Northern Hemisphere geography of ice-covered rivers

Katrina E. Bennett & Terry D. Prowse

2010

Pacific Climate Impacts Consortium (PCIC)

PCIC Publications

Original citation:

Bennett, K. E., & Prowse, T. D. (2010). Northern Hemisphere geography of ice-covered rivers. *Hydrological Processes, 24*(2), 235–240. https://doi.org/10.1002/hyp.7561

SCIENTIFIC BRIEFING
HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **24**, 235–240 (2010)
DOI: 10.1002/hyp.7561

Northern Hemisphere geography of ice-covered rivers

K. E. Bennett[1]*
and T. D. Prowse[2]

[1] *Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, Canada V8W 2Y2*
[2] *Water and Climate Impacts Research Centre, Environment Canada & University of Victoria, Victoria, BC, Canada V8W 2Y2*

*Correspondence to:
K. E. Bennett Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, Canada V8W 2Y2.
E-mail: kbennett@uvic.ca

Received 5 June 2009
Accepted 28 October 2009

Abstract

Although river ice is a major component of the cryosphere and is particularly important to many river processes, including extreme events, its full geographical coverage has never been documented. Recognizing that the freeze-up and break-up of river ice is closely linked to the timing of 0 °C air temperatures, this study analyses the spatial extent of river networks relative to the location of three 0 °C isotherm periods. These were defined to represent a suite of ice-affected conditions that would be experienced for 6, 3 or 0·5 month periods, the briefest interval possibly leading only to a very thin and transient ice cover or simply border/frazil ice formation. Four different GIS databases were used to represent the river networks. The percentages of the total Northern Hemisphere land mass (average river network) influenced by cold temperatures conducive to ice formation were 52, 45 and 25 (56, 47 and 28), respectively. The related southern position of the isotherms ranged from 33°N, 35°N and 50°N in central North America to a nearly consistent 27°N for Eurasia, reflecting the influence of the high-elevation central plateau region. Also identified are the lengths of major rivers that fall within the three 0 °C isotherm boundaries. Included are some of the world's largest rivers including the Lena, Mackenzie, Ob, Yellow, Yukon and Yenisey rivers, although their percentage of ice-affected coverage varied for the three isotherm periods from a consistent 100% for the Lena and Yukon rivers to as little as 23% at the 6-month interval for the Yellow River. Copyright © 2009 Her Majesty the Queen in right of Canada. Published by John Wiley & Sons, Ltd.

Key Words river ice; cryosphere; isotherm; northern rivers; GIS

Introduction

River ice is a major component of the terrestrial cryospheric system and plays a significant role in affecting a range of geophysical and biological systems (Prowse, 2001a, b, 2005; Beltaos, 2008). Moreover, for many cold regions, it is responsible for extreme hydrological events, such as ice-jam flooding, which result in major economic costs (e.g. Prowse *et al*., 2007). River ice has also been identified as being highly susceptible to changes in climate (e.g. Wrona *et al*., 2005), and significant changes in coverage and thickness have occurred over approximately the last half century (Walsh *et al*., 2005; Anisimov *et al*., 2007; Lemke *et al*., 2007).

Despite the above, and the multitude of local research studies conducted about river ice, it is one component of the cryosphere whose spatial extent and volumetric dimensions remain largely unquantified (e.g. Lemke *et al*., 2007). Obtaining a reliable estimate of the geographical footprint of ice-affected rivers is essential to, for example, fully understanding the scope of river-ice effects and evaluating how much of the globe may be influenced by climate-related changes in river-ice regimes and how this cryospheric component contributes to other climatic processes such as terrestrial freshwater storage and runoff.

Although national hydrometric monitoring programmes record ice conditions, this is only conducted at selected flow measurement sites. These are insufficient in number to be able to characterize patterns of river-ice coverage, particularly with so many ungauged rivers. Deriving spatial records from research records is also not a viable option as the majority of river-ice research has been conducted only as local case studies, and even in the rarer regional or national analyses, the full geographical scope of this cryospheric variable has never been assessed. Quantification of spatial coverage might be possible with an extensive assembly of remote-sensing products but achieving a multi-year chronology of average conditions would be extremely laborious and costly.

