FRESHWATER ICE MONITORING IN CANADA - AN ASSESSMENT OF CANADIAN CONTRIBUTIONS FOR GLOBAL CLIMATE MONITORING

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ABSTRACT
The ability to monitor the formation and decay of freshwater ice is of high interest in Canada because of the wide-ranging impacts (e.g. ecology, hydrology, recreation, transportation, safety), and the potential for inferring information on climate change over northern Canada which is data-sparse but lake-rich. Global Climate Model simulations suggest this area is likely to experience some of the largest warming in response to increasing levels of greenhouse gases. This paper provides a summary of Canada’s in situ and remotely sensed capabilities for monitoring freshwater ice, and the proposed strategy to meet national needs and international obligations such as the Global Climate Observing System. In addition, the paper presents an overview of a near real-time lake ice cover monitoring product developed by the Canadian Ice Service using AVHRR and RADARSAT for 136 lakes across North America. The paper also documents efforts at Laval University to develop an integrated lake ice database for Canada that incorporates in situ and remotely sensed data with climate data and information on lake characteristics. Plans to augment this freshwater-ice database with a companion set of river ice information being produced by the National Water Research Institute are also described.

INTRODUCTION
The ability to monitor the formation and decay of freshwater ice is of high interest in Canada because of the large surface area covered by freshwater (~ 8 % of total surface area - Adams, 1981), and the wide-ranging impacts (e.g. ecology, hydrology, recreation, transportation, safety). There is also interest in monitoring freshwater ice for climate purposes as the formation, thickness and break-up are important indicators of regional climate especially in data-sparse regions that characterize much of northern Canada.
Global Climate Model (GCM) simulations suggest that these areas are likely to experience some of the largest warming in response to increasing levels of greenhouse gases. Recent observational evidence (Magnuson et al., 2000) has confirmed a consistent trend toward later freezing and earlier breakup of lakes and rivers around the Northern Hemisphere from 1846 to 1995.

The Global Climate Observing System (GCOS) was initiated in response to the realization that the global climate observing infrastructure was inadequate to meet needs for climate change detection and model validation. Canada’s climate observing system in northern regions was subject to significant change during the 1990’s (network downsizing and a shift to auto stations) and ice observing networks were strongly affected (see Figure 2). The ability to monitor change and variability in the cryosphere (snow, sea ice, freshwater ice, permafrost, glaciers and ice caps) is essential in Canada where the cryosphere is one of the most important features of the physical and biological environment, and where the response of the cryosphere to climate warming will have major socio-economic and ecological impacts. The Canadian GCOS Committee recognized the importance of the cryosphere and sponsored a dedicated cryospheric component plan for the National GCOS Report. Component plans were tasked with addressing national and international requirements for climate monitoring to contribute to a comprehensive Canadian GCOS implementation plan. The development of the Canadian National Plan for Cryospheric Monitoring (Brown and O’Neill, 2002) was based on a series of three workshops and extensive consultations with the cryospheric monitoring and research community in Canada. This paper provides a summary of the freshwater ice monitoring material included in the plan, as well an overview of research being carried out in the Canadian CRYSYS project (CRYosphere SYStem in Canada – www.crysys.ca) to develop new approaches for freshwater ice monitoring from satellite SAR, passive microwave and scatterometer data.

**CURRENT IN SITU NETWORKS**

**Freeze-up/Break-up (fu/bu)**

The monitoring of ice phenology (dates of freeze-up and break-up) as a climate and ecological indicator has a well established history in the Northern Hemisphere, with regular observations extending over several centuries in countries such as Finland (Kuusisto, 1993). Barry and Maslanik (1993) provide an excellent review of lake fu/bu as a climate indicator. The Meteorological Service of Canada maintained a national network of fu/bu sites, and a national database of *in situ* ice observations for lake, river and coastal sea ice sites as part of WMO observing requirements for supplementary climate observations (Donmec Consulting Inc., 2000 - Appendix 10). The information collected included the timing of freeze-up and break-up, maximum seasonal ice thickness and the state of the ice surface with respect to the traffic it can support. The four main parameters reported in the database were first permanent ice (FPI), complete freeze over (CFO), first deterioration of ice (FDI), and water clear of ice (WCI). The database contains information from 567 lake, river and coastal sites, with data extending as far back as the early 1800s at a few locations (e.g. Toronto Harbour). The spatial distribution of the main sites in the lake fu/bu network is shown in Figure 1 and the temporal variability in reporting is shown in Figure 2. This network peaked in the mid-1970s with close to 140 sites, but declined rapidly to less than 20 sites by the end of the 1990s. Skinner (1993) determined that “sufficiently long and complete” records existed for at least 49 lakes for climate monitoring purposes. All the Canadian fu/bu data up to
1994 have been submitted to the Global Lake and River Ice Phenology Database at WDC-for-Glaciology, University of Colorado, Boulder.

