1. Introduction

CRYSYS (**CRY**ospheric **SYS**tem in Canada) is a Canadian-led Interdisciplinary Science Investigation (IDS) in the NASA Earth Observing System (EOS) Program. The main goals of CRYSYS are to develop capabilities for monitoring and understanding regional and larger scale variations in cryospheric variables of importance to Canada (sea ice, snow cover, freshwater ice, glaciers and ice caps, frozen ground/permafrost), and to improve understanding of the role of the cryosphere in the climate system. CRYSYS is also promoting the assembly, maintenance and analysis of key historical, operational and research cryospheric data sets to support climate monitoring and model validation.

CRYSYS is organized as a collaborative research project, and currently involves over 30 researchers from 14 universities, 6 federal research groups, and the private sector. A map of the current geographical extent of the CRYSYS network is shown in **Figure 1**. CRYSYS has been hosted and funded by the Meteorological Service of Canada since 1993. The Canadian Space Agency (CSA) plays an important role in CRYSYS since it became a major funding partner in 2000. The CSA aims to develop, demonstrate, and validate on an operational basis the use of EO data acquired from space to generate products for the assessment and monitoring of the cryosphere. This, in turn, will enable environmental prediction, ecosystem processes and the interaction between the changing climate and the cryosphere, in Canada and globally. This requires data from many different satellite sensors capable of providing a wide range of temporal and spatial resolutions, and includes further development of SAR capabilities using RADARSAT-1 and –2 for cryospheric science and operations.

The CRYSYS program develops and strengthens scientific partnerships between government departments, the Canadian Space Agency (CSA) and universities, and ensures that Canadian scientists and agencies maintain leadership, competence and visibility in the development of applications of space-based systems for studying the cryosphere and its response to climate change. This project and its extensive network of scientists will provide the Canadian Space Agency (CSA) and the technology sector a strong linkage to international missions where Canada can make a strong contribution to both the space segment and science component.

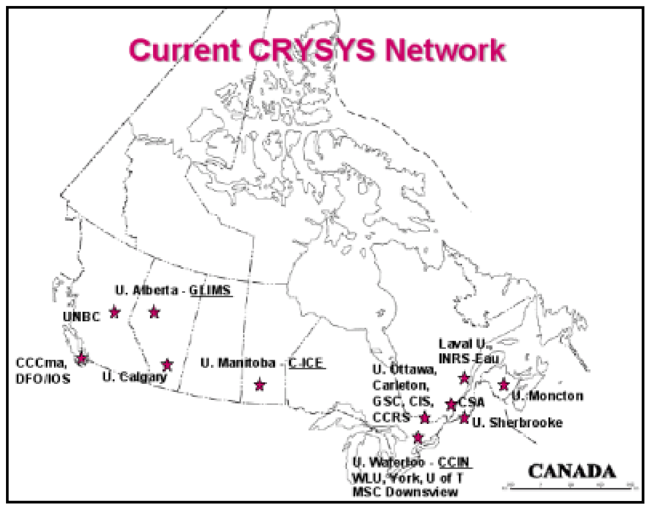


Figure 1: Geographical distribution of CRYSYS team members and partners.

The results of this project will provide timely and consistent information of cryospheric components that will allow regional and national planning and strategic decision making for environmental prediction, disaster management, and mitigation.

The purpose of this mini CD is to provide a quick overview of the key research activities being carried out by CRYSYS team members, and the cryosphere information provided through the CRYSYS-initiated "State of the Canadian Cryosphere" and "Canadian Cryospheric Information Network (CCIN)".

Definition of Cryosphere

The term "cryosphere" traces its origins to the Greek word “kruos” for frost. It is the portion of the climate system that consists of snow and ice deposits including ice sheets, ice caps, glaciers, sea ice, seasonal or permanent snow cover, lake and river ice, permafrost and frozen ground.

The cryosphere plays an important role in the climate system through linkages and feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, and atmospheric and oceanic circulation (**Figure 2**). Through these feedback processes, the cryosphere plays a significant role in global climate, and in climate model response to global change.

One of the most important feedback processes involving the cryosphere-climate system is the snow/ice-albedo feedback. Snow and ice have a much higher surface reflectivity (albedo) than most other natural surfaces (70-90% versus 15-20%), so changes in the area of snow and ice on the planet exert a positive feedback to Earth’s energy balance. For example, as the area of snow and ice decreases in response to an initial warming, more incoming solar radiation is absorbed which results in warmer temperatures (and vice versa). This feedback is involved in the large seasonal variation in snow and sea ice extent over the Northern Hemisphere (**Figure 3**).

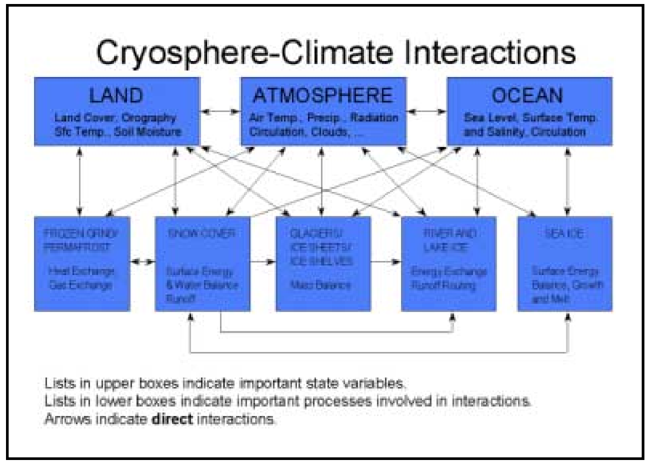


Figure 2: Schematic diagram outlining a number of the important interactions between the cryosphere and other major components of the climate system. ***Source:*** G. Flato, EOS Science Plan, 1999.t

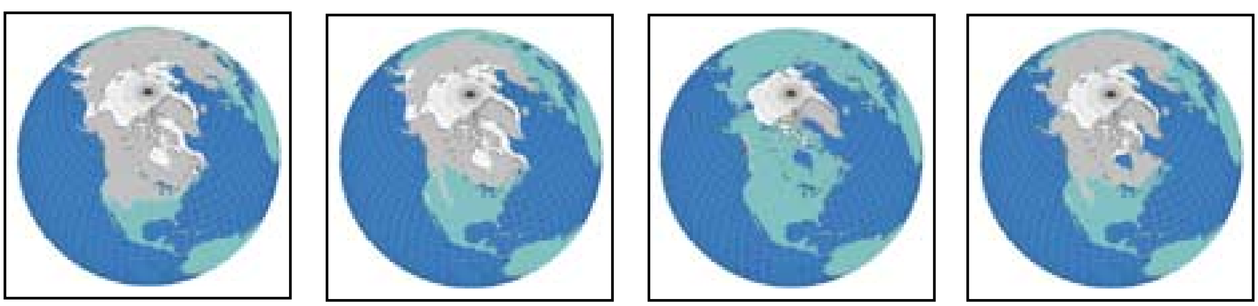


Figure 3: Mean monthly variation in snow cover (grey) and sea ice extent (white) over the Northern Hemisphere for the period 1978-1995. The animation loops from January to December, and is derived from the Northern Hemisphere EASE-Grid Weekly Snow Cover and Sea Ice Extent dataset compiled by the National Snow and Ice Data Center. ***Source:*** R. Brown, MSC/CCRP.

Cryosphere in Canada

In Canada, the cryosphere is one of the most important features of the physical and biological environment: most regions of Canada experience at least three months of snow cover each winter (**Figure 4**); nearly all Canadian navigable waters (with the exception of the west coast) are affected by an ice cover for some period during the winter (**Figure 5**); more than half of the country is covered by the permafrost zone (**Figure 6**); most of the territory experiences frozen ground, and Canadian terrestrial ice masses constitute the most extensive permanent ice cover in the Northern Hemisphere outside of Greenland.

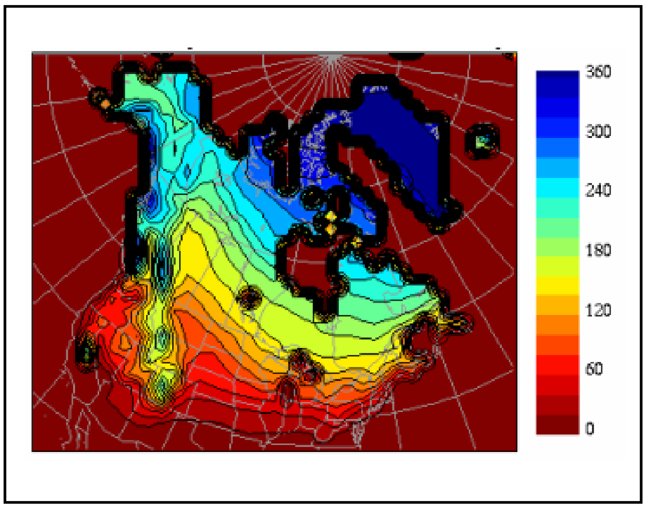


Figure 4: Mean annual duration of snow cover (days) over the 1972-94 period, as computed from satellite-derived maps of weekly snow cover extent. ***Source:*** R. Brown, MSC/CCRP (data supplied by D. Robinson, Rutgers University).

