Chapter 2. Climate variability and change in the Canadian Eastern Subarctic IRIS region (Nunavik and Nunatsiavut)

Lead authors

Ross Brown\textsuperscript{1,2} and Mickaël Lemay\textsuperscript{3}
\textsuperscript{1}Environment Canada, \textsuperscript{2}Ouranos, \textsuperscript{3}ArcticNet, Centre d’études nordiques, Université Laval

Contributing authors


Special Acknowledgements

Ouranos played an important role in the development of this IRIS assessment by providing output from the Canadian Regional Climate Model as well as climate-related expertise to the scientists working in the diverse fields covered in the assessment. This information is an essential building block for the assessment and development of local and regional adaptation strategies. Daniel Caya in particular is acknowledged for providing detailed and constructive review comments of the draft chapter.
Key messages

* Paleoclimate reconstructions indicate the climate of the Nunavik-Nunatsiavut IRIS region has experienced a long-term cooling trend over the past approximately 3000 years, with major climate fluctuations in the Medieval Warm Period (warming) and Little Ice Age (cooling). The climate began to warm during the 20th Century with a marked warming pulse after 1993 that has triggered a rapid response in the environment, especially the cryosphere (snow and ice cover, permafrost, and glaciers). Dendroecological evidence and climate observations show evidence of long term significant increases in precipitation over the region.

* There is some uncertainty in the timing of the recent period of warming. Satellite snow cover data and vegetation monitoring suggest the climate has been changing for at least 30-40 years while air temperature observations from coastal sites show warming did not occur until 1993. These differences may reflect different climate regimes between coastal areas and inland areas and/or different response processes.

* The cryosphere (solid precipitation, snow and ice cover, glaciers and permafrost) is responding very rapidly to recent warming. Snow and ice cover are forming later and melting earlier with annual losses of snow and ice cover duration on the order of 0.5 to 1.0 days/yr. Warming of permafrost by 2°C has resulted in a dramatic increase in the number of thermokarst lakes and active layer detachments, and glaciers in the Torngat Mountains lost ~20% of their area between 2005 and 2007. Traditional knowledge indicates that these changes are outside the envelope of previous community experience.

* Climate change projections for the 2041-2070 period (compared to the 1971-2000 period) indicate warmer temperatures and increased precipitation over the region. The largest changes are projected to occur in the winter season with the spatial pattern of projected changes typically exhibiting a NW-SE gradient with the largest changes over the north-western part of Nunavik. The results suggest a shortening of the snow and ice cover season by 3-4 weeks, an increase in growing season length by 2-3 weeks with up to 50% more growing degree days, and increases in annual precipitation of 15-25% with a larger fraction of annual precipitation falling as rainfall.

* The climate of the Nunavik-Nunatsiavut IRIS region is strongly influenced by variability in atmospheric and oceanic circulation at annual to multi-decadal scales. In particular, the year-to-year variability of the climate of Nunatsiavut is closely linked to the North Atlantic Oscillation. For some variables such as local precipitation, the internal climate variability will likely dominate any climate change signal over the next 30-50 year time period.

* Reliable and sustainable environmental monitoring and prediction systems are essential to supporting decision making and adaptation in the Nunavik-Nunatsiavut IRIS region. The merging of traditional and scientific knowledge in community-based monitoring initiatives appears to be a useful framework for improved monitoring and understanding of changing environmental conditions with the relevant connections to ensure that new information is translated into enhanced safety and improved decision making.
2.1 Introduction

The purpose of this chapter is to highlight the key characteristics of the climate of Nunavik and Nunatsiavut that are important for natural systems, ecosystem services and human activities, and present scenarios of projected changes in key climate variables and indicators that may occur over the next ~50 years. Climate is the key driver of processes such as snow and ice formation, frozen ground, spring thaw, water cycling, and plant growth that define the environment and sustain ecosystem services (see examples in Table 1). In this sense, climate represents a “resource” that influences the value and the quality of the environment, but it also entails management of “risks” particularly in the context of a changing climate (“Climate as Resource, Climate as Risk”, Stehr and vonStorch 2009).

The organization of the Chapter is as follows: Section 2.2 provides an overview of the sources (and limitations) of the information available for characterizing the climate of the region and its variability and change; Section 2.3 presents a general description of the main drivers of the climate of Nunavik and Nunatsiavut with sub-sections providing more detailed information on variability and change in important components of the climate system over the period of available historical and paleoclimatic data; Section 2.4 presents a summary of the climate change projections for 2050 provided in detail in Appendix A at the end of this Chapter. The Chapter ends with a summary and conclusions in Section 2.5 that are encapsulated in the “key messages” shown above.

2.2 Climate observations and information

There are a number of challenges to characterizing the climate of Nunavik and Nunatsiavut, foremost of which is the uneven spatial and temporal coverage of climate observations. Daily climate observations of temperature

<table>
<thead>
<tr>
<th>VARIABLE/ACTIVITY</th>
<th>CLIMATE SENSITIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater Resources (Chapter 4)</td>
<td>The amount, timing, temperature and chemical and biological properties of freshwater are sensitive to air temperature and to precipitation amount and type.</td>
</tr>
<tr>
<td>Traditional Foods (Chapter 5)</td>
<td>Winter hunting activities are particularly sensitive to snow and ice conditions. A projected shortening of the ice and snow cover seasons will affect both availability and access to fresh meat.</td>
</tr>
<tr>
<td>Infrastructure (Chapter 6)</td>
<td>Projected warming and increased winter snow accumulations contribute to permafrost thawing, a deepening of the active layer, and a host of related phenomena such as active layer detachments and enhanced erosion of coastal areas, all of which pose additional challenges for northern infrastructure.</td>
</tr>
<tr>
<td>Arctic Charr (Chapter 7)</td>
<td>Fish abundance and habitat are sensitive to ice cover, water temperature and water quality.</td>
</tr>
<tr>
<td>Vegetation Dynamics (Chapter 8)</td>
<td>Warming and changes in precipitation regimes are contributing to an increase in woody vegetation and a northward and up-slope expansion of treelines.</td>
</tr>
<tr>
<td>Caribou Dynamics (Chapter 9)</td>
<td>Caribou are sensitive to ice cover (migration routes), rain-on-snow events (affect access to winter forage), summer snow cover (residual snow patches reduce insect harassment) and the timing of vegetation green-up.</td>
</tr>
</tbody>
</table>
and precipitation are available for most communities but the length and period of observations are quite variable. For example, only Kuujjuaq, Goose Bay and Cartwright have continuous daily climate data available from pre-1950 to date; many of the other stations stopped reporting in the early 1990s or started reporting in the 1980s. The climate observing network is also almost completely co-located with coastal communities and may not necessarily reflect what is going on further inland. The main locations of the climate stations used in this Chapter are Inukjuak, Kuujjuarapik, Kuujjuaq and Schefferville in Nunavik, and Goose Bay, Cartwright, Makkovik, and Nain in Nunatsiavut (for location map see Figure 1, Chapter 1).

Climate data are also subject to random and systematic errors related to observers, instrumentation, and changes in measurement site and observing procedures. For example, precipitation is one of the more difficult climate variables to measure accurately, particularly snowfall (Doesken and Judson 1997, Goodison et al. 1998), and it has much more spatial and temporal variability than air temperatures and may not be adequately sampled over a particular region of interest. This is especially true of Nunavik and Nunatsiavut where there are only a handful of stations with sufficiently long periods of record suitable for monitoring variability and change in precipitation over the past 50-60 years, and most of these are located on the coast. Major data gaps exist over Ungava Peninsula and the Torngat Mountains so not much can be said about precipitation variability and change in these regions from the historical climate data archive. Satellite data can help fill in the gaps in surface networks for some variables e.g. surface temperature (Hachem et al. 2009) and snow cover extent (Brown 2010), but the period of coverage tends to be relatively short and there are few surface observations for validating satellite products over the interior. Longer-term climate information can be inferred from environmental indicators such as the areal extent of glaciers (Section 2.3.5), permafrost conditions (e.g. active layer depth and permafrost temperature – see Section 2.3.6) and various proxy sources of climate-related information such as permafrost temperature (e.g. Chouinard et al. 2007), temperature reconstructions from tree rings (e.g. Jacoby et al. 1988), reconstruction of past climates from analysis of fossil chironomids and pollen (e.g. Kerwin et al. 2004, Fallu et al. 2005) and reconstruction of information on snow depth and water levels from dendroecological analysis of tree morphology and ice abrasion (e.g. Lavoie and Payette 1992, Bégin and Payette 1988, Lemay and Bégin 2008).

