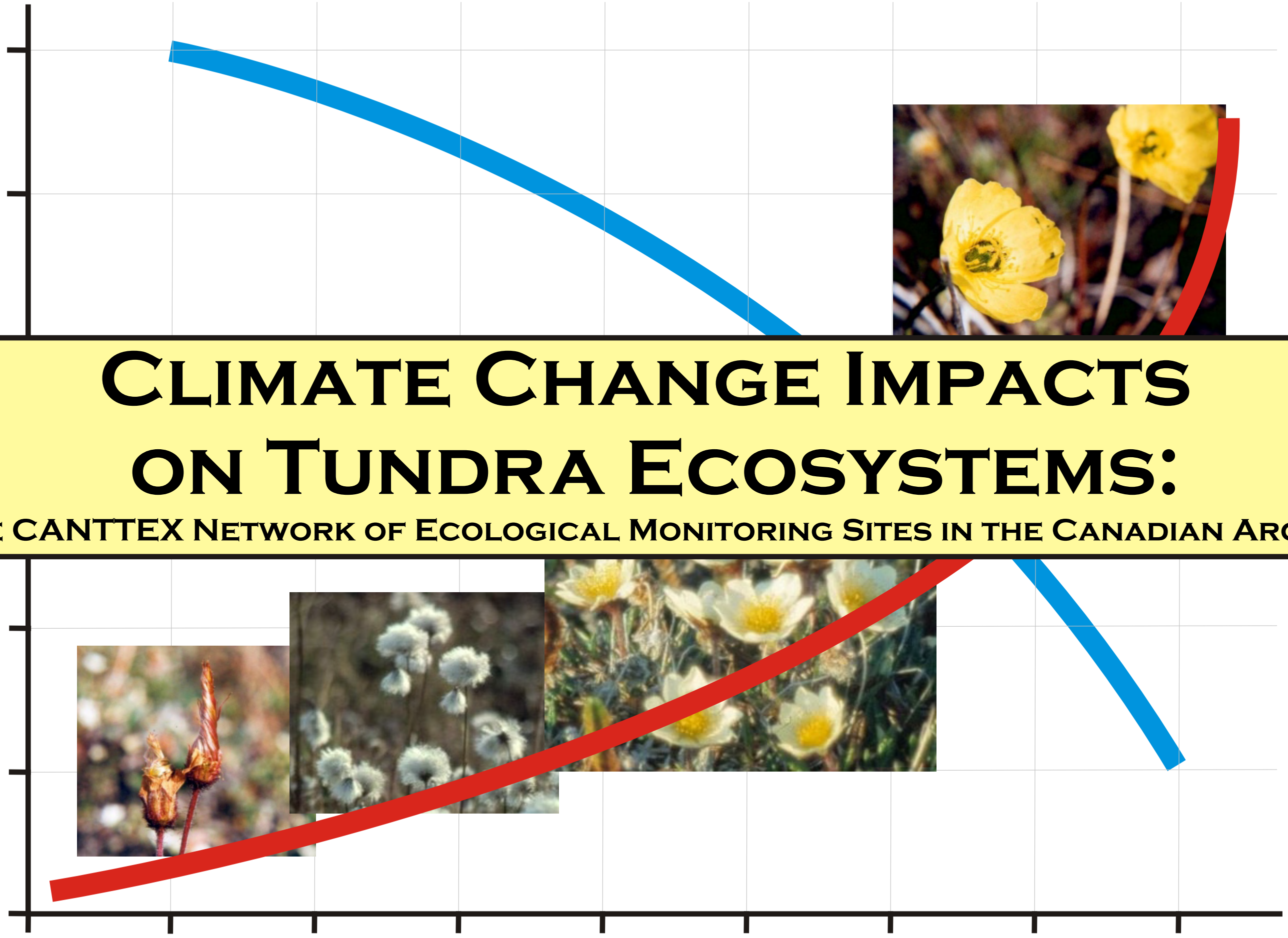
CANTTEX

CANADIAN TUNDRA AND TAIGA EXPERIMENT

ECOLOGICAL MONITORING IN THE CANADIAN ARCTIC



# CLIMATE CHANGE IMPACTS ON TUNDRA ECOSYSTEMS:

## THE CANTTEX NETWORK OF ECOLOGICAL MONITORING SITES IN THE CANADIAN ARCTIC

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EMAN NORTH

## *Introduction*

Most scientists now agree that global warming is taking place, largely due to the activities of humans such as air pollution and deforestation, which affects the concentrations of greenhouse gasses including carbon dioxide ($CO_2$) and methane ($CH_4$) (Houghton *et al*. 1995, Stott *et al*. 2001). The 1990s was the warmest decade on record and average temperatures continue to increase steadily along with considerable changes in precipitation patterns and other elements of the global climate (IPCC 2000). General circulation models designed to simulate global climate predict that warming and other changes will be most intense in the North (Maxwell 1992). Recent evidence supports these predictions (e.g. Sereeze *et al*. 2000, Jorgenson *et al*. 2001) and indicates that the effects of global warming are going to be witnessed over the next few decades. There has been a 25% decrease in the glacier cover in the Rocky Mountains since 1850 (Luckman and Kavanaugh 2000) and an overall downward trend in global glacier cover since the 1960s, particularly in the 1990s (Dyurgerov and Meier 2000, Paterson and Reeh 2001). Changes in the timing of sea ice break-up and freeze-up are impacting polar bear populations (Stirling *et al*. 1999) and will most likely affect marine mammals as well (Tynan and DeMaster 1997). Caribou populations are vulnerable to climatic change largely due to the low productivity of their forage and barriers to dispersal (Gunn and Skogland 1997, Ferguson 1997).

The vegetation of the north is also susceptible to change resulting from climate warming in terms of the position of alpine (Luckman and Kavanaugh 2000) and arctic (MacDonald *et al*. 1998) treeline, plant phenology (Molau 1993, 1997), physiological processes (Chapin *et al*. 1992) and plant community composition (Chapin *et al*. 1995). In central Alaska, Jorgenson *et al*. (2001) found that 30% of a birch forest was replaced by fens between 1949 and 1995 as a result of permafrost degradation. Using remote sensing, Myeni *et al*. (1997) detected an increase in NDVI over the northern high latitudes between 1981 and 1991 indicating greater overall leaf area. Global climate is a highly complex system of lags, responses and feedbacks which can result in changes in phenomena such as permafrost (Burn 1998), sea-ice extent (Wadhams 1995), and vegetation (Arft *et al*. 1999, Chapin and Starfield 1997) that are not in phase with temperature fluctuations. Individual species respond differently to environmental changes which will likely result in significant changes in both structure and function in tundra ecosystems (Chapin *et al*. 1995, Henry *et al*. 1986, Molau 1997). The changes in climate are expected to exhibit significant regional differences (Maxwell 1992) and the response of vegetation is expected to show equal regional differentiation resulting from the local changes in temperature, moisture and nutrient availability (Arft *et al*. 1999, Henry and Molau 1997).

There have been few long-term studies of vegetation response to climate change in the Arctic (Chapin *et al*. 1995). Billings (1997) lists the continuous monitoring of vegetation, soils and other environmental variables as the first priority in climate change research in the North and several authors have expressed the importance of multi-site experiments and monitoring to elucidate the relationships between vegetation and environment (e.g. Henry and Molau 1997). In order to properly monitor the changes in arctic terrestrial ecosystems that will result from climate warming in Canada, and provide information for the assessment of the changes, the formation of a network of integrated research stations is essential. The changes that are predicted will also provide timely opportunities for comparative climate impact research. These are the aims of the Canadian Tundra and Taiga Experiment (CANTTEX), a network of researchers within Canadian universities and government departments collaborating to study climatic and ecological changes in the Canadian North. In addition to sharing in active research results, CANTTEX is now working towards the development of an integrated strategy for monitoring environmental change throughout the Canadian Arctic. The aim of CANTTEX is to establish an effective long-term observation network for detecting the effects of climate change in all major ecoregions of the Canadian North.

This paper serves several purposes. It is an introduction to the CANTTEX network and shows the availability of existing data and the status of current ecological monitoring in the Canadian Arctic. A preliminary analysis of some of the many variables and methods of measurement and analysis is done to provide an indication as to which variables are sensitive to environmental changes and merit continued monitoring. This will aid the development of common monitoring protocols at CANTTEX sites. Finally, the presentation of data from the six major sites included in the analysis demonstrates the effectiveness of monitoring similar variables at many sites. However, it is clear that many more data are required to improve the inferences and predictive power that are desired in the field of climate change impacts research. In addition, it is hoped that this will encourage new researchers and agencies to implement CANTTEX monitoring programs at their research sites, expanding the geographical extent of the network.

The first section will briefly describe the origin and development of the CANTTEX network. Then the CANTTEX sites are described and a list of the past and present research and monitoring endeavours is provided. The results in the next section are meant to demonstrate the opportunity for multi-site analysis and the potential of the CANTTEX network. For this reason, results are presented for plant phenology and growth measurements for one or two widespread plant species in relation to climate data. As the descriptions of current monitoring activity at each site will attest, there are many more variables and data from more sites that will have to be considered in an exhaustive synthesis of all CANTTEX results.

## *Background*

The International Tundra Experiment (ITEX) was initiated in 1990 (Henry and Molau 1997). It is a collaborative, multi-site network using common monitoring protocols and, initially, temperature manipulation at 22 sites to examine variability in species response across climatic and geographic gradients of tundra ecosystems (Molau and Mølgaard 1996). There are currently five sites in Canada that are employing ITEX experimental manipulations and a further four sites using ITEX protocols to monitor vegetation phenology. The short-term results of ITEX manipulations on individual species and growth forms (functional groups; *cf* Chapin *et al*. 1996) were presented in a special supplement of the journal Global Change Biology (Henry 1997), and a recent meta-analysis from all active ITEX sites (Arft *et al*. 1999).

The need for cooperation among the few researchers carrying out ecological monitoring and research in the Canadian Arctic led to the establishment of the Canadian Tundra Ecosystem Monitoring Network (CANTEM-Net) at a workshop during the Ecological Monitoring and Assessment Network (EMAN) National Science Meeting in 1999. At the workshop in January of 2000 the name of the group was changed to the Canadian Tundra and Taiga Experiment (CANTTEX) to reflect both the range of environments covered by the network of sites and scientists, and the links to ITEX. The aim of CANTTEX is to encourage and facilitate sharing ideas, data and information, and cooperation in research and monitoring initiatives in arctic tundra and taiga ecosystems. CANTTEX encompasses two complimentary approaches involving both multiple site comparisons and intensive local site studies including experiments. The former focuses on comparisons of a set of basic biotic measurements along climatic or geographic gradients. The latter focuses on studies on various spatial scales including an experimental component, such as warming and/or fertilization. The success of the CANTTEX network depends on a community of researchers willing to maintain long-term sites where common protocols for monitoring are adopted.

Management of CANTTEX is provided by EMAN-North, a network for the coordination of ecological monitoring in northern Canada (Yukon, NWT, Nunavut and northern regions of some provinces). Support has been pieced together from various ephemeral and generally uninvolved agencies. However, the Northern Ecosystems Initiative (NEI), a program of Environment Canada, is funding this important phase in the development of CANTTEX and EMAN-North and it is hoped that these projects will raise the profile of CANTTEX and the importance of continuous ecological monitoring in Canada’s North.

## *CANTTEX Sites*

At the present time, there are 13 research and monitoring sites in the CANTTEX network (Fig. 1). The sites span a latitudinal gradient from the sub-arctic alpine site at the Kluane Research Station to Tanquary Fiord at the north end of Ellesmere Island, Canada’s most northern landmass. There is also a range in the intensity of monitoring and research among the sites depending on the resources and interests of the agency or people responsible for the site (see site descriptions below).

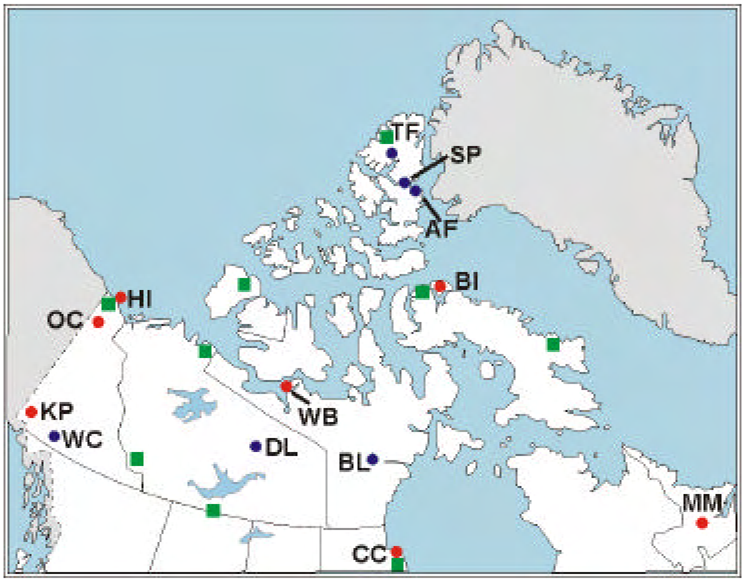

Figure 1. Canadian Arctic showing the locations of CANTTEX sites (circles) and National Parks (green squares) some of which are operating ecological monitoring programs. High Arctic sites: AF – Alexandra Fiord Lowland, BI – Bylot Island, SP – Sverdrup Pass, TF – Tanquary Fiord; Low Arctic sites: BL – Baker Lake, CC – Churchill Northern Studies Centre, DL – Daring Lake, HI – Hershel Island, OC – Old Crow, WB – Walker Bay; Subarctic alpine sites: KP – Kluane Park, MM – Mealey Mountains, WC – Wolf Creek. Blue circles are sites that contributed data to this review.

## High Arctic Sites:

### *Alexandra Fiord Lowland*

The Alexandra Fiord site is an 8 km$^2$ lowland located on the eastern side of Ellesmere Island (78° 53’ N, 75° 55’ W). It is an oasis relative to the surrounding polar desert and has been the subject of considerable ecological research over the last 20 years (Svoboda and Freedman 1994). The lowland is a roughly triangular outwash plain that slopes gently (1-3%) upwards from the shoreline at its northern border. The lowland topography is dominated by a series of well-defined beach ridges. At the southern end there are two outlet glaciers and the east and west sides are bordered by 500-700 m cliffs and talus slopes. The average annual temperature at Alexandra Fiord is -12°C and average temperature during the snow-free period is 5.1°C (Figure 2; Labine 1994). The average growing season length is 88 days.

