Development of a Historical Ice Database for the Study of Climate Change in Canada

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ABSTRACT: The Canadian government has been compiling various observations on freshwater and coastal sea ice conditions for many years. However, the records are not easily accessible and are dispersed within different government departments. Given this, a major effort was undertaken in order to gather all available observations into a common database – the Canadian Ice Database (CID). This database will respond to the needs for climate monitoring in Canada, the validation and improvement of numerical ice models and the development of new remote sensing methods. Indeed, several studies have shown that freshwater ice and sea ice are good proxy indicators of climate variability and change.

The first version of CID contains *in situ* observations from 757 sites distributed across Canada, which were originally kept on digital or paper records at the Meteorological Service of Canada Headquarters (MSC–HQ) and the Canadian Ice Service (CIS). CID holds 63,546 records covering the period from ice season 1822–1823 to 2000–2001. An analysis of the database allows to trace the temporal evolution of the ice networks. The Freeze-Up/Break-Up network of 2000–2001 only represents 4% of what it was in 1985–1986. A drastic decline of the Ice Thickness and Snow on Ice network is also observable. In 1997–1998, it represented only 10% of the network that existed in 1984–1985. The major budget cuts in Canadian government agencies during the late 1980s and the 1990s offer the most plausible explanation for the drastic decline in the ice observation networks. Weekly ice coverage determination on large lakes from satellite imagery by CIS and the national volunteer ice monitoring program, IceWatch, may provide a means of reviving, at least, the Freeze-up/Break-up network.

Keywords: Historical database, lakes, rivers, sea shore, freeze-up, break-up, ice thickness, Canada.

INTRODUCTION

Freshwater ice and sea ice are important components of the Canadian cryosphere and are known to be useful indicators of global climate change. Studies conducted in Finland, Wisconsin (USA) and, more recently, for a few lake and river sites with long historical records in the Northern Hemisphere, show that the freeze-up and break-up dates are especially sensitive to changes in air temperature (Palecki et Barry, 1986, Anderson *et al*., 1996, Magnuson *et al*., 2000). Understanding the response of the cryosphere to climate in a territory as large as Canada is important since there are likely to be significant regional differences. Therefore, there is a need to assemble a national database to permit the analysis of the response of ice cover to climate variability and change in Canada.

Various Canadian government agencies have been gathering *in situ* observations on freshwater and sea ice conditions across the country for many years. Dates of complete freeze-over (or ice coverage), maximum ice thickness, and the date when ice is safe to travel on are a few examples of such observations. At least three separate departments within Environment Canada have been compiling records on ice conditions: the Meteorological Service of Canada – Headquarters (MSC–HQ), the Canadian Ice Service (CIS), and the Water Survey of Canada (WSC). Although often complementary, no previous efforts have ever been undertaken to merge ice records from these three departments into a single, common, database. The development of a database of this type is an essential tool for present and future climate-related research activities in Canada such as the use of ice cover as an indicator of climate variability and change,

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the validation of numerical ice growth models, and the development and validation of remote-sensing algorithms.

The primary intent of this paper is to describe the development of a national historical ice database for Canada. In its first version, the database assembles data collected from conventional, observational, freshwater and sea ice networks operated by Environment Canada, and more specifically the MSC–HQ and CIS ice networks.

HISTORICAL DATA ON ICE COVER IN CANADA

The very first continuous observations on ice cover conditions by the Canadian government began in Toronto Harbour, Lake Ontario, in 1822. Gradually, other water bodies were added to the monitoring network. At the beginning of the 20th century, the number of water bodies had increased considerably and an important quantity of observations started to accumulate. After the Second World War (ice season 1947–1948), the ancestor of CIS began the exploitation of a network aimed at the collection of data in the Arctic Ocean. During that period, other northern countries such as Russia, Finland, Sweden and United States, to name a few, had already begun the gathering of their own data on freshwater ice. Today, the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, U.S.A., maintains a database of 746 lake and river ice sites through the Northern Hemisphere with time series spanning over more than 150 years. Some Canadian data on river and lake ice freeze-up and break-up dates (up until 1994) have been contributed to this database.

The gathering of observations on ice conditions in Canada was encouraged by a few research projects carried out by researchers of the CIS and MSC–HQ. The interest to compile all observations under a single database also stems from the fact that the accumulation of hard copies complicated the inventorying of data as well as the accessibility during consultations. The efforts of Allen (1977), Anderson (1987) and Gullet *et al.* (1992) have been instrumental in this respect. Some of these data have been used to study the spatio-temporal evolution of maximum ice thickness across the country while other data have been utilized to study climate variability through the analysis of freeze-up/break-up records on a Canada-wide scale (e.g. Allen, 1977; Anderson, 1987; Gullet *et al*., 1992; Skinner, 1992). Data on ice thickness and on-ice snow of the CIS have also been used for the validation of a numerical sea ice model (Flato and Brown, 1996). However, these studies have been limited to the analysis of one or two parameters at a time or over limited time periods. The development of a consolidated database grouping all possible ice parameters available from Canadian government agencies is a worthwhile goal which would permit to improve our understanding of the response of ice cover conditions to climate variability and change in Canada.

THE CANADIAN ICE DATABASE (CID)

The development of the Canadian Ice Database (CID) was primarily motivated by the commitment of Canada to contribute cryospheric-related information to the Global Climate Observing System (GCOS)[3] of the World Meteorological Organization (WMO) (Barry, 1995). As part of this effort, one aim is to identify a list of target lakes for long-term monitoring of freeze-up and break-up dates across the country. The database is also to come in support of research initiatives such as the Canadian CRYSYS[4] program and its related activities (e.g. State Of the Canadian Cryosphere (SOCC) Website[5], Canadian Cryospheric Information Network (CCIN)[6]) .