Traditional knowledge is another useful source of information for documenting anomalous events and trends, particularly ice and snow cover, that have major impacts on hunting and transportation. While this information is not quantitative, it provides a local-scale record of environmental change. For example, Elders of Quaqtaq, Umiujaq and Kuujjuaq report that since the 1980s ice forms later and melts earlier, rain is more frequent, there is less snowfall and wind patterns have changed in Hudson Bay and Hudson Strait (Tremblay et al. 2009, Clerc et al. 2011).

2.3 The climate of Nunavik and Nunatsiavut

Nunavik and Nunatsiavut are located between 55° and 63°N on the eastern margin of the North American continent (see Figure 1 in Chapter 1). The region is bounded on three sides by water bodies: Hudson Bay to the west, Hudson Strait and Ungava Bay to the north, and the Labrador Sea to the east, with a major north-south mountain chain (the Torngat Mountains with elevations of ~1500 m) in northern Nunatsiavut that acts as a barrier to Atlantic air masses moving into Nunavik. The geography of the Nunavik-Nunatsiavut IRIS region means it experiences a continental-type climate but with higher snowfall amounts than similar latitudes west of Hudson Bay (Phillips 1990). Snow and ice cover are present on average from November to May (Tables 2 and 4), and the region is affected by winter storms that follow preferred tracks up Hudson Bay to Foxe Basin, and up the Labrador Coast to Baffin Bay (Brown et al. 1986). These contribute to a dynamic coastal sea ice regime (Canadian Coast Guard,
The region is also characterized by strong northwest-southeast gradients in air temperature and precipitation (see Figure 2, p. 35, ArcticNet 2010), and strong coastal gradients in climate particularly over Nunatsiavut. Some idea of the gradient in climate is obtained by contrasting the temperature and precipitation regimes of Kuujjuaq and Nain either side of the Torngat Mountains (Figure 1).

The particular location of the Nunavik-Nunatsiavut IRIS region downstream from the North Pacific and adjacent to the North Atlantic means the climate is also influenced on time scales ranging from years to decades to centuries by modes of natural climate variability such as the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), the Pacific North-American pattern (PNA) (Leathers et al. 1991), the Atlantic Multidecadal Oscillation (AMO) (Trenberth et al. 2007) and the North Atlantic Oscillation (NAO) (Rogers and van Loon 1979). Recent studies (Sveinsson et al. 2008, Brown 2010) have shown that the influence of these modes of natural climate variability on the hydro-climate of Québec is highly dynamic in space and time with the zones of influence exhibiting strong gradients over Québec. In addition, there is evidence (Walter and Graf 2002, Yu and Zwiers 2007, Yu et al. 2007) that some of the major modes of circulation dynamically interact with each other (e.g. PDO and PNA, and AMO and NAO) which further complicates efforts to characterize and understand natural climate variability over northern Québec and Labrador.

### 2.3.1 Air temperature

Air temperature is a key climate variable in cold region climates where many processes are sensitive to changes in temperature e.g. freeze-up, spring melt, vegetation growth, ground thawing and freezing. Information on temperature variability over Nunavik and Nunatsiavut for the period of historical climate observations from the 1920s was obtained from the CRU gridded dataset of Brohan et al. (2006) for Québec and Labrador north of 55°N. The seasons are defined on the basis of the snow and ice cover (Figure 2) where fall (Oct.-Nov.) and spring (April-May) correspond to the periods of snow cover onset and snow melt. Summer (Jun.-Sept.) is usually free of snow and ice, and Winter (Dec.-Mar.) corresponds to the period with continuous snow and ice cover with the maximum snow accumulations typically occurring in March-April. It should be noted that the climate station data used in the CRU gridded dataset is biased to coastal locations, and there are larger uncertainties in regionally-average temperature series derived from the CRU dataset before
~1950 when there were fewer stations making observations. A single regionally-averaged temperature series covering both Nunavik and Nunatsiavut was used to document temperature variability over the IRIS region as separate Nunavik and Nunatsiavut series were found to be essentially identical using data from either the CRU dataset or the National Center for Environmental Prediction (NCEP) Reanalysis (Kalnay et al. 1996).

Figure 2 shows that temperature exhibits large interannual variability in all seasons except summer, with periods of winter cooling in the 1930s and late-1980s. The later period of the 20th Century is characterized by a rapid warming of about 2°C that is present in all four seasons. The exact reasons for this abrupt warming are unclear but it may be linked in part to a warming phase of the previously mentioned AMO cycle of sea surface temperature variability over the north Atlantic (Chylek et al., 2009). A short-lived period of spring warming is also apparent in the early 1950s that coincided with the last warm period peak in the AMO. The CRU regionally-averaged temperature series agree closely with series computed from the NCEP Reanalysis (Kalnay et al. 1996) available from 1948 (not shown). This provides a somewhat independent verification as the NCEP reanalysis does not assimilate land station air temperature observations directly (it assimilates temperature soundings from balloons, aircraft and satellites as well as sea-surface temperatures – see Kistler et al. 2001). Paleo temperature reconstructions have identified previous warm episodes affecting the region such as the Mid-Holocene Warming and the Medieval Warm Period (see Section 2.3.6). Traditional knowledge indicates that the recent warming is outside the envelope defined by previous community experience.
2.3.2 Precipitation

Precipitation is a key climate variable for the snow cover, water resources and ecology of the region. Regionally-averaged annual anomaly series (with respect to a 1971-2000 reference period) of annual total precipitation and annual total snowfall for the period from 1950 were generated from the rehabilitated monthly precipitation dataset of Mekis and Hogg (1999; updated to 2008). There were insufficient stations to compute a regional average for Nunavik after 2001. The smoothed lines are the result of applying a 9-term binomial filter.

Figure 3. Regionally averaged total annual precipitation amount anomalies (mm) with respect to a 1971-2000 reference period for climate stations with at least 40 years of data in the period since 1950 in the rehabilitated monthly precipitation dataset of Mekis and Hogg (1999; updated to 2008). There were insufficient stations to compute a regional average for Nunavik after 2001. The smoothed lines are the result of applying a 9-term binomial filter.

Figure 4. Regionally averaged total annual snowfall (cm) with respect to a 1971-2000 reference period for climate stations with at least 40 years of data in the period since 1950 in the rehabilitated monthly precipitation dataset of Mekis and Hogg (1999; updated to 2008). There were insufficient stations to compute a regional average for Nunavik after 2001. The smoothed lines are the result of applying a 9-term binomial filter.

Figure 3 shows that the regional series from both regions follow a similar pattern with strong interannual variability superimposed on cyclical variations of ~10-20 years with a significant (0.05 level) increase in annual precipitation in both regions over the period since 1950. Over the 1950-2001 period precipitation increased 17% for the stations included in the Nunavik regional average and 13% for the stations included in the Nunatsivut regional average. The increase in precipitation appears to be part of a longer-term trend based on dendroecological evidence of increasing lake-levels since the 17th Century (Bégin and Payette 1988) as well as evidence from climate observations of hemispheric-wide 20th Century increases in precipitation over higher latitudes (Min et al. 2008). The results for total annual snowfall (Figure 4) show patterns of variability similar to total precipitation but with decreases in snowfall amount after ~1985 over Nunatsiavut. Over the 1950-2001 period annual snowfall amount increased 23% (significant at the 0.05 level) for the stations included in the Nunavik regional average and 8% (not significant) for the stations included in the Nunatsivut regional average. The rapid drop in annual precipitation and snowfall amounts over Nunatsiavut from 1984-1993
is driven in part by more frequent positive NAO years (especially the strongly positive NAO winters of 1989 and 1990) that are associated with cold-dry conditions over the Labrador coast (Brown 2010). The influence of NAO on temperature and precipitation drops off quickly moving inland from the Labrador coast (see Figure 8) which may be why this decrease is less pronounced in the Nunavik series.

2.3.3 Snow cover

Snow covers land and ice in Nunavik and Nunatsiavut for more than six months of the year from November to May (Figure 5 and Table 2) and plays key roles in climate (e.g. insulates soils, modifies ice growth, and influences energy and water budgets), ecosystems (e.g. winter protection for plants and animals), and human activities (e.g. transportation and shelters). The key snow cover properties for

![Figure 5](image_url)
Table 2. 1971-2000 mean snow cover conditions at climate stations within or adjacent to the Nunatsiavut-Nunavik IRIS region with at least 10 years of daily snow depth observations in the 30 year period. Mean annual snowfall amounts were computed from the rehabilitated precipitation dataset of Mekis and Hogg (1999; updated to 2008). Source: R. Brown, Env. Canada, March 2010.