The primary objective of this work was to define the spatial extent of river ice for a number of winter periods. Recognizing that river ice is a relatively minor and usually highly transient feature of rivers in the Southern Hemisphere, limited primarily to higher elevations for brief periods, the focus of this study was on the terrestrial area of the Northern Hemisphere where it is well known to be a significant cryospheric variable. Given that the timing of freeze-up and break-up of river ice is closely linked to that of air temperature, specifically the occurrence of the spring and fall 0 °C air temperatures (e.g. Allen, 1978; Bonsal and Prowse, 2003), it was decided to employ an air temperature-based assessment of river-ice coverage. The selected periods, based on air temperature, approximate conditions that would be conducive to ice formation ranging from the establishment of multi-month ice cover to shorter-interval transient-ice effects, possibly involving only frazil or border ice formation (for discussion of thermal conditions and river-ice types see Beltaos, 2008; Gray and Prowse, 1993). A related objective was to identify the major river basins and their river lengths that are likely to experience significant ice coverage for the defined air-temperature-based intervals.

Approach and Analytical Methodology

As noted, the freeze-up and break-up of rivers have been shown generally to follow trends in the 0 °C air-temperature isotherm (e.g. Allen, 1978; Bonsal and Prowse, 2003). For this analysis, it is assumed that areas located north of this isotherm would be experiencing river-ice conditions. Total ice-affected areas are defined for three isotherm conditions: (i) coldest month of the year, which is assumed to be January for all Northern Hemisphere locations; (ii) main winter, average October to March air temperatures; and (iii) annual average air temperatures. Assuming that mean air temperatures are evenly distributed during these periods, these isotherms would refer to 0·5, 3 and 6-month periods of $<0\,^{\circ}\mathrm{C}$ air temperatures that are conducive to river-ice formation, and herein are referred to as $I_{0\cdot5}$, I_3 and I_6, respectively.

Isotherms were determined from a global climatology of mean-monthly air temperatures for a 30-year period, 1961–1990 (New *et al.*, 2002). Only climatological mean values were used and trends in the data were not considered. A geographical information system (GIS; ArcInfo 9·0) was used to generate raster grids and isotherm contours using an equal-area projection. Five spatial datasets were examined to determine the extent of ice-covered land surface areas and riverine features—one representing land mass and four riverine features. A polygon land mass data layer (ESRI, 1993) was used to delineate land areas north of the three 0° isotherms and to select other features, such as the river arcs and point locations noted below.

A number of spatial GIS products are available that permit quantification of various dimensions of river networks. Notably, this analysis only focuses on land areas of the Northern Hemisphere that have major drainage networks, and hence areas with extensive glaciers and ice caps, including all of Greenland, have been excluded. Recognizing potential variability in the GIS products, it was decided to use and compare four different data layers to represent the river networks. The first three included (1) the Environmental Systems Research Institute's (Danko, 1992; ESRI, 1993) rivers data layer (R_E) with a resolution of approximately $1:1 \times 10^6$; (2) a dataset of rasterized river features (R_R) from Graham *et al.* (1999) at 5-min resolution converted to polygons for this analysis; and (3) the Hydro1K stream network (R_{1K}), which is based on the 30-arc second digital elevation model (DEM) of the world (Verdin and Verdin, 1999; EROS, 1996). Although the R_{1K} was generated from 1×10^3 km^2 grid raster cells (Verdin and Verdin, 1999) that display tributaries and headwater branches of rivers and streams, it cannot be as readily interrogated as the R_E data for basic river identifications. It does, however, include other information, such as elevation for different segments.

