investigations Rep. 99-4204, 114 pp.

Brinkman, T. J., W. D. Hansen, F. S. Chapin, G. Kofinas, S. BurnSilver, and T. S. Rupp, 2016: Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources. *Climatic Change*, **139**, 413–427, https://doi.org/10.1007/s10584-016-1819-6.

Brubaker, M., J. Berner, R. Chavan, and J. Warren, 2011: Climate change and health effects in northwest Alaska. *Global Health Action*, **4**, https://doi.org/10.3402/gha.v4i0.8445.

Carothers, C., C. Brown, K. J. Moerlein, J. A. López, D. B. Andersen, and B. Retherford, 2014: Measuring perceptions of climate change in northern Alaska: Pairing ethnography with cultural consensus analysis. *Ecol. Soc.*, **19**, 27, https://doi.org/10.5751/ES-06913-190427.

Clark, D. G., J. D. Ford, L. Berrang-Ford, T. Pearce, S. Kowal, and W. A. Gough, 2016: The role of environmental factors in search and rescue incidents in Nunavut, Canada. *Public Health*, **137**, 44–49, https://doi.org/10.1016/j.puhe.2016.06.003.

Driscoll, D. L., E. Mitchell, R. Barker, J. M. Johnston, and S. Renes, 2016: Assessing the health effects of climate change in Alaska with community-based surveillance. *Climatic Change*, **137**, 455–466, https://doi.org/10.1007/s10584-016-1687-0.

EPA, 2016: Ice breakup in two Alaskan rivers. EPA, accessed 11 December 2016, https://www.epa.gov/climate-indicators/alaskan-rivers.

Gerard, R., 1990: Hydrology of floating ice. *Northern Hydrology: Canadian Perspectives*, T. D. Prowse, and C. S. L. Ommanney, Eds., National Hydrology Research Institute, 103–134.

Herman-Mercer, N., P. F. Schuster, and K. B. Maracle, 2011: Indigenous observations of climate change in the lower Yukon River basin, Alaska. *Hum. Organ.*, **70**, 244–252, https://doi.org/10.17730/humo.70.3.v88841235897071m.

Huntington, H. P., L. T. Quakenbush, and M. Nelson, 2016: Effects of changing sea ice on marine mammals and subsistence hunters in northern Alaska from traditional knowledge interviews. *Biol. Lett.*, **12**, 20160198, https://doi.org/10.1098/rsbl.2016.0198.

Jeffries, M. O., K. Morris, and C. R. Duguay, 2012: Floating ice: Lake ice and river ice. *Satellite Image Atlas of Glaciers of the World—State of the Earth's Cryosphere at the Beginning of the 21st Century: Glaciers, Global Snow Cover, Floating Ice, and Permafrost and Periglacial Environments*, R. S. Williams Jr., and J. G. Ferrigno, Eds., U.S. Geological Survey, A381–A424.

Johnson, I., T. Brinkman, K. Britton, J. Kelly, K. Hundertmark, B. Lake, and D. Verbyla, 2016: Quantifying rural hunter access in Alaska. *Hum. Dimens. Wildl.*, **21**, 240–253, https://doi.org/10.1080/10871209.2016.1137109.

Krupnik, I., C. Aporta, S. Gearheard, G. J. Laidler, and L. Kielsen Holm, 2010: *SIKU: Knowing Our Ice.* Springer, 501 pp.

Lacroix, M. P., T. D. Prowse, B. R. Bonsal, C. R. Duguay, and P. Menard, 2005: River ice trends in Canada. *13th Workshop on the Hydraulics of Ice Covered Rivers*, Hanover, NH, CGU HS Committee on River Ice Processes and the Environment, 14 pp.

Laidler, G. J., J. D. Ford, W. A. Gough, T. Ikummaq, A. S. Gagnon, S. Kowal, K. Qrunnut, and C. Irngaut, 2009: Travelling and hunting in a changing Arctic: Assessing Inuit vulnerability to sea ice change in Igloolik, Nunavut. *Climatic Change*, **94**, 363–397, https://doi.org/10.1007/s10584-008-9512-z.

Lindenschmidt, K.-E., and K. P. Chun, 2014: Geospatial modelling to determine the behaviour of ice cover formation during freeze-up of the Dauphin River in Manitoba. *Hydrol. Res.*, **45**, 645–659, https://doi.org/10.2166/nh.2013.193.