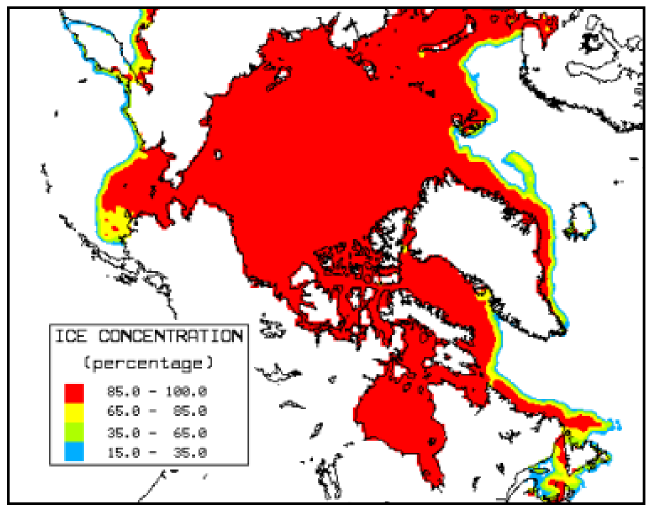


Figure 5: Mean sea ice concentration for March (month of maximum sea ice extent) derived from passive microwave satellite data over the period 1979 to 1996. ***Source:*** T. Agnew, MSC/CCRP.

Cryosphere in Canada

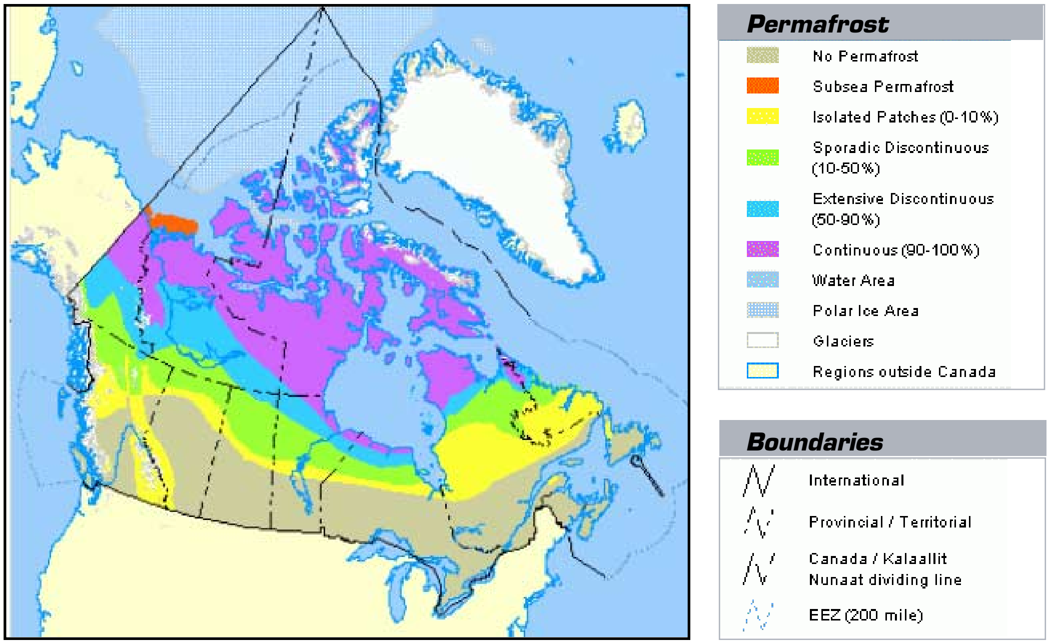


Figure 6: Canadian permafrost distribution.
Source: National Atlas of Canada, © 2002 Government of Canada with permission from Natural Resources

Importance of the Cryosphere in Canada

Canada is a cold climate country, and snow and ice are a fact of life for the majority of Canadians. Ecosystems, economy, and lifestyles are adapted to a cold winter climate and changes in winter climate will have significant impacts. For example, snow represents a significant resource for recreation, agriculture and hydro-power, and many plant and animal species depend on an adequate winter snow cover for survival. The extent, type (first-year, multi-year) and thickness of sea ice have important implications for marine transportation, marine ecology, native hunting, and ocean circulation. The duration and characteristics (thickness, temperature, white ice fraction) of lake ice cover exert an important control on the amount of light and energy received by lake ecosystems, and is also important for northern transportation (ice roads). Glaciers are important resources for tourism, summer water flow, and are implicated in recent sea level rise. The distribution of permafrost and its properties (thickness, temperature and active layer depth) are important for northern engineering, hydrology (run-off), and for chemical and gas exchanges to air and water.

Implications of Climate Change

A large area of the Canadian cryosphere exists at a temperature close to melting and is therefore highly sensitive to changes in temperature. Global climate model (GCM) climate simulations for doubled-C02 conditions consistently show enhanced warming over high latitudes, with winter temperature increases of as much as 5-10ºC. This warming is expected to be associated with profound changes in snow, ice and permafrost conditions across Canada. Historical records show that the Mackenzie Valley area has already warmed 1.5°C over the past 100 years (most of this in the winter and spring) and the effects of this warming can already be seen in a marked reduction of spring snow cover. Deepening of the active layer and increased frequency of active layer setachment slides have also been observed in the last decade. The impacts of warming on the cryosphere are widespread and cut across the physical environment, natural ecosystems and socio-economic systems. A review of potential impacts of climate change in various regions of Canada is presented in the Canada Country Study and in Climate Change Impacts Posters for Canada. Some of the key issues a changing cryosphere raises for Canada are highlighted below:

Implications of Climate Change : Glacier

Mountain glaciers represent a major store of water for maintaining water flows in rivers during the summer period of maximum water demand, and glacier melt water is a key factor in maintaining the cool water temperatures preferred by sport fish such as salmon and trout. CRYSYS-supported research at Wilfrid Laurier University revealed that glacier contributions to summer flow of the Bow River near Banff exceeded 50% in extreme low flow years. Current evidence shows that glaciers in western Canada are losing mass at an increasing rate, which has important implications for water supply, hydro-power generation and river ecosystems. The water supply issue will be particularly sensitive for rivers such as the Columbia, which flow into the United States.

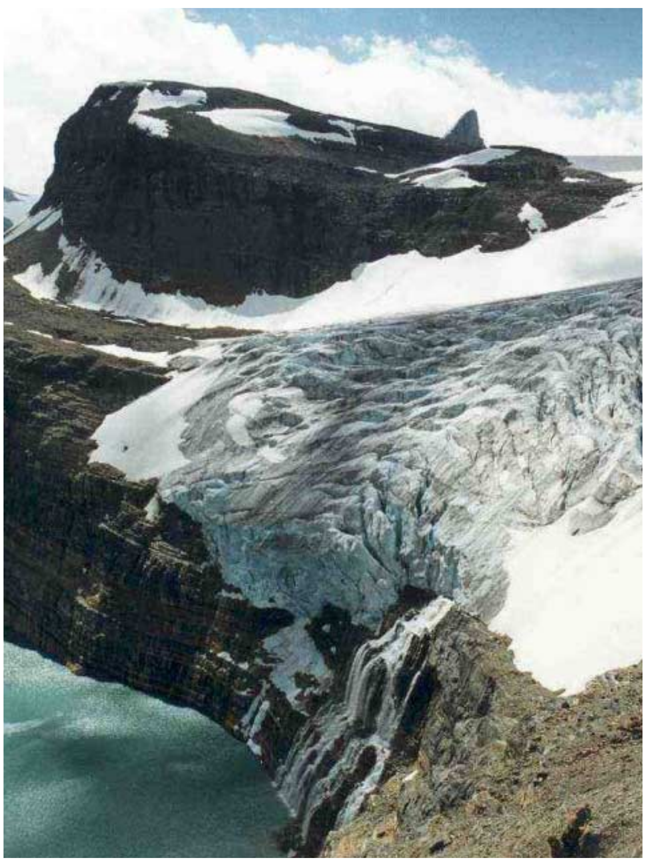


Figure 7: Bow Glacier, Canadian Rockies, Alberta.
Source: Chris Hopkinson.

Glacier melt is also a contributor to global sea level rise, and recent estimates suggest that large glaciers of Alaska and adjacent Canada are currently contributing to approximately half of the rate of global ice loss, exclusive of Greenland and Antarctic ice sheets. CRYSYS-supported research at the University of Alberta under the GLIMS project (Global Land Ice Measurement from Space) recently identified a total of 56 surge-type glaciers in the Canadian Arctic of which only 4 had previously been described in the literature. Since many of these surge-type glaciers terminate in the ocean and mass loss from iceberg calving increases dramatically during periods of surge, changes in the number of actively surging glaciers from year-to-year may have significant implications for the calculation of the contribution of Canadian Arctic glaciers to global sea level change.

Implications of Climate Change : Snow

A shorter snow accumulation season, earlier spring runoff and increased potential for soil evaporation will pose additional constraints on water resource management systems for agriculture and hydro-power. The Prairie region of Canada is particularly sensitive to changes in the snow cover, because much of the agriculture is dependent on winter snow to replenish soil moisture in the spring and fill storage reservoirs for the summer period. Hydro-electricity generation is also sensitive to changes in the amount of water stored in the snow pack and the timing of snowmelt. These changes will be of particular significance for Canada where hydro-electricity is the dominant source of electricity, representing nearly two-thirds of total generation.

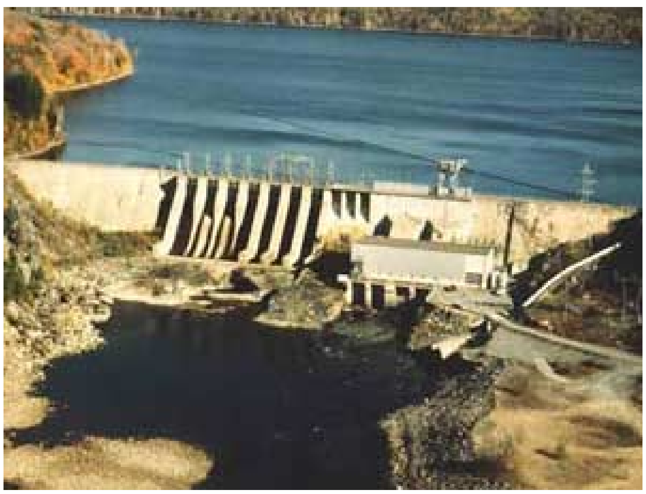


Figure 8: Red Rock Falls hydroelectric generating station, Mississagi River, Ontario. ***Source:*** Ontario Hydro (Copyright © 2002 Ontario Power Generation Inc., all rights reserved).