To provide an additional comparative value for the primary objective, but to also evaluate additional river characteristics, a point dataset (R_P) that documents the 200 largest rivers in the world (Dai and Trenberth, 2002) was employed. The R_P data points are located primarily close to or at river mouths and include information about, for example, river length and flow volume. The river mouth locations of the R_P points were used in reference to the positions of the three 0 °C isotherm datasets.

Differences in the form and resolution of the four datasets are illustrated in Figure 1 for the example St Lawrence River basin. The higher density stream network for the R_{1K}, which includes many small order tributaries, is evident when compared to the primarily main-stem features of the lower resolution R_E dataset. The R_P dataset illustrates the locations of the St Mauric, Ottawa and St Lawrence rivers as single points representing river mouths. The coarse nature of this dataset precludes an accurate portrayal of the location of the river mouth at this map scale. The R_R dataset is shown in light grey and, because of its 5-min resolution, tends to produce riverine features that appear blocky compared to the finer resolution datasets (e.g. the R_{1K}).

The percentages of the total Northern Hemisphere river network found within the three isotherm boundaries were calculated for all four sets of river data. For comparative purposes, the percentages of the total Northern Hemisphere, North American and Eurasian land masses with $<0\,^{\circ}\mathrm{C}$ temperatures for the three periods were computed from the L_E and R_{1K} databases. Specific river lengths of the 15 largest rivers in the Northern Hemisphere influenced by ice conditions were calculated using the additional reference data from R_E and R_P.

Results and Discussion

The percentage of the Northern Hemisphere river network affected by cold temperatures conducive to river-ice