Roughly 90% of the lowland is covered by closed or semi-closed vegetation (Muc *et al*. 1989), which is significantly greater than the 5% vegetation cover of the surrounding polar deserts (Bliss *et al*. 1994). There have been 96 species of vascular plants identified, 104 taxa of mosses and liverworts and at least 119 taxa of lichens. Approximately 50% of the lowland is covered by a mesic-xeric dwarf-shrub heath dominated by combinations of *Cassiope tetragona, Dryas integrifolia,* and *Salix arctica*. Wet-mesic soils support sedge meadows on 20% of the lowland and the remainder is covered by various other plant communities and some rock outcrops and barren ground (Muc *et al.* 1989).

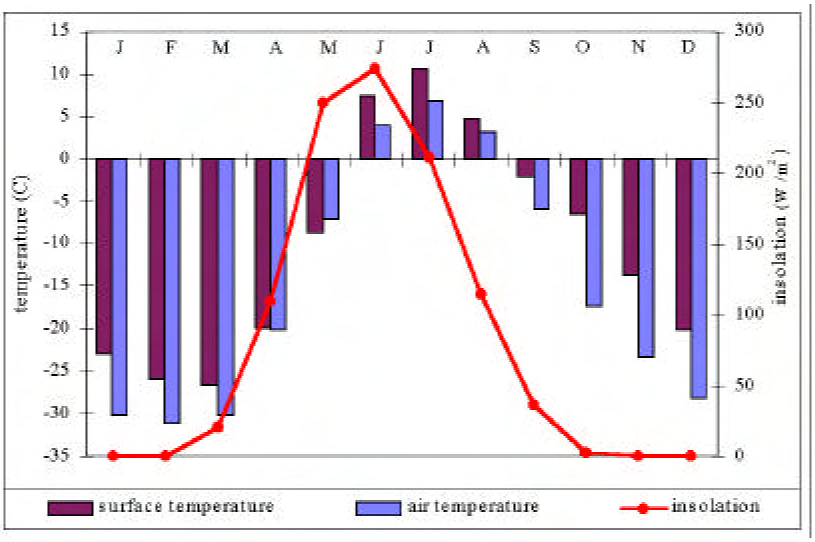

Figure 2. Mean monthly temperature and insolation at the Alexandra Fiord lowland based on data from 1989-2001.

*Table 1. Monitoring and Research at Alexandra Fiord*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | 1 climate station<br>2 autostations, 16 variables<br>Temperatures in and out of OTCs[1] | 1980 –1987 summer<br>1989 - present (all year)<br>1992 - present | No<br>Yes<br>Yes |
| Experimental manipulations | 14-20 OTCs for warming at each of 7 sites<br>OTCs ± snow , ± fertilizer<br>Snow manipulations in late-lying snowbed | 1992 – present<br>1995 – present<br>1992 – present | Yes<br>Yes<br>Yes |
| Vegetation composition | Cover and biomass data from all experimental plots | 1992 - present | Yes |
| Vegetation phenology | Phenological observations from all experimental plots | 1992 - present | Yes |
| Active layer depth | In OTCs and control plots<br>10 m X 10 m active layer grid | 1992 – present<br>1996 – present | Yes |
| Glacier retreat | Annual measurements from stakes established in previous year | 1980-1984,<br>1992- present | Yes |
| Bird arrival | Dates of first sightings and nests | 1980 – 1984<br>1992 - present | Yes |
| Woolly-Bear Caterpillar monitoring | Observing density and age-class of caterpillars along transects | 1993 – present | Yes |

[1] Open top chambers (OTCs) constructed of greenhouse fibreglass: octagonal, with inclined sides, 1.5 m across the top.

### *Bylot Island*

This site is located in a glacial valley on the northern part of Bylot Island (73° 08' N, 80° 00' W), which is located just north of Baffin Island. Research at this site is focused on the importance of the area for grazing snow geese. Site descriptions and recent research can be found in Gauthier *et al*. 1996 and Masse *et al*.

2001 among others. Figure 3 shows temperature data from Pond Inlet on Baffin Island, roughly 60km east of the Bylot Island site.

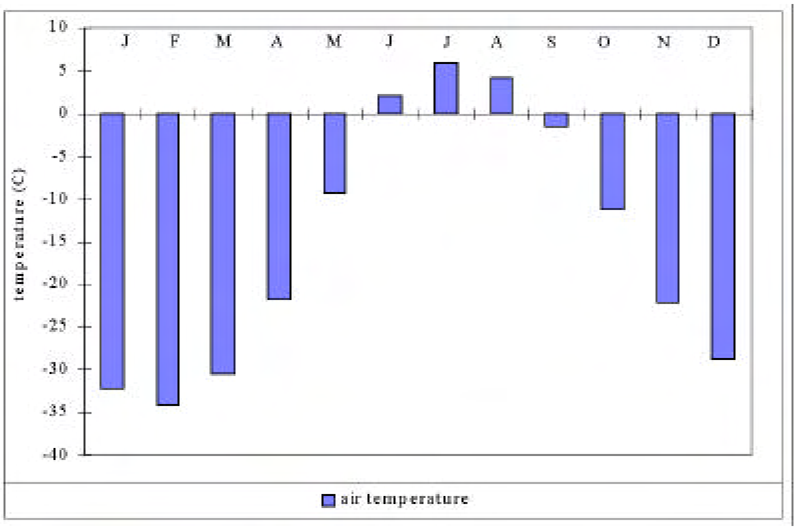

Figure 3. Mean monthly temperature at the Pond Inlet based on data from 1975-1999.

*Table 2. Monitoring and Research at Bylot Island*

| **Variables & studies** | **Sampling design & methods** | **Duration** | **Active** |
|---|---|---|---|
| Climate | Maintenance of an automated weather station<br>Monitoring of ground temperature in areas grazed and ungrazed by geese<br>Monitoring of spring snow-melt phenology. | 1995 – present<br>1995 – present<br>1995 – present | Yes<br>Yes<br>Yes |
| Goose population ecology | goose nest distribution and nesting activity<br>Goose survey and banding | 1995 – present<br>1995 – present | Yes |
| Other animal monitoring | nesting activity of other bird species, monitoring of lemmings and foxes | 1995 – present | Yes |
| Vegetation | Plant production in grazed and ungrazed wetlands<br>plant production in long-term exclosures | 1995 – present<br>1995 – present | Yes<br>Yes |
| ITEX | Monitoring of an ITEX site in wetlands<br>Monitoring of an ITEX site in mesic tundra | 1995 – present<br>1998 – present | Yes<br>Yes |

### *Sverdrup Pass*

Sverdrup Pass is an ice-free corridor running east-west across the centre of Ellesmere Island. It is considered to be a polar oasis like Alexandra Fiord and Truelove Lowland (Henry *et al*. 1986). On the valley floor the vegetation is a complex mosaic including willow fields and wet meadows (Bergeron and Svoboda, 1989) The research site is located at 79°10'N, 79°30'W at an elevation of 330 m a.s.l. A climate station was established in 1989 at a wet meadow in proximity to the base camp (Fig. 4). Ecological studies have been conducted in the valley since 1981, with most completed in the early 1990's (e.g. Lévesque and Svoboda 1992; Lévesque *et al*. 1997, Raillard and Svoboda 2000).

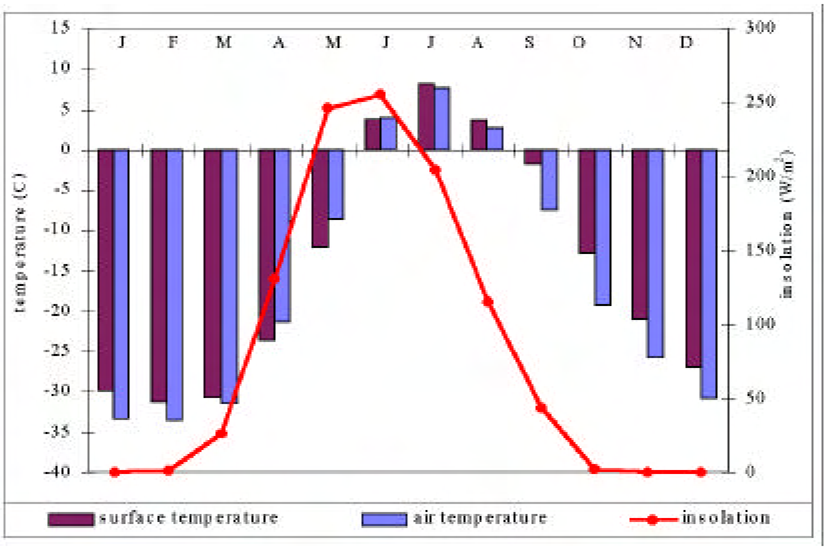

Figure 4. Mean monthly temperature and insolation at Sverdrup Pass based on data from 1986-2001.

*Table 3. Monitoring and Research at Sverdrup Pass*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | Polar desert climate station<br>Meadow climate station | 1988 – 1989<br>1989 – present | No<br>Yes |
| Plant phenology | Papaver radicatum | 1990 – 1993 | No |
| Competition experiment | Removal of dominant sedge species (*Carex stans*) from 50x50 cm plots | 1989 – present | Yes |
| Vegetation composition | Visual assessments from quadrats | 1986 | No |
| Effects of grazing by muskoxen | Observations and clipping experiments<br>Plant demography | 1986 – 1990<br>1995 – 1996 | No<br>No |

***Tanquary Fiord (Quttinirpaaq National Park)***

Tanquary Fiord (81°24' N, 76°52' W) is located within Quttinirpaaq National Park Reserve, which was formally established in 1988. The major entrance and headquarters for the park are located at Tanquary Fiord. Most of the area within the park reserve is classified as polar desert and semi-desert. Low precipitation, rapid ablation and sublimation of snow cover and surface moisture in springtime, and coarse surface rock debris limit the distribution and abundance of plants. *Papaver radicatum* and *Saxifraga oppositifolia* are the most common flowering plants, occurring wherever there are sufficient moisture and nutrients. Plant species lists for Quttinirpaaq National Park record 151 species of vascular plants, 192 bryophytes, and 44 lichens. Average annual temperature at Tanquary Fiord is -17°C, with mean July temperature reaching 6.5°C (Figure 5).

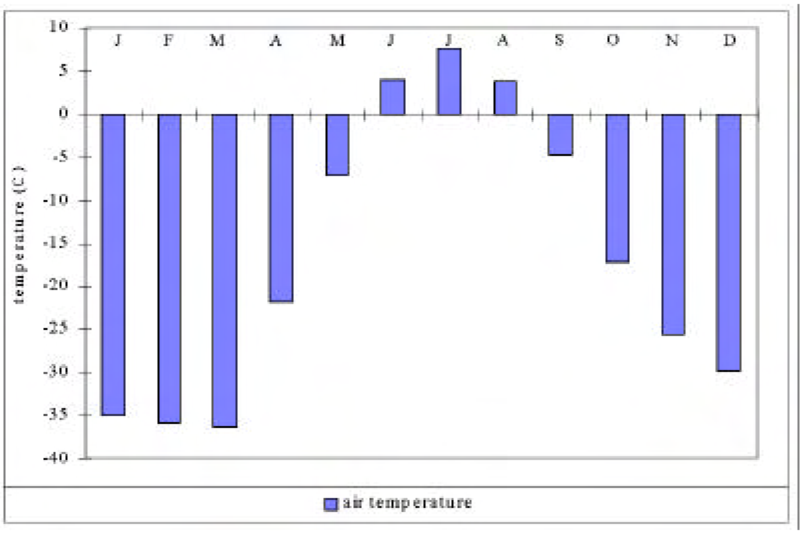

Figure 5. Mean monthly air temperature at Tanquary Fiord based on data from 1989-2001.

*Table 4. Monitoring and Research at Tanquary Fiord*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | Autostation recording 6 variables | 1986 - present | Yes |
| Plant phenology | 2 species | 1994 - present | Yes |

## Low Arctic Sites:

### *Baker Lake*

The community of Baker Lake is situated on the northwest shore of Baker Lake, near the mouth of the Thelon River (64° 12' N, 95° 30' W). The Hanbury, Kazan, and Dubawnt rivers also flow into the lake and it is connected to Chesterfield Inlet, which opens on the east coast of Hudson Bay. The community is located on relatively flat tundra, sloping up from the beach to rocky ridges one kilometre inland. The area is characterized by lowland plains covered with glacial moraines. Uplifted raised beach ridges follow the contours of the lake at increasing elevation. These shorelines are rocky with numerous cliffs on the north side of the lake. The Baker Lake area has a low arctic ecoclimate, with a mean annual temperature of –11°C. Mean summer temperature is 4.5°C and mean winter temperature is –26.5°C (Figure 6). The mean annual precipitation ranges from 200-300 mm with an average of 13.8 cm of rainfall and 100.0 cm of snowfall. Prevailing winds are from the north averaging 21.6 km/h (Outcrop 1990) and wind drifting of snow is extensive.