A reduction in snow cover also has major impacts for ecosystems. It reduces thermal protection for vegetation and animals, increases risk of frost penetration and root damage, and changes in habitat and species range. The latter is of particular significance to native communities who rely on hunting for a large part of their food supply. The ground thermal regime (e.g. frost penetration, permafrost temperature, active layer conditions) is also sensitive to snow cover properties such as depth, density, and duration

Implications of Climate Change : Permafrost

Changes in permafrost conditions associated with warming have important implications for northern infrastructure performance and maintenance (e.g. transportation, construction, resource development, water and sewage repair) and security (increased risk of terrain, slope and coastal stability). The Geological Survey of Canada (GSC), a CRYSYS partner, has developed a series of maps documenting the sensitivity of permafrost to warming. **Figure 8** shows the physical sensitivity of permafrost to warming i.e. the effect of thawing on ground stability. The ice content of frozen material is the key factor determining physical response and approximately 13% of the permafrost area was considered to have a high response potential.

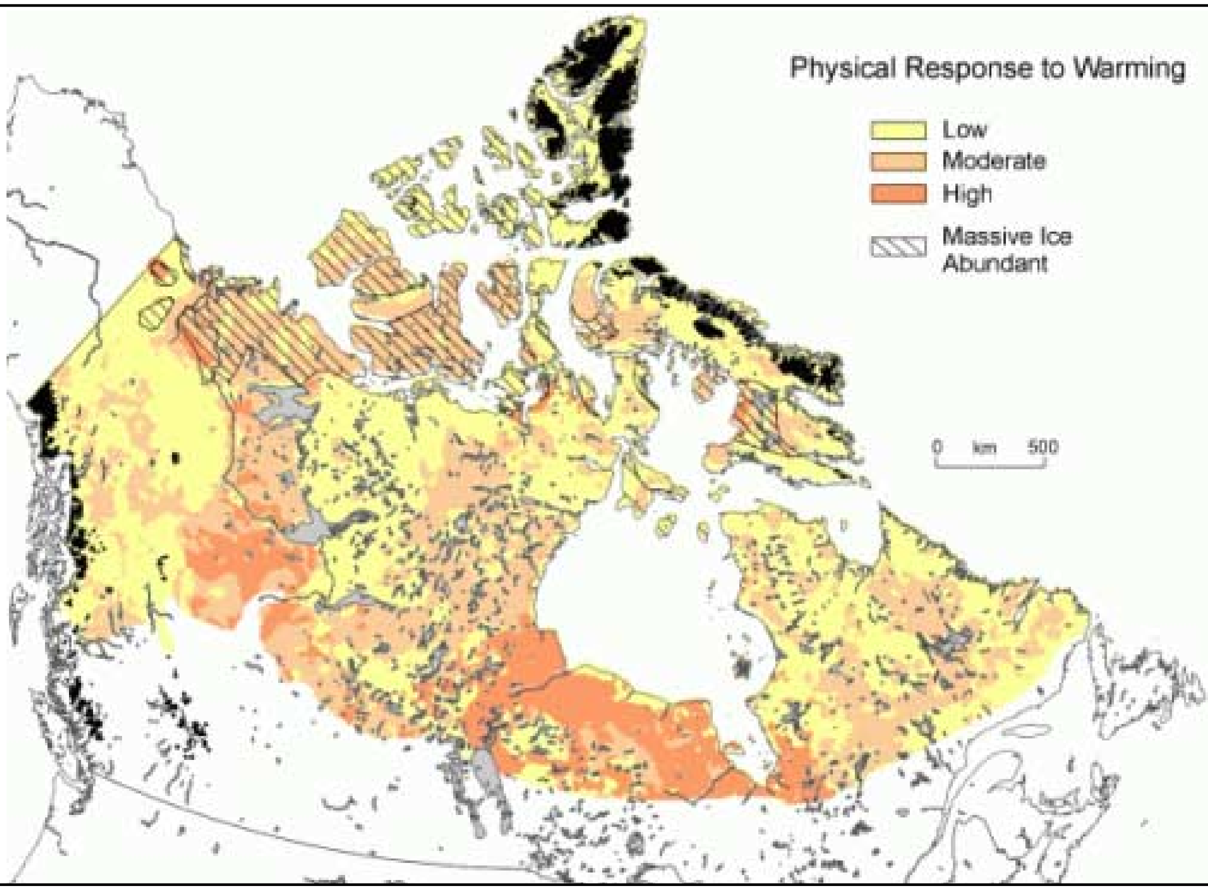


Figure 9: The relative physical response of permafrost to climate warming (from Smith and Burgess, 1998). Thaw subsidence will be greatest where ice-rich sediments are present. The structural ice content (pore ice and ice lenses) will generally be higher in fine-grained and organic material. In areas where massive ice is abundant the consequences of permafrost thaw could be more severe than indicated by the shading which reflects the structural ice content of the surficial material. ***Source***: Sharon Smith, GSC.

Implications of Climate Change : Sea Ice

Climate warming scenarios suggest an extensive reduction in sea ice extent in Canadian waters and the potential for increased shipping activity in Arctic waters. The possibility of year-round shipping though the Northwest Passage offers huge cost savings. However, this also greatly increases the risk of disturbance to the ecosystem. Another concern is that during the initial warming response of the Arctic, a reduction of first-year ice and major ice plugs blocking the western entrances to the Arctic Archipelago will result in an increased risk of shipping encountering more dangerous multi-year ice. Changes in sea ice climate will also have an impact on coastal (e.g. through increased risk of coastal wave erosion) and marine ecosystems and the habitat of the marine mammals that are important food sources for northern communities. Changes in the coastal fast ice regime also have safety implications, as they are major transportation corridors for native communities.

Figure 10: CCGS Louis St. Laurent in decayed ice.
Source: K. Wilson, CIS.

Implications of Climate Change : Lake and River Ice

Climate warming will be associated with major reductions in the duration and thickness of ice on lakes and rivers in Canada. There is already evidence of a consistent trend to later freeze-up and earlier break-up at many lake and river ice sites in the Northern Hemisphere. Reductions in lake ice cover and thickness have major implications for lake ecology, winter transportation and safety. Laval University, with support from CRYSYS, has implemented a national lake ice database for Canada that includes freeze-up, break-up, thickness, snow cover, and lake dimension information. This database is being used to study regional trends in lake ice conditions in Canada, and to provide validation data for lake ice models and satellite-based lake ice monitoring.

Figure 11: Melting lake ice cover on shallow lakes near Churchill, Manitoba. ***Source:*** C. Duguay, Laval U.

Implications of Climate Change

Cryospheric Response to Warming – Summer of 1998 Case Study

The warming response of the cryosphere is considerably more complex than a uniform retreat. There are numerous interdependencies, linkages and feedbacks involved, as well as processes operating over different time-scales. The CRYSYS team was able to investigate some of the processes and linkages in a collaborative project funded by the Climate Change Action Fund (CCAF) to examine the response of the Arctic cryosphere to the extreme warming in the summer of 1998. 1998 was the warmest year in the instrumental record for the Canadian Arctic (since ~1950), and was also the warmest year in the instrumental record for the Northern Hemisphere land area (since ~1850). The study permitted the construction of time series of climate and cryospheric variables in the Arctic for the period since 1960 (**Figure 12**) which revealed that other years had also generated a similar cryospheric response to 1998, notably 1962. Detailed examination of the different years showed that cryospheric response to warming depended strongly on preconditioning, critical events such as summer storms that broke-up multi-year sea ice plugs, and local-scale differences in the physical environment. These findings underscored the complexity of the Arctic cryospheric system, and demonstrated that warmer temperatures per se do not necessarily translate into a predictable response. The study results are summarized on the CRYSYS website and the datasets developed for the study are being consolidated at the Canadian Cryospheric Information Network.

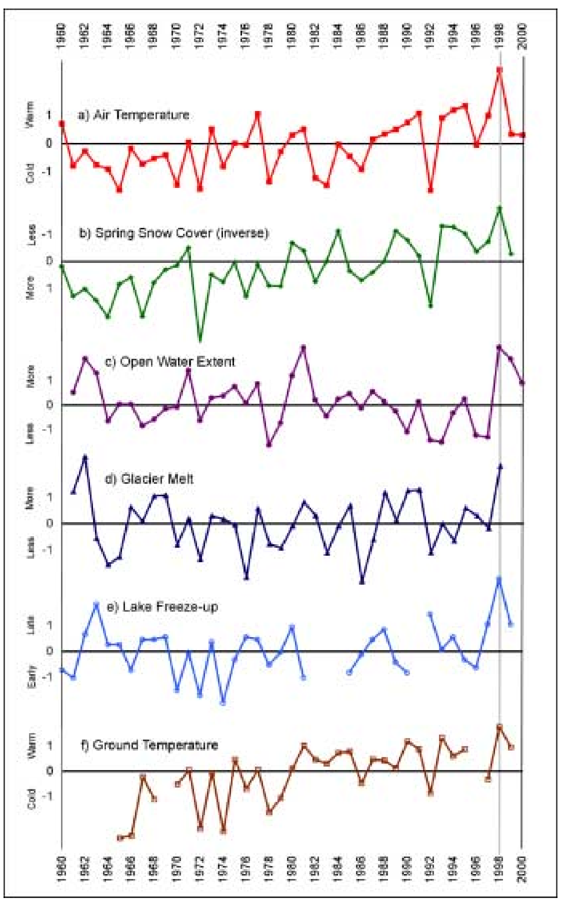


Figure 12: Variation in (a) NA Arctic May-October temperature anomalies over the 1960-2000 period and selected cryospheric time series from the Canadian Arctic: (b) spring snow cover duration at Canadian Arctic climate stations, (c) maximum open water extent in the Queen Elizabeth Islands, (d) summer melt on Devon Ice Cap, (e) date of lake freeze-up for Great Slave Lake, (f) July 100 cm ground temperature at Resolute A. All series were normalized with respect to the period 1968-1998. ***Source:*** R. Brown and B. Alt.