DOI: 10.1002/hyp

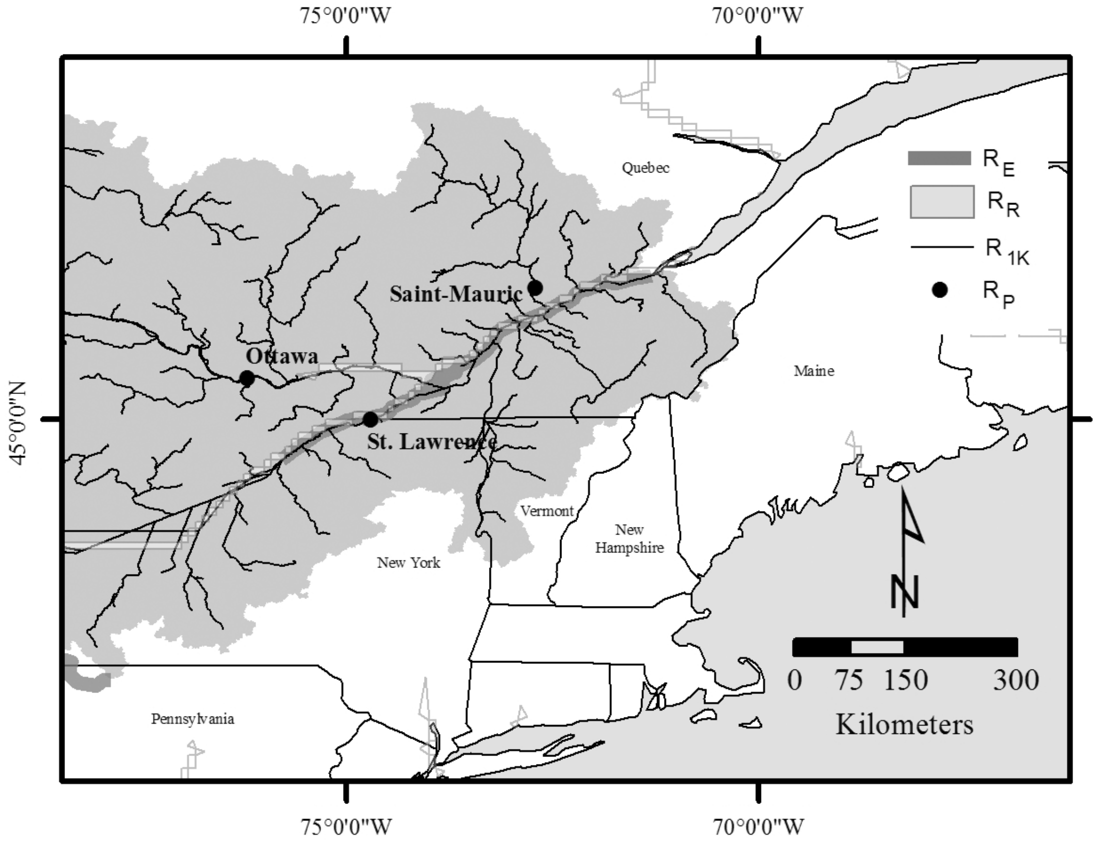

Figure 1. The St Lawrence river basin shown in grey to illustrate the various GIS river-data products used in the analysis: (a) Environmental Systems Research Institute's (Danko, 1992; ESRI, 1993) rivers data layer (R_E) with a resolution of approximately $1:1 \times 10^6$), shown by the dark grey linear feature on the main stem of the St Lawrence river; (b) a dataset of RR from Graham *et al.* (1999) at a 5-min resolution converted to polygons for this analysis, shown as a light grey polygon; (c) the Hydro1K stream network (R_{1K}), which is based on the 30-arc-second DEM of the world (Verdin and Verdin, 1999; EROS, 1996), shown in thin black linear features; and (d) a point data set (R_P) that documents the 200 largest rivers in the world (Dai and Trenberth, 2002), black filled circles illustrating the St Mauric, Ottawa and St Lawrence rivers. WGS 1984, scale 1 : 15 000 000

formation is presented in Table I for the various datasets and three isotherm scenarios. The average percentage coverage for the four GIS river networks is 57, 48 and 29, with the R_E and R_P datasets accounting for the largest (smallest) percentages at 66, 55 and 32 (48, 40 and 27), respectively. Major reasons for differences in results include variations in dataset scales, unequal representation of river networks by different feature types (e.g. point features versus line features) and contrasts between the source data and original intent of use (i.e. the R_P versus R_E, see Dai and Trenberth, 2002). Result differences are considered small, however, with coefficients of variation for the three GIS datasets being only 13, 13 and 8% for the three periods.

To place the river networks in a broader context, it is useful to consider the percentage of the total area of the Northern Hemisphere that experiences below-freezing temperatures for the three isotherm scenarios, and the approximate southern latitudes of these zones. As shown in Table II, the land values are 52, 45 and 25% for $I_{0.5}$, I_3 and I_6, respectively. In terms of the specific locations, the interior-continental southern boundaries of the mean January 0 °C, October to March and mean annual 0 °C isotherms are at about 33°N, 35°N and 50°N in central North America, while in Eurasia they are all found near 27°N—evidence of the strong cold climate influence of the high-elevation central-Asian plateau (Figure 2). Isolated cold zones are also evident in a number of locations (e.g. Iceland, Scotland, Japan), many but not all

Table I. Percentage of Northern Hemisphere land and river networks for three isotherm scenarios when average air temperatures are <0 °C (based on 1961–1990 climatology), and hence conditions are conducive to the presence of river ice

Feature description and type	Reference	Code	$I_{0.5}$	I_3	I_6
River features (line)	Danko (1992); ESRI (1993)	R_E	66	55	32
River features (line)	Verdin and Verdin (1999); EROS (1996)	R_{1K}	56	48	29
River features (point)	Dai and Trenberth (2002)	R_P	48	40	27
River features (polygon)	Graham *et al.* (1999)	R_R	57	48	27
Average river coverage			57	48	29
Coefficient of variation (%)			13	13	8

Terms are defined in the text.