*Table 5. Monitoring and Research at Baker Lake*

| Variables and Studies | Sampling design and Methods | Duration | Active |
|---|---|---|---|
| Climate | meteorological station at airport<br>1 autostation<br>temperatures in and out of OTCs<br>soil temperatures at snow fence | Pre-1990s-present<br>1995-present<br>1995-1998<br>1997-present | Yes<br>Yes<br>Yes<br>Yes |
| Experimental Manipulations | 5 OTCs in a *Dryas* heath<br>6m x 1.5km snow fence | 1995-present | Yes |

(Continued …)

*Table 5. Monitoring and Research at Baker Lake (continued)*

| Variables and Studies | Sampling design and Methods | Duration | Active |
|---|---|---|---|
| Plant phenology | 3 species monitored in controls<br>in and out of OTCs<br>in the snowdrift zone | 1992-present<br>1995-1998<br>1992-1998 | Yes<br>Yes<br>Yes |
| Vegetation structure | Abundance and composition along snow melt gradient | 1992 – present | Yes |
| Active layer depth | Four 3 m deep bore holes, 100 m apart | 1997-present | Yes |

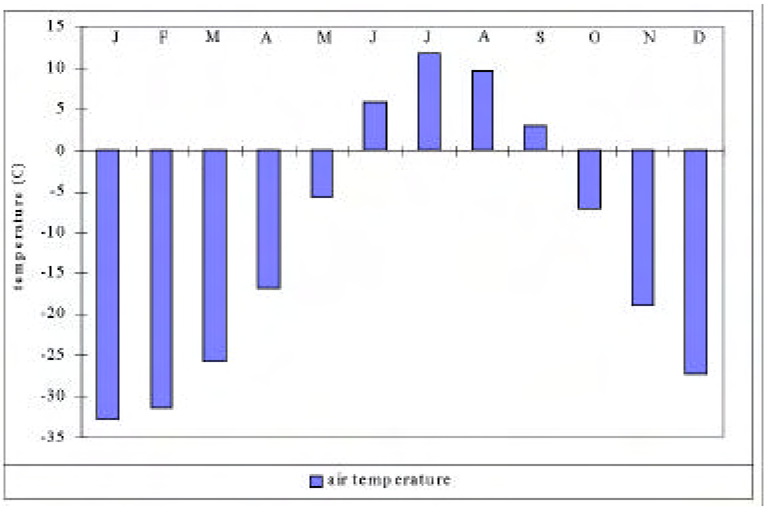

Figure 6. Mean monthly temperature at Baker Lake based on data from 1990-1999.

### *Churchill Northern Studies Centre*

The Churchill Northern Studies Centre has set up a suite of long-term research sites that are located on either side of the relatively abrupt treeline in the Churchill area. The sites represent tundra, disturbed tundra, and disturbed-treated tundra. Corresponding sites have been established in open lichen-spruce woodland. Monitoring will involve a series of parameters to include daily, seasonal, and annual processes. This will include, air temperature, rainfall, ground thaw, snow depth, snowmelt, plant phenology and growth. Preliminary research includes bioinventories, standing biomass/carbon, stored carbon, and disturbance history. This program is designed to provide monitoring data and background research as a contribution to other networks and to facilitate more intensive short-term projects either on, or between sites.

In addition to the Churchill Northern Studies Centre, local residents Bill and Diane Erikson have been monitoring phenology on *Dryas integrifolia*, *Saxifraga oppositifolia* and *Saxifraga tricuspidata* since 1995. Their site is located about 100m from the shore of Hudson Bay (59º 45’ N, 90º 04’ W). The site is located on a ridge of gravel deposits on coastal granitic bedrock in close proximity of a fully automated AES weather station.

*Table 6. Monitoring and Research at the Churchill Northern Studies Centre*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Plant phenology | 3 species monitored | 1995-present | Yes |

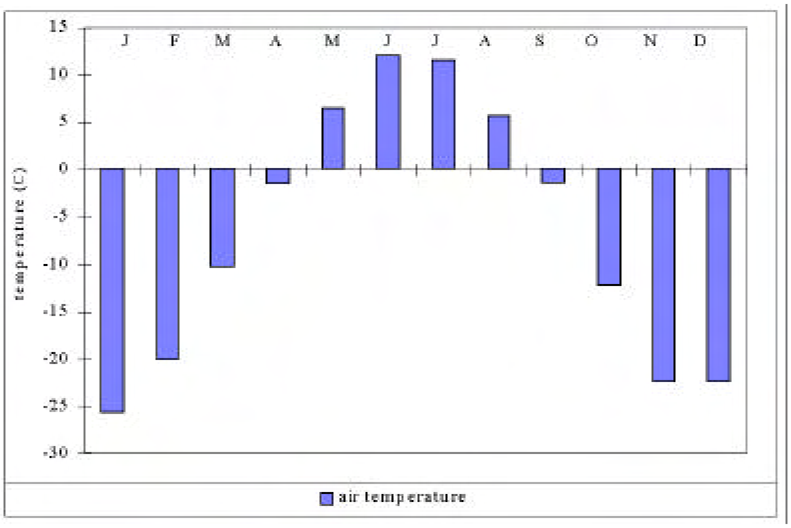

Figure 7. Mean monthly temperature for Churchill, Manitoba based on data from 1943-1999.

***Daring Lake***

The Tundra Ecosystem Research Station (TERS) was established in 1994 on the shore of Daring Lake (64° 52' N, 111° 35' W), approximately 350 km NE of Yellowknife. The station was established by researchers in the Dept of Renewable Resources, Wildlife and Economic Development (RWED), government of NWT, to provide a base of study and research of the southern low Arctic ecozone. The site is approximately 75 km northeast of treeline and is dominated by low arctic shrub tundra with continuous permafrost. A climate autostation has been operating since 1996, and the mean July air temperature is 12°C (Figure 8).

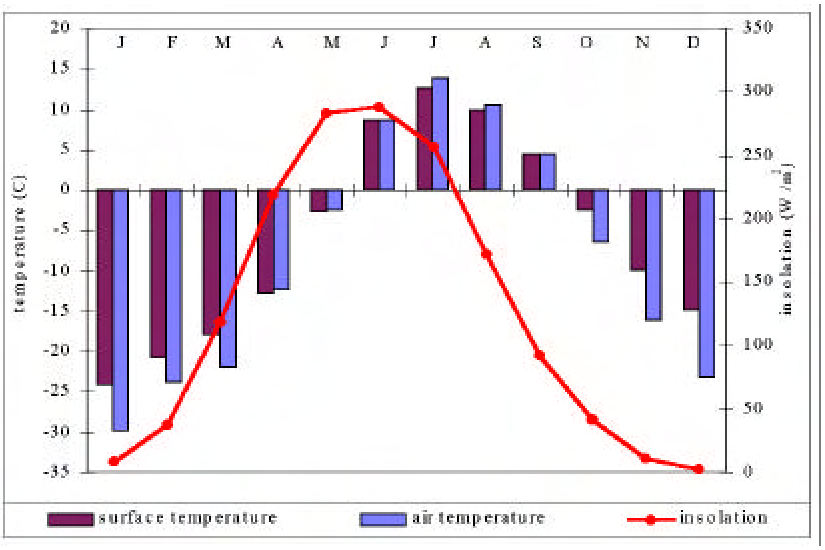

Figure 8. Mean monthly temperature and insolation Daring Lake based on data from 1996-2001. Surface temperature is at 0 cm in soil profile.

*Table 7. Monitoring and Research at Daring Lake*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | Autostation recording 14 variables | 1996-present | Yes |
| Vegetation composition | Cover data from OTCs | 1999 - present | Yes |
| Experimental manipulations | OTCs for warming, 3 species | 2000 - present | Yes |
| Plant Phenology | 8 species | 1996 – present | Yes |
| Hydrologic regime | Water balance of small tundra lake & various other | 1999 - present | Yes |
| Animal population and ecology | Grizzly bear | 1995 - present | Yes |
|  | Wolverine | 1995 - 2000 | No |
|  | Wolf | 1995 - present | Yes |
|  | Small mammals | 1995 - present | Yes |
|  | Arctic hare | 1999 - present | Yes |
|  | Raptors | 1995 - present | Yes |
|  | Caribou | 2000 - present | Yes |

***Hershel Island***

Hershel Island is located in the Beaufort Sea just off the coast of the Yukon Territory and the monitoring site is located within a territorial park. The Island has a maximum elevation of approximately 100 m a.s.l. Soils are composed primarily of silt and clay with minor sands and gravels. The upland soils of Herschel Island have an active layer that averages 20 to 40 cm thick overlying ice-rich permafrost. The tundra vegetation cover is composed of low shrubs with diverse forbs and graminoid cover. Three plant species are being monitored: *Salix arctica* in a coastal *Salix*/herb meadow community with sandy soils, *Dryas integrifolia* in a mesic *Dryas*/herb community with hummocky microtopography, and *Eriophorum vaginatum* in a mesic tussock tundra community.

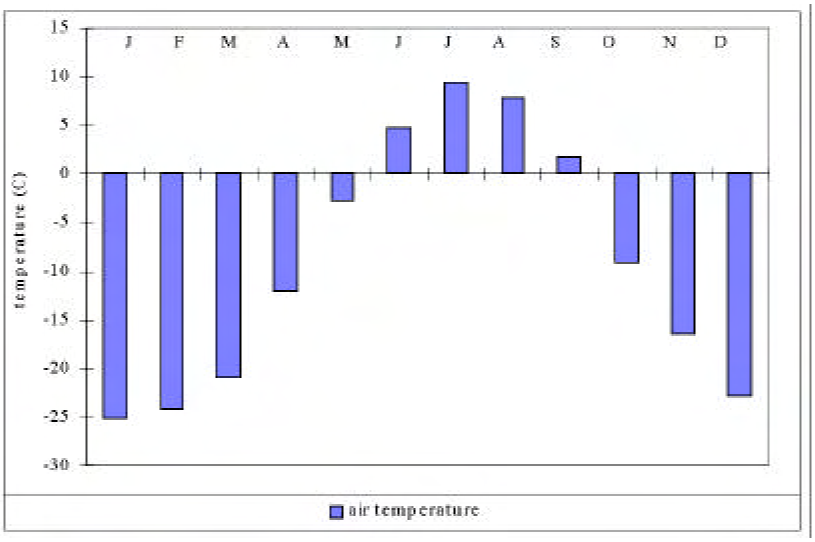

Figure 9. Mean monthly temperature for Hershel Island based on data from 1974-1999.

*Table 8. Monitoring and Research at Hershel Island*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | Soil and air temperature | 1999 – present | Yes |
| Vegetation | 5 long-term plant community monitoring plots | 1999 – present | Yes |
|  | Phenological observations for three species | 1999 – present | Yes |

### *Old Crow*

Old Crow is a community located in the northwest Yukon. This project is co-operatively maintained by the Old Crow Renewable Resource Council and Canadian Wildlife Service, as part of the Arctic Borderlands Ecological Knowledge Co-op. Start-up funds were supplemented by a grant from the Northern Research Institute of Yukon College. Permanent vegetation monitoring plots were established in three different vegetation types spanning an elevation gradient from the floodplain where the town is located to an area of adjacent alpine tundra. The lowest elevation site is in a poorly-drained lowland spruce (*Picea glauca* and *P. mariana*) woodland. The middle site is located in a moderately drained spruce woodland on an upland river terrace. Both woodland sites are characterized by widely-spaced trees with ground cover of abundant mosses and evergreen and deciduous shrubs. The highest elevation site is located in patterned tundra dominated by lichens and *Dryas octapetala* on raised hummocks and *Betula glandulosa* in inter-hummock areas.

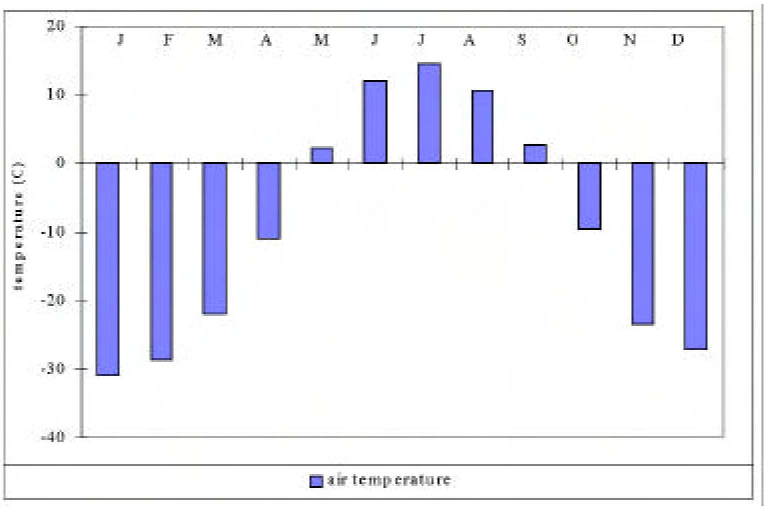

Figure 10. Mean monthly temperature for Old Crow based on data from 1951-1999.

*Table 9. Monitoring and Research at Old Crow*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | Soil temperature monitored at taiga site | 1997 – present | Yes |
| Vegetation | Six long-term vegetation monitoring plots in 3 community types | 1997 - present | Yes |

### *Walker Bay*

The Walker Bay study area (68°21’ N, 108°05’ W) is a shallow valley transected by a small sinuous river on the north-central coast of the Northwest Territories. The valley is characterized by a fine-grained mosaic of ponds 0.10-1.00 m deep, small lakes and meadows of various shapes on a silt bed. This site is characterized by a low arctic ecoclimate with a mean annual temperature of –14°C, a summer mean of 2°C and a winter mean of –28.5°C (Fig. 11). Daily temperatures are above 0°C for 115 days on average each year. Annual rainfall is approximately 7.3 cm and snowfall is within 80 cm every year. Several creeks and rivers drain the area and low gradient, permafrost and extreme hardness of the rock aggravate the drainage conditions causing a maze of lakes and rivers. The flora of the area is comprised of a nearly continuous cover of dwarf shrub tundra vegetation, consisting of dwarf *Betula*, *Salix*, *Dryas* spp., and *Vaccinium* spp. and wet sites are dominated by *Salix* and sedges. Twelve species of mammals and approximately 67 bird species have been observed at Walker Bay.

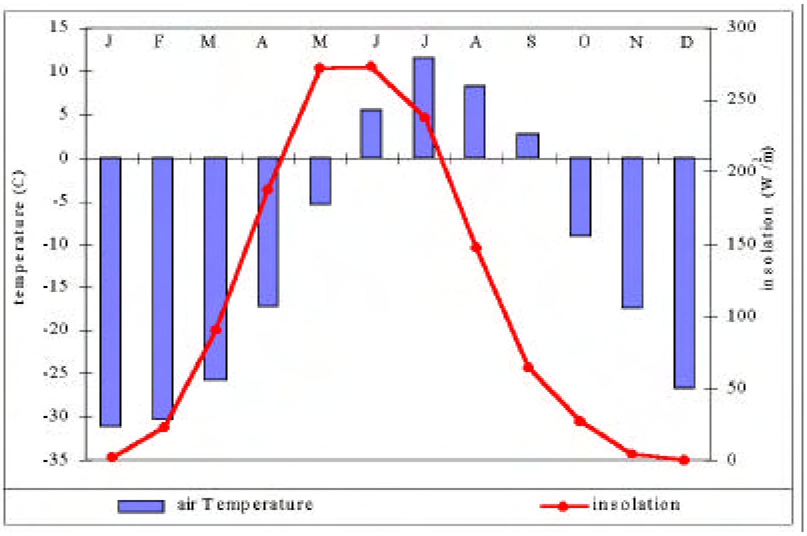

Figure 11. Mean monthly temperature and insolation at Walker Bay based on data from 1996-2000.