### Nunatsiavut Region

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>Goose Bay</th>
<th>Cartwright</th>
<th>Makkovik</th>
<th>Nain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station elevation (m)</td>
<td>46</td>
<td>14</td>
<td>66</td>
<td>6</td>
</tr>
<tr>
<td>Number of years data</td>
<td>30</td>
<td>30</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>Latitude, Longitude (°)</td>
<td>53.3°N, 60.4°W</td>
<td>53.7°N, 57.0°W</td>
<td>55.1°N, 59.2°W</td>
<td>56.5°N, 61.7°W</td>
</tr>
<tr>
<td>First date of any snow on the ground</td>
<td>Oct 9</td>
<td>Oct 7</td>
<td>Oct 27</td>
<td></td>
</tr>
<tr>
<td>First date of continuous snow cover*</td>
<td>Nov 13</td>
<td>Nov 7</td>
<td>Nov 29</td>
<td>Nov 9</td>
</tr>
<tr>
<td>Last date of continuous snow cover**</td>
<td>May 15</td>
<td>May 29</td>
<td>May 29</td>
<td>May 29</td>
</tr>
<tr>
<td>Last date of any snow on the ground</td>
<td>May 29</td>
<td>Jun 7</td>
<td>Jun 9</td>
<td></td>
</tr>
<tr>
<td>Annual snow cover duration (days)</td>
<td>182.9</td>
<td>203.4</td>
<td>197.9</td>
<td></td>
</tr>
<tr>
<td>Annual snowfall (cm)</td>
<td>530.6</td>
<td>593.6</td>
<td>683.6</td>
<td></td>
</tr>
<tr>
<td>Maximum snow depth (cm)</td>
<td>118.5</td>
<td>97.4</td>
<td>135.8</td>
<td></td>
</tr>
<tr>
<td>Date of maximum depth</td>
<td>Feb 27</td>
<td>Mar 16</td>
<td>Mar 17</td>
<td></td>
</tr>
<tr>
<td>Avg snow depth (cm) over period with continuous snow cover</td>
<td>53.1</td>
<td>47.1</td>
<td>58.9</td>
<td></td>
</tr>
</tbody>
</table>

### Nunavik Region

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>Schefferville</th>
<th>Kuujjarapiq</th>
<th>Kuujjuaq</th>
<th>Inukjuaq</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station elevation (m)</td>
<td>522</td>
<td>21</td>
<td>34</td>
<td>3</td>
</tr>
<tr>
<td>Number of years data</td>
<td>21</td>
<td>28</td>
<td>30</td>
<td>21</td>
</tr>
<tr>
<td>Latitude, Longitude (°)</td>
<td>54.8°N, 66.8°W</td>
<td>55.3°N, 77.8°W</td>
<td>58.1°N, 68.4°W</td>
<td>58.5°N, 78.1°W</td>
</tr>
<tr>
<td>First date of any snow on the ground</td>
<td>Sep 21</td>
<td>Oct 3</td>
<td>Sep 27</td>
<td>Sep 19</td>
</tr>
<tr>
<td>First date of continuous snow cover*</td>
<td>Oct 25</td>
<td>Nov 2</td>
<td>Nov 1</td>
<td>Oct 28</td>
</tr>
<tr>
<td>Last date of continuous snow cover**</td>
<td>May 23</td>
<td>May 13</td>
<td>May 20</td>
<td>Jun 2</td>
</tr>
<tr>
<td>Last date of any snow on the ground</td>
<td>Jun 6</td>
<td>Jun 7</td>
<td>Jun 7</td>
<td>Jun 22</td>
</tr>
<tr>
<td>Annual snow cover duration (days)</td>
<td>216.0</td>
<td>193.7</td>
<td>204.6</td>
<td>221.1</td>
</tr>
<tr>
<td>Annual snowfall (cm)</td>
<td>575.9</td>
<td>338.6</td>
<td>306.3</td>
<td></td>
</tr>
<tr>
<td>Maximum snow depth (cm)</td>
<td>104.2</td>
<td>46.8</td>
<td>62.6</td>
<td>57.8</td>
</tr>
<tr>
<td>Date of maximum depth</td>
<td>Mar 11</td>
<td>Mar 5</td>
<td>Feb 24</td>
<td>Apr 1</td>
</tr>
<tr>
<td>Avg snow depth (cm) over period with continuous snow cover</td>
<td>53.2</td>
<td>26.9</td>
<td>32.7</td>
<td>33.4</td>
</tr>
</tbody>
</table>

* Defined as the start of the first two week period with snow depths ≥ 2 cm

** Defined as the start of the first two week period with snow depths < 2 cm
ecosystem services are the duration of the snow cover, the depth, the amount of water stored in the snowpack (referred to as the snow water equivalent or SWE), and the physical structure of the snowpack which includes a range of properties such as the density, crystal structure, and the presence of surface crust and/or ice layers. These snow properties have implications for the ground thermal regime, transportation, snow shelter construction, and caribou grazing. Analysis of recent satellite snow cover data (Figure 5) shows that the longest seasonal snow cover in the IRIS region is found over the northern part of the Torngat Mountains (~270+ days) with the shortest snow cover season (~180 days) in the Hudson Bay coastal region around Kuujjuarapik. The main drivers of the regional pattern of snow accumulation are proximity to moisture sources and preferred tracks of winter storms, and terrain elevation. In the Nunavik-Nunatsiavut IRIS region the largest snowfall amounts and snow accumulations are found along the Nunsiavut coast and over the Churchill Falls region (Table 2 and Figure 5A). The depth of snow that accumulates each year varies greatly with terrain, vegetation and elevation as snow deposition in open environments is strongly affected by blowing snow processes (Pomeroy and Gray 1995, Liston and Sturm 1998). This is evident in Figure 6 that shows SWE observations made every ~3 m along a ~1.7 km transect near Puvirnituq in late-February 2008. The large peaks in SWE coincide with terrain conditions that favour snow deposition while the low SWE areas are where snow was exposed to wind scour.

Providing reliable information on snow accumulation over the Nunavik-Nunatsiavut IRIS region is a challenge because of the paucity of surface observations and difficulties developing reliable satellite-based methods for monitoring SWE or snow depth over forest and tundra. Development of new satellite boreal and tundra algorithms specific to the Arctic region (e.g. Derksen et al. 2008, Lemmetyinen et al. 2009) may overcome some of the limitations of previous global satellite SWE retrievals. Surface-based SWE observations are made from weekly snow surveys at several hundred sites in Québec and Labrador but the station distribution is strongly biased to southern regions and over the main hydro-electric producing corridor traversing the La Grande Basin into Churchill Falls. The number of survey sites also varies considerably over time and there are no sites in Nunavik or Nunatsiavut with consistent long term data for looking at variability and trends in SWE. A number of gridded SWE datasets have been developed over Québec in recent years (e.g. Brown et al. 2003, Brown and Tapsoba 2007, Brown 2010) and multi-decadal series of simulated SWE information are available from runs of the Canadian Regional Climate Model (CRCM) driven by reanalysis data (Frigon et al. 2008). Dorsaz (2008) showed that there are large differences between the various SWE products over Nunavik and Nunatsiavut.

There are relatively few climate stations with long periods of snow cover observations for monitoring changes in snow cover conditions in Nunavik and Nunatsiavut.
Of the eight stations summarized in Table 2, only four had sufficiently complete data to compute trends over the 1950/51 to 2006/07 period (Goose Bay, Cartwright, Kuujjuarapik and Kuujjuaq). The results (Table 3) show decreases in snow cover duration and maximum snow depth at three of the sites. Cartwright was the exception showing a rather dramatic increase in maximum snow depth of over 1 meter over the 57 years. It is unclear what is driving this increase as total annual snowfall only increased by 11% over the same period, and Goose Bay located just over 200 km inland showed no evidence of any increases in maximum depth or snowfall. The two Nunavik sites differed from the Labrador sites with trends toward an earlier date of maximum snow depth of ~40 days over the 57 years. Of the four sites, Kuujjuaq showed the most significant changes in snow cover over the 57 year period with a more than 40 day reduction in snow cover duration driven by 30 day earlier melt in the spring, with a 60 cm reduction in annual maximum snow depth.

It is important to note when discussing the above snow trends that daily snow depth observations at climate stations are made at open grassed sites, often near airports, that may not be representative of the surrounding terrain. These sites will certainly not reflect any changes in snow accumulation related to enhanced growth of arctic shrubs (Sturm et al. 2001 and Chapter 8 of this report). However, analysis of trends in snow cover from the National Oceanic and Atmospheric Administration (NOAA) satellite dataset (Robinson et al. 1993) for the period from 1972 to 2010 (Figure 7) confirm the station trends showing that the strongest reductions in snow cover in the Nunavik-Nunatsiavut IRIS region are found over northern areas with the largest changes in the melt season. According to the satellite data, annual snow cover duration has decreased 3-4 weeks over Nunavik and Nunatsiavut since 1972.