Snow Monitoring

One of the main goals of the CRYSYS project is to develop capabilities for improved satellite-based approaches for monitoring the cryosphere. Some of the key satellite and related integral ground-based activities are presented below. A listing of recent scientific journal publications by CRYSYS team members is included in this CD.

One of the main objectives of the CRYSYS snow research is to develop, validate and refine empirical and theoretical algorithms for snow cover properties (extent, water equivalent, wet/dry state) in varying climatic regions and landscapes of Canada, using passive and active microwave data. Since 1995, a major effort has been made to extend passive microwave SWE retrievals to the boreal forest, taiga, Arctic tundra and sea ice. Current CRYSYS-supported research at the University of Moncton is looking at the application of physically-based inversion methods such as the HUT model for estimating SWE in heavily forested areas. The University of Manitoba has developed an approach for estimating SWE over sea ice using the relationship between the SWE and brightness temperature at 37 GHz (550) H polarization as well as air temperature. A new CRYSYS-supported research project at the University of Calgary will use multiple satellite sensors (visible, passive microwave and SAR) and ground based radiometer observations to monitor and understand the rapid snow ablation that occurs over southern Alberta during Chinook events. CRYSYS team members have also been involved in validating snow products from the MODIS satellite, and will be participating in the validation of AMSR data.

On the operational side, a method for estimating SWE from RADARSAT data developed at INRS-Eau has been running operationally at Hydro Quebec since 1998/99, and the Meteorological Service of Canada has continued to refine the near real-time SSM/I-based prairie SWE product which is widely used in water resource planning and operations. The prairie SWE product is now being issued in several formats to provide users with more information on anomalous conditions. A sample product is shown in **Figure 13**.

CRYSYS also provides regularly updated information on snow cover variability and change in Canada through the State of the Canadian Cryosphere website (SOCC). A synthesis of surface-based and satellite information is provided in the SOCC feature article “Is snow cover changing in Canada?”.

Snow Monitoring

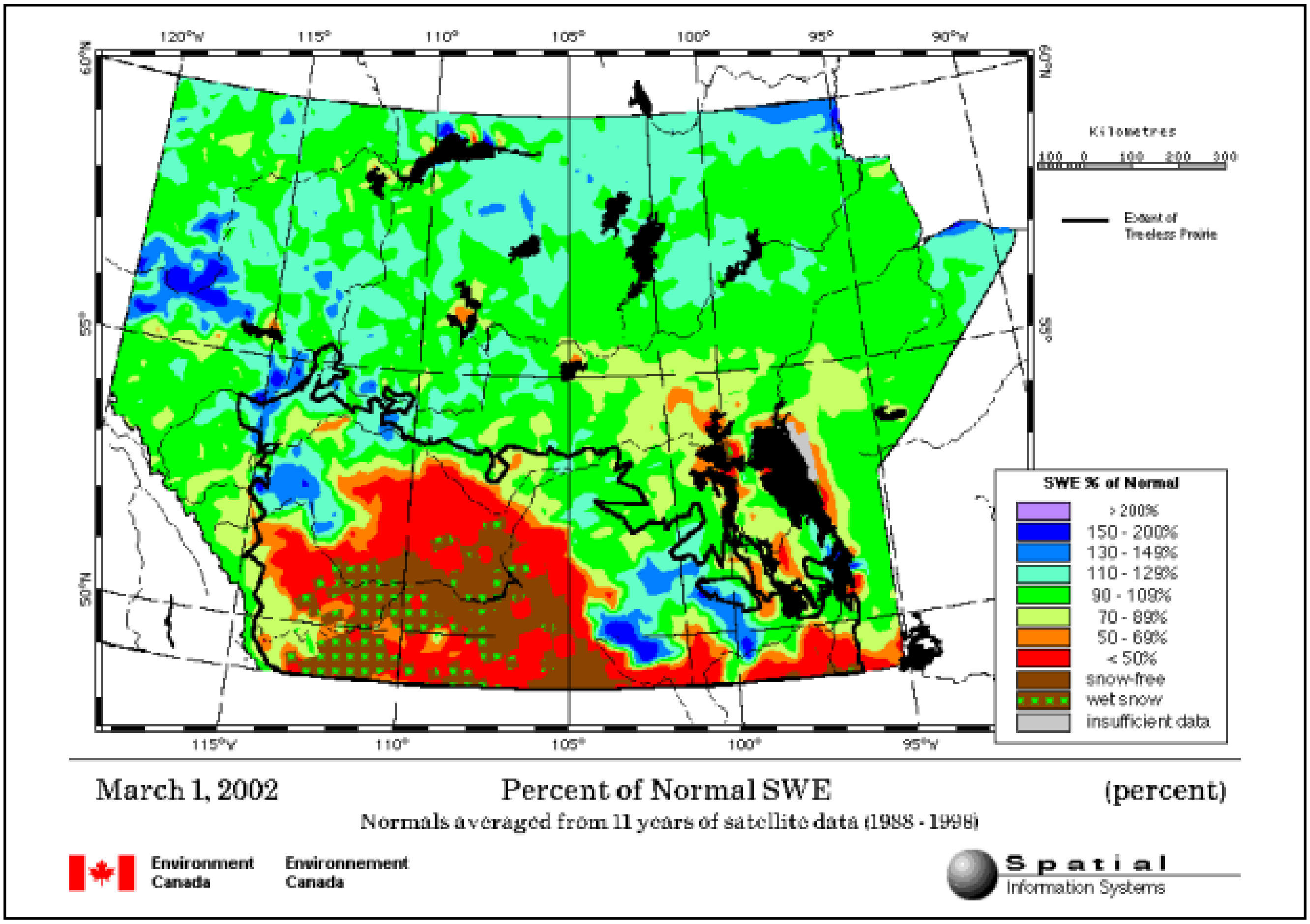


Figure 13: Snow water equivalent anomaly map (% of normal SWE) generated for the Canadian Prairie region from SSM/I passive microwave data. ***Source:*** A. Walker, MSC.

The Canadian Ice Service (CIS) is an important CRYSYS partner who is responsible for the forecasting and monitoring of sea ice conditions in Canadian waters. CIS operations are heavily based on RADARSAT data, but use is also made of other satellites (visible and passive microwave), aircraft and surface observations. CIS have active R&D activities in SAR applications (e.g. automated ice motion extraction, extraction of surface wind vectors), sea ice modeling and evaluation/validation of new sensors such as QuickSCAT, ENVISAT and multiple polarization SAR data. The CIS also provides data and support to the CRYSYS team; its digital database of weekly ice charts represents the most comprehensive sea ice data in Canadian waters for climatological and applied studies. Extensive use was made of this data in the "Summer of 1998" project discussed earlier.

The Department of Fisheries and Oceans at the Institute of Ocean Sciences (IOS) is also a federal government partner in CRYSYS and contributes data and ice-ocean modeling expertise for the Beaufort Sea region. IOS has maintained an upward looking sonar buoy program in the Beaufort Sea for ice draft (thickness) measurements since 1990; these data are extremely valuable for understanding ice dynamics and interannual variability in ice thickness and ridging.

In the university community, CRYSYS is supporting research at the University of Waterloo to develop improved automated methods for ice edge demarcation and texture classification for SAR imagery. CRYSYS is also encouraging research at the University of Manitoba to relate seasonal variation in SAR signatures to surface physical processes. The University of Manitoba maintains an important sea ice field site near Resolute (C-ICE) for the study of physical and microwave-related processes. The University of Manitoba, CIS and CRYSYS were recently part of a major collaborative international project to understand the North Open Water polynya (NOW). **Figure 14** shows ice motion vectors for the NOW region extracted from RADARSAT imagery using an automated feature tracking algorithm.