*Table 10. Monitoring and Research at Walker Bay*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | Autostation recording 10 variables | 1996 - present | Yes |
| Snow phenology | 2 Snowmelt transects | Not available | |
| Active layer depth | 2 Thaw transects | Not available | |
| Bird phenology | Arrival and nesting dates of bird species | Not available | Yes |
| Waterfowl ecology | Population ecology study on geese and sandhill cranes | 1987 - present | Yes |
| Small mammal studies | Lemming population study | 1994 - 1997 | No |

## Subarctic Alpine Sites:

### *Kluane Research Station*

Kluane Lake Research Station (KLRS) is located near the Alaska Highway, 220 km northwest of Whitehorse, Yukon, on the south shore of Kluane Lake. The extreme elevation difference between Kluane Lake and the crest of the St. Elias Mountains establishes a strong gradient in environmental characteristics and results in a remarkable diversity of research opportunities within a small geographical area. This diversity is reflected in the unique scientific legacy of KLRS (e.g. Graham and Turkington 2000, Hik 1995, Krebs *et al*. 2001). Since 1961, when the base was founded, it has fostered research projects spanning the disciplines of glaciology, geomorphology, geology, biology, botany, zoology, hydrology, limnology, climatology, high-altitude physiology, anthropology and archaeology.

Table 11. *Monitoring and Research at the Kluane Lake Research Station*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | Autostation(s) | Not available | |
| Small Mammal Ecology | Population dynamics of collared pikas, Arctic ground squirrels and hoary marmots | Not available | |

(Continued …)

Table 11. *Monitoring and Research at the Kluane Lake Research Station (continued)*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Vegetation | Effects of herbivory on species composition, productivity and demography of alpine meadows<br>Chemical and nutritional characteristics of alpine plants | Not available | |
| Experimental Manipulations | Herbivore Exclosures<br>OTCs<br>Snow manipulations<br>Nutrient additions | Not available | |

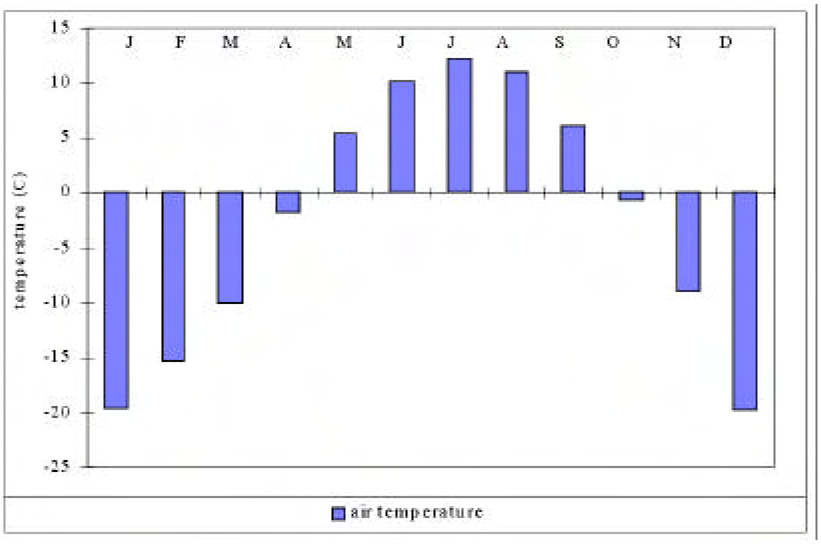

Figure 12. Mean monthly temperature at Kluane Lake (conditions in boreal forest) based on data from 1946-1983.

### *Mealey Mountains*

The Mealey Mountains site was initiated in the summer of 2001 to fill a major gap in the spatial coverage of the CANTTEX network. The study area is approximately 20 km SE of Lake Melville, on the south side of an unnamed 1057 m mountain in the Mealy Mountain range in eastern Labrador (53° 38' N, 58° 52' W). The study area includes the mountain and the adjacent eastward-trending valley, which drains into the Eagle River Basin. The upper site is located in alpine tundra with vegetation occurring on a series of south-facing terraces with seepage areas intermixed with exposed bedrock. On the drier edges of the terraces *Diapensia lapponica* occurs frequently, whereas *Silene acaulis* is uncommon and found on a few fine gravely till areas. Patterned ground in the form of frost boils is prevalent in many of these areas. Seepage areas are dominated by *Carex bigelowii* and *Salix herbacea* as a sedge-willow community, whereas the slope communities between each terrace consist of *S. herbacea*, *Cassiope hypnoides*, *Sibbaldia procumbens* and *Gnaphalium supinum.* The lower site is located in taiga vegetation on the open crest of an esker and consists of prostrate growing ericaceous shrubs such as *Arctostaphylous alpina*, *Empetrum nigrum*, *Rhododendron* (*Ledum*) *groenlandicum*, *Vaccinium vitis-idaea*, and *V. uliginosum.* On the edges of the esker, *Picea mariana* and *Betula glandulosa* dominate and are dense with an erect growth habit.

*Table 12. Monitoring and Research at the Mealey Mountains Site*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | Autostation | 2001 – present | Yes |
| Vegetation | Composition<br>Phenology of *Salix* and *Diapensia* | 2001 – present<br>2001 – present | Yes<br>Yes |
| Experimental Manipulations | 4 OTCs | 2001 – present | Yes |
| Permafrost and active layer monitoring | | 2001 – present | Yes |

***Wolf Creek***

The Wolf Creek study site is located in the alpine zone within the Wolf Creek drainage basin (60°34' N, 135°08'W) in southeastern Yukon Territory. The site is located *ca*. 1 km from the Wolf Creek alpine climate station on the same ridge system. The site is characterized by a relatively homogeneous vegetation community dominated by mat-forming shrubs (*Dryas* sp. and *Salix* sp.), lichens (*Alectoria* sp. and *Cetraria* sp.), *Festuca altaica* and *Lupinus arcticus*. Soils are mesic to xeric, with a high gravel and rock component, little to no humus development, and frequent bare areas caused by active frost boils. Experimental plots are located in an area with a SSE aspect and a shallow slope (estimated at 3-5°). Evidence of current grazing activity is sparse, although lemming/vole and ptarmigan feces were observed at the study site and ground squirrels and ptarmigans have been seen in the general area. Figure 8 shows the mean monthly surface temperature pattern at Wolf Creek over the past 3 years.

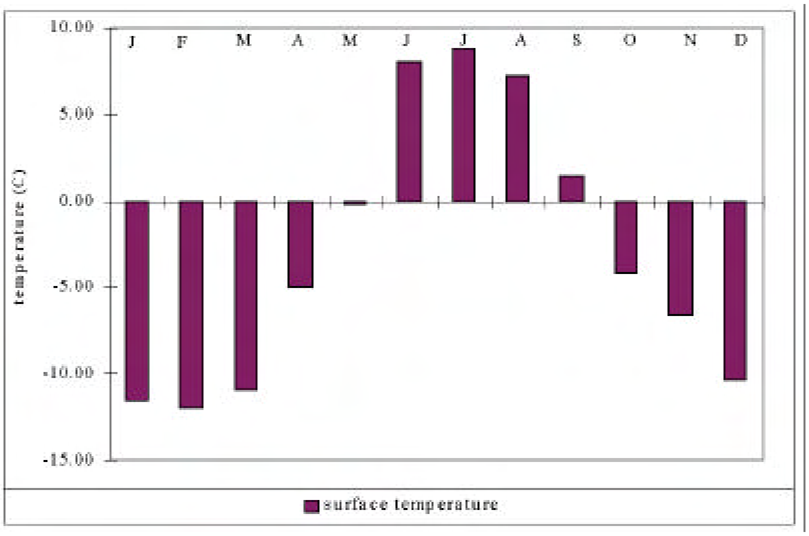

Figure 13. Mean monthly surface temperature at Wolf Creek based on data from 1998-2001.

*Table 13. Monitoring and Research at Wolf Creek*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Climate | data loggers record above ground and below temperatures and relative humidity in and out of OTCs;<br>Nearby climate station records 13 variables | 1998 - present<br>September 1993 - present | Yes<br>Yes |
| Experimental manipulations | 10 controls and 10 OTCs. | July, 2001 – present | Yes |
| Vegetation composition | Cover and biomass data from OTCs and control plots | Plant Cover - 1998<br>Biomass - 1999. | N/A |

(continued …)

*Table 13. Monitoring and Research at Wolf Creek (continued)*

| Variables & studies | Sampling design & methods | Duration | Active |
|---|---|---|---|
| Density of reproductive structures | # of reproductive structures by species is counted every July in 1m x 1m quadrat | 1998 – present | Yes |
| Plant Measurements | Measurements of *Dryas octopetala*, *Polygonum viviparum*, *Salix arctica*, and *Lupinus arcticus* in all 20 plots are taken every July. | 1999-present | Yes |

## Methods

Due to the variability of environment, monitoring intensity, and length of record it was not possible to compare identical observations at each site. However, many sites monitor plant phenology and growth variables and have climate stations that have been operating for several years (see previous section). The field methods used at each of the sites are similar, all of which are based on the ITEX protocols (Molau and Mølgaard 1996). The results presented below represent an example of the observations that are being made at the various sites. The sites included are only those with a minimum of three years of climate and vegetation growth and/or phenology measurements. At sites with warming or other manipulations, the observations are only those from the unmanipulated control plots. The analyses were limited to two or three variables from one or two plant species per site. Observations based on less than five plants were discarded.

There are two ways to study these data: as a time series looking for a long-term trend in the biological variable being measured, and in comparison to environmental data to examine the relationships between abiotic variability and biotic response. The dates of important phenological stages and measures of annual growth and reproductive effort are, therefore, plotted in time-series and against the total thawing degree-days (TDD, sum of average daily air temperatures > 0°C) for the growing season to show both trends over time and relationships to summer temperatures. Arctic plants are known to store resources and prepare leaf and flower buds in the year before they open (Sørenson 1941, Bell and Bliss 1980). For this reason, the phenological observations were also compared to the previous year's thawing degree-days. The date of snowmelt was the last environmental variable that was examined. The phenological stages described in the results refer to the first date at which one flower on the monitored plant reached the stage. Regressions were calculated on the site mean values and results are presented on a site-by-site basis.

## Results

## High Arctic Sites:

### *Alexandra Fiord*

At the Alexandra Fiord site observations and measurements are made in four community types arrayed along a soil-moisture gradient. The Meadow site is located in a wet sedge community dominated by *Carex stans*, *C. membranacea* and *Eriophorum angustifolium*. The Cassiope site is in a mesic heath community, dominated by the evergreen dwarf shrub, *Cassiope tetragona*. The Willow site is located on a relatively dry riverbank, and is dominated by the deciduous dwarf shrub, *Salix arctica*. The Dryas site is a mesic community, dominated by *Dryas integrifolia*. Results are presented for two phenological stages and one growth measurement in *Dryas integrifolia* at the Cassiope site and three phenological stages of *Papaver radicatum* at the Dryas site.

The time-series of observations from Alexandra Fiord, like the other stations, is not long enough to show a long-term trend (Figs. 14A&B and Fig. 15A). Monitoring over several more years will be required to detect any sustained change in phenology, growth or reproductive output. The relationship between *Dryas* observations and thawing degree-days presents some more interesting results. In 1996 the thawing degree-days were 315, which was 28% lower than the average of the 9 years of record. *Dryas* Phenological events occurred much later in 1996 at most sites (Fig. 14C). Linear regression shows a negative relationship between thawing degree-days and first flower bud of *Dryas* ($R^2 = 0.64$, $P<.03$), though this relationship is dominated by the influence of the 1996 data. If the 1996 data are disregarded, the rest of the record shows a contraction of the time between flowering and fruiting as thawing degree-days increase. The flower height of *Dryas integrifolia* demonstrates a more reliable trend decreasing in both height ($R^2 = 0.64$, $P< .02$) and variability as thawing degree-days increase. The *Dryas* results are supported by the *Papaver* data. There is a weak trend towards earlier dates of phenological stages with increasing current season's thawing degree-days (Fig. 15B). For new leaves and elongating flower buds linear regression results in an $R^2$ of 0.52 ($P<.03$) and 0.53 ($P<.03$), respectively.