Analysis of reconstructed snow cover over the 1948-2005 period by Brown (2010) provided evidence of a clear north-south gradient in trends in annual maximum SWE (SWEmax) and spring snow cover duration over Québec, with significant local decreases over southern Québec and significant local increases over north-central Québec. The increase in SWEmax over northern Québec is consistent with reconstructed lake levels (Bégin 2000), analysis of black spruce growth forms (Lavoie and Payette 1992), hemispheric-wide trends of increasing precipitation over higher latitudes (Min et al. 2008), projec-
important influence on temperature, precipitation and snow cover along the Labrador coast, but the influence, especially for precipitation, does not extend far inland (Figure 8).

2.3.4 Ice cover

Snow cover variability in Québec is significantly linked to most of the major atmospheric circulation patterns affecting the climate of eastern North America but the influence is characterized by strong multidecadal-scale variability (Sveinsson et al. 2008, Brown 2010). The North Atlantic Oscillation (NAO), defined previously, has a particularly important influence on temperature, precipitation and snow cover along the Labrador coast, but the influence, especially for precipitation, does not extend far inland (Figure 8).

Figure 7. Trend (days.10y-1) in snow cover duration (SCD) at the start (left) and end (right) of the snow season over 1972/73 to 2009/2010 snow seasons from the NOAA weekly dataset of Robinson et al. (1993). Trends were computed using the method of least squares. Source: R. Brown, EC.

Figure 8. Correlation of mean surface air temperature (left) and precipitation rate (right) from the NCEP Reanalysis for the November to April period with the corresponding seasonally-averaged values of the NAO index over the period 1980-2009. Source: NOAA/ESRL Physical Sciences Division (http://www.esrl.noaa.gov/psd/data/correlation/).
including over-ice transport, hydroelectric production, human infrastructure and numerous ecological and water quality characteristics (Beltaos and Prowse 2009, ArcticNet 2010). Recent changes in the precipitation regime and the length and intensity of the cold season (Furgal et al. 2002, Lafortune et al. 2006, Tremblay et al. 2009) are adversely affecting ice trails and safe access to the territory and its resources with important socioeconomic consequences for Northern residents (Furgal and Tremblay 2010). Ice cover formation, melt and dynamics are sensitive to a range of meteorological variables (e.g. wind speed, temperature, precipitation (rain and snow), cloudiness, solar radiation and humidity) and changes in any of these can influence ice composition, thickness, stability and the complex interactions between hydrodynamic, mechanical and thermal processes (Beltaos and Prowse 2001, Morse and Hicks 2005, Beltaos 2007, Prowse et al. 2007a,b, Hicks 2009, Shen 2010). Coastal zones and particularly large river mouths where settlements tend to be located have been shown to be particularly sensitive environments to recent change (ArcticNet 2010), and ice conditions in these environments can be especially hazardous due to the dynamic nature of the ice regime.

There are a number of challenges for monitoring changes in the ice climate of Nunavik. There are few in situ records (Duguay et al. 2006) and satellite observations have various limitations related to the frequency, consistency and length of coverage. Regular weekly measurements of ice thickness close to shore were made at a number of communities in the region over various periods from the 1950s to the 1990s. Analysis of the period with the most complete data (1972-1990, Table 4) shows that for this particular time period, ice safe enough to travel on was present for approximately six months from December to May, with maximum ice depths of 1 to 2 m in April. For the six sites with data, maximum ice thickness varies approximately with latitude; the thickest ice forming at Inukjuak (58.5°N) and the thinnest at Goose Bay (53.3°N).

Unfortunately there are few ice measurements after the early-1990s to document the response of ice cover to the recent period of warming (Duguay et al. 2006). Freeze-up and break-up observations from the Koksoak River near Kuujjuaq (Figure 9) over the period from 1951 to 1995 show a statistically significant trend toward earlier melt by 0.7 days/yr over the period but no trend in date of freeze-up. However, the net impact on ice cover duration was offset by a compensating trend toward earlier ice onset up to ~1980. The greater variability evident in ice onset date compared to ice-off date is typical as the former is more sensitive to a wider range of processes than melt (Duguay et al. 2006, Brown and Duguay 2010). The ice cover duration inferred from Figure 9 stayed relatively constant until the early 1980s when duration decreased rapidly and became more variable in response to trends toward later ice formation and earlier ice melt. While

<table>
<thead>
<tr>
<th>SITE</th>
<th>NYRS</th>
<th>MAX THICKNESS (CM)</th>
<th>DATE OF MAXIMUM THICKNESS</th>
<th>DATE OF FIRST THICKNESS MEASUREMENT</th>
<th>DATE OF LAST THICKNESS MEASUREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AVG</td>
<td>STD</td>
<td>AVG</td>
<td>STD (DAYS)</td>
</tr>
<tr>
<td>Inukjuak</td>
<td>18</td>
<td>226.8</td>
<td>30.2</td>
<td>Apr. 24</td>
<td>17.0</td>
</tr>
<tr>
<td>Kuujjuaq</td>
<td>19</td>
<td>143.2</td>
<td>20.4</td>
<td>Apr. 25</td>
<td>14.8</td>
</tr>
<tr>
<td>Kuujjuarapik</td>
<td>19</td>
<td>142.6</td>
<td>25.3</td>
<td>Apr. 08</td>
<td>15.4</td>
</tr>
<tr>
<td>Schefferville</td>
<td>17</td>
<td>132.5</td>
<td>12.6</td>
<td>Apr. 22</td>
<td>11.3</td>
</tr>
<tr>
<td>Cartwright</td>
<td>19</td>
<td>110.9</td>
<td>21.8</td>
<td>Apr. 10</td>
<td>17.2</td>
</tr>
<tr>
<td>Goose Bay</td>
<td>18</td>
<td>99.2</td>
<td>15.1</td>
<td>Apr. 12</td>
<td>14.3</td>
</tr>
</tbody>
</table>

Table 4. Summary of ice thickness information from weekly ice thickness measurements made over 1972-1990. The first and last measurement dates provide a rough indication of when ice was safe to travel on. Source: R. Brown, Env. Canada, March 2010.
these results are only from one site, the observed trend toward a shorter ice season at Kuujjuaq is consistent with trend analysis of lake ice cover from remote sensing and in-situ observations that showed ice break-up is occurring earlier and freeze-up later for most lakes in Canada (Laticofvic and Pouliot 2007). The trend toward earlier melt of freshwater ice is also seen offshore. Recent analysis of trends in summer sea ice concentration in Canadian waters over the 1968-2008 period (Figure 10, Tivy et al. 2011) shows that some of the largest and most significant decreases have occurred in marine areas adjacent to the Nunavik-Nunatsiavut IRIS region (e.g. Hudson Strait: $-16.0 \pm 3.4\%$ per decade; North Labrador Sea: $-17.8 \pm 4.8\%$ per decade). Summer sea ice concentration trends in East Hudson Bay were also negative ($-11.5 \pm 6.8\%$ per decade) but not statistically significant. Atmospheric teleconnection patterns have also been shown to play a role in the regional response of lake ice over North America (Walsh et al. 2005, Bonsal et al. 2006), although the results from Bonsal et al. (2006) suggest the linkages are strongest over western Canada.

The decreasing ice cover observed at Kuujjuaq is also consistent with the previously documented trends toward a shortening of the snow cover season and with traditional knowledge. For example, a general decrease of ice thickness has been observed on rivers and lakes in Nunavik during winter (Furgal and Prowse 2008) and, the Kuujjuaqmiut have reported an increase of ice instability on the Koksoak River that has triggered safety concerns and al-

Figure 9. Annual variation in dates of complete freeze-up and melt for the Koksoak River at Kuujjuaq from 1951-1995. Complete freeze-up dates are plotted with respect to Jan 01 as the date can vary from December to February. Source: Figure prepared by R. Brown with data from Lenormand et al. (2002).

Figure 10. Trend in summer sea ice concentration from 1968 to 2008; units are % per decade. Only trends significant to the 95% confidence level are shown. From Tivy et al. (2011).
tered traditional ice routes for harvesting and subsistence purposes (Tremblay et al. 2009, Clerc et al. 2011). Northern communities in the Northwest Territories, Nunavut and Alaska have reported similar experiences (Tremblay et al. 2006a,b). Elders of Quaqtaq, Umiujaq and Kuujjuaq have observed later ice formation, earlier spring thaw, more rain, reduced snow fall and a change in wind patterns in Hudson Bay and Hudson Strait since the 1980s (Clerc et al. 2011).