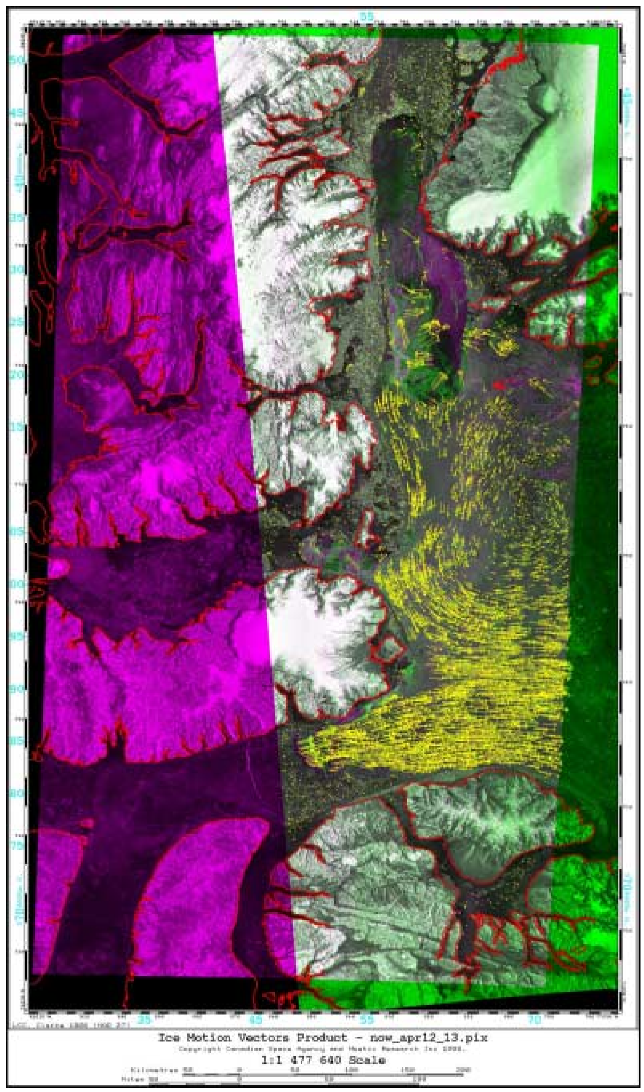
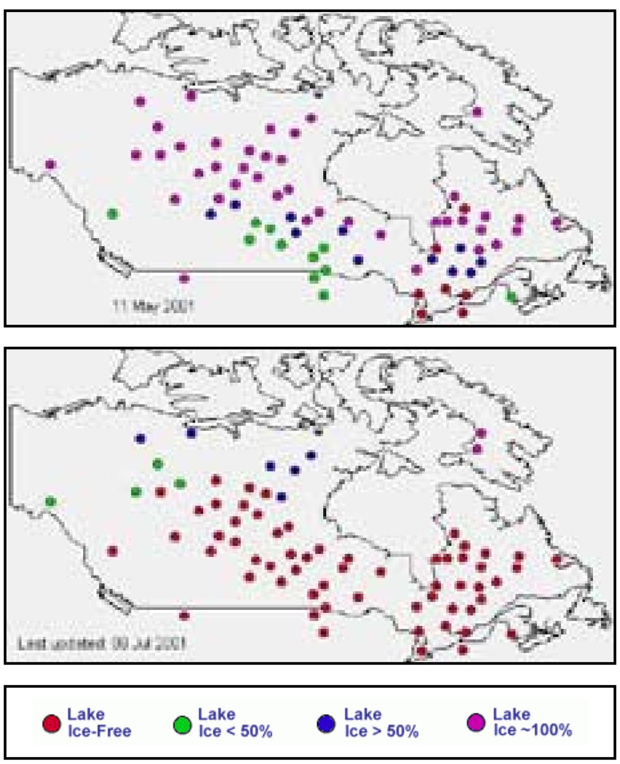


Figure 14: Example of ice motion vectors obtained in the NOW region using automated feature-tracking software with successive RADARSAT images. ***Source:*** K. Wilson, CIS.

5. Freshwater Ice Monitoring

With a rapid decline of manual observations of lake and river ice freeze-up and break-up, there has been a major push by CRYSYS team members to develop satellite-based and modeling approaches for monitoring freshwater ice conditions in Canada. Lake ice activities are being spearheaded by Laval University who is combining in situ information, satellite data and modeling into a multi-pronged strategy to place current satellite-observations of ice conditions into the context of the historical variability inferred from observed and ice models. This research has involved the construction of a national lake ice database, and the development of a thermodynamic lake ice model. Extensive research has also been carried out at Laval in the Churchill region of Manitoba on the determination of ice thickness from shallow lakes with ERS-1/2 and Landsat, and the potential and limits of RADARSAT-1 standard beam mode imagery for monitoring lake ice cover and related processes. Scientists at INRS-Eau are also investigating the utility of RADARSAT data for monitoring river ice. The Meteorological Service of Canada has an active research activity to monitor ice cover on large Canadian lakes from SSM/I passive microwave data. This information was used in the “Summer of 1998” project to document interannual variability in ice break-up over Great Slave Lake. Research is also being carried out at the National Water Research Institute (NWRI) to understand spatial and temporal patterns in freeze-up/break-up variability, and to relate these to atmospheric circulation patterns.



Since 1995, the Canadian Ice Service has been monitoring ice cover fraction on 118 lakes in North America for specification of surface boundary conditions for weather forecast models at the Canadian Meteorological Center. The monitoring is carried out on a weekly basis and uses a combination of RADARSAT data and visible imagery. A subset of this information is provided in graphical form on the “State of the Canadian Cryosphere” website; a sample animation is provided below that covers the 2001 spring break-up period.

Figure 15: Animation of lake ice clearance during the spring of 2001. ***Source:*** SOCC website (data from Canadian Ice Service).

The Geological Survey of Canada is an important CRYSYS partner who is responsible for the National Glaciology Program which includes monitoring and research activities at key reference sites in the western Cordillera and the Canadian Arctic. Glacier monitoring activities at the GSC's National Glaciology Program currently include seasonal and annual mass balance measurements at three sites in the Cordillera and six sites in the Canadian Arctic Islands. The GSN program involves extensive collaboration with university partners to carry out ground-based mass balance surveys, and contributes surface-based observations and historical data to the Canadian GLIMS Center for the Canadian High Arctic located at the University of Alberta (see below). GSC is also involved in the application of remotely sensed data to glaciers and has investigated the potential of RADARSAT data for estimating glacier mass balance. Airborne LASER Terrain Mapper (ALTM) is currently being assessed for the provision of high-resolution topographic information over an entire glacier or extensive areas of glacier cover. This detailed topographic information is necessary for geometric and radiometric correction of SAR imagery, for use in basin hydrological and mass balance models, and to assist in the validation of elevation data generated by satellite-based laser altimeters such as CryoSat (ESA) and ICESat (NASA). An example of a detailed ALTM survey for the Wapta Icefield is provided in **Figure 16**.

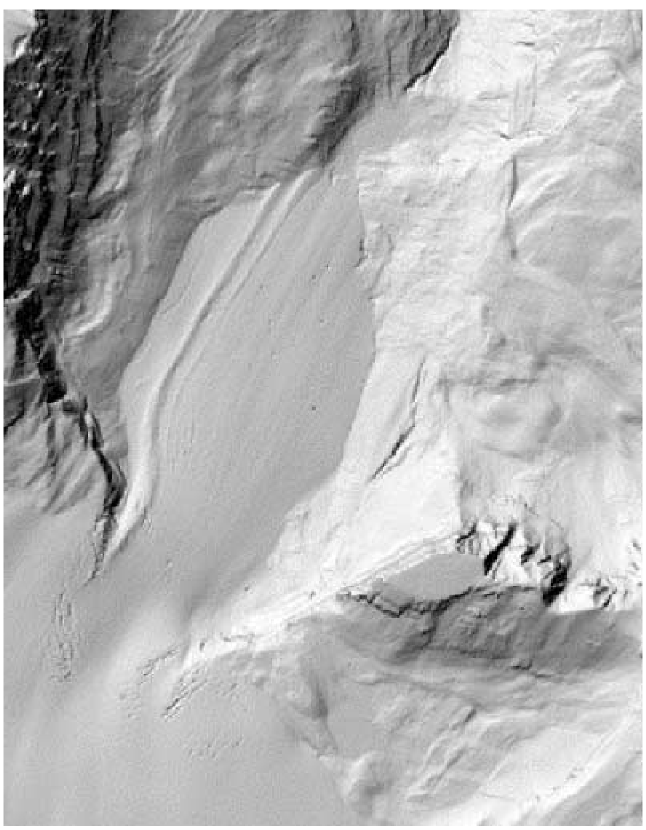


Figure 16: Portion of a shaded-relief rendering of a 2 meter-resolution (horizontal) digital elevation model derived from laser altimetry for the Wapta Icefield, Canadian Rocky Mountains. The tongue of the Peyto Glacier can be seen in the center of the image extending up towards the top-right corner.
Source: M. Demuth, GSC.

GLIMS (Global Land Ice Measurement from Space) is an international project whose aim is to develop a detailed global inventory of land ice that will provide a basis for detecting past and future climate change, and for determining the contribution of land ice to sea level rise. The GLIMS project is built on a series of distributed regional centers, and in 2000, a regional center for the Canadian High Arctic was established at the University of Alberta with funding support from the Canadian Space Agency. The main science goals of the Center are to:

> *Catalogue the present day distribution and geometry of Arctic glaciers and ice caps*
> *Carry out glacier area/volume change assessments from 1960-2000 using aerial photography obtained in 1959/60*
> *Identify surging and surge-type glaciers in Arctic Islands*
> *Remote detection of surface ice velocity fields and ice fluxes*
> *Remote detection of snow and ice properties and their seasonal evolution*

Since 2000, the GLIMS center has established a comprehensive database of present-day and historical digital imagery for all glaciated areas of the Queen Elizabeth Islands. This includes Landsat, ASTER, RADARSAT and ERS 1-2 imagery, over 10,000 digitized aerial photographs from 1959/60, and Canadian digital elevation data (CDED) with 100 m grid spacing. These data will be made available to the scientific community and a mirror archive will be established at the CCIN. Comparison of Landsat imagery with 1959/60 aerial photography has resulted in the first systematic study of the distribution of surging glaciers in the Canadian High Arctic. A total of 56 surge-type glaciers were identified of which only 4 had previously been described in the literature. SAR interferometry and image correlation have also been applied to map the surface velocity of Devon Ice Cap and velocities of 200-300 m/year were observed which is an order of magnitude higher than was previously thought. An example of a surface velocity map is provided in **Figure 17**.