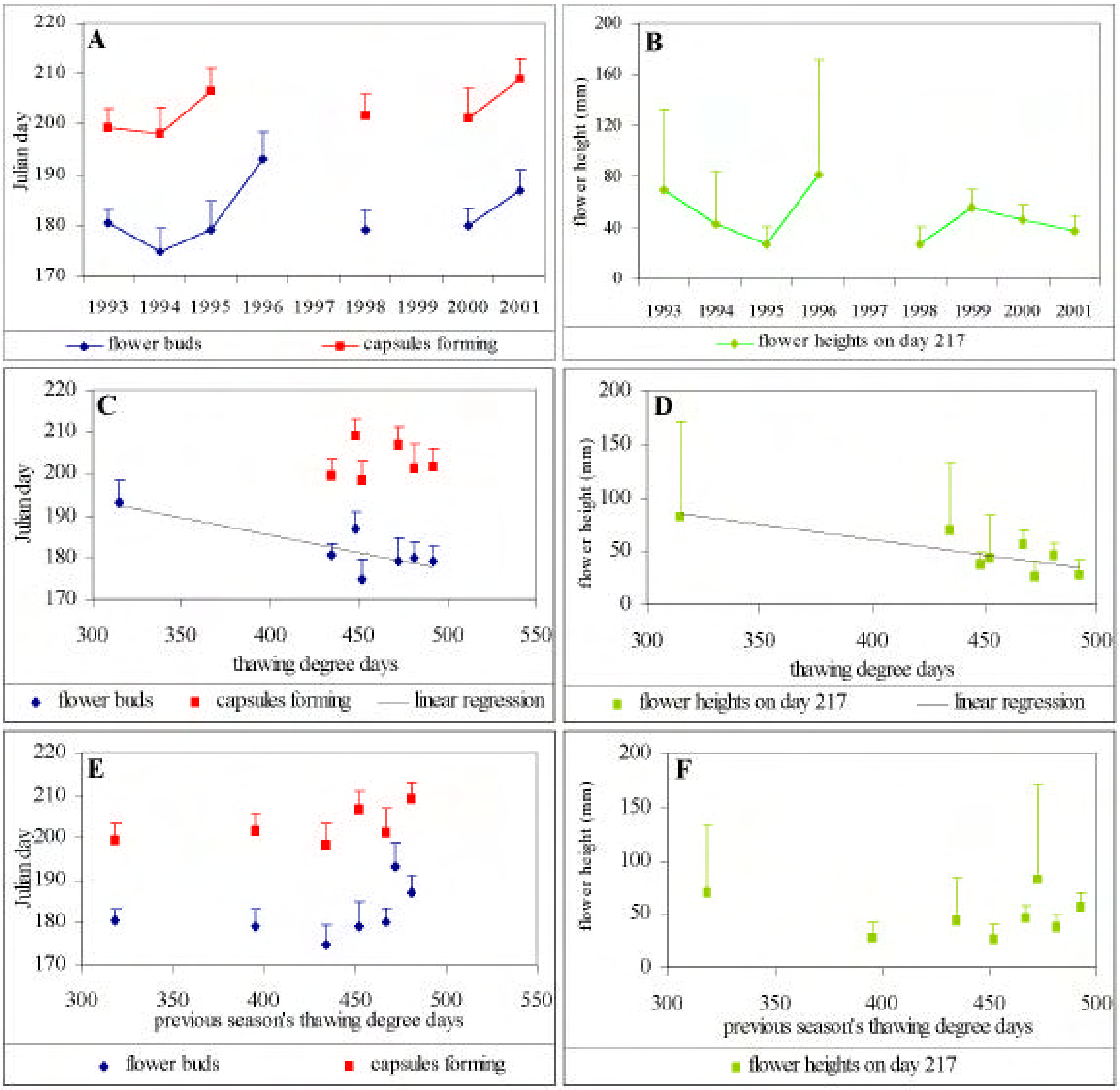

Figure 14. Data on *Dryas integrifolia* phenology and growth in control plots at Alexandra Fiord: **A)** and **B)** time series of phenology and growth observations, respectively; **C)** and **D)** phenology and growth plotted against the current season's thawing degree-days; and **E)** and **F)** observations plotted against the previous growing season's thawing degree-days. Error bars represent standard deviations.

The results of comparing *Dryas* phenological observations to the previous year's thawing degree-days demonstrate a more consistent relationship (Fig. 14E). As the previous season's thawing degree-days increase, the dates of phenological events tend to be later though the relationship is not statistically significant. This weak relationship is consistent for all observed phenological stages of *Dryas* at all the sites at Alexandra Fiord. No relationship between the previous season's thawing degree-days and flower height was discernable in the data. The same relationship was found with *Papaver* phenology (Fig. 15B). The one outlier in the regression was 1992 which had extremely low thawing degree-days and thus very late dates for phenological events. This shows the interaction between the influences of current and previous year's heat accumulation, which will be discussed in the next section. With the 1992 data removed, $2^{nd}$ order polynomial regressions for new leaves, elongating flowers and mature flowers had an $R^2$ of 0.73 ($P<.04$), 0.84 ($P <.01$) and 0.79 ($P <.02$), respectively (Fig. 15C).

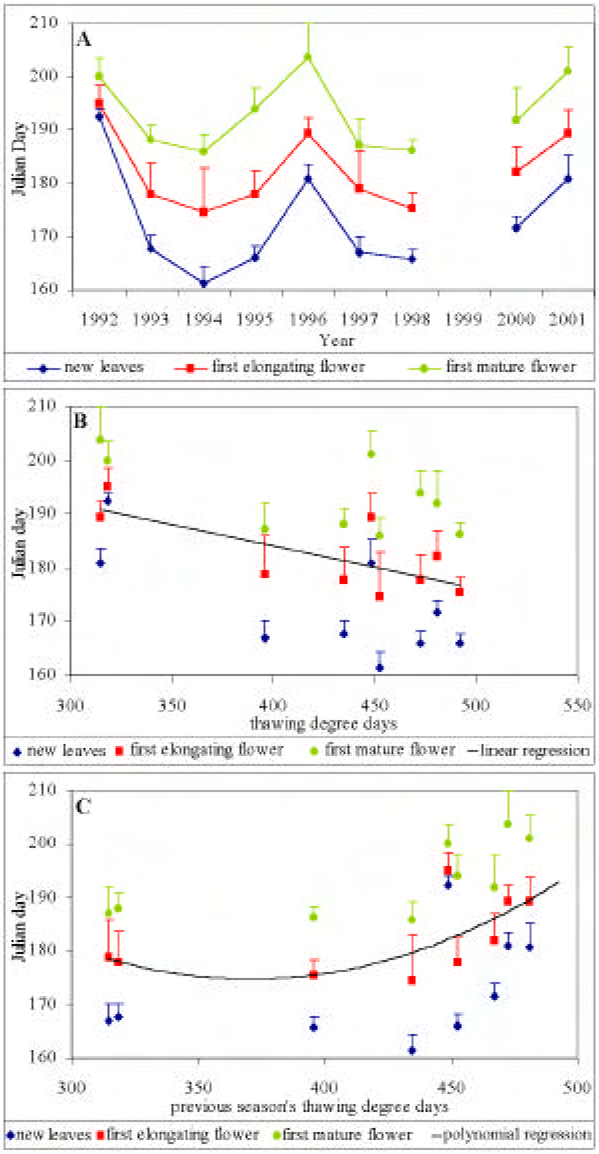

Figure 15. Data on *Papaver radicatum* phenology in control plots at Alexandra Fiord: **A)** time series of phenology **B)** phenology plotted against the current season's thawing degree-days; and **C)** observations plotted against the previous growing season's thawing degree-days. Error bars represent standard deviations.

The relationship between snowmelt date and phenological stages was more consistent than with thawing degree-days (Fig. 16). Long-lasting snow cover retards phenological development but the effects are attenuated over the growing season with later stages being less well correlated to snowmelt date. For *Dryas* bud development the regression yields an $R^2 = 0.88$ ($P<.002$) but some other factor delayed phenology in 1995 which resulted in a non-significant relationship with the capsules forming stage although the rest of the record had the same trend. The regressions of *Papaver* variables with date of snowmelt all showed strong positive relations: new leaves $R^2 = 0.92$ ($P<.0001$), first elongating flower – $R^2 = 0.89$ ($P<.0004$) and first mature flower – $R^2 = 0.80$ ($P<.003$).

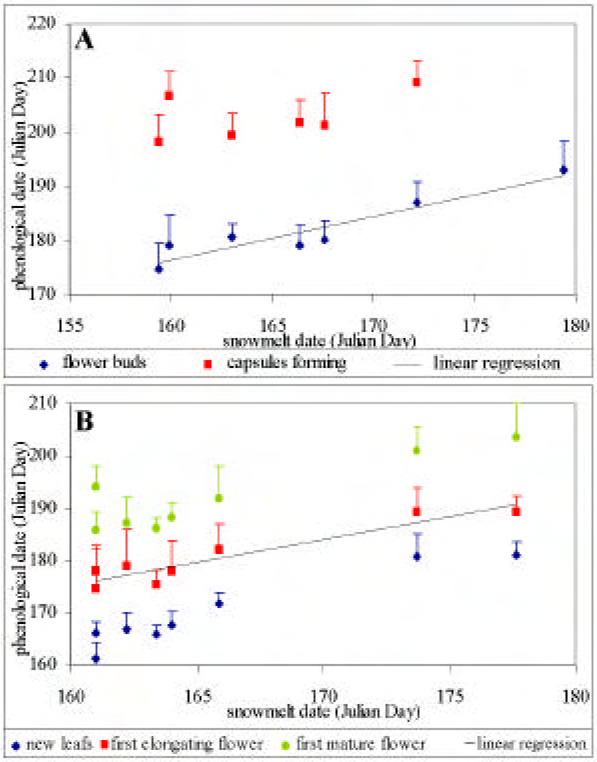

Figure 16. The relationship between the date of snowmelt and phenological dates for *Dryas integrifolia* **(A)** and *Papaver radicatum* **(B)** in control plots at Alexandra Fiord. Error bars represent standard deviations.

One way to study the interaction between variables is to use multiple regression. A simple multiple linear regression using thawing degree-days, the previous season's thawing degree-days and the snowmelt date to predict *Dryas* flower bud break had the following parameters: $R^2 = 0.92$, root mean squared error (RMSE) = 2.44 and $P<0.004$. With the previous thawing degree-days removed from the model the RMSE drops to 2.12 and $P<0.006$. A similar result was obtained using all three variables to predict the first new *Papaver* leaves, with parameters: $R^2 = 0.94$, RMSE = 2.35 and $P<0.007$. Without the previous season's thawing degree-days $R^2$ is unchanged, the RMSE becomes 2.16 and $P<0.001$.

### *Sverdrup Pass*

Phenology data on *Papaver radicatum* were collected at Sverdrup Pass from 1990 to 1993 and discussed in detail by Levèsque *et al*. (1997). Data were collected at two sites: one on a granite substrate and one on a dolomite substrate. Plots were set up along an altitudinal gradient. The date of flower senescence (first petal dropped) decreased with decreasing thawing degree-days but the emergence of flower buds did not demonstrate a consistent relationship with growing season thawing degree-days (Fig. 17B&E). Neither phenological stage responded consistently to the previous growing season's thawing degree-days (Fig. 17C&F), however all of these results are based on a small number of data points.

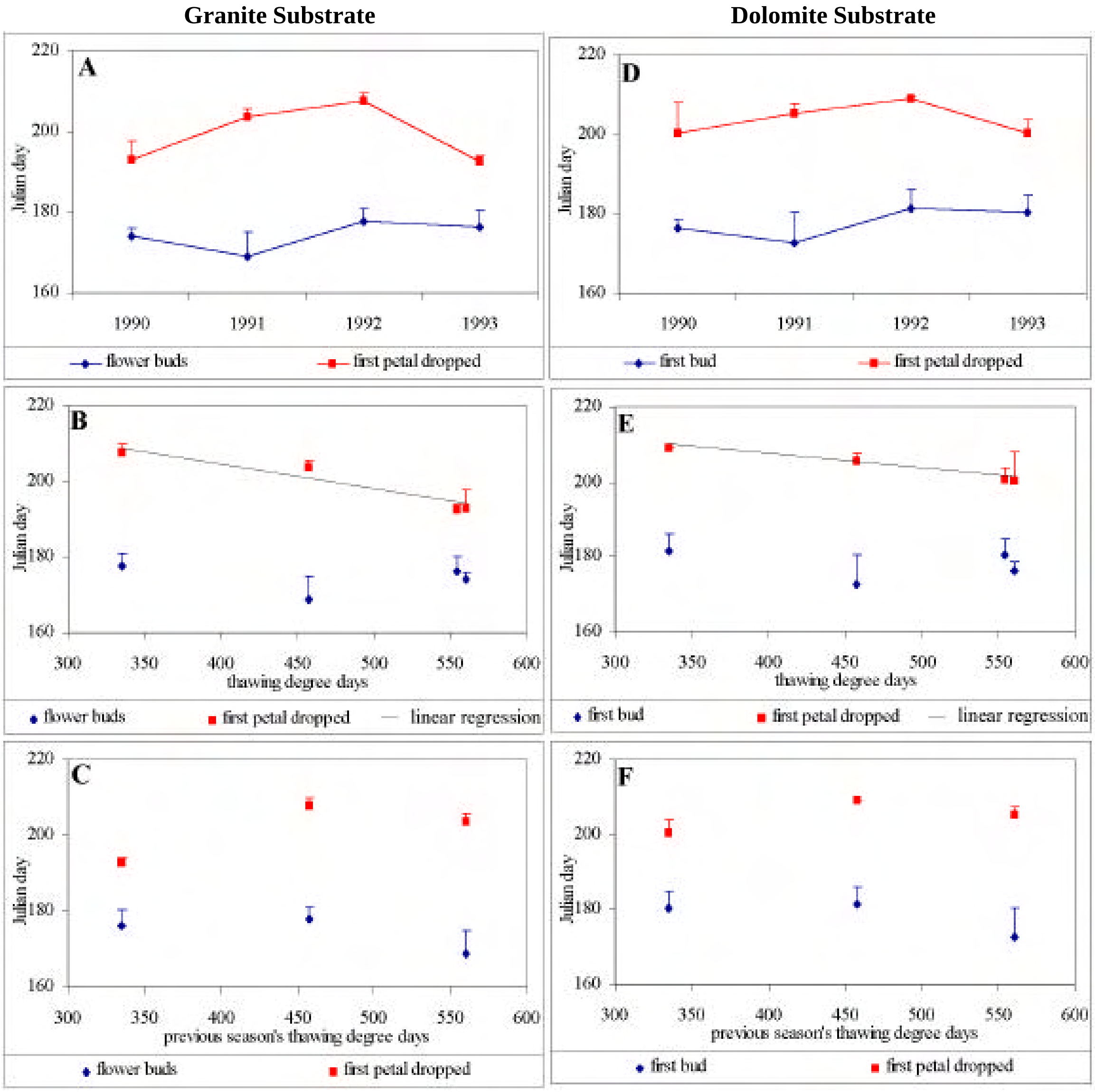

Figure 17. Data on *Papaver radicatum* phenology at Sverdrup Pass. **A-C** are the sites on the granite substrate and **D-F** are the sites on the dolomite substrate. **A and D)** a time-series of observations; **B and E)** phenological observations against the current season's thawing degree-days; and **C and F)** observations against the previous season's thawing degree-days. Error bars represent standard deviations.

### *Tanquary Fiord (Quttinirpaaq National Park)*

Phenological data on *Dryas integrifolia* and *Saxifraga oppositifolia* are shown for Tanquary Fiord, the most northerly site in the network, with corresponding climate data. There appeared to be a slight trend towards earlier dates for phenological events over the seven-year record for *Dryas* (Fig 18A) but not for *Saxifraga* (Fig. 19A). Both the date of first flower buds and capsule formation in *Dryas* occured somewhat later in years with higher thawing degree-days (Fig. 18B), which is contrary to most of the other results presented here. The relationship between the previous season's thawing degree-days and dates of phenological stages was also different from other sites with a slight tendency towards earlier phenological dates for *Dryas* with increasing thawing degree-days (Fig. 18C), though none of the relationships were statistically significant. Several years for which there are phenological date lack climate data but there might be some opportunity in the future to estimate the missing climate parameters using any adjacent sites where climate data is being collected.