Table II. As per Table I, the percentage of land and river networks derived from R_{1k} and L_E databases for each of the three isotherm scenarios

		Northern Hemisphere (%)	North America (%)	Eurasia[a] (%)
$I_{0\cdot5}$	Rivers	56	69	50
	Land	52	65	47
I_3	Rivers	48	59	45
	Land	45	55	41
I_6	Rivers	29	38	26
	Land	25	33	22

[a] Excluding Scandinavia and Iceland.

also related to the effects of elevation. Contrasting North America and central Eurasia, it is the former that has a greater percentage of area affected by cold temperatures for all temperature periods, reflecting the relatively larger component of the continental mass of Eurasia found in more southerly warm latitudes (Table II).

Wholly or partially contained within the isotherm-based definitions of cold regions defined above are many of the world's largest/longest rivers. Based on the main-stem and river identification information accessible in the R_E database, the 15 longest rivers found within each isotherm region are listed in Table III. Also identified are their central length and percentage of length that fall within the three 0 °C isotherm boundaries. Considering the broadest geographical definition, $I_{0\cdot5}$, virtually the entire length of all of the 15 major rivers will experience ice conditions for at least part of the month of January. Of this large-river group, the least complete ice coverage is that of the Yellow River where only 6% is unlikely to be affected by ice conditions and this is located in the warmest lower reaches. It is also noteworthy that some degree of ice condition can even be expected in the higher elevation headwaters of, for example, the Ganges (70 km) and Tigris (11 km) rivers (not shown in Table III).

The names of the 15 largest rivers for I_3 are very similar to that for $I_{0\cdot5}$, although the order changes slightly because of decreases in the ice-affected total length of some. Specifically, the Volga, Missouri and Yellow rivers