[3] The Global Climate Observing System (GCOS) was established in 1992 to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users. GCOS is intended to be a long-term, user-driven operational system capable of providing the comprehensive observations required for monitoring the climate system, for detecting and attributing climate change, for assessing the impacts of climate variability and change, and for supporting research toward improved understanding, modelling and prediction of the climate system. It addresses the total climate system including physical, chemical and biological properties, and atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes (World Meteorological Organization, 2001).

[4] CRYSYS is a specialist research group studying snow and ice in Canada. It was initiated by scientists in 1988 and is a Canadian contribution to NASA's Earth Observing System (EOS) Program. CRYSYS offers Canadian scientists opportunities to play a significant role in developing methods for extracting information on the cryosphere from conventional and remote sensing systems (CRYSYS, 2002).

[5] A website designed to provide, in one convenient location, up-to-date information on the past, present, and future state of important cryospheric variables in Canada (snow, sea ice, lake ice, glaciers and ice caps, frozen ground and permafrost) (SOCC, 2002).

Sources and formats

The inception of CID began with a search of all data available within MSC–HQ and CIS. As a first step, documents under two supports (digital files and paper copies) were acquired from the two departments. Data in digital form were available in two formats. MSC–HQ had begun the development of a database under Microsoft Access© (Skinner, pers. comm., 2000), with observations extending to 1994 only, while CIS had its data available in « text » files up to 1998. It is worth mentioning that the data from MSC–HQ are collected on an annual basis and those from CIS are taken several times during a given ice season. Another difference between these two networks is the type of data collected. The data from MSC–HQ mainly relate to Freeze-Up/Break-Up (FU/BU) dates while the data from CIS provide information on Ice Thickness and Snow on Ice (ITSI). Figure 1 presents the totality of sites inventoried for both the FU/BU and the ITSI networks, ever since the first observations in 1822. The sites are grouped into four water-body categories. In Figure 1, the numbers in bracket represent the number of sites per category in CID. The term « Others » includes sites such as locks and channels, the mouth of rivers flowing into a lake or in the ocean.

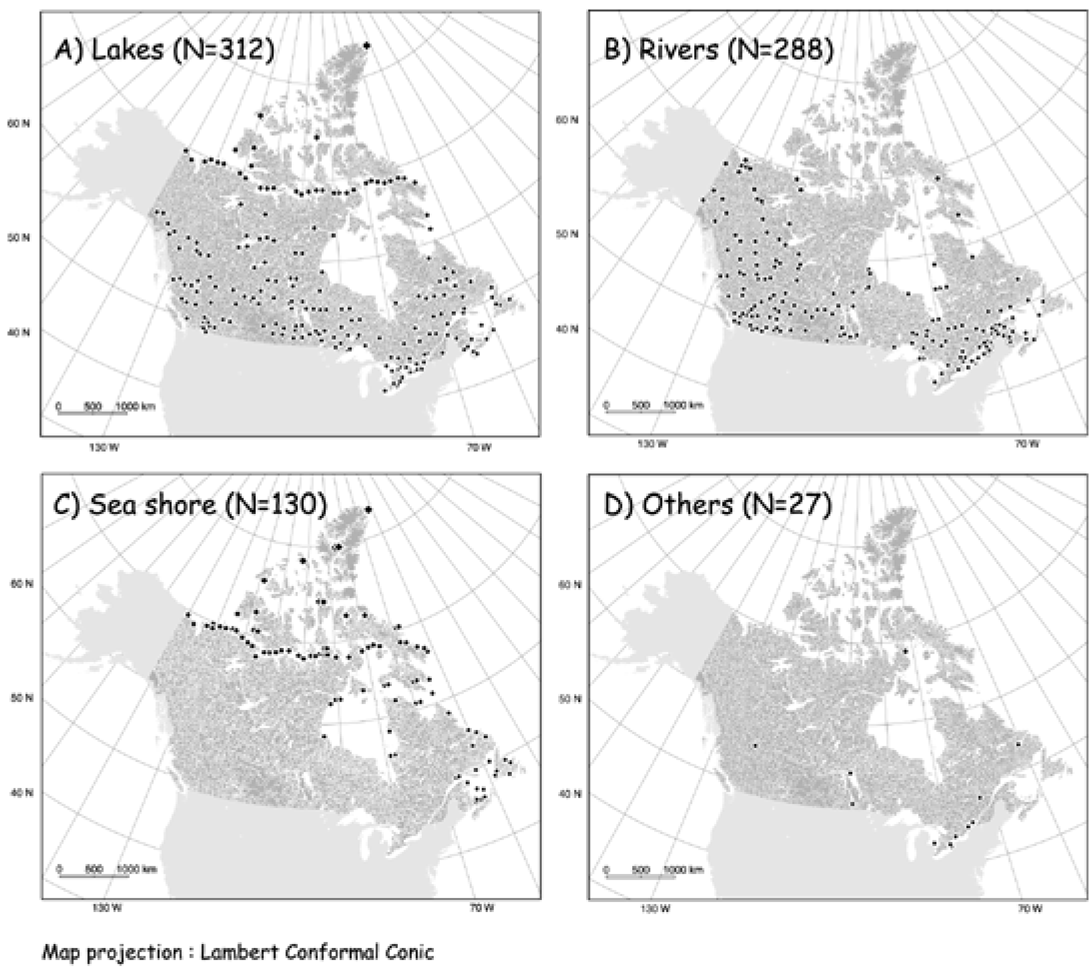

Figure 1. Location of 757 sites of the Canadian Ice Database (CID).