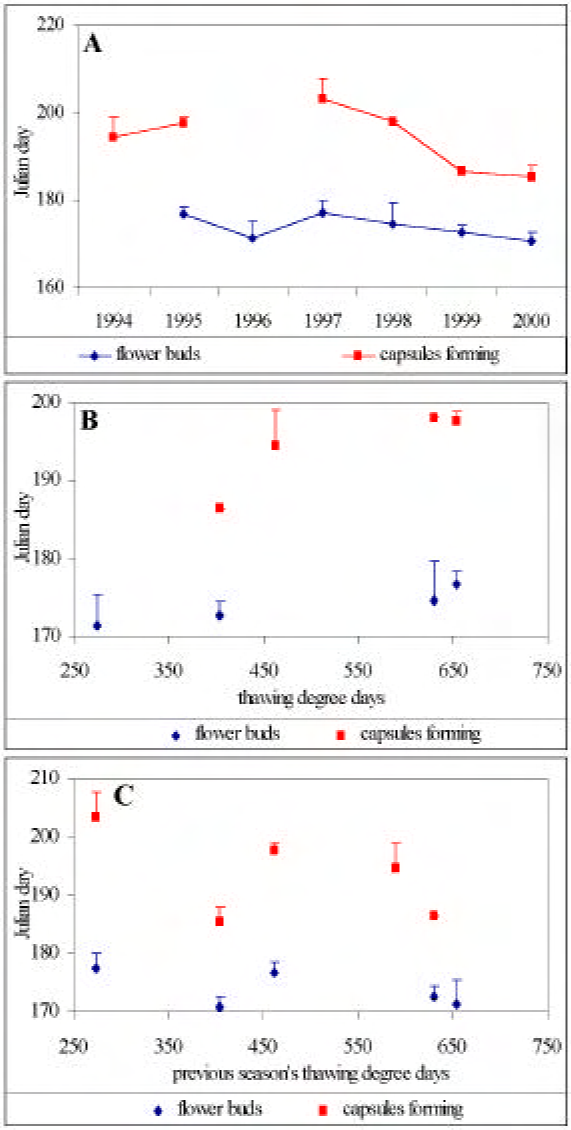

Figure 18. Data on *Dryas integrifolia* phenology at Tanquary Fiord. **A)** a time-series of observations; **B)** the observations against the current season's thawing degree-days, and **C)** a plot of observations against the previous season's thawing degree-days. Error bars represent standard deviations.

There was no apparent relationship between *Saxifraga* phenology and the current season's thawing degree-days (Fig. 19B). However, *Saxifraga* did have a relationship with the previous season's thawing degree-days with a tendency towards later dates of phenological events when previous years were warmer. However, none of the relationships were statistically significant. This contrasts with the *Dryas* results from this site but is consistent with the observations of both *Dryas* and *Papaver* at Alexandra Fiord. *Saxifraga oppositifolia* flowers quite early in the season and is thus phenological development is probably more dependant on snowmelt date than accumulated warmth over the growing season which occurs after most of the phenological stages are already complete. To date there is no information on the timing of snowmelt at Tanquary Fiord.

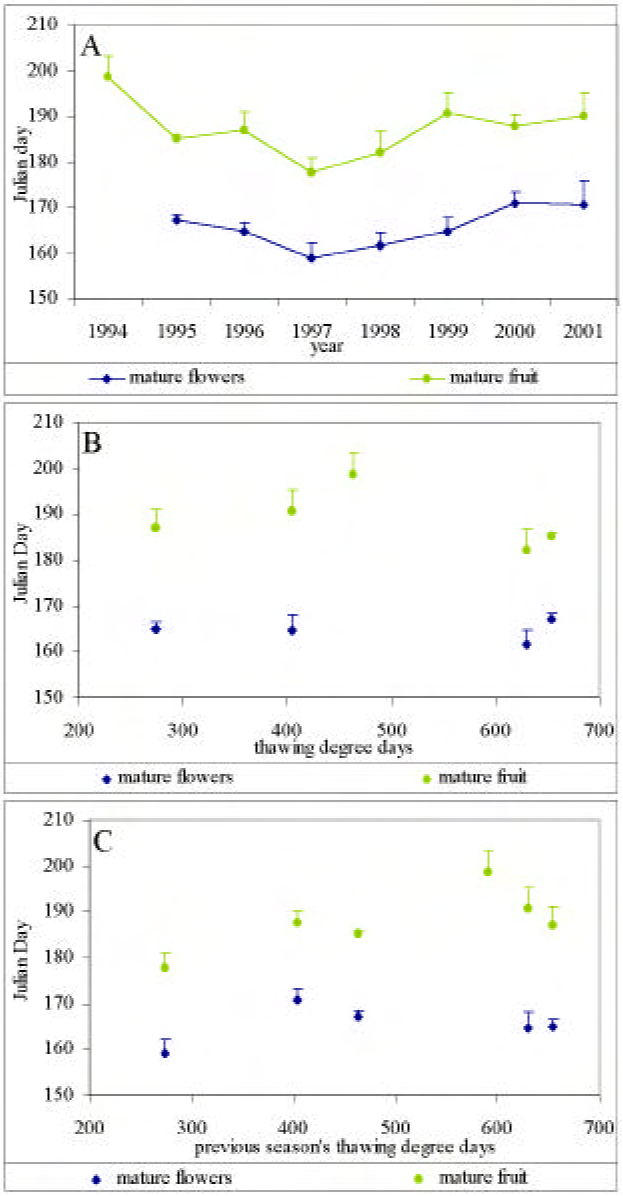

Figure 19. Data on *Saxifraga oppositifolia* phenology at Tanquary Fiord. **A)** a time-series of observations; **B)** the observations against the current season's thawing degree-days, and **C)** a plot of observations against the previous season's thawing degree-days. Error bars represent standard deviations.

## Low Arctic Sites:

### *Baker Lake*

Baker Lake is home to one of the longest records in the network with phenological observations beginning in 1992 (Fig. 20A). Results are described for the first appearance of flower buds and capsule formation in *Dryas integrifolia* and flower bud-break of *Saxifraga tricuspidata* with climate data available from 1992 to 1999. No trend was evident in the time-series of the observations, though noteworthy is the fact that the two phenological stages in *Dryas* shown here do not necessarily follow the same pattern. 1992 was the coldest growing season on record at Baker Lake being 36% lower than the mean of the eight years of record. This year also corresponds to the latest date for the first flower bud. As with Alexandra Fiord, the date of first bud was earlier as thawing degree-days increase ($R^2 = 0.74$, $P<.03$), but the date of capsule formation was insensitive to variability in thawing degree-days (Fig. 20B). Unfortunately, the date of capsule formation was not recorded for 1992. No relationship between either of the phenological stages and the previous growing season's thawing degree-days was found (Fig. 20C).

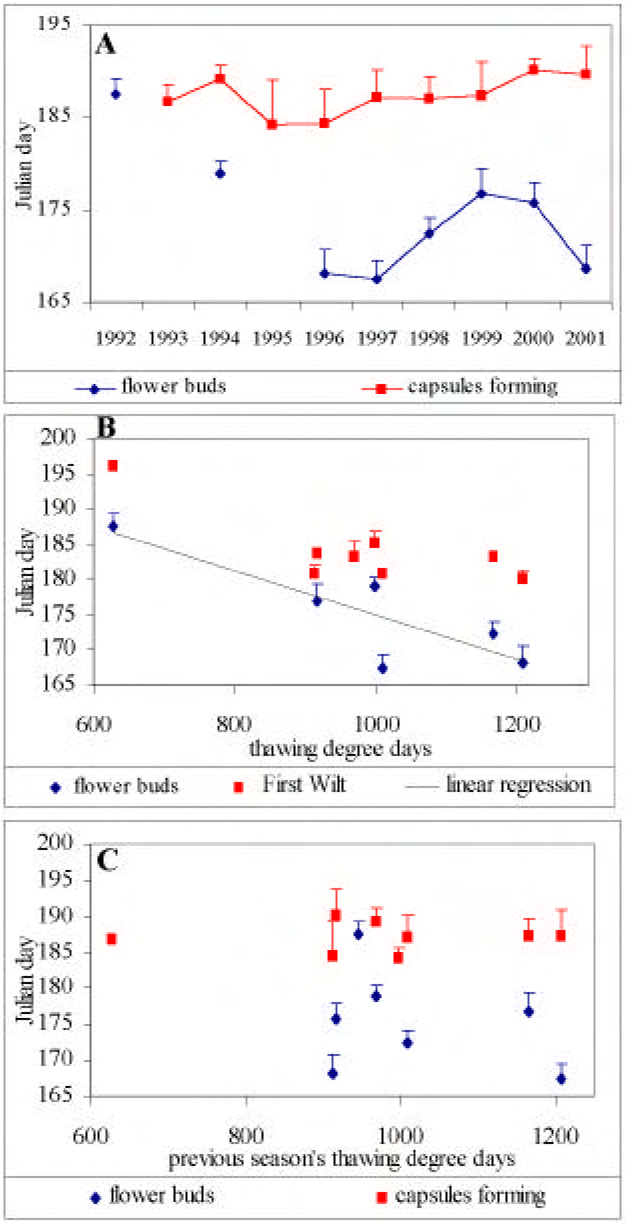

Figure 20. Data on *Dryas integrifolia* phenology at Baker Lake. **A)** shows a time-series of observations, **B)** is the observations against the current season's thawing degree-days, and **C)** is a plot of observations against the previous growing season's thawing degree-days. Error bars represent standard deviations.

The time series for *Saxifraga* had a slight tendency towards later date of flower bud break and a greater proportion of plants producing flowers (Fig. 21A) but this was amid considerable variability and a much longer record would be required to infer any real trend. There was a non-significant negative relationship between *Saxifraga* flower bud break and the current season's thawing degree-days (Fig. 21B) and a tendency towards a greater proportion of plants producing flowers in years in which the previous growing season's thawing degree-days were high (Fig. 21C), but this is also not statistically significant.

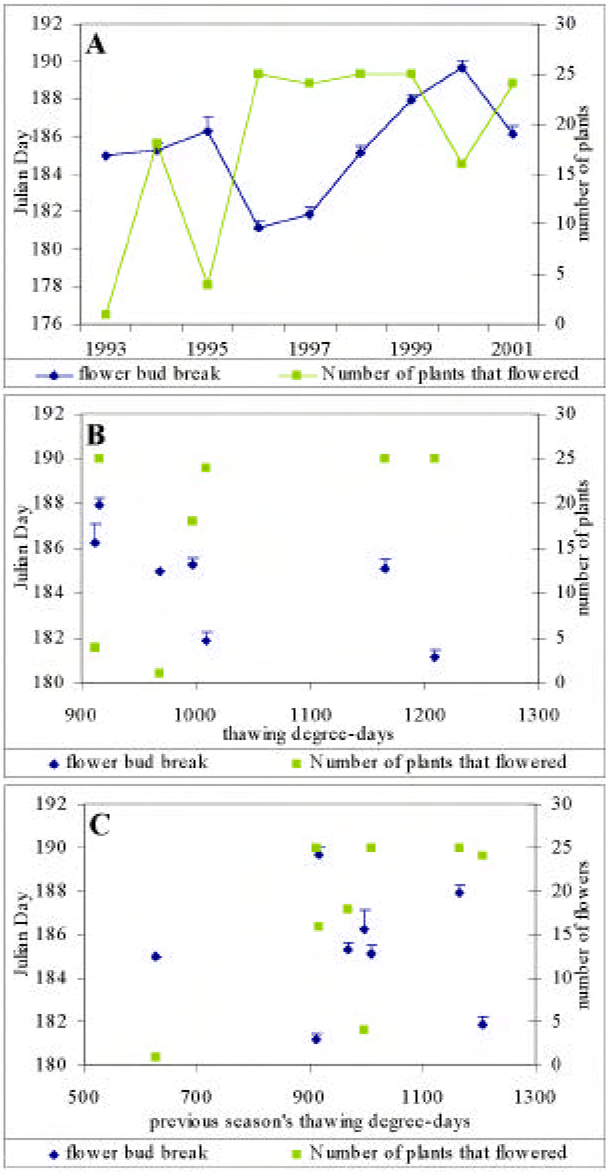

Figure 21. Data on *Saxifraga tricuspidata* phenology at Baker Lake. **A)** shows a time-series of observations, **B)** is the observations against the current season's thawing degree-days, and **C)** is a plot of observations against the previous growing season's thawing degree-days. Error bars represent standard errors.

### *Daring Lake*

The Daring Lake record is based on five years of vegetation observations and measurements and four years of climate data. Results are presented for two phenological stages and flower counts for *Betula glandulosa*, three phenological stages and three growth measurements for *Eriophorum vaginatum* and climate data from 1998 to 2001. No trend over time is detectable in this short record (Figs. 22A&B and 23A&B). In the comparison with thawing degree-days, there was a tendency towards earlier dates for phenological stages as thawing degree-days increased though the relationship was not clear due to the small number of data points (Figs. 22C and 23C). However, 1998 had by far the greatest thawing degree-days and the earliest date for each of the phenological stages for *Betula,* consistent with the observations made at the other sites.

In 1997 all major phenological events for *Betula* occurred within a much shorter period of time, with only three days elapsing between first catkins and first pollen shed. The variability among plants was also lowest during this year but no consistent relationship between variability and thawing degree-days is apparent to date. *Eriophorum* phenology also had a non-significant negative relationship with thawing degree-days. There was no relationship between *Betula* phenology and the previous season's thawing degree-days but with *Eriophorum* phenology there was a positive though not statistically significant relationship.

Data on the number of *Betula* catkins produced were only available for four years and do not show a consistent relationship with either current or previous growing season's thawing degree-days based on the currently available data (Fig. 22D&F). Sex ratios remained relatively balanced in all years. The quantitative measures on *Eriophorum* did not show any relationship to either current or previous year's thawing degree-days (Fig. 23D&F).

