CGU HS Committee on River Ice Processes and the Environment
14th Workshop on the Hydraulics of Ice Covered Rivers
Quebec City, Quebec, Canada, June 20-22, 2007

Observed Climate Variability Impacts and River Ice in the United States

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River ice jams pose a threat to public safety, infrastructure, and the environment due to flooding, ice impacts, and secondary impacts such as scour and resuspension of contaminated sediments. Because ice jams can form suddenly, design and operation of ice jam mitigation measures has depended on some degree of predictability in ice conditions. Observed changes in the formation mechanisms and timing of ice events over the course of the past several years suggest that climate variability is resulting in fundamentally different ice conditions that we have experienced in the past. This decreases the predictability and thus increases the risk and uncertainty associated with ice jam response and mitigation. A more flexible, adaptive approach to ice jam mitigation that embraces the potential for unexpected or surprise scenarios such as those occurring due to changing climate. This paper presents information on climate variability impacts on river ice and suggests future research to support mitigation approaches that integrate potential climate variability.

1. Introduction

River ice jams tend to form suddenly, and the resulting (flooding and related infrastructure impacts) is generally highly localized. These characteristics impact both emergency management and long-term mitigation strategies. Rapid and effective emergency response depends on prior knowledge or quick assessment of ice jam severity, flood inundation area, depth and velocity, and the utility of various response techniques. The localized nature of ice jam flooding, combined with the requirement for positive benefit-to-cost ratios common in US flood risk reduction efforts, often entail low-cost solutions. This leads to more use of temporary or nonstructural solutions, which frequently depend on knowledge about site-specific ice processes. Decreasing costs for structural solutions can result in increasing constraints on engineering design, since material and construction costs are generally rising.

Both characteristics of ice jams, therefore, rely to some extent not only on past observations of ice jams and the meteorological and hydrological conditions that result in ice jams, but on stationarity of these records as well. Recent heightened awareness of the potential impacts of climate variability and climate change suggest that the stationarity of historical data should be closely examined, especially in the case of planning and design for flood risk reduction projects. The USACE is currently updating planning and design guidance to include temporal and spatial system changes such as relative sea-level rise, climate variability impacts, regional changes in rainfall-runoff characteristics, and major seismicity. This paper presents information on climate variability impacts on river ice and suggests future research to support mitigation approaches that integrate potential climate variability.

2. Ice Jam Observations in the United States.

Open-water floods have generally been closely observed in the United States, and large amounts of historic data are available, ranging from automated records of the US Geological Survey (USGS) to newspaper reports, books, oral histories, and ancestral records of flooding such as those shown in Native American pictographs (e.g., Howard 1960). Yet, despite the fact that much of the continental United States is impacted by ice jams, relatively few records exist for ice jam events compared to open-water flood events. This is particularly true for sparsely populated areas. Ice records must often be developed from a variety of sources including gaging stations, anecdotal information from local residents, physical evidence such as tree scars, and photographs (USACE 1991). The reliability and objectivity of historical data vary considerably, depending on the type of source (e.g. USGS gaging station vs. anecdotal evidence) as well as on the time that has elapsed since a certain water level occurred.

The primary source for ice event observations in the United States is the US Army Corps of Engineers (USACE) Cold Regions Research and Engineering Laboratory (CRREL) Ice Jam Database (IJDB). Ice events included in the IJDB fall under the broad definition used by the International Association for Hydraulic Research (IAHR) Working Group on River Ice Hydraulics (1986): “a stationary accumulation of fragmented ice or frazil that restricts flow.” The IJDB was initiated in the early 1990’s after CRREL researchers recognized that the lack of systematically compiled data on ice events hampered effective ice jam emergency response and hindered research and development in the areas of ice processes. The original objectives were to provide data for use assist in emergency management, research and development of ice processes, and support engineering design in ice-affected rivers (White 1996). The IJDB is served via the internet (http://www.crrel.usace.army.mil/ierd/ijdb/). The IJDB continues to input historical data while tracking current-year ice events in near-real time and now contains information on over 15,500 ice events in the United States between 1780 and 2007 (Figure 1). USGS gaging station records are the source of about 80% of the historical information in the IJDB, while the National Weather Service (NWS) is the primary source since near-real-time monitoring began in the mid 1990's. Both rely in large part on hydrometeorological gages, and are thus considered highly reliable data sources.