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[6] The Canadian Cryospheric Information Network (CCIN) has been developed as a collaborative partnership between the Federal Government, the University of Waterloo and the private sector to provide the data and information management infrastructure for the Canadian cryospheric community. The main objective of the CCIN is to enhance awareness and access to Canadian cryospheric information and related data (CCIN, 2002).

Observations from the FU/BU network for all ice seasons up until 1996 were also made available from MSC–HQ in digital text files. These were used for QA/QC checks and for updating the original Access© database which ran up until ice season 1993–1994. Paper records compiled by MSC–HQ for ice season 1996–1997 to 2000–2001 were then entered manually through the use of CID database input forms described later in this paper. The ITSI database contained the following variables: relevant date, ice thickness, one-ice snow depth, water body identifier and the water feat. The FU/BU database had more detailed information than the ITSI database. It contained observations such as: the first ice date, the date of complete freeze over (freeze-up), the maximum ice thickness, the ice free date (break-up), the date when a vehicle can travel safely on the ice, as well as several parameters. The two databases complement each other well and, together, provide a very complete picture of the seasonal evolution and interannual variations in ice cover across Canada.

Database design

The FU/BU database was chosen as the entry point for the design of CID, since most of the ice parameters were already well identified and they had been compiled under Microsoft Access©. The choice of MS Access© is purely technical because the queries and the creation of forms considerably improve the consultation and the extraction of data. Moreover, Access© is one of the most common database software packages, which increases the number of users which can consult the CID.

The difference in the frequency of data acquisitions between MSC–HQ (seasonal basis) and CIS (almost weekly basis) necessitated, as a first step, the creation of two distinct data tables under Access©. These two tables were associated with an index table to simplify the consultation (Figure 2). An index table already existed under Access© for the FU/BU data while the index table for the ITSI data was available from CIS in a text file.

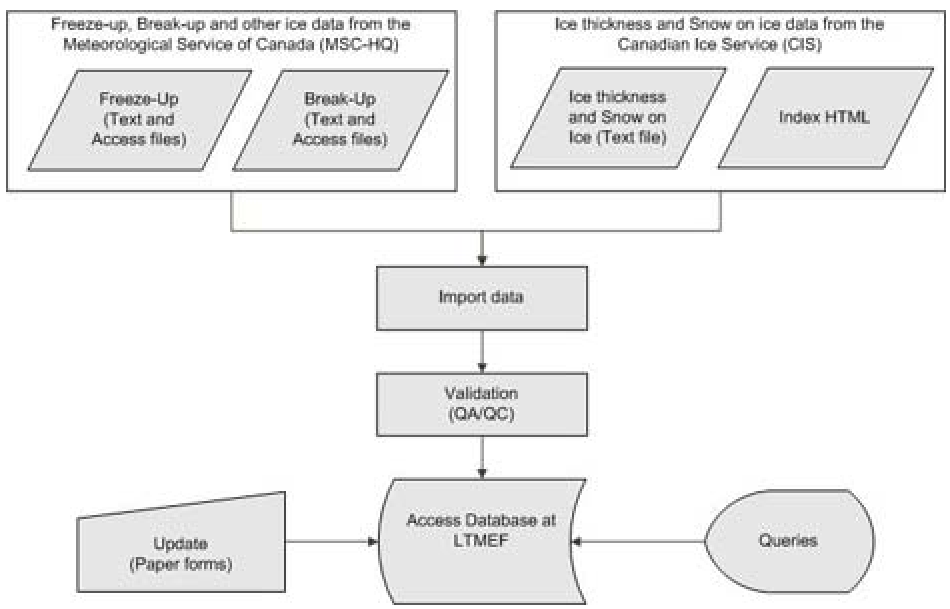


Figure 2. Database design flow diagram.

The second step consisted of creating a « Key » to link the data tables with their respective index and, later, link the index between them. Temporary keys already existed between the ITSI data table and its index and the FU/BU table and its index, but none of these two keys could be used to establish a relation between the four tables (i.e. two index tables and two data tables). The ITSI table was linked to its index by the « Station Identifier » field, which is a station code attributed by CIS. The FU/BU table and its index were linked by the « LATLONG » field. This field specifies the geographic location of the water body and consists of nine digits, four for the latitude and five for longitude (expressed in degrees-minutes). This last key was not effective considering that certain « LATLONG » were identical for more than one site. The most logical solution to this problem was to create a key from the concatenation of field « LATLONG » and field « WATER_BODY », a field which represents the name of the water body. With this concatenation, it is impossible to find two identical keys. The same process was applied to the ITSI table and its index.

Afterwards, exclusion queries were performed to find the links that did not work between the index and the data tables. All records resulting from the queries were corrected one by one. Most of the time, spelling mistakes or errors in geographical location had been introduced into the raw data. The typography of the new key was carefully checked because a single mistake in the name of the water body and the relations between tables would not work correctly. The manual revision of all the failing bonds was necessary to make the database fully operational. This work was necessary to clean the tables and to avoid duplication.

User interface and forms

The development of a database of this breadth requires not only some processing on the data but also work on a user interface. In this case, the interface had to be built from scratch. The Access© software allows the design of a user-friendly interface which is activated when the database is launched. As CID is a Canadian tool, English and French interfaces were created, except for the metadata which are only available in English at the moment. The creation of the interface windows followed the order: Choice of the language, Main Menu, Metadata (or Metafile), Update Forms and About CID... All windows were developed in Visual Basic©. The link between the interface and the tables were pre-programmed in the software through a suite of readily available functions.

Two forms are also accessible from the main menu. The purpose of these forms is to facilitate the manual entry of observations from paper records into the database for regular updates. There is a form for the « Ice Thickness and Snow one Ice » table and one for the « Freeze-up/Break-up » table. The forms contain all possible fields. The data entered into the forms are automatically saved in their respective table.