While we have a reasonable understanding of how climate changes will affect the thickness and duration of ice cover (Dumas et al. 2006, Dibike et al. 2011a,b), our understanding of how climate change will alter other freshwater-ice processes such as ice-cover composition and break-up dynamics remains poor (Prowse et al. 2006a,b, Beltaos and Prowse 2009). Real-time satellite information on ice cover properties and dynamics is a potentially useful tool for gaining this understanding and adapting to a changing ice regime. Synthetic Aperture Radar (SAR) has been shown to be very effective for monitoring ice conditions in coastal environments and rivers as the information is obtained at high resolutions and is not limited by solar illumination or cloud cover. The high resolution (8 m for RADARSAT 1 in Fine beam) and very high resolution (3 m for RADARSAT-2 Ultra-fine mode) also allow for the monitoring of medium sized rivers and more recently the Koksoak Estuary (Weber et al. 2003, Gauthier et al. 2006, Drouin 2007, Untershultz et al. 2008, Bleau 2011). The radar signal is sensitive to the ice roughness (surface scattering) and to the shape, size and density of air inclusions within the ice cover (volume scattering), and can be used to discriminate different freshwater ice types or ice formations (Gherboudj et al. 2007). Further efforts have been made to merge RADARSAT all-weather ice monitoring capabilities with local knowledge of ice conditions at several northern communities (www.noetix.on.ca/floeedge.htm) and for the Koksoak River at Kuujjuaq (climatechange.krg.ca/kuujjuaq.html). For example, Figure 11 shows a close match between aerial observations and a RADARSAT-derived map of river ice conditions (Gauthier et al. 2010). Traditional knowledge has been incorporated in the process of ice cover classification and mapping from RADARSAT at Koksoak River.
Table 5. Description of river ice cover classes shown in Figure 11 based on traditional knowledge interpretation of RADARSAT imagery. Modified from Gauthier et al. (2010).

<table>
<thead>
<tr>
<th>CLASS</th>
<th>MAP LEGEND DESCRIPTION</th>
<th>CLASSES FROM USER WORKSHOP (TRADITIONAL KNOWLEDGE)</th>
<th>INUKTITUT TERMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Open water</td>
<td>Smooth ice cover / Undisturbed ice cover</td>
<td>Uluaguti / Tuvaq</td>
</tr>
<tr>
<td>#2</td>
<td>Smooth, clear lake ice or border ice. May apply to water with some moving ice floes</td>
<td>Drifting frazil pans</td>
<td>Sikuat</td>
</tr>
<tr>
<td>#3</td>
<td>Sparse to moderately dense moving ice floes / Rougher lake ice</td>
<td>Ice pans start to concentrate and agglomerate together</td>
<td>Puttaat / Ittiniit</td>
</tr>
<tr>
<td>#4</td>
<td>Dense moving ice floes to agglomerated ice floes / Rough ice in side channels or on sand banks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>Agglomerated ice (rough)</td>
<td>Agglomeration completed</td>
<td>Puttaat / Ivuniit</td>
</tr>
<tr>
<td>#6</td>
<td>Consolidated ice (rougher)</td>
<td>Thermal or frazil ice blocks piling up</td>
<td>Ivuniit / Maniiligaat</td>
</tr>
</tbody>
</table>

Figure 11. Positive match between aerial observation and RADARSAT derived river ice map for Consolidated (class # 6 and 5) and smoother ice (class # 2 to 4) on the 29 February 2008. Modified from Gauthier et al. (2010).

Table 5 presents the classified ice types shown in Figure 11 and the corresponding Inuktitut terminology based on consultations with local elders carried out as part of an International Polar Year project.

The installation of moored upward looking sonar systems for continuous measurement of river ice thickness would complement RADARSAT all-weather ice monitoring capabilities (Marko and Jasek 2010). There are ongoing challenges to make such systems fully operational at locations not serviced with AC power and more effort is needed to expand capabilities for baseline observations of ice conditions in Nunavik and Nunatsiavut in support of adapting to a dynamic changing ice regime. The merging of traditional and scientific knowledge in community-based monitoring initiatives (Huntington 2008) appears to be a useful framework for improved monitoring and understanding of changing ice conditions with the relevant connections to ensure that new information is translated into enhanced safety and improved decision making.
2.3.5 Glaciers of the Torngat Mountains, northern Labrador: how many and for how long?

Although the occurrence of glaciers in northern Labrador is largely unknown to Canadians and their contribution to Canadian terrestrial ice volume is negligible, their geographic importance as the only glaciers on mainland North America east of the Rocky Mountains and the southernmost glaciers along the highland rim of the Eastern Canadian Arctic makes them of particular interest for scientific study. The glaciers are located in the Torngat Mountains National Park and as such comprise an important component of the natural landscape of Labrador’s arctic wilderness; the dependence of other local ecosystems - from tundra vegetation to fiord habitats - on glaciers and their meltwater is not well understood. The glaciers occupy and form part of the natural and cultural landscape of the Labrador Inuit whose Inuktitut term for glacier – simmik – translates to Never Melting Ice (Willie Etok, personal communication 2008).

Many will be surprised to learn that the earliest photographic documentation of one of the Torngat glaciers dates back over 100 years. In 1908, E.S. Bryant and H.S. Forbes hiked up from the coast and photographed a small north-facing glacier on Mt. Tetragona from the position of a small recessional moraine (i.e. a ridge of debris formed at the stationary margin of a glacier during overall retreat) located several hundred metres from the ice front (Figure 12). N.E. Odell and B. Morris subsequently revisited the glacier during D.L. Forbes’ expedition to northern Labrador in 1931 – they refer to it as Bryant’s Glacier - and photographed the ice terminus from the same ground position (Figure 12). Over the intervening 23 years the glacier margin had retreated 70 to 90 m (Odell 1933). In 1956 the ice terminus was photographed by J.D. Ives (Ives 1957). In commemoration of the first photograph and as a legacy of the third International Polar Year, Bryant’s Glacier was revisited and re-photographed in 2008 by T. Bell and employees of Parks Canada and the Nunatsiavut Government (Figure 12). Over the course of a century, Bryant’s Glacier has shrunk significantly and is now largely composed of two smaller ice masses only partially visible in the 2008 photograph (Figures 12 and 13).

Several inventories have been made of the glaciers of northern Labrador, but unfortunately they are either incomplete or unpublished. The earliest inventory was conducted for the Forbes 1931 northern Labrador mapping expedition. The map published by Forbes (1938) shows 61 glaciers in the region north of Nachvak Fiord. As Mercer (1958) and Fahn (1975) noted, “some of these are extremely small, however, and may not deserve the name ‘glacier’” (p. 676). A Glacier Map of southern Baffin Island and northern Labrador was compiled by W.E. Henoch and A. Stanley and published in 1968. It contained a total of 62 glacier locations also in the region north of Nachvak Fiord (Henoch and Stanley 1968).

J. Stix (Dartmouth College, New Hampshire) conducted a reconnaissance inventory of glaciers in the Nachvak Fiord region in 1979. He photographed and reported on the flow conditions of ten ice masses, which he classified as cirque glaciers, cirque glacierettes or upland ice/snowfields (Stix 1980). He compared the ground photography in 1979 with 1:62,572-scale aerial photographs from 1964 to detect any changes in ice extent. He concluded that two of the cirque glaciers may have been advancing, while the others were stagnant or retreating.

More recently, Leblanc and Bell (2008) generated a composite inventory of glaciers in the region using previously published data, National Topographic Series 1:50,000-scale maps, and an unpublished observational database from Parks Canada (A. Simpson, personal communication 2008). The composite inventory of all previous observations suggested that there may be as many as 86 ice bodies in the Torngat Mountains, 65 north of Nachvak Fiord and the remainder farther south, but no assessment of glacier activity was made.
Figure 12. A century of change at the terminus of Bryant’s Glacier on the north face of Mt Tetragona in the Torngat Mountains. Top: Bryant and Forbes, 1908; Middle: Odell, 1931; Bottom: Bell 2008. The active ice front is located at the moraine in the foreground in 1908. By 1931, the terminus is located 70-90 m behind the moraine. In 2008, the glacier is almost split in two with the termini of the two tributary glaciers located on either side of the bottom photograph. See Figure 13 for an aerial perspective of the proposed ice loss and the location of the photographer’s position on an end moraine in front of the glacier.
The first scientific study of the glaciers was undertaken by R.J. Rogerson of Memorial University of Newfoundland in the early 1980s. He and his field crew spent 4 seasons (1981-84) measuring the mass balance and morphological characteristics of four glaciers that drain into Ivitak Valley (Ivitak is the Inuit name for the McCormick river valley that appears on NTS topographic maps), on the south side of Nachvak Fiord. During this period, two glaciers experienced overall positive net mass balance (i.e. the difference between accumulation from snowfall and ablation from melting on a glacier) while the other two were consistently negative; interestingly, the smallest glacier with a negative mass balance advanced its terminal position in each of the study years by an average of 1.2 m (Rogerson 1986).