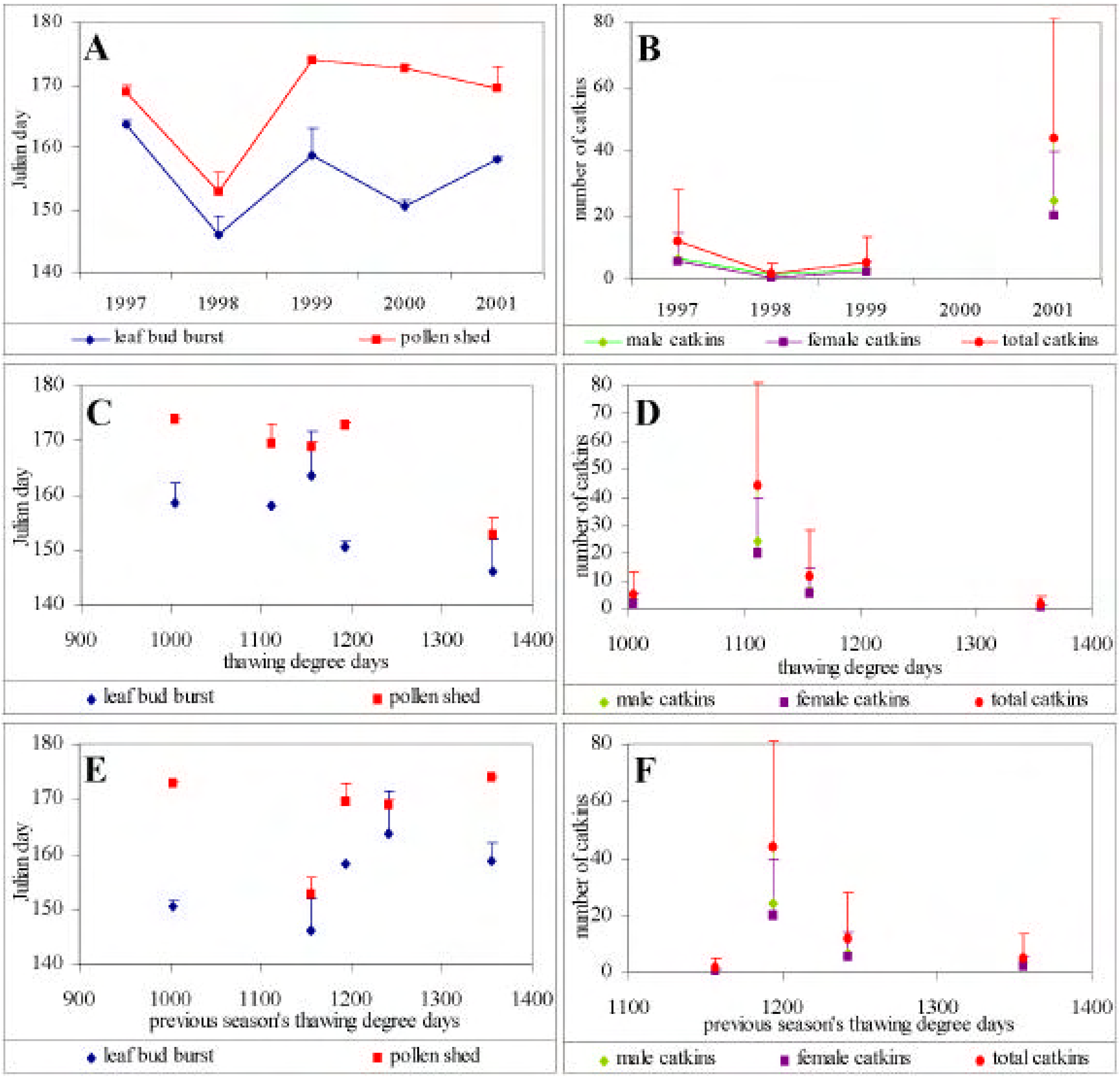

Figure 22. Data on *Betula glandulosa* phenology and catkin production at Daring Lake. **A)** and **B)** show time-series of observations, **C)** and **D)** are observations plotted against the current season's thawing degree-days, and **E)** and **F)** are observations plotted against the previous growing season's thawing degree-days. Error bars represent standard deviations.

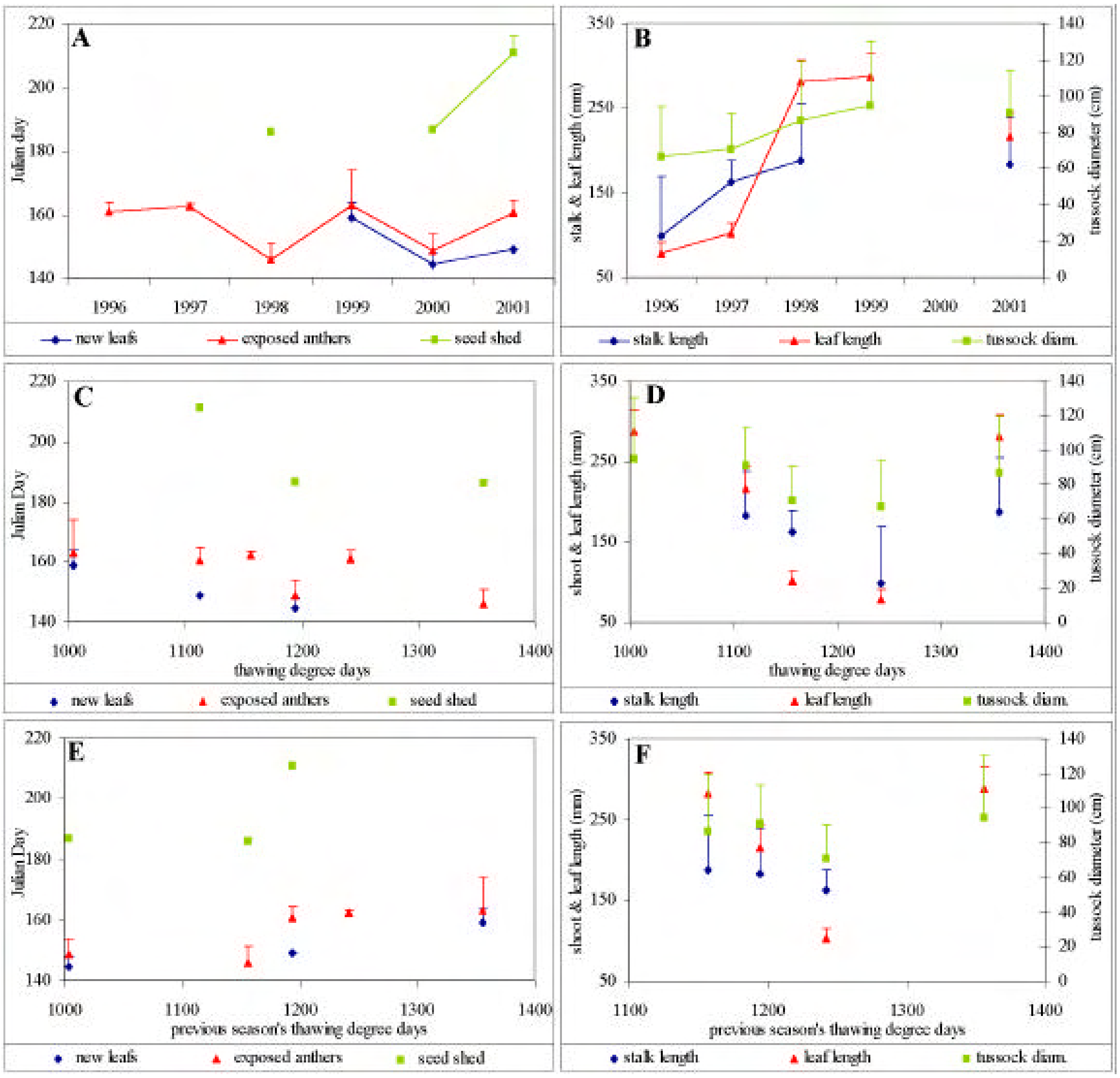

Figure 23. Data on *Eriophorum vaginatum* phenology and growth at Daring Lake. **A)** and **B)** show time-series of observations, **C)** and **D)** are observations plotted against the current season's thawing degree-days, and **E)** and **F)** are observations plotted against the previous growing season's thawing degree-days. Error bars represent standard deviations.

As with Alexandra Fiord data, there was a positive relationship between snowmelt date and all phenological stages for both species (Fig. 24A&C), though only *Betula* leaf bud burst was significant ($R^2$ = 0.93, $P$<.009). No relationship was found with the number of *Betula* catkins (Fig. 24B), but there seemed to be a decrease in the lengths of stalks and leaves in years when snowmelt occurs late (Fig. 24D); however, much more data are required to confirm this relationship.

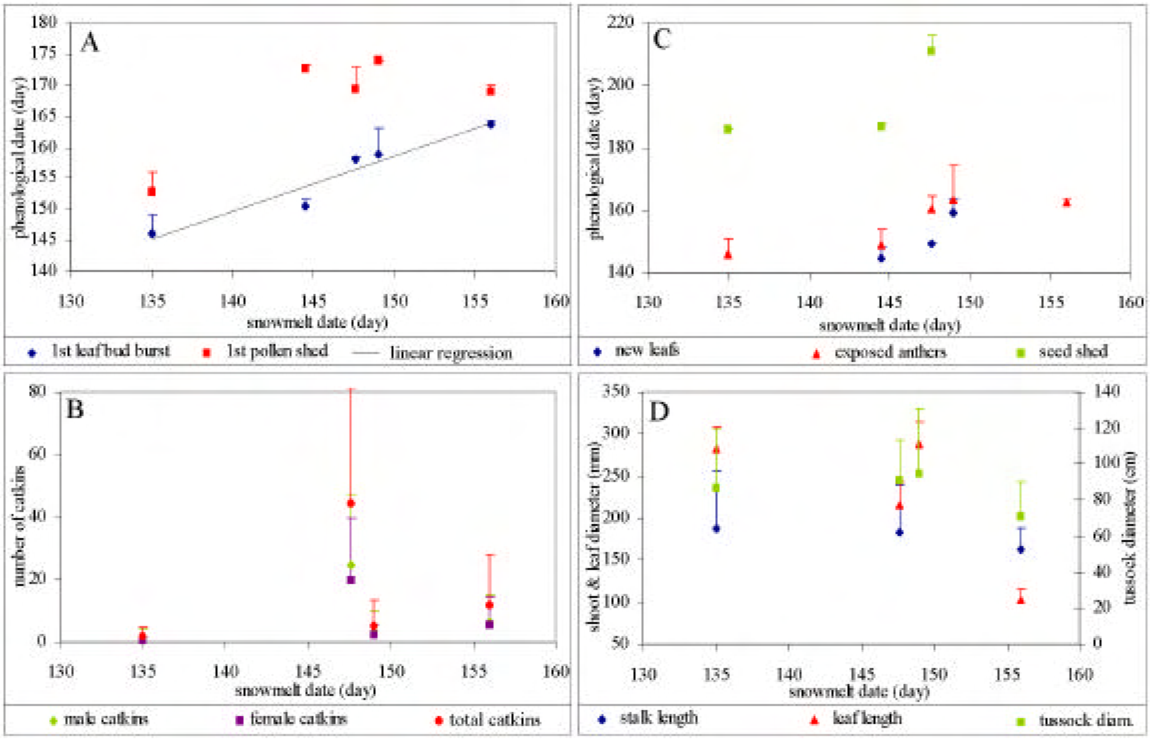

Figure 24. The relationship between the date of snowmelt and phenological dates for *Betula glandulosa* **(A** and **B)** and *Eriophorum vaginatum* **(C** and **D)** in control plots at Daring Lake. Error bars represent standard deviations.

## Subarctic Alpine Sites:

### *Wolf Creek*

The Wolf Creek data spans four years and data collection is ongoing. Measurements are made on four plant species, including *Dryas integrifolia* and the density of reproductive structures has been determined for all species in the plots. No trend is detectable in the flower densities of the dominant species (Fig. 19A). The total number of *Dryas* flowers varies less that the ratio of fertilized to non-fertilized (or aborted) flowers. The measurements of petiole and leaf lengths show a steady decline over the three years (Fig. 19B) but there is considerable variability around this trend and a much longer record is required to infer the presence of a general trend.

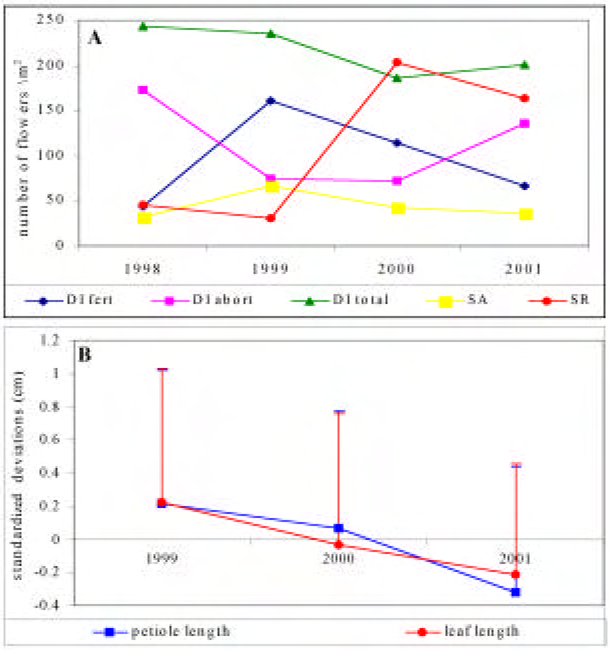

Figure 25. Data on reproductive and vegetative growth at Wolf Creek. **A)** shows flower counts for fertilized *Dryas integrifolia* flowers (DI fert), aborted *Dryas* flowers (DI abort), total *Dryas* flowers (DI total), *Salix arctica* flowers (SA) and *Salix reticulata* flowers (SR) in a 1m$^2$ quadrat. **B)** plots the measured petiole lengths and leaf lengths standardized by the mean and standard deviation for each plant. Error bars represent standard deviations.