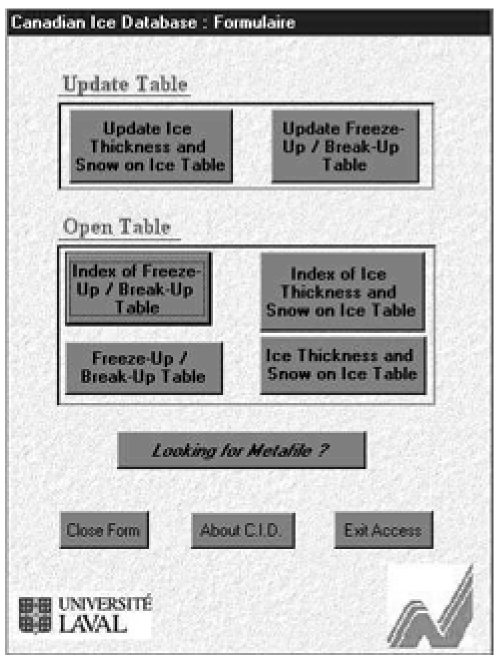


Figure 3. Main menu interface of CID.

Queries

As soon as the database is activated, the user must choose the language of consultation. The choice of the language leads to the main menu shown in Figure 3. Starting from the main menu, the user can consult one of the four tables, the metadata (or metafile) or the two forms for data updates (Figure 4). A query cannot be performed directly from the main menu. The user must follow the normal procedure for data querying under Access©. It should be noted that basic pre-programmed queries are envisaged in a future version of the database.

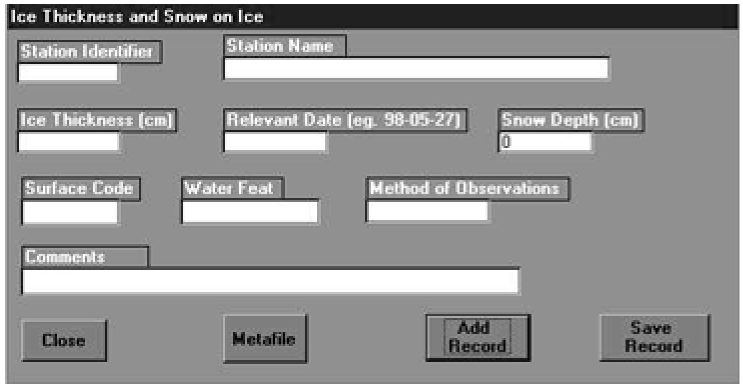


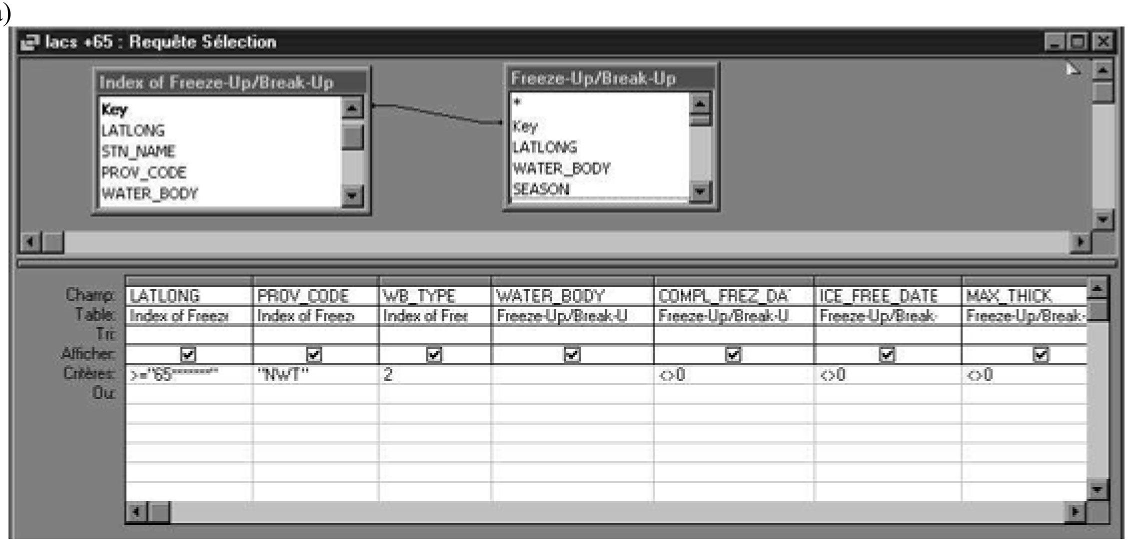
Figure 4. Ice Thickness and Snow on Ice database update form.

CID allows the consultation of data, the development of queries and other manipulations on 63,546 indexed records from 757 sites of which 567 are from MSC–HQ and 195 from CIS. The sites are dispersed across the Canadian territory, from north to south (Alert to United States border) and from west to east (Vancouver Island to Newfoundland). The data cover a period of up to 179 years, from ice season 1822–1823 to 2000–2001. The consultation and the extraction of data are carried out without difficulties and the flexibility of the Access© software allows the user to save the data in several formats.