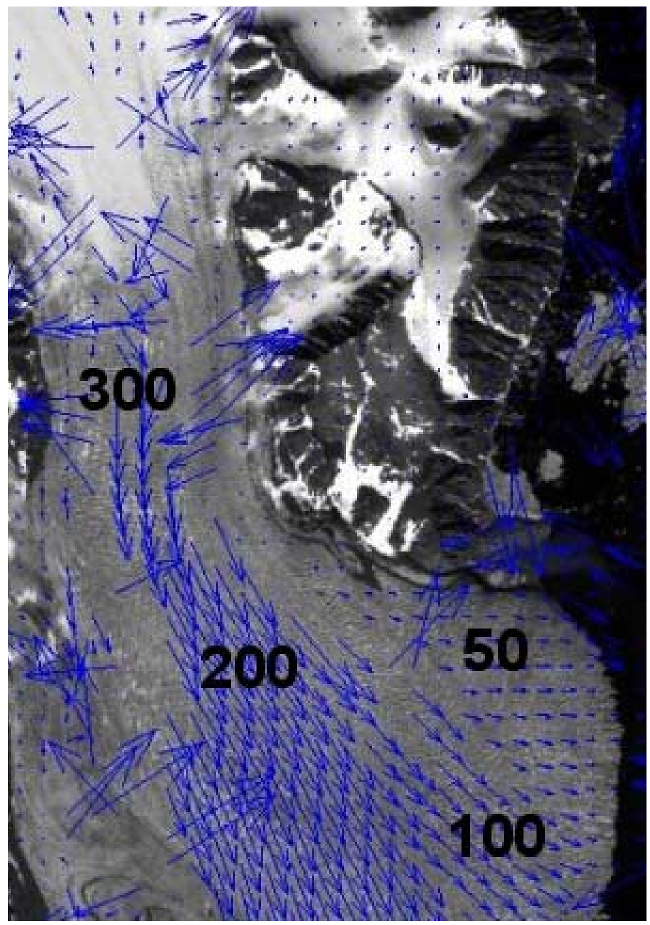


Figure 17: Estimated glacier surface ice velocities (m/yr) derived from image correlation of Landsat 7 imagery from 1999 and 2000 for an unnamed surging glacier from western Manson Icefield, to the south of Clarence Head (76 40N, 77 55W).
Source: Luke Copland, U. Alberta.

The Geological Survey of Canada is an important CRYSYS partner who is responsible for national permafrost monitoring activity in Canada. GSC is also the host agency for the Global Terrestrial Network for Permafrost (GTN-P), and along with other agencies, maintains an extensive network of sites for monitoring permafrost temperature and active layer (Figure 18). The GSC also maintains an extensive ground temperature and active layer database as well as a national database which is accessible online. NRCan has also been involved in the application of IKONOS satellite data to map and analyze changes in permafrost landscape features (e.g. permafrost affected peat lands and coasts). Satellite data products are also used in assessing, mapping, and modeling of the sensitivity of permafrost terrain to a warmer climate, at scales ranging from local to regional to national. This information and assessments are particularly important for land use planning and decision-making for the sustainability and development of northern communities.

CRYSYS is supporting research at Laval University and INRS-Eau to develop means for mapping seasonally and perennially frozen ground and associated features, thereby facilitating the assessment of future change in aerial coverage. Supporting ground truth data collection programs are underway at a number of locations to provide baseline data for developing satellite-based mapping methods and for validating and improving spatially-distributed heat transfer models. These heat transfer models are needed to investigate the effect of changes in air temperature and surface conditions on the thermal regime of the active layer and permafrost.

Multidimensional SAR configurations (i.e. multi-frequency, -temporal, -polarization, -incidence angle) are also being investigated to improve the approaches developed thus far, so that permafrost maps can be produced of other sites in the discontinuous and continuous permafrost zones of Canada. The potential of multi-temporal SAR data (ERS-1/2 and RADARSAT) for monitoring the seasonal freeze/thaw cycle of sub arctic tundra and forest is also being evaluated with the intent to incorporate freeze/thaw maps into energy and water balance models.

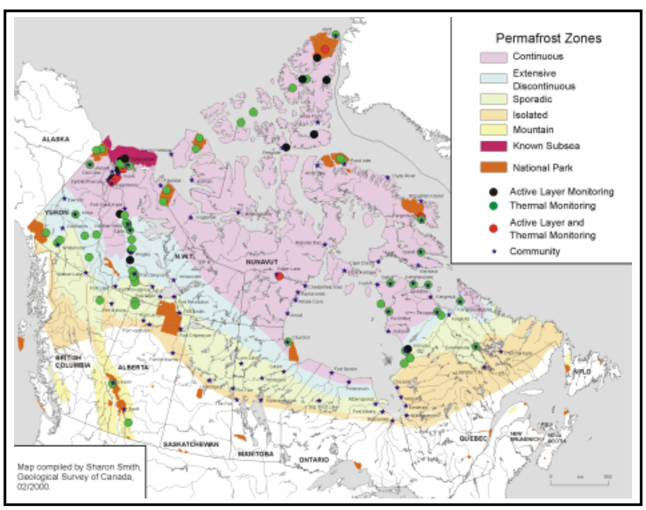


Figure 17: Existing Canadian permafrost thermal and active layer monitoring sites proposed or contributing to the GCOS/GTOS global permafrost monitoring network, the GTN-P, and active layer monitoring sites in CALM network component of the GTN-P. ***Source:*** M. Burgess.

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.

Between 1999 and 2001, members of the CRYSYS team participated in the development of a comprehensive observing strategy for cryospheric monitoring that allows Canada to meet international obligations for climate monitoring under the Global Climate Observing System (GCOS), as well as domestic needs for information on the cryosphere. The process included several workshops and extensive consultation with the Canadian cryosphere community. The main objectives of this process were to: document current observing capabilities, identify the critical gaps, examine ways to fill these gaps (e.g. remote sensing), identify problems related to data quality control and management, and finally to develop a plan of what needs to be done. The final plan and copies of the workshop reports that went into the plan are provided on the CRYSYS website at http://www.crysys.ca/science/documents/GCOS/cdn_gcos_plan_title.htm.

Some of the key recommendations contained in this report have already been implemented under the Action Plan 2000 program to improve cryospheric monitoring capability in the Canadian Arctic.

There are several approaches that can be taken to assess information on future cryospheric conditions in Canada. These include sensitivity studies, process models driven with output from global climate model simulations, and cryospheric conditions simulated by fully coupled ice-ocean-atmosphere climate models. Information from these various sources are provided on the State of the Canadian Cryosphere website under the "future conditions" selection for each component of the cryosphere. All of these methods have inherent limitations and assumptions, and some effort should be made to familiarize oneself with the literature before using the results.

In Canada, fully coupled sea-ocean-atmosphere climate model simulations are carried out by the Canadian Center for Climate Modelling and Analysis (CCCma). Results from the various scenario runs are available from their website. Higher resolution Regional Climate Model simulation results are also available at the CCCma site. Because of the relatively coarse resolution of most global models, only large-scale components of the cryosphere have been simulated to date e.g. snow cover, sea ice extent and the major ice sheets. However, with increasing resolution, GCM modelers are now beginning to include lake ice and glacier models into GCMs.

Figure 19 below presents simulations from the Canadian GCM of the change in snow cover extent over the globe between 1980 and 2050.

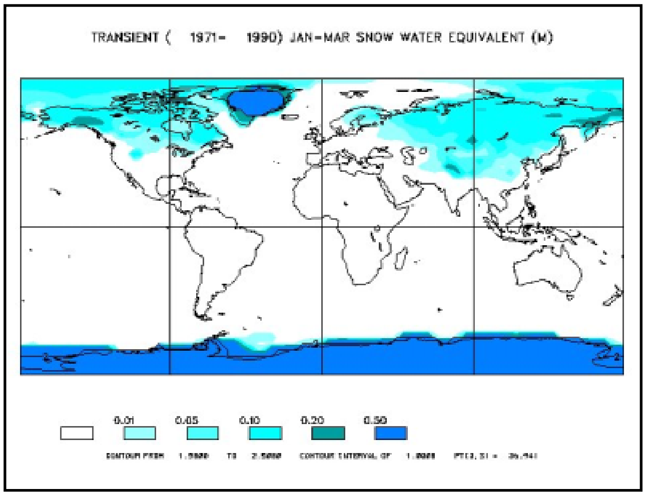


Figure 19a: Snow water equivalent (m) obtained from the CCCma Coupled Global Climate Model for March, averaged over years 1971-1990.
Source: G. Flato, CCCma.

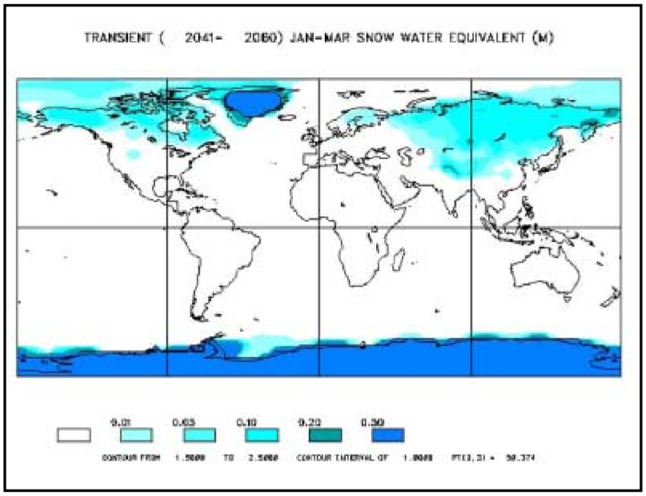


Figure 19b: Snow water equivalent (m) obtained from the CCCma Coupled Global Climate Model for March, averaged over years 2041-2060.
Source: GFlato, CCCma.