The current study of the glaciers of the Torngat Mountains was initiated as part of ArcticNet’s Nunatsiavut Nuluak project, in partnership with Parks Canada and the Nunatsiavut Government. It has as its primary goal to establish a baseline of current glacier conditions to be used for future monitoring, recent change detection and local hydrological assessment. The research plan involves remote sensing, field surveys and local knowledge from Inuit elders who lived and travelled in the Torngat Mountains. Here we present a brief summary of the first systematic assessment of glacier extent, together with a preliminary estimate of glacier change over the period 2005-2008, using remote sensing techniques only. Data sources and analytical methods were reported in Barrand et al. (2010).

A total of 103 active glaciers were mapped from 1:40,000-scale, colour aerial photographs taken in 2005. The glaciers ranged in size from 0.02 to 1.26 km² for a total glacier area of 19.8 km². Of the 103 glaciers, 17 were not identified in previous inventories; however, it is unlikely that these glaciers have grown in recent decades and more probable that they were missed in previous mapping. The glaciers occur within a coastal region defined by latitude 58.59° and 59.84° North. Most of the glaciers (80%) are smaller than 0.25 km² and only one is larger than 1 km². Glaciers in the Torngat Mountains typically occupy cirque basins with high backwalls and many are heavily debris-covered at lower elevations (Figure 14). Roughly 70% have a northerly aspect (315-45° azimuth), which would maximize the shading effect from high backwalls, but significantly, 10% face south (135-235° azimuth). The elevations of the glacier ter-

**Figure 13.** An aerial perspective of a century of ice loss on Bryant’s Glacier. The 1908 and 1931 ice margins are interpreted from the ice outline visible in ground photographs (see Figure 12) and the overall form of the glacier in the 2005 aerial photograph. The 2008 ice margin was mapped from SPOT5 HRS satellite imagery. The total decrease in aerial extent of Bryant’s Glacier between 1908 and 2008 is estimated to be 0.344 km² or 38%. For comparison, the recent change between 2005 and 2008 was measured at 0.144 km² or 16% of its 1908 area.
mini vary from 290 m to 1140 m above sea level (asl), with 14 (14%) having a terminus above 1000 m asl. Approximately 78% of the glaciers are located within 30 km of the Labrador coast.

Glacier mapping from 2008 SPOT5 HRS satellite imagery produced a total of 96 glacier outlines, seven less than the 2005 inventory due to cloud and snow cover masking ice margins. The 96 glaciers covered an area of 16.99 km² and ranged in size from 0.014 to 1.25 km². This represents a decline of 1.74 km² or 9.3% of the 2005 area covered by the same 96 glaciers. Eighty-seven or 91% of the glaciers experienced an areal decrease, with an average discernable decline of 0.024 km². Twenty-two glaciers recorded a change in area of less than 0.05 km², which given the spatial resolution of the imagery likely means an undetectable change.

Figure 14. View looking south at Abraham (left) and Hidden (right) glaciers in the Cirque Mountain Range, south of Nachvak Fiord. Note the high backwalls shading the accumulation zones of both glaciers.

For the first time there is a complete inventory of northern Labrador glaciers, a measurement of their aerial extent and an assessment of their recent change. The 9.3% reduction in the areal extent of Torngat Mountain glaciers between 2005 and 2008 is dramatic, but needs to be viewed in the context of long-term trends in areal extent and climate. A study of the former is in progress but available published data suggest that glaciers in the Nachvak Fiord region were in retreat in the late 1970s and early 1980s (Stix 1980; Rogerson 1986). The overall mean of the annual net mass balances of four glaciers in Ivitak Valley between 1981 and 1984 was -0.26 m water equivalent per year (Rogerson 1986). Climate data for the period 1997-2008 for the Nachvak Fiord region (see Table 6 caption for details of climate data) indicates an anomalously warm decade compared to the average summer temperature conditions for the past 60 years (Table 6). In fact, 2007 and 2008 were the two
warmest summers on record, and 2008 was 2.57°C warmer than the 60-year average.

Rogerson (1986) concluded that winter precipitation is the controlling climatic variable in the mass balance of the four study glaciers. Winter precipitation for 2005-2007 was above average for the past 60 years or so; but perhaps of greater relevance was the extended period of below-average precipitation since 1983 (16 of 22 years) and for 5 of the 7 years prior to 2005 (Table 6). The dramatic recent decline in areal extent may therefore be primarily a response to a multi-decadal trend in lower winter precipitation, coupled with anomalously warm summers.

It is too early in our analysis to determine a long-term prognosis for the survival of glaciers in the Torngat Mountains. We are currently applying a distributed, temperature-index melt model (cf. Hock 2003) to analyse the mass balance sensitivity of selected glaciers to climate variables, topographic conditions and surface debris cover and simulate glacier responses to future climate scenarios (King et al. 2009). Once our analysis is complete and we have a longer-term perspective on glacier change, we will be able to test Rogerson’s (1986) hypothesis that:

“The survival of glaciers in the Torngat Mountains seems likely for the immediate future even if climate improves slightly. Warmer temperatures in the winter could cause high snowfalls... Furthermore, even if higher temperatures caused much [surface] melt and substantially eroded the glaciers, any reduction in the surface elevation of the glaciers would increase the amount of shading...” (pp 217-218).

### 2.3.6 Permafrost as a climate indicator

Permafrost’s presence and temperature are directly related to local and regional climate, albeit through conditions at the ground surface (e.g. vegetation and snow cover). A description of the permafrost regime in the Nunavik-Nunatsiavut IRIS region is provided in Chapter 6 along with a map showing the spatial distribution of the zones of continuous, discontinuous and sporadic permafrost (see Chapter 6, Figure 1). At depths in the order of tens to hundreds of meters, the vertical temperature profile in permafrost records variations of past surface temperatures, providing a means to reconstruct past climates. Another way to reconstruct paleoclimates in permafrost terrain is to analyse and date (with C-14) the paleosoils and peat layers associated with changes in the dynamics of soil structures and surface landforms (polygon network, palsas, etc.) since these soil features are found under variable surface climatic conditions. This approach uses reconstructed past surface conditions as a proxy for past climates.
In Nunavik, deep borehole thermal profiles were recently used for past climate reconstruction (Chouinard et al. 2007). Ice wedges were studied for several years in an attempt to identify climate thresholds that control ground frost cracking and to reconstruct periods of warm and cold climate regimes (Allard and Kasper 1998, Kasper and Allard 2001). Also, the radiocarbon dating of summital peat on top of palsas (peat covered mounds in the subarctic region near the treeline) in the Umiujaq region determined the period when their surface first heaved above bog level and dried up because of ice formation in the ground and inception of permafrost during cold periods (Marchildon 2007).

Deep borehole temperature profiles at the Raglan Mine in northern Nunavik were used to reconstruct ground surface temperature histories (GSTH) (400 and 800 yr) and to capture Little Ice Age (LIA) cooling (for more details on methods see Chouinard et al. (2007)). They clearly detected the onset of the LIA (800 yr reconstitution) characterised by a drop in ground surface temperature to 0.42 K below the mean surface temperature reference (~ -8.57 °C) (Figure 15). Their results also highlight the warming that took place in the early 20th Century, some cooling in the second half of the Century and the recent warming observed since the early 1990s.

Results from ice-wedge studies, frost cracks and past active layer thickness variations by Kasper and Allard (2001) in northern Nunavik revealed the presence of six distinctive climate periods in the 3400 year period prior to 2000. Although these methods did not provide accurate temperature reconstruction values, the highlighted climate periods corresponded to those identified using other methods such as pollen analyses, climate reconstruction through deep permafrost thermal profiles (central Ungava Peninsula) (Taylor and Judge 1979, Richard 1981), and backward modelling of temperature profiles in Greenland ice cores of the GRIP and Dye 3 drilling projects (Dahl-Jensen et al. 1998). All of these studies showed a general cooling around 3200 BP, followed by a warming associated with the Medieval Warmth (950 to 1100). A clear signal of a cold climate was highlighted during the LIA (Table 7). In the Subarctic, the discontinuous permafrost wetlands in palsa fields had a first major expansion phase starting around 2300 years ago. The period from 1000 to 500 years ago was warmer as some palsas thawed, but the period from 500 to 100 years ago (roughly from the late 13th Century to the end of the 19th Century, corresponding to the Little Ice Age) was particularly cold.