Below is an example of a typical query that can be carried out by a user interested in studying lakes of northern Canada. Figure 5a presents the query structure under Microsoft Access©, while query results are shown in Figure 5b. The query conditions are as follows:

- Sites above 65°N
- Located in the Northwest Territories
- Water Body Type : Lake
- Lake with Freeze-Up <u>AND</u> Break-Up
- Lake with Maximum Ice Thickness > 0

a)



b)

lacs +65 : Requête Sélection

LATLONG	PROV_CODE	WB_TYPE	WATER_BODY	COMPL_FREZ_DATE	ICE_FREE_DATE	MAX_THICK
652911022	NWT	2	CONTWOYTO LAKE	70-10-14	71-07-13	145
652911022	NWT	2	CONTWOYTO LAKE	71-10-22	72-07-27	198
652911022	NWT	2	CONTWOYTO LAKE	72-10-07	73-07-08	173
652911022	NWT	2	CONTWOYTO LAKE	73-10-30	74-07-15	231
652911022	NWT	2	CONTWOYTO LAKE	75-10-19	76-07-12	183
652911022	NWT	2	CONTWOYTO LAKE	76-10-22	77-07-11	183
652911022	NWT	2	CONTWOYTO LAKE	77-10-20	78-08-02	201
652911022	NWT	2	CONTWOYTO LAKE	78-10-11	79-08-03	183
652911022	NWT	2	CONTWOYTO LAKE	79-10-11	80-07-04	150
660511802	NWT	2	GREAT BEAR LAKE	52-11-17	53-07-04	188
660511802	NWT	2	GREAT BEAR LAKE	53-11-15	54-07-08	213
660511802	NWT	2	GREAT BEAR LAKE	54-11-20	55-07-05	203
660511802	NWT	2	GREAT BEAR LAKE	55-11-16	56-07-12	249
660511802	NWT	2	GREAT BEAR LAKE	56-11-13	57-07-26	132
660511802	NWT	2	GREAT BEAR LAKE	57-11-25	58-07-11	142
660511802	NWT	2	GREAT BEAR LAKE	58-11-28	59-07-23	173
660511802	NWT	2	GREAT BEAR LAKE	69-11-25	70-07-08	193

Enr: 1 sur 272

Figure 5. Example of query in Canadian Ice Database : a) query structure in CID ; b) query result.

This particular query results in the identification of 272 records from 22 different sites within the database. The results can then be sorted by fields or extracted to serve specific purposes (creation of graphics in Excel©, use for validation of numerical models, etc.). Querying is very simple and can be adapted for any kind of needs.

EVOLUTION AND STATE OF THE NETWORK

An analysis of the evolution of FU/BU and ITSI networks was possible once all data had been gathered into CID. In order to obtain an overall picture of the state of the networks, frequency histograms for lakes, rivers, sea shore, and other water bodies were produced. The results are very worrisome. The number of sites of the FU/BU network has dramatically declined since the early 1980s for lake, river and coastal sea ice sites (Figure 6).

Table I. Summary of evolution of FU/BU network and ITSI network since the 1970/71 ice season.

	Freeze-up/break-up				Ice thickness and snow on ice			
	1970/71	1985/86	2000/01	Maximum	1970/71	1985/86	2000/01	Maximum
Lakes	140	126	5	143 (1962/63)	14	43	n/a	50 (1979/80)
Rivers	105	101	3	114 (1957/58)	37	70	n/a	81 (1984/85)
Sea shore	51	46	4	54 (1971/72)	18	19	n/a	26 (1975/76)
Others	7	6	0	9*	4	5	n/a	5**
Total	303	279	12	320	73	137	n/a	162

* Maximum number of 9 sites were monitored from 1959/60 to 1961/62.
** Maximum number of 5 sites were monitored from 1976/77 to 1996/97, except for 3 seasons during that time period.

The same is to be said about the ITSI network, although the decrease is proportionally less than that of the FU/BU network since they were originally fewer ice thickness sites being monitored. Also, in contrast to the FU/BU network, the ITSI network peaked in the 1980s rather than the 1970s. Table I summarizes the details of the histograms of Figures 6 and 7. During the 2000–2001 ice season, freeze-up and break-up observations were reported for only 12 water bodies across the country. As for the ITSI network, some observations were probably made but were not readily available from CIS. The erosion of the two ice networks is mainly attributable to budget cuts in the federal government that started in the late 1980s. The safety of the employees is also a factor that can possibly explain the decrease of ice thickness network. Indeed, some unfortunate casualties raised the important issue of health and safety for the observers. Given this very bleak picture of the Canadian ice networks, is there any hope of ever increasing or even keeping a reasonable number of sites operational in the future?