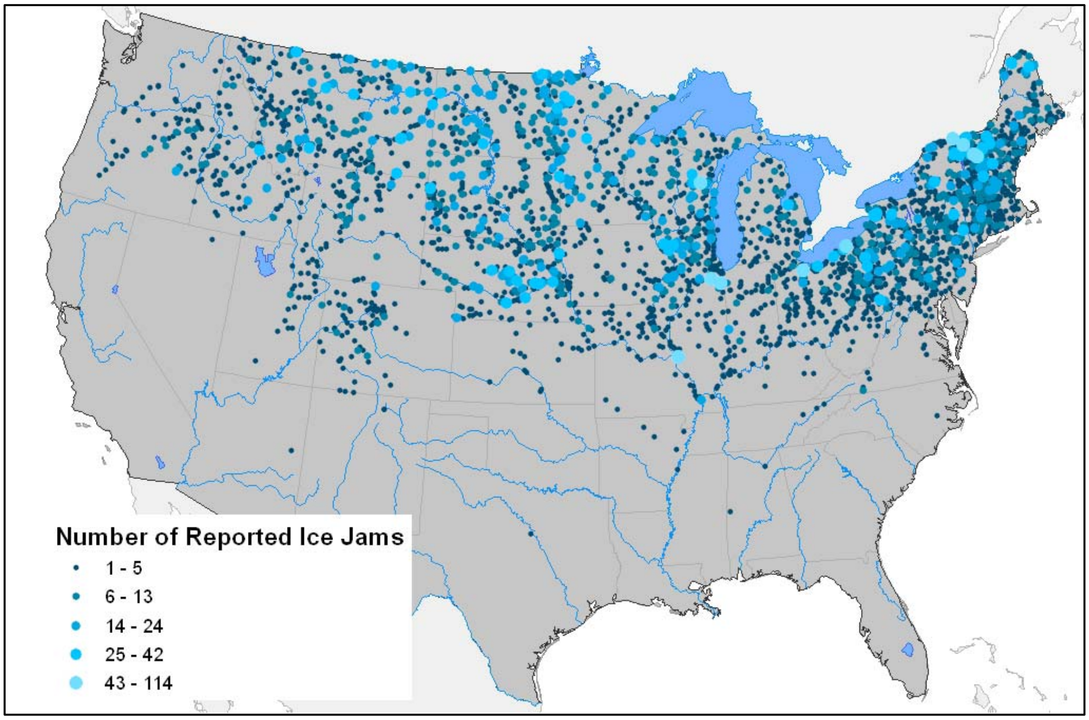

Figure 1. Locations of ice jams reported in the CRREL Ice Jam Database (June 2007).

3. Observed Climate Variability Impacts on Ice Regime in the United States.

Literature relating to climate variability impacts on river ice in North America is largely Canadian (e.g., Beltaos and Prowse 2001, Beltaos and Burrell 2003, Beltaos 2004, Prowse and Bonsal 2004), probably because the entire country is impacted by seasonal ice covers. In contrast, some regions of the US never experience river ice. Thus, studies of observed climate variability impacts on river ice in the US are limited. For example, although the US Global Climate Change Research Program (USGCRP) has supported regional-scale assessments of climate variability impacts as well as research and development activities, the National Assessment Synthesis Team (NAST 2001) had only one reference to observed river ice impacts: the Alaska regional report notes that shorter river ice seasons have been observed.