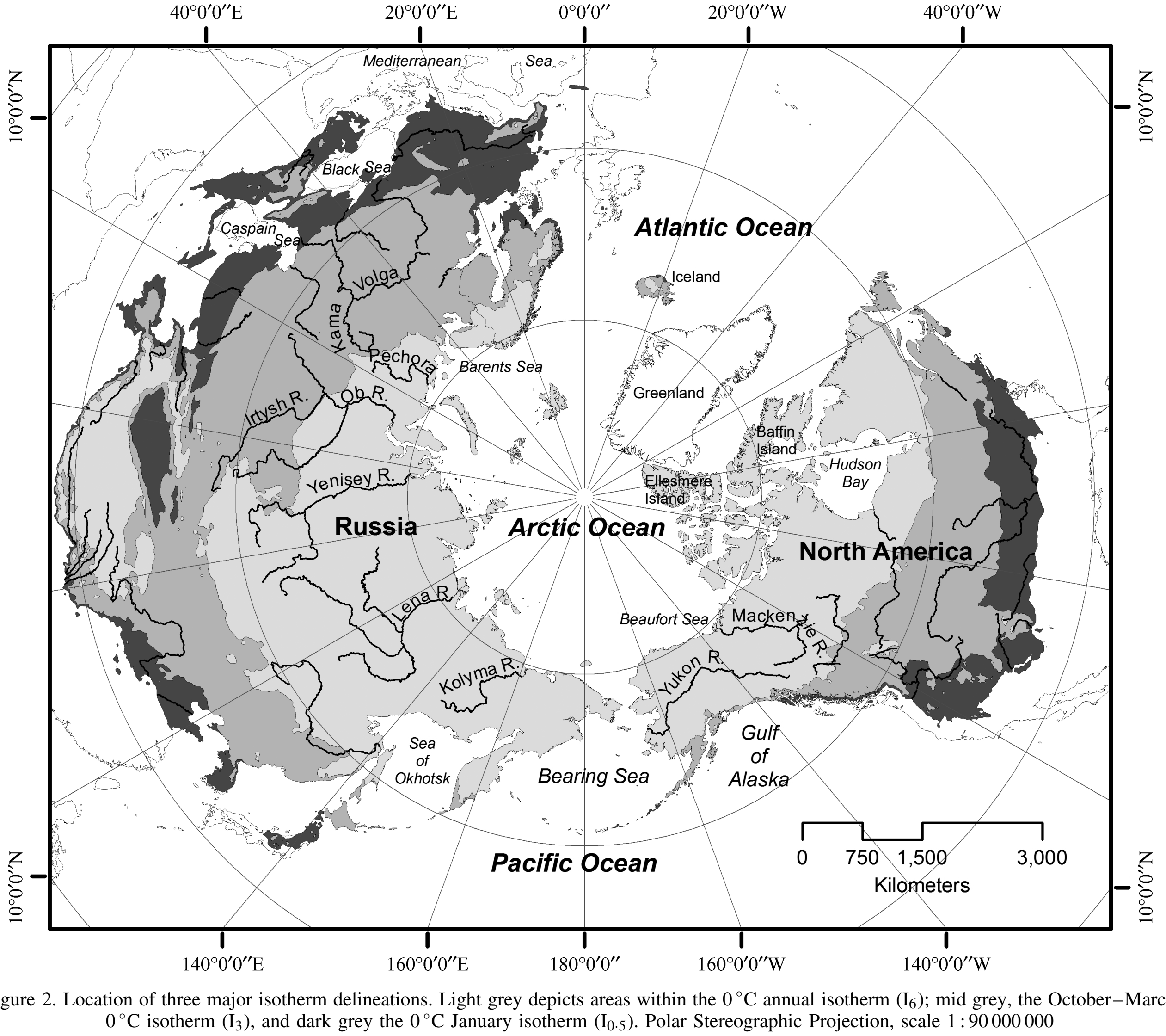

Figure 2. Location of three major isotherm delineations. Light grey depicts areas within the 0 °C annual isotherm (I_6); mid grey, the October–March 0 °C isotherm (I_3), and dark grey the 0 °C January isotherm ($I_{0\cdot5}$). Polar Stereographic Projection, scale 1 : 90 000 000

DOI: 10.1002/hyp

Table III. Total ice-affected length (km) and percentage of total length (%) of the main stem reaches of the 15 longest rivers in North America, defined for three isotherm scenarios

Rivers	$I_{0.5}$	km	%	I_3	km	%	I_6	km	%
1	Lena	5217	100	Lena	5217	100	Lena	5217	100
2	Ob	4912	100	Ob	4912	100	Yukon	4465	100
3	Yellow	4484	94	Yukon	4465	100	Yensiey	3598	85
4	Yukon	4465	100	Yenisey	4245	100	Ob	3575	73
5	Yenisey	4245	100	Amur	4232	100	Vilyuy	3449	100
6	Amur	4232	100	Irtysh	4017	100	Amur	3195	76
7	Irtysh	4017	100	Volga	3842	97	Kolyma	3194	100
8	Volga	3950	100	Vilyuy	3449	100	Aldan	2824	100
9	Missouri	3689	100	Yellow	3334	70	L. Mackenzie	2246	100
10	Vilyuy	3449	100	Kolyma	3194	100	Pechora	2110	100
11	Danube	3288	99	Aldan	2824	100	Angara	2103	100
12	Kolyma	3194	100	Missouri	2708	73	Liard	1405	100
13	Aldan	2824	100	Peace	2359	100	Peace	1356	57
14	Peace	2359	100	L. Mackenzie	2246	100	Yellow	1084	23
15	L. Mackenzie	2246	100	Saskatchewan	2123	100	Yangtze	1077	21

The L. Mackenzie refers to the portions of the Mackenzie River below Great Slave Lake. Length statistics are derived from R_E river data in Danko (1992) and ESRI (1993).

decreased from 100, 100 and 94% ice-affected total river length to 97, 73 and 70%, respectively. The Danube also falls out of the top 15 list to be replaced by the shorter Saskatchewan River but with 100% ice effects.