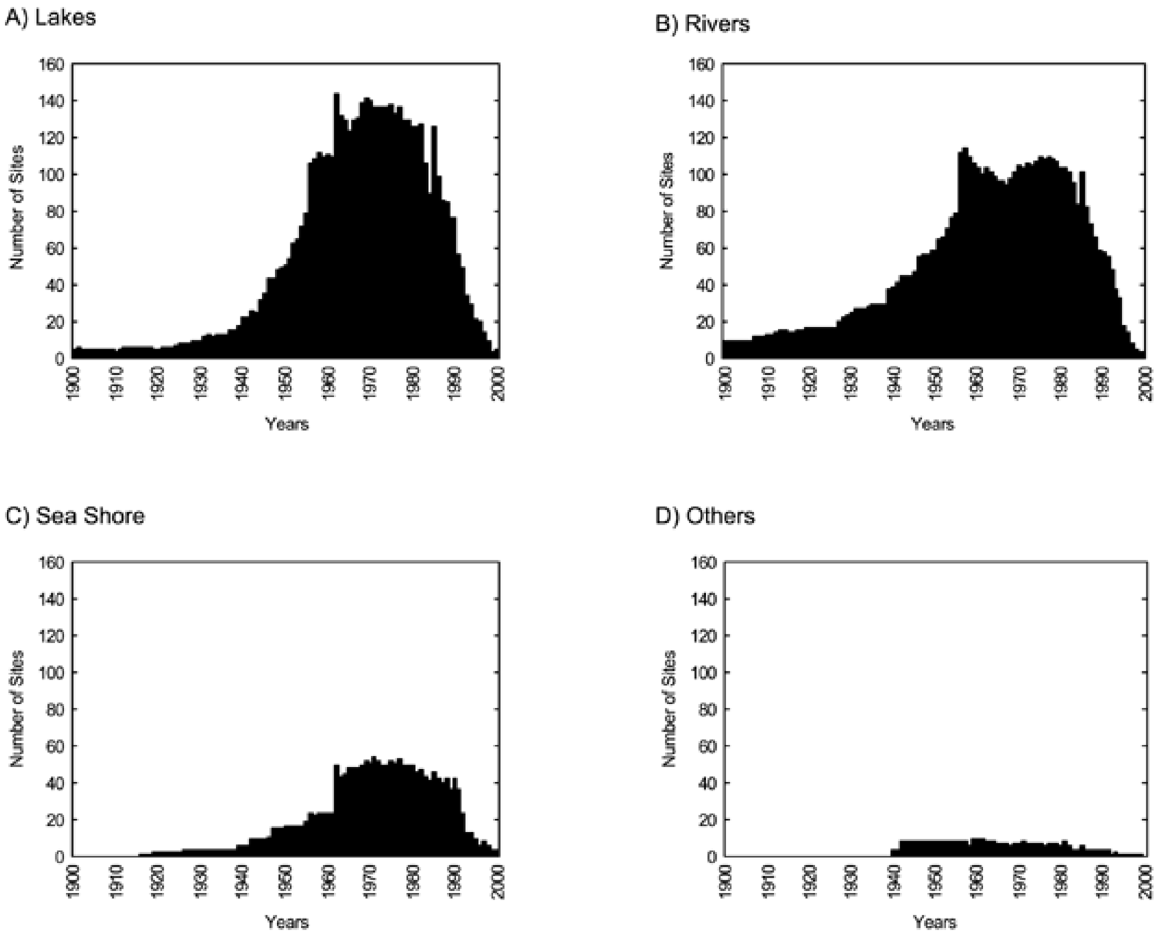


Figure 6. State of Freeze-up/Break-up network for: a) lake sites; b) river sites; c) sea shore sites; d) other sites.

There are two ongoing activities that may offer a solution for maintaining at least part of the lake and river ice FU/BU network. One is the recently launched IceWatch program. IceWatch (2002) is the latest addition to the NatureWatch series hosted by the Canadian Nature Federation and Environment Canada's Ecological Monitoring and Assessment Network Coordinating Office (EMANCO)[7]. The series is part of a suite of national volunteer monitoring programs designed to help identify ecological changes that may be affecting our environment. Through IceWatch, scientists are engaging citizens across Canada in reporting the yearly ice-on and ice-off dates at local lakes and rivers. The data are to be used to monitor the effects of climate change on aquatic ecosystems in Canada.

[7] The Ecological Monitoring and Assessment Network (EMAN) is a network of people working at long-term, multidisciplinary research and monitoring sites located over the whole country, with the objective of understanding what changes are occurring in the ecosystems and why. The network also needs to be a mechanism for site participants to provide input to indicator development and reporting, assessments and other ecological endeavours (Environment Canada, 2000).