Table 1 summarizes observed trends on river ice regime in the US. An early study of trends in the dates of ice cover formation and ice-out in Wisconsin, Minnesota, and Michigan rivers was presented by Wing (1943). Unfortunately, the data were not presented in detail, the rivers were not identified, and the numbers of rivers in each state were not reported, except to note that 16 rivers was the maximum for any one state. The average number of days of ice effect for Minnesota rivers showed a slight decreasing trend between about 1912 and 1932, and averaged 96.9 days for the period 1901 through 1936. Wisconsin rivers exhibited a more variable length of ice-effect, and average 103.0 days per winter for the period 1901 through 1936. Magnuson *et al* (2000) report trends in breakup for the Red River of the North, which flows from Minnesota and North Dakota into Southern Manitoba, Canada. Based on 180 years of record (1799 to 1993), a statistically significant trend ($P<0.001$) in ice cover breakup was noted, with breakup occurring 10.6 days earlier per century.

More detailed regional information is available for river ice-related climate variability impacts on American rivers in Alaska and New England (Table 1). Two studies examined breakup dates on the Tanana River. Keyser *et al* (2000) reported a trend to ice breakup 5.75 days earlier over the period 1917-1999. Sagarin and Micheli (2001) found a statistically significant trend toward earlier ice cover breakup. They also noted that the record showed periods of earlier (1920-1940 and 1970-2000) and later (1940-1970) breakup corresponding to similar periods for the Northern Hemisphere reported by Magnuson *et al* (2000). They also noted anecdotal evidence that thermal ice cover breakup has been more common recently than mechanical ice cover breakup.

Table 1. Summary of reported US river climate impacts on river ice (where + is later, - is earlier, NS=not significantly different)

Location	Period of record	Change in ice cover formation	Change in ice-out	Total number of days of ice effect
Tanana River, AK[1]	1917-1999		-5.74	
Tanana River, Nenana, AK[2]	1917-2000		-5.5, $P=0.01$	
Machias River, Whitneyville, ME[3]	1930-1977	+14 days $P=0.0293$	-18 days $P=0.0202$	-37 days $P=0.0012$
Narraguagus River, Cherryfield, ME[3]	1948-2000	NS	-8.5 days $P=0.0529$	-15 days $P=0.0379$
West Branch Union River, Amherst, ME[3]	1930-1979	+14 days $P=0.0041$	NS	-37days $P=0.0295$
Sheepscot River, North Whitefield, ME[3]	1939-2000	NS	-12 days $P=0.0534$	NS
Royal River, Yarmouth, ME[3]	1950-2000	NS	-8.5 days $P=0.0773$	-15 days $P=0.0849$
Piscataquis River, Dover-Foxcroft, ME[4]	1912-2001		-15 days $P=0.0046$	

[1] Keyser *et al* (2000)

[2] Sagarin and Micheli (2001), ice breakup rather than ice-out

[3] Dudley and Hodgkins (2002)

[4] Huntington *et al* (2003)

In New England, Dudley and Hodgkins (2002) reported statistically significant trends for earlier ice cover formation (two of five rivers), ice-out (four of five rivers), and reduced total number of days of ice effect — not assumed to be equal to the difference between the two dates (four of five rivers) — for five Maine rivers. For these rivers, cold and/or snowy weather was thought to be the cause of a reversal in the trend during the 1960's. Huntington *et al* (2003) investigated detailed records of river ice conditions made by the USGS during discharge measurements of the Piscataquis River near Dover-Foxcroft, ME. Their analysis was based on ice thickness measurements taken close to the date of 28 February for the period 1912-2001, and ice-out dates for the period 1931-2002. They found statistically significant decreases in ice thickness (-0.26—0.25 cm/yr depending on the method used to treat ice-free years, P=0.0021) and ice-out. Ice thickness showed a reversal of the trend between about 1950 and 1975, said to be consistent with regional cooling during this period. Ice out did not exhibit a similar reversal. Hodgkins *et al* (2003, 2005) examined 16 rivers in Northern New England and reported that four had significantly later change in the date of ice cover formation (P=0.1); 12 rivers had significantly earlier dates of ice out (P=0.1); and 12 had significantly fewer days of ice effect.