Figure 1: Spatial distribution of Canadian lake sites with at least 20 years of fu/bu information. Numbers refer to terrestrial ecozones. *Source*: Lenormand et al. (2002).

Figure 2: Temporal distribution of Canadian lake break-up reports inferred from the start and end dates of sites with at least 20 years of break-up observations. Data supplied by R. Gauthier, Laval U.
The Ecological Monitoring and Assessment Network of Environment Canada (http://www.naturewatch.ca/english/icewatch/) is currently building a national volunteer ice phenology network in Canada (“IceWatch”). After one year, the network has over 50 volunteers signed up to contribute observations, and was successful in recovering a large volume of previously undocumented ice phenology observations. These observations are currently undergoing quality control and verification procedures prior to being released to the public (H. Vaughan, personal communication 2002).

**Ice Thickness**

The Canadian Ice Service (CIS) maintains a national database of weekly ice thickness and corresponding on-ice snow depth measurements for coastal, river and lake sites. These data were obtained from manual measurements. Dates of freeze-up and break-up are also recorded at some of these sites. There are a total of 195 sites in the database, and about one half are freshwater sites. The spatial distribution of stations at the peak of the observing network (1980s) is shown in Figure 3. The longest records (from the late 1940s) come from Arctic sites, but most of these were discontinued during the 1990s, and the few remaining stations were closed in 2000 due to increased costs associated with new safety regulations. Funding was obtained under the federal government *Action Plan 2000* program to activate 10 of the Arctic ice thickness sites by the winter of 2002–2003. However, there is an urgent need to develop a remote method for *in situ* ice thickness measurements and corresponding snow depth to eliminate the risk to observers. 30-year ice thickness and on-ice snow depth normals for the 1961–1990 period were published for 135 locations in 1992 (CIS, 1992).

![Figure 3: Maximum extent of the network of weekly ice thickness reporting stations. Source: CIS, 1992. There are currently ~10 stations still reporting.](image-url)
The ice thickness data have been used extensively in engineering (e.g. design of shore installations) and transportation (e.g. design of ice roads), and recently in a prototype fast ice break-up monitoring and forecast system developed by CIS for several northern communities. The research community has used the thickness data to investigate the role of snow cover in ice thickness variability (Brown and Cote, 1992), and to evaluate 1-D thermodynamic models for sea ice (Flato and Brown, 1996) and lake ice (Duguay et al., 2002). The weekly ice thickness data have been incorporated into the Canadian Ice Database at Laval University (Lenormand et al., 2002).

**River Ice**

River ice information has been collected by the Water Survey of Canada (WSC) as ancillary data from their hydrometric measurement program. When a river is ice covered, an indirect measurement of ice thickness can be inferred from recorded data on ice draft. This information has to be carefully interpreted since processes such as snow loading also affect draft. The thickness data have been collected on an infrequent basis. Ancillary information on ice fu/bu can also be inferred from an ice cover qualifier (code “B”) that is applied to indicate if a river is subject to ice effects. Again, care is needed in interpretation, e.g. the “B” code may be applied to an open water site if up- or down-stream ice is known to be affecting discharge. Bonsal et al. (2001) carried out a limited analysis of trends in these data and of the relationship of break-up to the spring 0 °C isotherm. Zhang et al. (2001) analyzed a 249 station subset of these data (the Reference Hydrometric Basin Network) to infer information on river fu/bu trends across Canada over the 1947–1996 period. The results showed an interesting regional difference with rivers over western Canada generally showing trends toward earlier break-up, and rivers over the Maritimes showing later break-up.