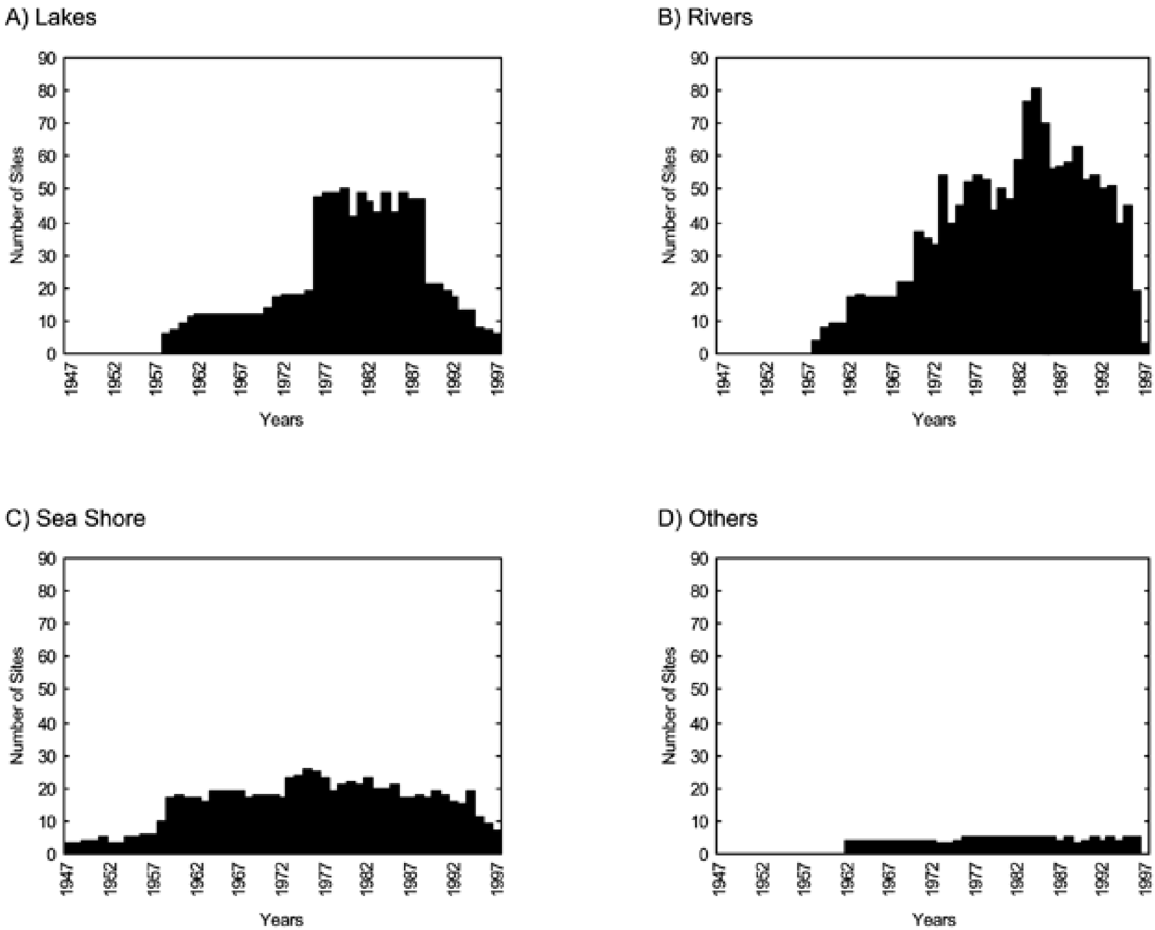


Figure 7. State of Ice Thickness and Snow on Ice network for: a) lake sites; b) river sites; c) sea shore sites; d) other sites.

Another, and complementary, solution is to use data on ice coverage derived from satellite remote sensing by CIS. CIS began weekly monitoring of ice extent on large lakes in 1995 using NOAA AVHRR and RADARSAT imagery in support of Canadian Meteorological Centre (CMC) needs for lake ice coverage in numerical weather models. The amount of ice (tenths) on each lake is determined by visual inspection of AVHRR and RADARSAT imagery. The program started with 34 lakes and was increased to 136 lakes in 2002 (Figure 8). It is possible to derive freeze-up and break-up dates with an accuracy of +–1 week using this dataset (Brown *et al*., 2002).

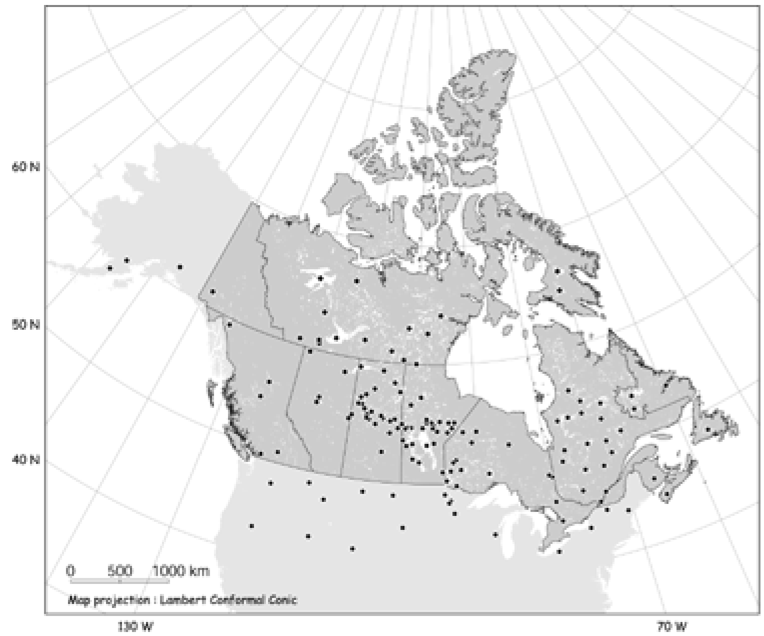


Figure 8. Lakes currently being monitored with remotely sensed data on a weekly basis by the Canadian Ice Service (N=136).

The map of Figure 9 presents 91 lake ice sites that have historical records for 20 or more ice seasons. The list of lakes could be used to guide the choice of lake ice sites for the IceWatch program and CIS remote sensing activities. This would permit to continue or re-activate monitoring at sites that have the longest historical records, and even add new ones in regions (terrestrial ecozones) of the country where large gaps exist.

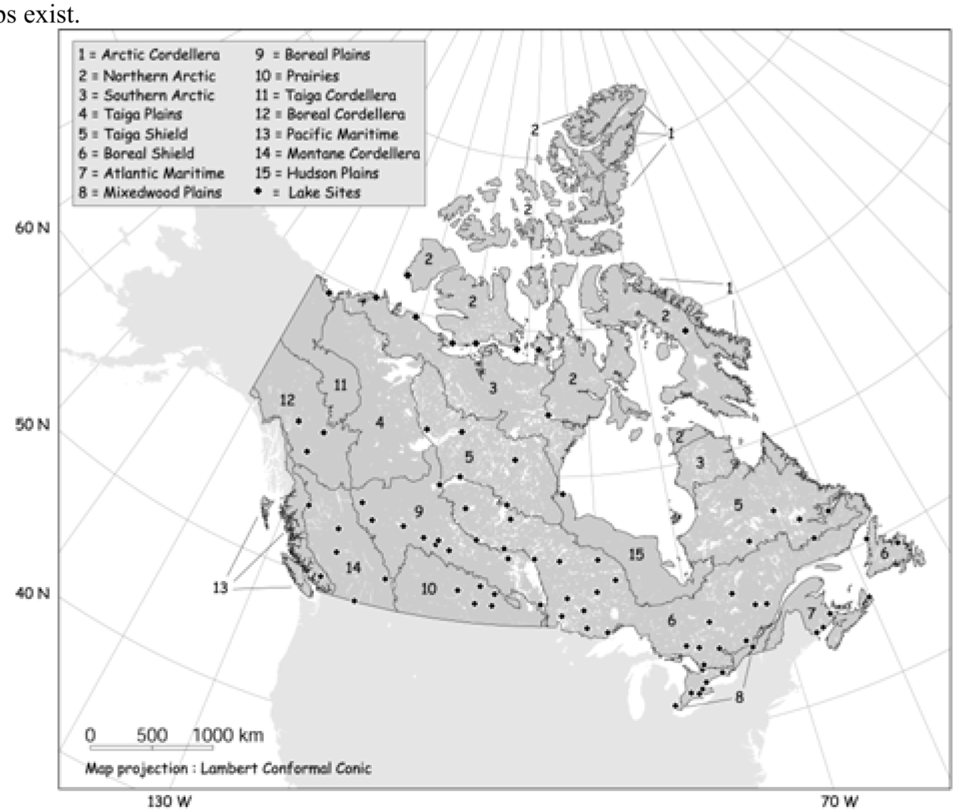


Figure 9. Location of lake ice sites with at least 20 years of freeze-up and break-up records (N=91) overlayed on map of terrestrial ecozones of Canada.