In the early twentieth-century, a warming trend was detected through cessation of ice-wedge activity (Kasper and Allard 2001). A continuous ground surface warm-
Chapter 2 CLIMATE VARIABILITY AND CHANGE

Table 7. General climate period identified through ice-wedge activity and paleoecological interpretations. Timescale is not linear: 0 is year 2000. Modified from Kasper and Allard (2001).

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>CLIMATE</th>
<th>VEGETATION</th>
<th>ICE-WEDGE ACTIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-0</td>
<td>Cooling</td>
<td>Sedge and moss</td>
<td>Progressive reaction of ice-wedges</td>
</tr>
<tr>
<td>100-50</td>
<td>Warm</td>
<td>Sedge and moss</td>
<td>Cessation of activity</td>
</tr>
<tr>
<td>500-100</td>
<td>Cold(est)</td>
<td>Moss dominated</td>
<td>Intense activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedge and moss</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grass dominated</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slope process</td>
<td></td>
</tr>
<tr>
<td>970-500</td>
<td>Cooling</td>
<td>Sedge and moss</td>
<td>Activity generally increasing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grass dominated</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slope process</td>
<td></td>
</tr>
<tr>
<td>1860-970</td>
<td>Generally moist and warm</td>
<td>Sphagnum dominated</td>
<td>Activity generally decreasing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Alteration of activation and deactivation</td>
</tr>
<tr>
<td>3400-1860</td>
<td>Generally cold and dry</td>
<td>Sedge dominated</td>
<td>Generally active. Formation of low-center polygons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aeolian activity</td>
<td></td>
</tr>
</tbody>
</table>

In the last 10 to 15 years GSTHs provided by Chouinard et al. (2007) showed a clear increase of 2.3 K above the reference temperature. The total temperature perturbation inferred since the end of the LIA (-0.4 K) showed an increase of 2.7 K above the reference temperature by the end of the 1990s. For the past 15 years, results from Chouinard et al. (2007) inferred an increase of about 1.8 K (Figure 15), which is also supported by the recent increase in SAT modeled from the North American Regional Reanalysis (Mesinger et al., 2006) air temperatures for northern Nunavik. Furthermore, these results correlate with the regional air temperature portrait given by meteorological station measurements of Environment Canada in Iqaluit, Kuujjuarapik, Kuujjuaq and Kuujjuaq. The observed temperatures show increasing trends for the last several years which are also reflected by the ongoing degradation of permafrost landforms observed throughout Nunavik (Marchildon 2007, L’Hérault 2009, Payette et al. 2004).

In summary, paleoclimate reconstructions using permafrost temperature profiles, landforms and soil structures provide a general history of climate cooling in Nunavik during the Late Holocene, i.e. roughly since 3000 years ago. The reconstructions also identify two important climate periods. The Medieval Warm Period from roughly the year 1000 to the 14th Century was somewhat warmer, but variable and gradually cooling. The Little Ice Age stands out as having been particularly cold. The 20th Century was characterized by gradual warming ending with a warm pulse that has continued into the 21st Century.

2.4 Climate change projections

Climate change scenarios for the Nunavik-Nunatsia-vut IRIS region were developed at Ouranos by physically downscaling outputs from Global Climate Models
(GCMs) run at a 200-400 km to 45 km resolution using the Canadian Regional Climate Model (CRCM) (Caya et al. 1995, Caya and Laprise 1999, Plummer et al. 2006, Music and Caya 2007). The projected changes are derived from the difference between 30 year averages computed over a 1971-2000 “current climate” period and a 2041-2070 “future climate” period corresponding to the 2050 time-frame, and assumed the SRES A2 scenario for future greenhouse gas emissions (Nakicenovic et al. 2000). The 2050 time-frame was selected as this corresponds to a period when the climate change signal is apparent over Eastern North America (Christensen et al. 2007) and corresponds to the planning horizon for many decision makers. A total of six pairs of current and future climate runs from the latest version of CRCM 4.2.3 (de Elia and Côté 2010) were used; five driven by the third generation Canadian Coupled Global Climate Model (CGCM3) (Scinocca et al. 2008, Flato and Boer 2001) and one driven by the ECHAM5 global model from the Max Plank Institute (Roeckner et al. 2003, Jungclaus et al., 2006). The calculated mean change (Δ) from the six different CRCM runs was mapped over the study region along with the standard deviation (STD) of the projected changes to provide some idea of the consistency (or uncertainty) which in this case is mainly related to the internal variability of the climate system as simulated by CGCM3. A more complete description of the methodology including an evaluation of the climate model performance is provided in Appendix A at the end of this Chapter.

A total of 14 variables were selected for scenario construction based on previous studies (Sharma et al. 2009, Williamson et al. 2009) and their relevance to Nunavik-Nunatsiavut IRIS ecosystems. Further details on the justification for variable selection and the definitions are provided in Appendix A.

- Annual, winter (Oct. to Apr.) and summer (May to Sept.) air temperature
- Sums of thawing degree-days and freezing degree-days with respect to a 0°C threshold
- Sum of growing degree-days with respect to a 5°C threshold
- Start and end dates of summer season with respect to a 0°C threshold
- Annual total precipitation and total solid precipitation
- Mean and maximum snow depth
- Duration of snow cover in first (Aug.-Jan.) and second (Feb.-Jul.) halves of the snow year
- The frequency of winter thaws, freeze-thaw cycles and rain-on snow events

Figure 16. Seasonal character of projected change in monthly mean temperature (left panel) and total precipitation (right panel) from six CRCM runs for 2050 period, averaged over all grid cells in the study region. The outer lines represent the range in the six simulations.
Interactive lake and coastal ice processes are not included in the current version of the CRCM but results from recent lake and sea ice modelling studies (Dibike et al. 2011a,b, Dumas et al. 2006, Joly et al. 2010) were examined and are discussed in Appendix A.

The amplitude and seasonal pattern of the projected changes in air temperature and total precipitation averaged over the entire study domain are shown in Figure 16, while the spatial pattern of the changes in annual temperature and precipitation are shown in Figure 17. These two figures encapsulate most of the key features observed in the various climate indicators presented in Appendix A. The two main points are: (1) the largest changes are projected to occur in the winter season with an average 5°C warming and 35% increase in precipitation in January; (2) the spatial pattern of projected changes typically exhibits a NW-SE gradient over the region with the largest changes over the NW part of Nunavik (although this pattern can be inverted depending on the variable selected). A summary of the magnitude and regional pattern of change in each of the 14 variables is presented in Table 8 for Nunavuk and Nunatsiavut. The results suggest a markedly different
Table 8. Summary of projected changes in climate variables for Nunavik and Nunatsiavut corresponding to 2050. Maps showing the spatial pattern of the projected changes are included in Appendix A. Results are from Ouranos CRCM runs unless specified otherwise. Continued on next page.