Because hydraulic (and human) effects are generally more significant in rivers than lakes, data on river ice are considered less useful as climate indicators than are data on lake ice (Walsh, 1995). However, there is a strong scientific rationale for expanding the river ice observation program in Canada given the potential effects of climate on the frequency and severity of extreme events (ice-jam floods and low flows) plus associated impacts on infrastructure and riparian ecosystems (Prowse and Beltaos, 2002). For example, Beltaos and Prowse (2001) found that increased incidence of mid-winter melt and associated breakup events in some temperate parts of Canada can actually enhance the frequency and severity of ice jams. The Canadian National Water Research Institute (NWRI) is currently using indicators of flow resistance recorded on the original water-level charts to more accurately identify historical information about the timing and severity of river fu/bu. It is planned to contribute these data to the Canadian Ice Database when this work is complete.

**POTENTIAL FOR REMOTE SENSING**

**Canadian Ice Service Weekly Lake Ice Cover Product**

Ice cover on freshwater bodies can be readily monitored from space using visible (e.g. AVHRR), active radar (e.g. RADARSAT) and passive microwave (e.g. SSM/I) sensors (Hall and Martinec, 1985). The Canadian Ice Service began regular weekly monitoring of ice extent on large Canadian lakes in 1995 using NOAA AVHRR and RADARSAT imagery to provide the Canadian Meteorological Centre (CMC) with lake ice coverage for numerical weather prediction models. This need corresponded to the increasing ability of such models to resolve lakes, and the sensitivity of the models to the correct
specification of ice or water at the surface during the winter season.

The amount of ice (tenths) on each lake is determined by visual inspection of AVHRR and RADARSAT imagery by a trained operator. The product started in 1995 with 34 lakes and was increased to 118 lakes by the end of 1998. 18 lakes from the US Midwest, western Canada and the Yukon were added in 2002. Regular monitoring of ice coverage on small lakes is only possible with high resolution RADARSAT data (100 m resolution) and is costly. For this reason the current lake ice monitoring program is limited to roughly 200 RADARSAT frames a year. It is possible to derive CFO and WFI with an accuracy of ±1 week using this dataset, but this does not meet GCOS requirements of ±1–2 days (GCOS-32, Cihlar et al., 1997). The Canadian GCOS report recommended that CIS increase the frequency of RADARSAT coverage during the main fu/bu periods to help meet GCOS requirements. The accuracy of the information in the CIS lake ice extent database depends on the amount of cloud cover over a particular lake (NOAA AVHRR imagery is weather dependent) and the frequency of RADARSAT coverage. The RADARSAT data used for lake ice monitoring (mostly ScanSar Wide from RADARSAT-1 at 100 m resolution) also have some limitations - lake ice is smoother than sea ice, and at times the lack of features on small lakes makes ice difficult to see. Lack of ground truth data is sometimes a problem, and accurate mapping of lake ice concentration is difficult when ice concentration varies on a less than weekly basis e.g. when ice is thin and sensitive to wind action. The CIS weekly lake ice information is contributed to CMC and archived internally but is not available publicly as it is still considered a research product. A 4-level classification of the lake ice cover information is presented on the “State of the Canadian Cryosphere” Website (www.socc.ca).

**Passive Microwave Lake Ice Monitoring**

Satellite-based passive microwave sensors, such as SSM/I, provide the capability for all-weather, daily monitoring of ice cover. The theory is covered in Hall and Martinec (1985) and Hall (1993) provides a review of passive microwave remote sensing for lake ice studies. The major disadvantage of SSM/I is the coarse spatial resolution (approximately 25 km for 37 GHz and 12.5 km for the highest frequency 85 GHz channel), which limits monitoring activities to large lakes. With the May 2002 launch of the Advanced Microwave Scanning Radiometer (AMSR) on NASA’s Aqua satellite, the capability to extend monitoring capabilities to smaller lakes may be possible with the availability of higher spatial resolution data (5 km and 10 km for the 89 and 36.5 GHz channels).