More dramatic changes to the list of the largest rivers are experienced for I_6. The rivers Irtysh, Volga, Missouri and Saskatchewan are replaced from the I_3 list by the Pechora, Angara, Liard and Yangtze rivers. Some rivers, such as the Yellow and Yangtze, are now restricted to 6-month ice effects affecting less than one-quarter of their main-stem length. Similarly, even the mid-to-western large Siberian rivers, the Ob and Yenisey, are only partly ice-affected (73 and 85%, respectively), reflecting the portions contained in the more westerly, less continental climatic regions. The entire lengths of the eastern Siberian Lena River, its major tributary the Aldan River and the North American lower Mackenzie River, however, remain 100% ice-affected for all three isotherm scenarios reflecting their cold continental locations. Similar conditions apply to the large, high-latitude Yukon and Kolyma rivers.

A somewhat different list of rivers would result if flow volume rather than length was considered in the above assessment. Of rivers with annual flows exceeding 200 km^3 $year^{-1}$, the list would include the St Lawrence River, which falls within the $I_{0.5}$ and I_3 isotherm regions, and the Columbia River for just $I_{0.5}$, reflecting only short-term ice conditions.

Conclusions

The results of this analysis provide the first full estimate of the extent of ice-covered rivers in the Northern Hemisphere. The percentages of the total Northern Hemisphere land mass (average river network) influenced by cold temperatures conducive to ice formation were 52, 45 and 25 (56, 47 and 28), respectively. The related southern position of the isotherms ranged from 33°N, 35°N and 50°N in central North America to a nearly consistent 27°N for Eurasia because of the influence of the high-elevation central plateau region. These cold regions include some of the world's longest rivers, such as the Lena, lower Mackenzie, Ob, Yellow, Yukon and Yenisey, all of which exceed 4000 km. For those in the cold continental regions such as the Lena and lower Mackenzie, or at high latitudes such as the Yukon, ice conditions can be expected for over half the year. By contrast, only portions of the Ob (73%) and Yellow (23%) rivers experience such long-term ice effects.

This paper outlines an approach to approximate the spatial extent of the 0 °C air-temperature isotherm, based on the generalized relationship between freeze-up and break-up events. The study focuses on analysis of the climatologic mean, and a detailed examination of correlations between river ice break-up and freeze-up events within differing hydroclimatic regimes was considered outside the scope of the work. Some exceptions will exist that may be determined using a more in-depth study of regional-scale events or extremes. Therefore, the possibility remains that individual 'cold' years, or an analysis of shorter time periods (i.e. 10 years or less), may yield effects at a regional level that is not impacted by the broad scale climatological mean 0 °C air-temperature isotherms presented here. This information could be used to determine if these outliers have an impact on infrastructure and ecology at regional scales, and to consider the importance of these impacts in engineering and planning initiatives.

Although this analysis focused on using 0 °C air temperatures to define river-ice conditions, the same GIS-based approach could be used to evaluate other cryo-hydrologic variables, such as lake ice or snow cover, whose presence/absence is known to also be closely linked to the timing of the spring and fall 0 °C isotherms. A climate change analysis could also be conducted to examine the change in the location of the future 0 °C air-temperature isotherm relative to the historical climatological mean isotherm presented in this study. For river ice, the next step to assess its importance relative to other cryospheric variables as has been undertaken by the Intergovernmental Panel on Climate Change (Lemke *et al*., 2007) will be to assess its volume. Again, this should be possible using GIS-based information about river areas within the same isotherm regions and additionally to calculate ice thickness using a degree-based ice-growth formula and gridded air-temperature data. These two variables would then permit the first volumetric calculation of river ice in the Northern Hemisphere.

References

Allen WTR. 1978. *Freeze-up, break-up of rivers and lakes*. Plate 19 in Hydrological Atlas of Canada. Fisheries and Environment Canada.

Anisimov OA, Vaughan DG, Callaghan TV, Furgal C, Marchant H, Prowse TD, Hjalmar Viljalmasson H, Walsh JE. 2007. Polar regions (Arctic and Antarctica). In *Climate Change 2007: Impacts, Adaptation and Vulnerability*, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Perry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds). Cambridge University Press: Cambridge; 653–685.