<table>
<thead>
<tr>
<th>CLIMATE VARIABLES</th>
<th>NUNAVIK</th>
<th>NUNATSIAVUT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PROJECTED CHANGE OVER REGION</strong></td>
<td><strong>COMMENTS</strong></td>
<td><strong>PROJECTED CHANGE OVER REGION</strong></td>
</tr>
<tr>
<td>Winter air temperature</td>
<td>+3.0 to +5.0°C</td>
<td>NW-SE gradient with strongest warming over northwestern Ungava</td>
</tr>
<tr>
<td>Summer air temperature</td>
<td>+1.5 to +2.0°C</td>
<td>Strongest warming over north and south with lowest warming over Hudson Bay coastal region</td>
</tr>
<tr>
<td>Summer start date</td>
<td>6 to 11 days earlier</td>
<td>Largest changes over northeastern Ungava; smallest change over southwest region around James Bay</td>
</tr>
<tr>
<td>Summer end date</td>
<td>8 to 19 days later</td>
<td>Largest change over southwest region around James Bay and Hudson Bay coast; smallest change over Ungava Peninsula</td>
</tr>
<tr>
<td>Thawing degree-days</td>
<td>30 to 65% increase</td>
<td>Largest relative changes over northeastern Ungava; smallest change over southwest region around James Bay</td>
</tr>
<tr>
<td>Growing degree-days</td>
<td>50 to 150% increase</td>
<td>Largest relative changes over northeastern Ungava; smallest change over southwest region around James Bay</td>
</tr>
<tr>
<td>Annual total precipitation (rainfall + snowfall)</td>
<td>12 to 25% increase</td>
<td>Largest relative increases over western Ungava Peninsula and Hudson Bay coast; smallest increases over southern margins</td>
</tr>
<tr>
<td>Annual solid precipitation (snowfall)</td>
<td>1 to 24% increase</td>
<td>Largest relative increases over northern Ungava Peninsula; smallest increases over southeast</td>
</tr>
<tr>
<td>Winter thaw events (not shown)</td>
<td>Little change</td>
<td>No pattern</td>
</tr>
<tr>
<td>Freeze-thaw cycles (not shown)</td>
<td>Little change</td>
<td>No pattern</td>
</tr>
<tr>
<td><strong>CLIMATE VARIABLES</strong></td>
<td><strong>NUNAVIK</strong></td>
<td><strong>COMMENTS</strong></td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Start of snow season</td>
<td>5 to 14 days later</td>
<td>Largest change over coastal region north of James Bay; smallest change over Ungava Peninsula</td>
</tr>
<tr>
<td>End of snow season</td>
<td>3 to 11 days earlier</td>
<td>Largest increases over northern Ungava Peninsula; smallest increases over southwest region around James Bay</td>
</tr>
<tr>
<td>Mean snow depth</td>
<td>-7 to +7%</td>
<td>Decreases dominate with one area of increase over northern Ungava Peninsula; largest decreases over southern and eastern regions</td>
</tr>
<tr>
<td>Maximum snow depth</td>
<td>0 to +15%</td>
<td>Same as mean snow depth</td>
</tr>
<tr>
<td>Rain-on-snow days</td>
<td>Increase of 1-2 ROS days per year</td>
<td>Increases confined to southern part of Nunavik</td>
</tr>
<tr>
<td>Lake ice freeze-up</td>
<td>8-14 days later</td>
<td>Largest changes along Hudson Bay coast</td>
</tr>
<tr>
<td>Lake ice break-up</td>
<td>14-18 days earlier</td>
<td>Largest changes along west coast of Ungava Peninsula</td>
</tr>
<tr>
<td>Lake ice maximum thickness</td>
<td>20-30 cm less ice</td>
<td>Largest changes along west coast of Ungava Peninsula</td>
</tr>
<tr>
<td>Sea ice freeze-up</td>
<td>25 to 30 days later over Hudson Bay, James Bay and Foxe Basin</td>
<td>Ungava Bay and James Bay regions most strongly affected in the results presented in Joly et al. (2010)</td>
</tr>
<tr>
<td>Sea ice break-up</td>
<td>22 to 24 days for Foxe Basin and Hudson Bay; 39 days earlier for James Bay</td>
<td>Ungava Bay and James Bay regions most strongly affected in the results presented in Joly et al. (2010)</td>
</tr>
<tr>
<td>Sea ice thickness</td>
<td>30 to 50% reduction in winter ice thickness in coastal zone</td>
<td>Ungava Bay and James Bay regions most strongly affected in the results presented in Joly et al. (2010)</td>
</tr>
</tbody>
</table>
climate variability and change

Chapter 2

Climate variability and change

Climate in the Nunavik-Nunatsiavut IRIS region in 2050: the snow and ice cover season will be shortened by 3-4 weeks, the growing season will be 2-3 weeks longer with up to 50% more growing degree days, and there will be increases in precipitation of 15-25% with a larger fraction of annual precipitation falling as rainfall. The sea ice modelling scenarios presented by Joly et al. (2010) for the Hudson Bay region show extensive reductions in early winter ice amount in all coastal regions of Nunavik, with the largest relative decreases in ice thickness over eastern Hudson Bay north of James Bay (in the vicinity of the community of Whapmagoostui) and also in Ungava Bay off Kuujjuaq (Figure 18).

It should be noted that 45 km resolution of the RCM used to generate the results shown in Appendix A is still too coarse to capture much of the smaller scale topographic variability over Nunavik and Nunatsiavut. Brown and Mote (2009) showed that the response of snow cover to changes in temperature and precipitation depends strongly on the climate regime and elevation, with the strongest responses in maritime mountainous regions. This point was also raised in Chapter 8 where it was noted that in Labrador during the relatively warm winter of 2009-10 (characterized by strongly negative NAO conditions) there were increased amounts of snowfall above 600 m but more frequent rain and thaw events at lower elevations. Additional downscaling of the RCM output to meet the needs of local decision makers can be carried out through a variety of approaches (e.g. Mearns et al. 2003). Higher resolution runs of the RCM at 15 km will be available in the next few years.

2.5 Summary and conclusions

The available paleo-climate, historical climate and proxy information from the Nunavik-Nunatsiavut IRIS region suggest the climate of the region has been in a period of gradual cooling over the past ~3000 years apart from a short period of warming in the Medieval Warm Period (950-1250) and markedly cooler temperatures during the Little Ice Age (1400-1900). Various data sources show that the second half of the 20th Century has been warmer, but there is some uncertainty as to when the recent period of warming began due to the large interannual variability of the climate of the Nunavik-Nunatsiavut IRIS region. The instrumental temperature record shows a period of rapid warming starting in the early 1990s but there is evidence from a number of other sources (e.g. snow cover trends, tree-ring records, vegetation changes) suggesting the climate has been warming over the past 40-50 years. This can clearly be seen in summer maximum temperature reconstructions from tree-ring data back to 1800 (Figure 19) where summer max temperatures are relatively stable from the late-1800s until 1950-1975 when a warming trend emerges. The differences between the various data sources are likely related to a number of factors including different regional responses to climate warming (e.g. the historical temperature record for the Nunavik-Nunatsiavut IRIS region reflects coastal locations that are strongly influenced by ocean temperatures), and different processes (e.g. ground temperatures respond to changing...
vegetation and snow cover as well as to mean annual air temperatures).

While there may be some uncertainty as to the timing of the recent period of warming over the Nunavik-Nunatsiavut IRIS region, there is no denying the rapidity of the changes that have occurred over the last few decades. Air temperatures have warmed by more than 2°C since 1993, snow cover duration has decreased 3-4 weeks over northern Nunavik and Nunatsiavut since regular satellite observations began in the early 1970s, ice on the Koksoak River at Kuujjuaq in the 1990s (when observations ceased) was melting an average of 3 weeks earlier than it did in the 1950s, warming of permafrost has resulted in a dramatic increase in the number of thermokarst lakes and active layer detachments (Chapter 6), glaciers in the Torngat Mountains lost ~20% of their area between 2005 and 2007 (Section 2.3.5), and marked increases in tree and shrub abundance have been documented at many locations (Chapter 8). The unusual nature of these changes is clearly visible in the paleo-temperature records (e.g. Figure 15) and is confirmed from traditional knowledge (Tremblay et al. 2006a,b).

The future changes projected by the climate models are, for the most part, a continuation of current trends with the largest increases in air temperature and precipitation projected over the northern Ungava Peninsula. Projected changes are generally of similar magnitude and sign over Nunavik and Nunatsiavut with the exception of snowfall which is projected to increase over Ungava Peninsula and decrease over much of Nunatsiavut. The future climate may also include changes in the frequency and severity of extreme events such as warm spells and heavy rainfall events (Meehl et al. 2007b). There is already documented evidence of increasing precipitation over the Arctic region as well as evidence of increases in the frequency of extreme precipitation events, both attributable to human influences on the climate system (Min et al. 2008, 2011). Scenarios for changes in extreme events were not presented in this chapter as these need to be developed based on particular user needs and locations using the most appropriate downscaling methods for the variables being considered (e.g. Kallache et al. 2011). On a final note, it should be reiterated that the Nunavik-Nunatsiavut IRIS region is characterized by important sources of climate variability that influence the regional climate on decadal and multi-decadal time scales. For some variables such as local precipitation, the internal climate variability will likely dominate any climate change signal over the next 30-50 year time period.
2.6 Acknowledgements

The GCM data used to drive the CRCM were obtained from the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007a). We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP’s Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy. The CRCM output were generated and supplied by the Ouranos Climate Simulation Team.

2.7 References


Furgal, C., Martin, D., Gosselin, P., Viau, A., Nunavik Regional Board of Health and Social Service/Nunavik and Health Committee, Labrador Inuit Association and Labrador Inuit Health Commission. 2002. Climate change and
health in Nunavik and Labrador. What we know from science and Inuit knowledge. Public Health Research Unit, CHUL Research, CHUQ, Québec.


Henoch, W. E., and Stanley, A. 1968. Glacier map of southern Baffin Island (District of Franklin) and Northern Labrador Peninsula. I.W.B. 1006, 1:1,000,000 scale. Glaciology Section, Inland Waters Branch, Department of Energy, Mines and Resources, Ottawa, Ontario.


Kasper, J. N., and Allard, M. 2001. Late-Holocene climatic changes as detected by the growth and decay of ice wedges on the southern shore of Hudson Strait, northern Québec, Canada. The Holocene, 11:563-577.