The Meteorological Service of Canada (MSC) Climate Research Branch has developed the capability to monitor lake ice freeze-up and break-up over Great Slave Lake and Great Bear Lake using SSM/I passive microwave satellite data (Walker and Davey, 1993). Two approaches are used. One employs brightness temperature images from 85 GHz data (the best spatial resolution) to map the spatial evolution of ice and open water. The second approach uses 37 GHz brightness temperature time series to identify the dates of freeze-up and break-up from the change in brightness temperature (Close, 2000). The advantages of the second approach are that the 37 GHz channel is less susceptible to atmospheric interference, and fu/bu information can be inferred back to 1979 using SMMR data. A time series (1987 to present) of freeze-up and break-up images has been compiled for Great Slave and Great Bear Lakes using the EASE-Grid
SSM/I brightness temperature product distributed by the U.S. National Snow and Ice Data Center. This time series is being used to investigate and document the spatial and temporal variability of ice cover growth and decay over these northern lakes, and to examine relationships between the remotely sensed and conventional data sources. The lake ice data derived from SSM/I are also being used to validate lake ice models (e.g. Ménard et al., 2002) and to assist in understanding and modelling regional energy and water exchanges of the large lakes in the Mackenzie River Basin (a contribution to Canada’s Mackenzie GEWEX Study). Data series derived from passive microwave are particularly relevant for GCOS climate monitoring objectives as continuity of the SSM/I data stream is built into future operational satellites.

SAR Lake and River Ice Monitoring R&D
Regular, all weather monitoring of river ice cover requires high resolution SAR data which is expensive to obtain, and not always available due to scheduling conflicts with other users. In addition, the interpretation of river ice information from SAR imagery is complicated by the highly variable and dynamic ice conditions found in river channels. CRYSYS-supported research at INRS-Eau (Bernier et al., 2002) conducted detailed ground-data collection to evaluate the utility of RADARSAT for monitoring ice conditions in the Saint François River, southern Québec. There is a growing need for information on river ice conditions to support the safety of winter recreational activities, such as ice fishing and snowmobiling, and for river flood forecasting in areas susceptible to ice jams. B.C. Hydro, a major hydroelectric company, regularly uses RADARSAT data during the break-up season to monitor ice jamming on the Peace River. A CRYSYS-supported collaborative research project involving Laval University, MSC, CCRS and McMaster University is developing an operational method for mapping freeze-up and break-up dates over large areas of Canada using SAR (ASAR Global Monitoring Mode) and optical (AATSR) data from the ENVISAT satellite. The advantage of ENVISAT is its 1-km resolution and 2–3 day repeat coverage.

RECOMMENDED MONITORING STRATEGY
Canada’s *in situ* networks are no longer adequate to provide the primary information desired from a Canadian lake ice monitoring program. The data are sparse, and it is difficult to assess the homogeneity and representativeness of the observations because of their inherent local and subjective nature. Remote sensing offers a more suitable observing strategy for lake ice monitoring over vast uninhabited regions of Canada. However, the satellite data record is still relatively short, which restricts its applicability to the past two decades for documenting variability and change. What is required are the development of approaches to merge available *in situ* and satellite observations to create a consistent long term time series of lake ice *fu/bu* and ice cover processes. The Canadian GCOS report recommended that a limited number of sites be established with high quality *in situ* measurements of ice thickness and on-ice snow depth for evaluation of satellite data, and for development and validation of lake ice models for up- and down-scaling *in situ* and satellite ice cover information. The addition of snow information was considered vital as this has a major influence on the heat flux from ice-covered lakes, and on lake ecology (e.g. light and PAR transmission). River ice is more difficult to monitor routinely with remotely sensed data, and it was recommended that a minimum river ice observing network be maintained as part of the 230 sites in the Reference Hydrometric Basin Network.
Another major recommendation of the GCOS workshop was to consolidate the various Canadian ice databases in one location, and to make these widely available to the research community. Laval University, with support from the CRYSYS project, has assembled all the available Canadian fu/bu and ice thickness data into a comprehensive digital database (Lenormand et al., 2002) including complementary information such as lake characteristics (depth, area, perimeter) and lake ecozone. It is intended to make these data widely available to the research community through a standard Z39.50 data query interface at the recently established “Canadian Cryospheric Information Network” (CCIN) at the University of Waterloo. This network is being established with funding support from the Canadian Space Agency and the Meteorological Service of Canada. The Global Lake and River Ice Phenology Database at WDC-G currently has all the Canadian FU/BU data up to 1994, but the current Canadian database includes additional information at some sites such as ice thickness and on-ice snow depth, and the state of the ice for over-ice transport.

REFERENCES