Beltaos S (ed). 2008. *River Ice Breakup*. Water Resources Publications, LLC: Highlands Ranch; 462 pp.

Bonsal BR, Prowse TD. 2003. Trends and variability in spring and autumn 0 °C-isotherm dates over Canada. *Climatic Change* **57**: 341–358.

Dai A, Trenberth KE. 2002. Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. *Journal of Hydrometeorology* **3**: 660–687.

Danko DM. 1992. The digital chart of the world. *GeoInfo Systems* **2**: 29–36.

EROS (Earth Resource Observation and Science), U.S. Geological Survey. 1996. *HYDRO1k Geographic Database Developed from the USGS' 30 arc-second Digital Elevation Model (DEM) of the world (GTOPO30)*. U.S. Geological Survey (USGS) in cooperation with UNEP/GRID Sioux Falls. URL: http://edc.usgs.gov/products/elevation/gtopo30/hydro/index.html. Accessed June 5, 2009.

ESRI (Environmental Systems Research Institute). 1993. *Digital Chart of the World* 1 : 1 M.

Graham ST, Famiglietti JS, Maidment DR. 1999. Five-minute, 1/2° and 1° data sets of continental water sheds river networks for use in regional and global hydrologic and climate system modeling studies. *Water Resources Research* **35**: 583–558.

Gray DM, Prowse TD. 1993. Snow and floating ice, chapter 7. *Handbook of Hydrology*, Maidment D (ed). McGraw-Hill: New York; 7-1–7-58.

Lemke P, Ren J, Alley R, Allison I, Carrasco J, Flato G, Fujii Y, Kaser G, Mote P, Thomas R, Zhang T. 2007. Observations: changes in snow, ice and frozen ground. In *Climate Change 2007: The Physical Science Basis*, Contribution to of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon S, Qin D, Mannging M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge and New York; 337–383.

New M, Lister D, Hulme M, Makin I. 2002. A high-resolution data set of surface climate over global land areas. *Climate Research* **21**: 1–25.

Prowse TD. 2001a. River-ice ecology: Part A) Hydrologic, geomorphic and water-quality aspects. *Journal of Cold Regions Engineering* **15**(1): 1–16.

Prowse TD. 2001b. River-ice ecology: Part B) Biological aspects. *Journal of Cold Regions Engineering* **15**(1): 17–33.

Prowse TD. 2005. River-ice hydrology. In *Encyclopedia of Hydrological Sciences*, vol. 4, Anderson MG (ed). John Wiley and Sons: West Sussex, England; 2657–2677.

Prowse TD, Bonsal B, Duguay CR, Hessen DO, Vuglinsky VS. 2007. River and lake ice, chapter 8. *Global Outlook for Ice & Snow*. *United Nations Environment Programme*: DEW/0924/NA. Available from Earthprint.com; 201–214.

Verdin KL, Verdin JP. 1999. A topological system for delineation and codification of the Earth's river basins. *Journal of Hydrology* **218**(1–2): 1–12.

Walsh J, Anisimov O, Hagen JO, Jakobsson T, Oerlemans J, Prowse TD, Romanovsky V, Savelieva N, Serreze M, Shiklomanov A, Shiklomanov I, Solomon S. 2005. Crysophere and hydrology, chapter 6. *Arctic Climate Impact Assessment*. Cambridge University Press: Cambridge; 183–242.

Wrona FJ, Prowse TD, Reist JD, Beamish R, Gibson JJ, Hobbie J, Jeppesen E, King J, Koeck G, Korhola A, Levesque L, Macdonald R, Power M, Skvortsov V, Vincent W. 2005. Freshwater ecosystems and fisheries, chapter 8. *Arctic Climate Impact Assessment*, Cambridge University Press: Cambridge; 353–452.