Unfortunately, spatial and temporal variability in the IJDB resulting from data collection limit the use of the IJDB for country-wide evaluation and prediction of climate variability impacts (White and Eames 1999, Jones *et al* 2004). However, data collection efforts focused on a several regions and states do support more detailed analyses on a local or regional level. These include New Hampshire, Vermont, Alaska and Montana (White and Eames 1999), Wisconsin (Furman *et al* , in prep), the Susquehanna River Basin (White 1999a), the Allegheny River Basin (Furman *et al* , in prep), and the St. Louis District of the Corps of Engineers (White 1999b). Other rivers studied in detail for which trend analyses might be possible include the Israel River, New Hampshire; the Connecticut River in New Hampshire, Vermont, Massachusetts, and Connecticut; the Moreau River, South Dakota; the Winooski River near Montpelier Vermont, the Clark Fork River, Montana, and the Grasse River, New York.

Where detailed studies are available, climate variability impacts on ice can be reported in qualitative terms. Vuyovich and White (2006) note that freezeup ice jams were first noted on the Israel River in northern New Hampshire in 1996, although breakup ice jams have been documented at the site since 1886, and detailed studies have been undertaken by CRREL since the early 1960's. They show no trend in average winter season temperatures to explain this changing ice regime, but this period does coincide with trends to later ice cover formation along with increasing December streamflow in coastal Maine rivers (Dudley and Hodgkins 2002) and cooler winters (Huntington *et al* 2003). Sudden cold temperatures during an open water period with relatively high discharge resulted in anomalous freezeup jams along the Grand River in Michigan in December 1996, January 2005, February 2006, and February 2007 (Ice Jam Database). A similar event in Montpelier VT in January 2007 was the first reported freezeup ice jam in a history that is well-researched after 1900 and includes a 1785 event (Ice Jam Database)

4. Predicted Climate Variability Impacts on Ice Regime in the United States.

Predictions of climate variability impacts on river ice regime in the US are even more limited than observed impacts. The 2001 NAST report provided only one prediction related to ice: in the Midwest region, reduced ice covers are expected to extend the navigation season. Jones *et al* (2004) examined the relationship between accumulated freezing degree days (AFDD) calculated for first-order National Weather Service stations (NOAA 1950–2004) and cooperative stations (NOAA 2001).and several climate indices. They reported a significant correlation between the annual maximum AFDD and the Pacific North American Pattern (PNA) and North Atlantic Oscillation (NAO), with less significant effects from the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation Index (SOI). They note that practical application of their results awaits further development of climate index forecasts.

Several Canadian studies (e.g., Prowse *et al* 2002, Prowse and Bonsal 2004) examined trends in river ice breakup. Prowse *et al* (2002) identified a northern region (north of the mean annual 0°C isotherm) and a temperate region (lying between the 400 and 1000 AFDD (°F-days) isolines calculated from mean daily air temperatures during the period December through February). The temperate region was further subdivided into Western, Central, Eastern, and Atlantic sub-regions as shown in Figure 2. The northern region is generally characterized by a