11. Canadian Cryospheric Information Network

Reliable, timely information on the state of the Canadian cryosphere is required for making operational and policy decisions at all levels of government and in the private sector, for supporting the climate research community, for ongoing development and validation of climate and hydrological models and processes, and for improved public awareness on environmental changes occurring in Canada. The data sources needed to meet these objectives include historical observations, surface-based measurement networks, dedicated field campaigns and an ever increasing amount of satellite data. In Canada, this data is dispersed across a number of administrative jurisdictions. Most of the data is in a variety of formats, yet in some cases, digital format is not available. In 1995, an independent review of Canada's ability to contribute to international efforts to monitor the cryosphere concluded that the archival situation in Canada was "desperate" (Barry, 1995).

The CRYSYS project initiated a series of feasibility studies in 1997 and 1998 to determine various options to improve the availability and access to Canadian cryospheric data. The favoured option was to establish a virtual data node to act as a central archive and distribution node for Canadian cryospheric data and information. In 1999 the University of Waterloo, in collaboration with Canadian industrial (SGI Ltd.) and private sector partners (Noetix Ltd., Compusult Ltd.), presented a proposal to MSC and the Canadian Space Agency to establish a Canadian Cryospheric Information Network (CCIN) at the University. The design of the CCIN reflects the Canadian CEONet concept of "virtual data shopping", and is built on hardware and software used by the Canadian Ice Service under the Federal Government "Geoconnections" program. CCIN supports Z39.50 query and is linked to the Canadian Ice Service and to CEONet. Current data collaborators include Environment Canada (Meteorological Service of Canada and the Canadian Ice Service), Natural Resources Canada (Geological Survey of Canada, Geomatics Canada, Polar Continental Shelf Project), Fisheries and Oceans Canada (MEDS Data Centre), and university and private holdings (e.g. University of Waterloo, McMaster University, Laval University).

Data rescue is an important activity in CCIN, and a project was completed in the spring of 2002 to rescue a large volume of meteorological observations from the Queen Elizabeth Islands that were stored on decaying 9-track tape. Public outreach is also a major objective of CCIN reflecting the increasing demand for government on-line. This will be delivered through the companion "State of the Canadian Cryosphere" (SOCC) website which is designed to provide Canadians with a concise overview of what is happening to snow and ice in Canada. Efforts are currently in progress to implement a number of tools that will permit near real-time display and analysis of Canadian cryospheric data archived at CCIN through the SOCC website.

To consult the CCIN website, please click here.

12. Science Linkages

The CRYSYS project has extensive linkages to national and international science project through the activities of team members. A list of the some of the important linkages are provided below:

AMIP II

The **Atmospheric Model Intercomparison Project** (AMIP) is a standard experimental protocol for evaluating the performance of global atmospheric general circulation models (AGCMs). Virtually the entire international climate modeling community has participated in this project since its inception in 1990. CRYSYS is participating in AMIP through the Canadian AGCM and through a project to develop snow validation data for AMIP from spatial analysis of snow depth observations over North America.

BERMS

The **Boreal Ecosystem Research and Monitoring Sites** project is a joint initiative of Canadian government agencies in collaboration with national and international research partners. The main objective of BERMS is to understand the role that Canadian boreal forest plays in global climate warming through the study of carbon, water and energy cycles. BERMS is an extension of BOREAS (Boreal Ecosystem-Atmosphere Study) and builds on the BOREAS field infrastructure. CRYSYS has links to BERMS through the use of the data for validating satellite SWE algorithms, and through study of the role of frozen ground and snow cover on carbon fluxes.

CALM

The **Circumpolar Active Layer Monitoring** (CALM) program is designed to monitor and model changes in the thickness of the seasonal thawing (active) layer above permafrost. It currently consists of 81 research sites operated by researchers from Austria, Canada, China, Denmark/Greenland, Kazakstan, Poland/Svalbard, Russia, Sweden/Svalbard, Switzerland, and United States. Canada currently contributes a total of 20 sites to the CALM network.

CASES

The C**anadian Arctic Shelf Exchange Study** (CASES) is an international project to understand the biogeochemical and ecological consequences of sea ice variability and change on the Mackenzie Shelf. CRYSYS investigators from the University of Manitoba and DFO/IOS are participating in CASES.

C-ICE

The **Collaborative Interdisciplinary Cryospheric Experiment** (C-ICE) is a multi-disciplinary, multi-year field experiment following on from the SIMMS project (Seasonal Sea Ice Monitoring and Modeling Site) that has maintained a spring field program on sea ice near Resolute since 1990.
C-ICE incorporates many individual projects, each with autonomous goals and objectives that range from understanding the processes of sea ice ablation to ecosystem studies. C-ICE is led by the University of Manitoba and CRYSYS has supported several C-ICE projects since 1997.

CliC

The **Climate and Cryosphere** (CliC) project was established by the World Climate Research Programme in March 2000 to study important cold region processes globally. CliC addresses the entire cryosphere. CRYSYS investigators were extensively involved in the development of the CliC science and coordination plan, and the science implementation plan.

EOS

The **Earth Observing System** (EOS) is the centerpiece of NASA's Earth Science Enterprise (ESE). It consists of a science component and a data system supporting a coordinated series of polar-orbiting and low inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans. CRYSYS is an Interdisciplinary Science Investigation in the NASA/EOS program.

GEWEX/MAGS

The **Mackenzie GEWEX Study** (MAGS) is Canada's contribution to the international Global Energy and Water Cycle Experiment (GEWEX) program. The main aim of the MAGS study is to improve understanding and modelling of cold region, high latitude hydrological and meteorological processes, and the role they play in the global climate system. CRYSYS participants have important links to the MAGS study through research on cryospheric monitoring and cold-climate processes.

GTN-G

The **Global Terrestrial Observing System Glacier Network** (GTN-G) was created in 1998 to provide a basis for internationally coordinated systematic observations of glacier mass balance, from temperature and glacier dimensions. The GTN-G is managed by the World Glacier Monitoring Service (WGMS). GSC is the Canadian National Correspondent to the WGMS and reports annual mass balance data and assessments for GTN-G. Data from the CRYSYS-supported regional GLIMS center for the Canada High Arctic will also be contributed data and information to GTN-G.

GTN-P

The **Global Terrestrial Network for Permafrost** (GTN-P) was initiated by the **International Permafrost Association** (IPA) to organize and manage a global network of permafrost observatories for detecting, monitoring, and predicting climate change. The network, authorized under the Global Climate Observing System (GCOS) and its associated organizations, consists of two observational components: the active layer (the surface layer that freezes and thaws annually) and the thermal state of the underlying permafrost. The GTN-P is currently managed by the Geological Survey of Canada.

MAGICS

Mass Balance of Arctic Glaciers and Ice Sheets in relation to Climate and Sea Level Changes (MAGICS) was initiated in 1996 by the Working Group on Arctic Glaciology (WGAG) under the auspices of the International Arctic Science Committee, to facilitate a better understanding of glacier response to climate change, and to quantify the contribution of glacier ice to sea level rise. The National Glacier Program and the GLIMS regional center for the Canadian Arctic are both contributing data and information to meet MAGICS objectives.

NOW

The **International North Water Polynya Study** (NOW) is part of the International Arctic Polynya Programme (IAPP) of the Arctic Ocean Sciences Board. The research program involved a concerted effort over several years (1997-1999) to understand the functioning and importance of the North Water ecosystem. CRYSYS investigators played a major role in research activities related to sea ice cover dynamics.

SnowMIP

The main objective of the **Snow Model Intercomparison Project** (SnowMIP) is to identify the key processes and parameterizations required to simulate a snow cover under various climate conditions by undertaking a controlled intercomparison of a range of snowpack models with differing levels of complexity. CRYSYS is involved in SnowMIP through its support of the participation of the Canadian Land Surface Scheme.

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14. CRYSYS Project Team

Principal Investigator:

Dr. Barry E. Goodison	Meteorological Service of Canada

Co-Investigators: (submitted to NASA in September 1997)

Dr. David Barber	University of Manitoba
Dr. Monique Bernier	INRS-EAU, Université du Québec
Dr. Mindy Brugman	Meteorological Service of Canada
Ms. Margo Burgess	Geological Survey of Canada
Mr. Ross Brown	Meteorological Service of Canada
Mr. Mike Demuth	Geological Survey of Canada
Dr. Claude Duguay	Université Laval
Dr. Mike English	Wilfrid Laurier University
Dr. Greg Flato	Meteorological Service of Canada
Dr. Roy Koerner	Geological Survey of Canada
Dr. Ellsworth LeDrew	University of Waterloo
Mr. Terry Pultz	Canada Centre for Remote Sensing
Mr. Bruce Ramsay	Canadian Ice Service
Dr. Martin Sharp	University of Alberta
Dr. Ric Soulis	University of Waterloo
Ms. Anne Walker	Meteorological Service of Canada

Other members of the CRYSYS Network with significant research roles:

Mr. Tom Agnew	tMeteorological Service of Canada
Dr. Bea Alt	Balanced Environments Associates
Dr. Chris Burn	Carleton University
Mr. Tom Carrieres	Canadian Ice Service
Dr. David Clausi	University of Waterloo
Dr. Chris Derksen	Meteorological Service of Canada
Dr. Steven Fassnacht	University of Waterloo
Dr. Kalifa Goita	University of Sherbrooke
Mr. Tom Hirose	Noetix Research Inc.
Dr. Antoni Lewkowicz	University of Ottawa
Dr. Humfrey Melling	Department of Fisheries and Oceans (IOS)
Dr. Dan Moore	University of British Columbia
Dr. Scott Munro	University of Toronto
Dr. Joe Piwowar	University of Waterloo
Dr. Terry Prowse	National Hydrology Research Institute
Dr. Alain Royer	University of Sherbrooke
Dr. Sharon Smith	Geological Survey of Canada
Dr. Roger Wheate	University of Northern B.C.
Ms. Katherine Wilson	Canadian Ice Service
Dr. Hok Woo	McMaster University
Dr. John Yackel	University of Calgary