CONCLUSION

For the first time, all data concerning the past and current state of the lake ice, river ice and coastal sea ice available from CIS and MSC–HQ have been collated into a single, common, database—CID. CID is a database grouping together data relating to the state of the ice cover in Canada since 1822. The user interface built around CID allows to enter, consult and extract data concerning ice cover conditions in Canada over a period of 179 years. From a break-up date to an ice thickness measure, the data can be used in several areas of investigation concerned with the impact of climate variability and change on freshwater and coastal marine ecosystems.

A database such as CID is a tool in constant evolution. Now that the first version of the database has been developed, ice cover data from other sources can be added to it, whether they come from in situ or remote sensing observations. As an example, river ice information have been collected by the Water Survey of Canada (WSC) hydrometric program, as ancillary data from their river discharge measurement program. The data can be used to infer information on river freeze-up/break-up dates. A logical next step will then be to integrate this data into CID in collaboration with the National Water Research Institute (NWRI) of Environment Canada.

Finally, CID will permit to examine temporal and spatial trends in several ice parameters across Canada in respect with the objectives of the Global Climate Observing System (GCOS) regarding the cryosphere (Brown *et al*., 2002). The parameters of most relevance to GCOS and available in CID are coastal sea ice thickness and lake freeze-up and break-up dates. The first version of the CID will be available later this year on the CCIN website.

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REFERENCES

Allen WTR. 1977. Freeze-up, break-up and ice thickness in Canada. *Fisheries and Environment Canada, AES, CLI-1-77*, 185.

Anderson JC. 1987. On the use of lake ice conditions to monitor climatic change. *Canadian Climate Center Report*, 87(8), AES, 53.

Anderson WL, Robertson DM, Magnuson JJ. 1996. Evidence of recent warming and El Niño-related variationsin ice break-up of Wisconsin lakes. *Limnology and Oceanography* **41**: 815–821.

Ashton GD. 1986. *River and lake ice engineering*. Water Resources Publications: Littleton, CO; 485.

Barry RG. 1995. Observing systems and data sets related to the cryosphere in Canada: A contribution to planning for the Global Climate Observing System. *Atmosphere–Ocean* **33**: 771–807.

Brown RD. 2000. *Weekly landfast ice thickness monitoring by MSC: Methods, Challenges and Network Resolution*. Unpublished Report, Meteorological Service of Canada, 5.

Brown RD, O'Neill D. 2002. *National plan for cryospheric monitoring—A Canadian Contribution to the Global Climate Observing System*, Unpublished Manuscript, Meteorological Service of Canada, Climate Research Branch, Climate Processes and Earth Observations Division, Downsview, Ontario; 81.

CCIN, 2002. Canadian Cryospheric Information Network, http://www.ccin.ca

CRYSYS, 2002. http://www.crysys.uwaterloo.ca

Environment Canada, 2000. EMAN—What it is, how it works and why we need it… What do we expect of the Network?, http://www.eman-rese.ca/eman/program/vision/part5-e.html

Environment Canada, 1995. The state of Canada's climate: Monitoring variability and change, *A State of the Environment Report* **95**: 19–30.

Flato GM, Brown RD. 1996. Variability and climate sensitivity of landfast arctic sea ice. *Journal of Geophysical Research–Ocean* **101**(C10): 25767–25777.

Goodison BE, Brown RD, Brugman MM, Duguay CR, Flato GM, LeDrew EF, Walker AE. 1999. CRYSYS—Use of cryospheric system to monitor global change in Canada: Overview and Progress. *Canadian Journal of Remote Sensing* **25**: 3–11.

Gullett D, Skinner W, Vincent L. 1992. Development of a historical Canadian climate database for temperature and other climate elements. *Climatological Bulletin* **26**: 125–131.

IceWatch, 2002. http://www.cnf.ca/icewatch/

Magnuson JJ, Robertson DM, Benson BJ, Wynne RH, Livingstone DM, Arai T, Assel RA, Barry RG, Card V, Kuusisto E, Granin NG, Prowse TD, Stewart KM, Vuglinski VS. 2000. Historical trends in lake and river ice cover in the Northern Hemisphere. *Science* **289**: 1743–1746.

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

Robertson DM, Ragotzkie RA, Magnuson JJ. 1992. Lake ice records used to detect historical and future climatic changes. *Climatic Change* **21**: 407–427.

Skinner WR. 1992. Lake ice conditions as a cryospheric indicator for detecting climate variability in Canada. *Canadian Climate Centre Report No. 92-4*, Atmospheric Environment Service, Downsview, Ontario, 46.

SOCC, 2002. State of the Canadian Cryosphere Website, http://www.socc.uwaterloo.ca/

Walker AE, Davey MR. 1993. Observation of Great Slave Lake ice freeze-up and break-up processes using passive microwave satellite data. *Proceedings of the 16th Canadian Symposium on Remote Sensing*, Canadian Remote Sensing Society, 233–238.

World Meteorological Organization, 2001. Global Climate Observing System (GCOS) Home Page, http://www.wmo.ch/web/gcos/gcoshome.html