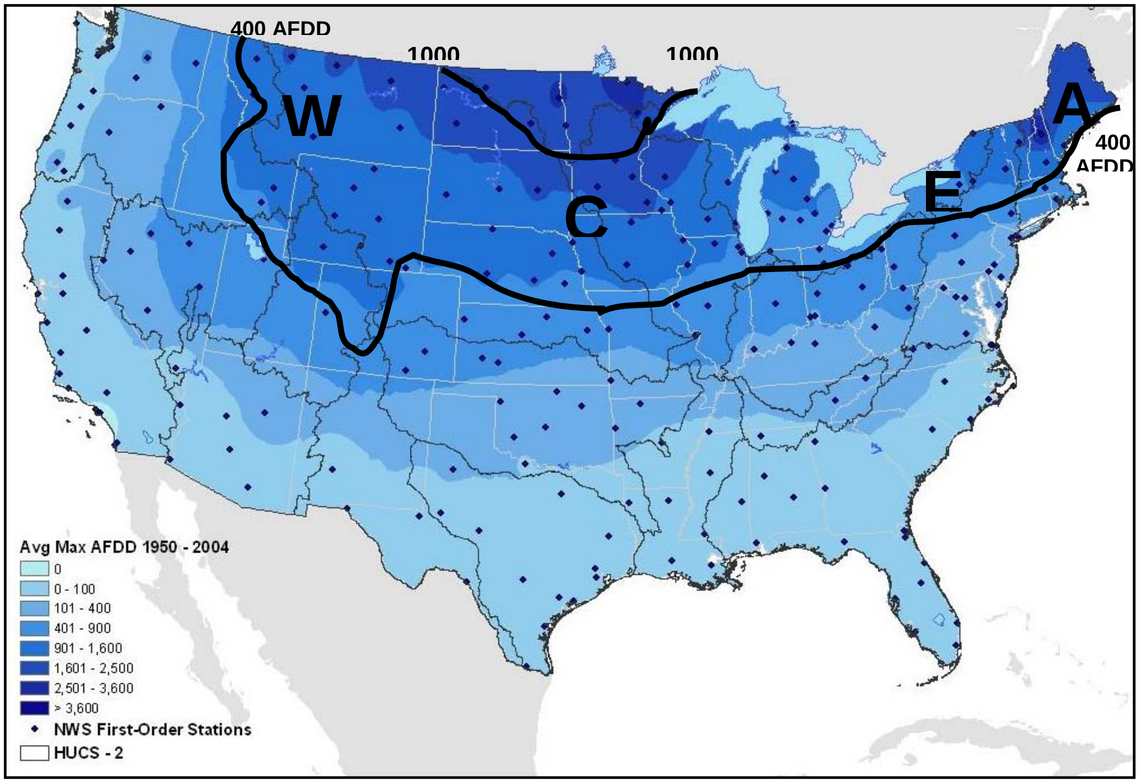

Figure 2. Comparison of area-weighted mean maximum AFDD (°F-days) from Jones *et al* 2004 and temperate ice regime region bounded by the 400 and 1000 AFDD isolines as defined by Prowse *et al* 2002 with (W=Western, C=Central, E=Eastern, A=Atlantic). Their northern region lies to the north of the 1000 AFDD isoline.

single spring breakup event, while the temperate regions exhibit midwinter temperature and hydrologic events that can result in midwinter ice cover breakup and jamming. Prowse *et al* (2002) report an increasing trend for midwinter breakup in the temperate region over the 20th century, and a major northern shift of the temperate region under two warming scenarios (2° and 6° C) (see Figure 3).

They predicted that this shift will cause midwinter breakup and jamming in Canadian regions which do not currently experience midwinter events. Figure 3 shows the projected shift compared to reported ice events in the IJDB as of June 2007. While the lower boundary of the temperate region should be shifted to capture more ice-jam impacted rivers in the Mid-Atlantic States, the upper boundary appears reasonable (Figure 4). The impact of a northward shift in the temperate zone in the US will be to increase the variability of ice jams in the lower temperate zone, and to increase the occurrence of midwinter jamming in the upper temperate zone. Both effects will impact ice jam mitigation in the US.

Mitigation measures for ice jams in the US can be generally classified as short term or long-term (i.e., temporary or permanent) and nonstructural (e.g., Haehnel 1998) or structural (e.g., Tuthill 1995, 2005; White 1994; Tuthill and Lever 2006; USACE 2006). Ice formation and freezeup ice jam mechanisms are different from ice breakup mechanisms, thus methods and design approaches to mitigate freezeup ice jams are often quite different than for breakup ice jams. Changes in ice regime from breakup-dominated to midwinter jamming, or from breakup-dominated to freezeup and breakup jamming, will require a fundamentally different approach to ice jam mitigation that is flexible, adaptable, and embraces the potential for unexpected or surprise scenarios.

Uncertainty will be increased, particularly in locations where a single, snowmelt-driven breakup ice jam (relatively predictable) is replaced with a regime marked by midwinter breakup and jamming (relatively unpredictable). For midwinter jamming, prediction of ice cover breakup and jamming will take on increased significance. Ice strength will become a more important factor in ice jam morphology since ice covers are typically stronger and more competent earlier in the season.