1. Snow:

Meteorological Service of Canada
(national snow observing programs, snow water equivalent maps for the Canadian prairies, surface and airborne radiometers, snow cover variability)

Ms. Anne Walker
Climate Processes and Earth Observation Division
Meteorological Service of Canada
4905 Dufferin Street
Downsview, Ontario
CANADA
M3H 5T4

Tel. (416) 739-4357
E-mail: anne.walker@ec.gc.ca

INRS-Eau:
(satellite snow mapping, snow field studies, snow modelling)

Dr. Monique Bernier
INRS-Eau
2800, rue Einstein, suite 105
Case postale 7500
Sainte-Foy, Québec
CANADA
G1V 4C7

Tel. 418) 654-2585,
E-mail: Monique_Bernier@inrs-eau.uquebec.ca

University of Manitoba:
(remote sensing and modelling of snow on sea ice, snow and Arctic ecosystems)

Dr. David G. Barber
Director, Centre for Earth Observation Science
University of Manitoba
Winnipeg, Manitoba
CANADA
R3T 2N2

Tel. (204) 474-6981
E-mail:dbarber@Ms.UManitoba.CA

2. Sea ice:

Canadian Ice Service:
(national sea ice forecasting program, Canadian sea ice databases, satellite applications, sea ice modelling)

RADARSAT - Mr. Dean Flett
Satellite Applications - Ms. Katherine Wilson
Sea ice Modelling – Mr. Tom Carrieres

373 Sussex Drive
Block E, Third Floor
Ottawa, Ontario
K1A 0H3
Canada

Tel. (613) 996-1550
E-mail: cis.client@ec.gc.ca
URL: www.cis.ec.gc.ca

University of Manitoba:
(remote sensing and modelling of sea ice processes; sea ice and Arctic ecology, North Open Water project, CASES project, C-ICE field program)

Dr. David G. Barber
Director, Centre for Earth Observation Science
University of Manitoba
Winnipeg, Manitoba
CANADA
R3T 2N2

Tel. (204) 474-6981
E-mail: dbarber@Ms.UManitoba.CA

3. Freshwater Ice:

National Hydrology Research Institute:
(river ice freeze-up and break-up, large scale climatic controls of river ice break-up, hydrological processes of ice covered rivers, ice jam flooding)

Dr. Terry D. Prowse
Project Chief & Senior Research Scientist
National Water Research Institute at NHRC
11 Innovation Blvd.
Saskatoon, Saskatchewan
CANADA
S7N 3H5

Tel.(306) 975-5737
E-mail: Terry.Prowse@ec.gc.ca

Laval University:
(Canadian national lake ice database, remote sen sing and modelling of lake ice, lake ice field studies)

Dr. Claude R. Duguay
Laval University
Laboratoire de télédétection et de modélisation
des environnements froids,
Département de géographie &
Centre d'études nordiques
Université Laval
Québec, Quebec
G1K 7P4 Canada

Tel. (418) 656-2131, Ext. 3461
E-mail: claude.duguay@ggr.ulaval.ca

4. Glacier and Ice Caps:

National Glaciology Program:
(national mass balance network, Canadian correspondent to the World Glacier Monitoring Service, RADARSAT and laser altimetry applications for glacier mapping, glacier hydrology, investigation of past climate variations from ice cores)

Mr. Michael N. Demuth
Glaciologist-Snow and Ice Specialist
Geological Survey of Canada
Terrain Sciences Division
601 Booth Street
Ottawa, Ontario
K1A 0E8
CANADA

Tel: (613) 996 0235
E-mail: mdemuth@nrcan.gc.ca

GLIMS Regional Centre for the Canadian High Arctic:
(satellite-based inventory of Canadian Arctic Glaciers as part of the Global Land Ice Monitoring from Space program, SAR interferometry, glacier mass balance modelling, field observations and process studies, GPR surveying, glacier hydrology, glacier- response to atmospheric circulation patterns)

Dr. Martin J. Sharp
Department of Earth and Atmospheric Sciences
University of Alberta
Edmonton, Alberta
T6G 2E3

Tel: (780) 492-4156
E-mail: Martin.Sharp@ualberta.ca

5. Permafrost and Frozen Ground:

National Permafrost Monitoring Program:
(borehole and active layer monitoring networks national and international permafrost databases, permafrost sensitivity studies, application of remote sensing for mapping permafrost response to warming, Canadian correspondent to International Permafrost Association)

Ms. Margo Burgess and Dr. Sharon Smith
Terrain Sciences Division
Geological Survey of Canada
601 Booth St.
Ottawa, Ontario
CANADA
K1A 0E8

Tel. (613) 996-9317 / (613) 947-7066
E-mail: mburgess@nrcan.gc.ca / ssmith@nrcan.gc.ca
URL: http://sts.gsc.nrcan.gc.ca/permafrost/

Laval University:
(remote sensing application for frozen ground mapping)

Dr. Claude R. Duguay
Laval University
Laboratoire de télédétection et de modélisation
des environnements froids,
Département de géographie &
Centre d'études nordiques
Université Laval
Québec, Quebec
CANADA
G1K 7P4

Tel. (418) 656-2131, Ext. 3461
E-mail: claude.duguay@ggr.ulaval.ca

6. Canadian Cryospheric Information Network:

Portal for Canadian cryospheric data, cryospheric data rescue, information on variability and change in cryospheric conditions in Canada.

Dr. Ellsworth LeDrew
Faculty of Environmental Studies,
University of Waterloo
Waterloo, Ontario
CANADA
N2L 3G1

Tel.
E-mail: ells@watleo.uwaterloo.ca
URL:www.ccin.ca

7. CRYSYS Project:

Principal Investigator

Dr. Barry Goodison
Climate Processes and Earth Observation Division
Meteorological Service of Canada
4905 Dufferin Street
Downsview, Ontario
CANADA
M3H 5T4

Tel.(416) 739-4357
E-mail:barry.goodison@ec.gc.ca

CRYSYS Secretariat

Mr. Ross Brown
Meteorological Service of Canada Service
2121 Trans Canada Highway
Dorval, Quebec
CANADA
H9P 1J3

Tel. (514) 421-4772
E-mail: ross.brown@ec.gc.ca
URL: www.crysys.ca, www.socc.ca

16. List of Acronyms

ALTM	Airborne LASER Terrain Mapper
AMIP	The Atmospheric Model Intercomparison Project
AMSR	Advanced Microwave Scanning Radiometer (EOS)
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer (EOS)
BERMS	Boreal Ecosystem Research and Monitoring Sites
CALM	Circumpolar Active Layer Monitoring
CASES	Canadian Arctic Shelf Exchange Study
CCAF	Climate Change Action Fund
CCCma	Canadian Centre for Climate Modelling and Analysis (MSC)
CCIN	Canadian Cryospheric Information Network
CCRP	Climate Processes and Earth Observation Division (MSC)
CCRS	Canadian Centre for Remote Sensing (NRCan)
CEONet	Canadian Earth Observation Network (now "GeoConnections")
C-ICE	Collaborative Interdisciplinary Cryospheric Experiment
CIS	Canadian Ice Service (MSC)
CliC	Climate and Cryosphere Program (WCRP)
CryoSat	Cryosphere Satellite (ESA)
CRYSYS	Cryospheric System in Canada (www.crysys.ca)
CSA	Canadian Space Agency
DFO	Department of Fisheries and Oceans
EASE-Grid	Equal-Area Scalable Earth Grid
EC	Environment Canada
ENVISAT	Environmental Satellite (ESA)
EOS	Earth Observing System (NASA)
ERS 1-2	European Remote-Sensing Satellite (SAR)
ESA	European Space Agency
GCOS	Global Climate Observing System
GCM	Global Climate Model / General Circulation Model
GEWEX	Global Energy and Water Cycle Experiment (WCRP)
GLIMS	Global Land Ice Measurements from Space
GSC	Geological Survey of Canada (NRCan)
GTN-G	Global Terrestrial Network for Glaciers (GTOS network)
GTN-P	Global Terrestrial Network for Permafrost (GTOS network)
GTOS	Global Terrestrial Observing System (of GCOS)
HUT	Helsinki University of Technology
ICESat	Ice, Cloud and land Elevation Satellite (EOS)
ICSI	International Commission on Snow and Ice
IDS	Interdisciplinary Science Project (EOS)
IOS	Institute of Ocean Sciences (DFO)
INRS-Eau	Institut national de la recherche scientifique, U. Québec.
NASA	National Aeronautics and Space Administration (U.S.)
NRCan	Natural Resources Canada
MAGICS	Mass Balance of Arctic Glaciers and Ice Sheets in relation to Climate and Sea Level Changes
MAGS	Mackenzie GEWEX Study
MODIS	Moderate-Resolution Imaging Spectroradiometer (EOS sensor)

MSC	Meteorological Service of Canada (EC)
NOW	North Water Polynya Study
NWRI	National Water Research Insititute (EC)
QuickSCAT	Quick Scatterometer (NASA)
RADARSAT	Radar Satellite (CSA)
RCM	Regional Climate Model
SAR	Synthetic Aperture Radar
SnowMIP	Snow Model Intercomparison Project (ICSI)
SOCC	State of the Canadian Cryosphere (www.socc.ca)
SSM/I	Special Sensor Microwave Imager
SWE	Snow water equivalent
WCRP	World Climate Research Programme