Lovecraft, A. L., and H. Eicken, 2011: *North by 2020: Perspectives on Alaska's Changing Social-Ecological Systems.* University of Alaska Press, 736 pp.

Magnuson, J. J., and Coauthors, 2000: Historical trends in lake and river ice cover in the Northern Hemisphere. *Science*, **289**, 1743–1746, https://doi.org/10.1126/science.289.5485.1743.

McFeeters, S. K., 1996: The use of the normalized difference water index (NDWI) in the delineation of open water features. *Int. J. Remote Sens.*, **17**, 1425–1432, https://doi.org/10.1080/01431169608948714.

McNeeley, S. M., and M. D. Shulski, 2011: Anatomy of a closing window: Vulnerability to changing seasonality in Interior Alaska. *Global Environ. Change*, **21**, 464–473, https://doi.org/10.1016/j.gloenvcha.2011.02.003.

Prowse, T. D., B. R. Bonsal, C. R. Duguay, and M. P. Lacroix, 2007: River-ice break-up/freeze-up: A review of climatic drivers, historical trends and future predictions. *Ann. Glaciol.*, **46**, 443–451, https://doi.org/10.3189/172756407782871431.

——, and Coauthors, 2011: Past and future changes in Arctic lake and river ice. *AMBIO*, **40**, 53–62, https://doi.org/10.1007/s13280-011-0216-7.

Romero-Lankao, P., J. B. Smith, D. J. Davidson, N. S. Diffenbaugh, P. L. Kinney, P. Kirshen, P. Kovacs, and L. Villers Ruiz, 2014: North America. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*, V. R. Barros et al., Eds., Cambridge University Press, 1439–1498.

Sagarin, R., and F. Micheli, 2001: Climate change in nontraditional data sets. *Science*, **294**, 811, https://doi.org/10.1126/science.1064218.

Schneider, W., K. Brewster, K. Kielland, and C. Jones, 2013: On dangerous ice: Changing ice conditions on the Tanana River. The Oral History Program, Elmer E. Rasmuson Library, and the Institute of Arctic Biology, University of Alaska Fairbanks Rep., 76 pp.

Šmejkalová, T., M. E. Edwards, and J. Dash, 2016: Arctic lakes show strong decadal trend in earlier spring ice-out. *Sci. Rep.*, **6**, 38449, https://doi.org/10.1038/srep38449.

USGS, 2015: Product guide: Provisional Landsat 8 Surface Reflectance Product, version 2.1. U.S. Geological Survey Rep., 40 pp.

——, 2017: Landsat imagery. USGS, accessed from 1 September 2016 through 1 March 2017, http://earthexplorer.usgs.gov.

Van Lanen, J. M., C. Stevens, C. L. Brown, K. B. Maracle, and D. S. Koster, 2012: Subsistence land mammal harvests and uses, Yukon Flats, Alaska: 2008-2010 harvest report and ethnographic update. Alaska Department of Fish and Game, Division of Subsistence Tech. Rep. 377, 193 pp.

Walsh, J. E., 2014: Intensified warming of the Arctic: Causes and impacts on middle latitudes. *Global Planet. Change*, **117**, 52–63, https://doi.org/10.1016/j.gloplacha.2014.03.003.

——, P. A. Bieniek, B. Brettschneider, E. S. Euskirchen, R. Lader, and R. L. Thoman, 2017: The exceptionally warm winter of 2015/16 in Alaska. *J. Climate*, **30**, 2069–2088, https://doi.org/10.1175/JCLI-D-16-0473.1.

Wendler, G., and M. Shulski, 2009: A century of climate change for Fairbanks, Alaska. *Arctic*, **62**, 295–300, https://doi.org/10.14430/arctic149.

——, B. Moore, and K. Galloway, 2014: Strong temperature increase and shrinking sea ice in Arctic Alaska. *Open Atmos. Sci. J.*, **8**, 7–15, https://doi.org/10.2174/1874282301408010007.

Wilson, N. J., M. T. Walter, and J. Waterhouse, 2015: Indigenous knowledge of hydrologic change in the Yukon River basin: A case study of Ruby, Alaska. *Arctic*, **68**, 93, https://doi.org/10.14430/arctic4459.