Increased midwinter jamming also leads to the potential for the later occurrence of freezeup ice jams at higher discharges. This situation can result in near-flood conditions for an extended period in contrast to the relatively short-duration breakup ice jams. An example is the 2005 Grand River ice jams in Michigan, which caused stages to remain near the 100-yr flood level for several weeks. Midwinter ice jams that freeze in place are known to obstruct flow and cause later breakup jams to reach much higher stages than anticipated.

5. Future Research

Emergency responders and designers must be prepared to deal with unexpected ice events. Engineers and scientists should perform additional research to develop prediction methods, decision support tools, and design specifications for ice mitigation methods. This research will

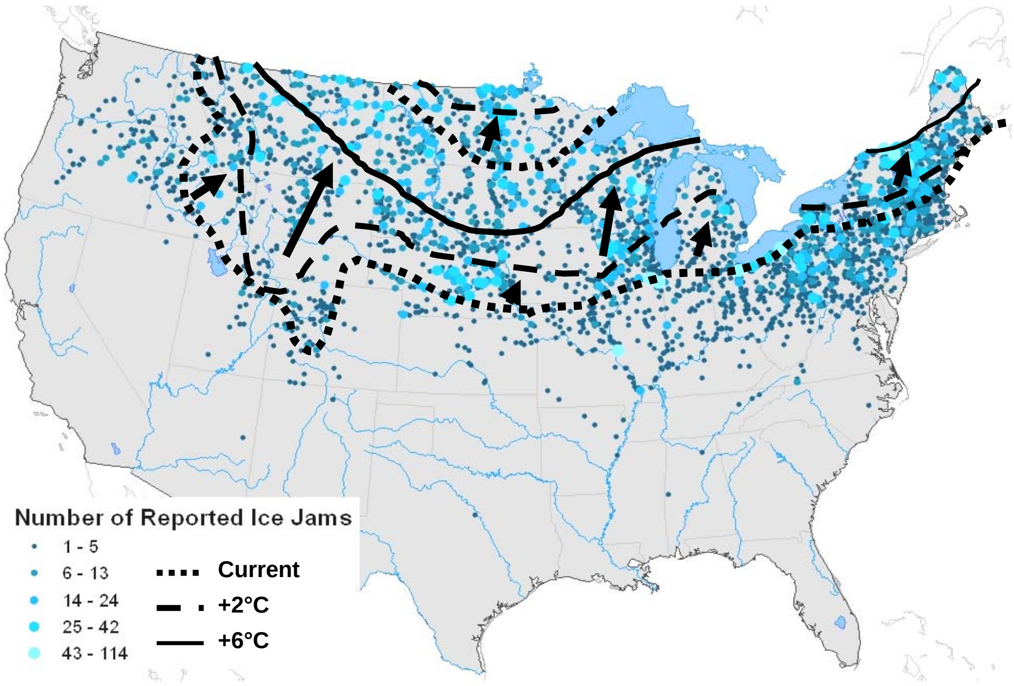

Figure 3. Projected shift in temperate region according to Prowse *et al* (2002) compared to locations of ice jams reported in CRREL IJDB (June 2007).

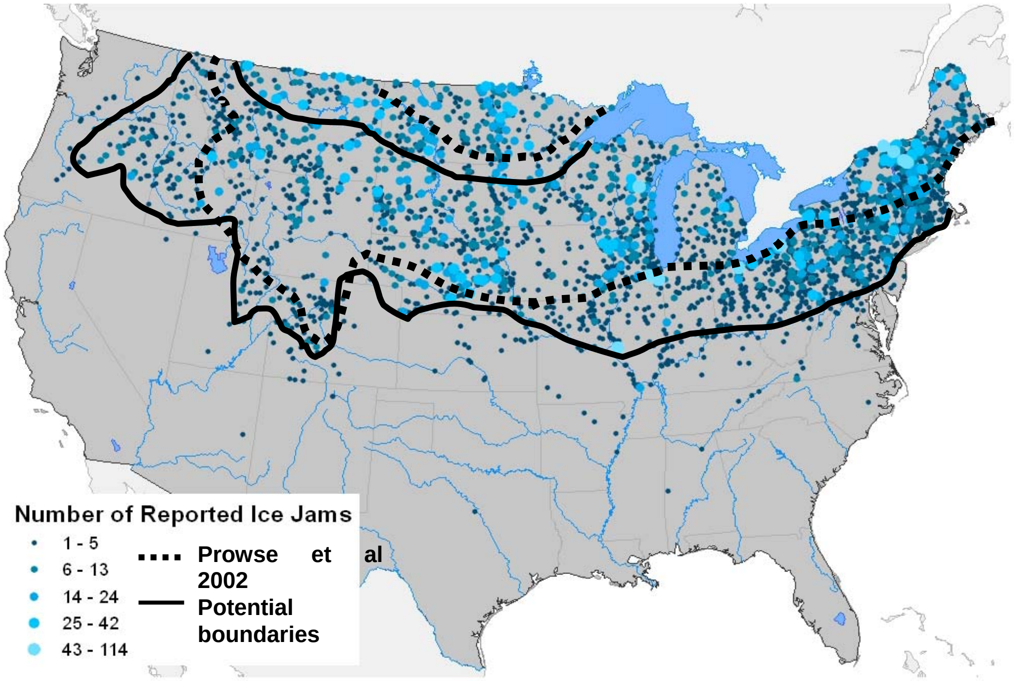

Figure 4. Alternative temperate zone boundaries in the US compared to those of Prowse *et al* (2002).

rely heavily on improved data collection and compilation of existing data into databases. For example, the work of Wing (1943) and reconstruction of the record would be very useful in northern Wisconsin, Minnesota, and Michigan, which could be expected to move from northern to temperate conditions (Prowse et al 2002). There is a real lack of river ice data for the US in the Global Lake and River Ice Phenology (GLRIP) Database (Benson and Magnuson 2006). Records of ice-affected flows at USGS gaging stations (see e.g., Hodgkins *et al* 2003) is generally difficult for non-USGS staff to obtain, but is invaluable in assessing ice impacts in design, and should be provided for all ice-affected rivers. This data and observed river ice data from the US Weather Bureau series "Daily river stages at river gage stations on the principal rivers of the United States" should be added to the GLRIP Database. The IJDB should be updated for all states for the period 1965 through 1995.

Emergency response and ice mitigation design will also benefit from a better understanding of the ice trends in the Mid-Atlantic, Central, and Western Regions of the US. In these regions, studies similar to the research conducted for New England (Dudley and Hodgkins 2002, Huntington *et al* 2003, Hodgkins *et al* 2005) is necessary. Further research on the connections between observed climate indices and expected meteorology and hydrology for the current season should improve prediction and forecasting. Additional exploration of the impacts of mild days during winter, a better method for determining thawing degree days during winter, and the use of competence ratio (Beltaos 2004) and breakup initiating discharge (Beltaos and Prowse 2001) are required. This information should allow researchers to better identify potential ice jam formation locations under different hydrological scenarios using geospatial analysis methods.

6. Conclusions

Observed changes in the formation mechanisms and timing of ice events suggest that climate variability is resulting in fundamentally different ice conditions than have been experienced in the past. This decreases the predictability and thus increases the risk and uncertainty associated with ice jam response and mitigation. A more flexible, adaptive approach to ice jam mitigation that embraces the potential for unexpected or surprise scenarios such as those occurring due to changing climate is required. This adaptive approach will require additional data collection, further research focused on river ice processes, more detailed regional river ice trend analyses than exist at the current time, and additional study related to potential climatic changes that can be expected to occur in regions with river ice covers.

Acknowledgements

This work was funded in part by US Army Corps of Engineers Civil Works Direct-Funded research in the Flood and Coastal Storm Damage Reduction Research Program focus areas of Functional Design and Performance of Structures (Ice-Affected Structures work unit), Emergency Management Technologies (Program Management), and Water Supply Technologies (Climate Variability Impacts work unit). The Civil Emergency Management Branch of the USACE Directorate of Homeland Security has supported the involvement of the authors in emergency response as well as the development and continued improvement of the CRREL Ice Jam Database.

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