## Discussion

The ability to initiate leaf growth early in the Arctic growing season is vital to allow plants to maintain a positive carbon balance over the short growing season (Crawford *et al*. 1993, Molau 1993). Both vegetative and reproductive phenology have been shown to be responsive to climatic variability (Molau 1997). In predictions of vegetation response to climate warming, earlier timing of phenological events is almost always listed as a likely consequence (e.g. Henry and Molau 1997, Molau 1997). The time series of observations described here did not show any consistent pattern among sites and this is in keeping with our knowledge of the regional climate patterns and the predicted regional differences expected with climate change. The *Dryas* phenology data from Tanquary Fiord were the only ones that showed a trend towards earlier dates for phenological events but continued monitoring is required to determine if this trend will be sustained or if it is simply within the range of normal variability at that location. At Wolf Creek mean *Dryas* leaf lengths decreased over the three years of record but this is far too short to infer a trend and it was overwhelmed by the within-year variability in the data. The timing of phenological events did follow the growing season temperatures. The series for Alexandra Fiord showed much later dates for flowering in 1996, the coldest year on record, whereas, dates were much earlier in 1998 at Daring Lake, the warmest year in much of the central and western Arctic. A summary of the phenological responses to thawing degree-days in both the current and previous season is given in Table 14.

The relationship between phenology and snowmelt date is consistently positive at all sites in both the High and Low Arctic. The relationship to thawing degree-days was not as clear as would have been expected. This is due both to the complexity of vegetation response to climatic change, and the use of the whole season thawing degree-days rather than the accumulated thawing degree-days for the specific phenological period. However, in most cases, and in all cases from the Low Arctic where a relationship was observed, the phenological dates were earlier when current season’s thawing degree-days were higher. There appeared to be a greater sensitivity to thawing degree-days in phenology of plants in the Low Arctic sites, which was consistent with results of a meta-analysis of the short-term results from ITEX sites (Arft *et al*. 1999). Particularly interesting is the seeming contradiction of results from Alexandra Fiord and Tanquary

Fiord, in terms of the relationship between flowering phenology in *Dryas* and thawing degree-days in both the current and previous growing season, although the relationships at Tanquary Fiord were weak. Based on the summary table below, it would appear that the influence of the previous growing season's thawing degree-days is more important in the High Arctic than in the Low Arctic, but this is not unequivocal based on these results.

*Table 14. Summary of phenological responses (var1- var3) to thawing degree-days and snowmelt date. A negative relationship is denoted by (-), a positive relationship by (+) and no relationship by (X). Statistical significance is identified by * - p<0.05, ** - p<0.01, and *** - p<0.001.*

| **Ecozone** | **Site** | **Genus** | **Current thawing degree-days** | | | **Previous thawing degree-days** | | | **Snowmelt** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | var1 | var2 | var3 | var1 | var2 | var3 | var1 | var2 | var3 |
| **High Arctic** | Alexandra Fiord | *Dryas* | $-^{*}$ | X | | + | + | | $+^{*}$ | + | |
| | | *Papaver* | $-^{*}$ | $-^{*}$ | - | $+^{*}$ | $+^{**}$ | $+^{*}$ | $+^{***}$ | $+^{**}$ | $+^{**}$ |
| | Sverdrup Pass | *Papaver* | X | $-^{*}$ | | X | X | | | | |
| | Tanquary Fiord | *Dryas* | + | + | | - | - | | | | |
| | | *Saxifraga* | X | X | | + | X | | | | |
| **Low Arctic** | Baker Lake | *Dryas* | $-^{*}$ | - | | X | X | | | | |
| | | *Saxifraga* | - | | | X | | | | | |
| | Daring Lake | *Betula* | $-^{*}$ | X | | X | X | | $+^{**}$ | + | |
| | | *Eriophorum* | - | - | X | + | + | X | + | + | + |

Plant performance in any given season is a function of many variables including temperatures in the current and previous growing season, and also light, nutrient and moisture levels. The timing of snowmelt is also an important variable in determining timing of phenological stages (Kudo 1991, Shaver and Kummerow 1992) and that has been shown in the strong correlations found at Alexandra Fiord and Daring Lake. Several authors have hypothesized that arctic vegetation is inherently limited by nutrient availability (e.g. Chapin *et al*. 1995) and that this attenuates any response to differences in temperature or other variables. The lack of correlation between temperature and biotic variables in some cases might also be a result of some periodicity in the plants' growth and reproductive output as internal resources are accumulated and exhausted (Johnstone and Henry 1997; Lévesque *et al*. 1997). Many studies have shown that differences in phenology are often larger among species or functional groups than among sites (Kudo 1991, Murray and Miller 1982, Shaver and Kummerow 1992). Some authors have noted that changes in climate variability might be more important than any long-term trend (Zasada *et al*. 1992), and more data are required to test all of these hypotheses.

One of the purposes of this review is to evaluate the responsiveness and consistency of the variables being monitored at each site. One of the primary goals of CANTTEX is to establish common monitoring protocols at all sites in the network and this includes selecting variables that are appropriate and provide reliable and informative results. The Alexandra Fiord site is the most intensively studied site in the network and the results from there will be instrumental in making decisions about the value of variables and approaches to making observations and measurements. Only two or three variables have been considered for each site in this analysis, all of which are based on observations of individuals of species. It is clear that simple observations of phenology and measurement of growth provide important information on responses of plants to variations in climate. Assessments of whole vegetation and ecosystem responses will need to be incorporated into the CANTTEX suite of variables. A comprehensive analysis of all the observations and measurements being made at all CANTTEX sites will be undertaken in order to select relevant and responsive variables and to standardize field practices whenever possible.

The analysis of data from the sites in the CANTTEX network has provided some interesting results. The overwhelming conclusion however, is that there is a lack of data, spatially and temporally. To detect long-term trends it is necessary to have long-term monitoring programs operating in a wide range of environments and covering as wide a geographic distribution as possible. The same is true for the detection of relationships between biotic and environmental variables. The six records presented here are meant to characterize vegetation-climate relations in environments ranging from low-arctic alpine tundra to polar desert and are not sufficient for this purpose. Climate change and variability are not constant over time or space. For example, in the period from 1961-1990 there has been a slight warming in average annual temperatures in the Yukon-Mackenzie region, whereas there has been a slight decrease in the Baffin-Davis region (Maxwell 1997). Several CANTTEX sites have only been up and running for 1-3 years and the true value of the research will only be realized after several more years. Only the continued monitoring of sites at many locations will allow us to elucidate the pattern of change and the relationships resulting from climate change and variability.

## Data Sources

Alexandra Fiord:
Greg Henry, Dept. of Geography, University of British Columbia

Baker Lake
Josef Svoboda, Dept. of Botany, University of Toronto
Richard Saniforth, Dept. of Biology, University of Winnipeg

Daring Lake:
Karin Clark and Steven Matthews, Wildlife and Fisheries Division, Department of Resources, Wildlife and Economic Development, Government of Northwest Territories, and
Bob Reid, Water Resources, Dept. of Indian and Northern Affairs

Sverdrup Pass:
Esther Lévesque, Département de chimie-biologie, Université du Quebec a Trois-Rivières
Greg Henry, Dept. of Geography, University of British Columbia

Tanquary Fiord (Quttinirpaaq National Park):
Paula Hughson, Nunavut Field Unit, Parks Canada

Walker Bay:
Bob Reid, Water Resources, Dept. of Indian and Northern Affairs

Wolf Creek:
Joan Eamer, Mike Gill and Val Loewen, Environment Canada

## References

Arft, A.M., Walker, M.D., Gurevitch, J., Alatalo, J.M., Bret-Harte, M.S., Dale, M., Diemer, M., Gugerli, F., Henry, G.H.R., Jones, M.H., Hollister, R.D., Jonsdottir, I.S., Laine, K., Lévesque, E., Marion, G.M., Molau, U., Molgaard, P., Nordenhall, U., Raszhivin, V., Robinson, C.H., Starr, G., Stenstrom, A., Stenstrom, M., Totland, O., Turner, P.L., Walker, L.J., Webber, P.J., Welker, J.M. and Wookey, P.A. 1999. Responses of tundra plants to experimental warming: Meta-analysis of the International Tundra Experiment. Ecological Monographs. 69: 491-511

Bell, K.L. and Bliss, L.C. 1980. Plant reproduction in a high arctic environment. Arctic and Alpine Research. 12: 1-10.

Bergeron JF, Svoboda J (1989) Plant communities of Sverdrup Pass, Ellesmere Island, N.W.T. The Muskox, 37: 76-85

Billings, W.D. 1997. Introduction: Challenges for the future: Arctic and alpine ecosystems in a changing world. In: Global Change and Arctic Terrestrial Ecosystems. Oechel, W.C., Callaghan, T., Gilmanov, T., Holten, J.I., Maxwell, B., Molau, U. and Sveinbjörnsson, B. (eds.). New York: Springer. pp. 1-20.

Bliss, L.C., Henry, G.H.R., Svoboda, J., and Bliss, D.I. 1994. Patterns of plant distribution within two polar desert landscapes. Arctic and Alpine Research. 26: 46-55.

Burn, C.R. 1998. Field investigations of permafrost and climatic change in northwest North America. Conference proceedings. Permafrost, Seventh International Conference, June 23-27, Yellowknife, Canada. Edited by A.G. Lewkowicz and M. Allard, Universite Laval, Centre d'Etudes Nordiques, Collection Nordicana, Issue 57.

Chapin III, F.S., Jefferies, R.L., Reynolds, J.F., Shaver, G.R. and Svoboda, J. (eds.) 1992. Arctic Ecosystems in a Changing Climate. San Diego: Academic Press.

Chapin III, F.S. and Starfield, A.M. 1997. Time lags and novel ecosystems in response to transient climatic change in arctic Alaska. Climatic Change, 35:449-461.

Chapin III, F.S., Bret-Harte, M.S., Hobbie, S.E. and Zhong, H. 1996. Plant functional types as predictors of the transient response of arctic vegetation to global change. Journal of Vegetation Science 7:347-358.

Chapin III, F.S., Shaver, G.R., Giblin, A.E., Nadelhoffer, K.J. and Laundre, J.A. 1995. Responses of arctic tundra to experimental and observed changes in climate. Ecology. 76: 94-711.

Crawford, R.M.M., Chapman, H.M., Abbott, R.J. and Balfour, J. 1993. Potential impact of climate warming on arctic vegetation. Flora, 188:367-388.

Dyurgerov M.B. and Meier, M.F. 2000. Twentieth century climate change: Evidence from small glaciers. Proceedings of the National Academy of Sciences of the United States of America, 97: 1406-1411.

Ferguson, M. 1997. Arctic tundra caribou and climatic change: Questions of temporal and spatial scales. Geoscience Canada 23: 245-252.

Gauthier, G., Rochefort, L. and Reed, A. 1996. The exploitation of wetland ecosystems by herbivores on Bylot island. Geoscience Canada, 23: 253-259.

Graham, S. and Turkington, R. 2000 Population dynamics response of Lupinus arcticus to fertilization, clipping, and neighbour removal in the understory of the boreal forest. Canadian Journal of Botany, 78: 753-758.

Gunn, A. and Skogland, T. 1997. Response of caribou and reindeer to global warming. In: Global Change and Arctic Terrestrial Ecosystems. Oechel, W.C., Callaghan, T., Gilmanov, T., Holten, J.I., Maxwell, B., Molau, U. and Sveinbjörnsson, B. (eds.). New York: Springer. pp. 189-200.

Henry, G.H.R. (ed.) 1997. The International Tundra Experiment (ITEX): Short-term Responses of Tundra Plants to Experimental Warming. Global Change Biology, 3(Suppl. 1), 164 p.

Henry, G.H.R., Freedman, B. and Svoboda, J. 1986. Effects of fertilization on three tundra plant communities of a polar desert oasis. Canadian Journal of Botany. 64: 2502-2507.

Henry, G.H.R. and Molau, U. 1997. Tundra plants and climate change: the International Tundra Experiment (ITEX). Global Change Biology. 3(Suppl. 1): 1-9.

Hik, D.S. 1995. Does risk of predation influence population dynamics – evidence from the cyclic decline of snowshoe hares. Wildlife Research, 22:115-129.

Houghton, J.T., Meira Filho, L.G., Callender, B.A., Harris, N., Kattenberg, A. and Maskell, K. (eds.) 1995. The Science of Climate Change - Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2000. Summary for Policy Makers.

Jorgenson, M.T., Racine, C.H., Walters, J.C. and Osterkamp, T.E. 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Climatic Change 48:551-579

Johnstone, J. F. and G. H. R. Henry. 1997. Retrospective analysis of growth and reproduction in *Cassiope tetragonal* and relations to climate in the Canadian High Arctic. Arctic and Alpine Research 29:459-469.

Krebs C.J., Boonstra, R., Boutin, S. and Sinclair, A.R.E. 2001. What drives the 10-year cycle of snowshoe hares? Bioscience, 51:25-35.

Kudo, G. 1991. Effects of snow-free period on the phenology of alpine plants inhabiting snow patches. Arctic and Alpine Research. 23: 436-443.

Labine, C.L. 1994. Meteorology and climatology of the Alexandra Fiord Lowland. In: Ecology of a Polar Oasis: Alexandra Fiord, Ellesmere Island, Canada. Svoboda, J. and Freedman, B. (eds.), Toronto: Captus University Press. pp. 23-39.

Lévesque, E., Henry, G.H.R. and Svoboda, J. 1997. Phenological and growth responses of Papaver radicatum long altitudinal gradients in the Canadian High Arctic. Global Change Biology. 3(suppl.): 125-145.

Lévesque, E., and Svoboda, J. 1992. Growth of Arctic Poppy in contrasting habitats of a polar oasis and a polar desert. The Musk-Ox. 39: 148-156.

Luckman, B. and Kavanagh, T. 2000. Impact of climate fluctuations on mountain environments in the Canadian Rockies. Ambio 29:371-380.

MacDonald, G.M., Szeicz, J.M., Claricoates, J. and Dale, K.A. 1998. Response of the central Canadian treeline to recent climatic changes Annals of the Association of American Geographers, 88: 183-209.

Masse, H., Rochefort, L. and Gauthier, G. 2001. Carrying capacity of wetland habitats used by breeding greater snow geese. Journal of Wildlife Management, 65: 271-281.

Maxwell, B. 1992. Arctic climate: potential for change under global warming. in: Arctic Ecosystems in a Changing Climate. Chapin III, F.S., Jefferies, R.L., Reynolds, J.F., Shaver, G.R. and Svoboda, J. (eds.), San Diego: Academic Press. pp. 11-34.

Maxwell, B. 1997. Recent climate patterns in the Arctic. In: Global Change and Arctic Terrestrial Ecosystems. Oechel, W.C., Callaghan, T., Gilmanov, T., Holten, J.I., Maxwell, B., Molau, U. and Sveinbjörnsson, B. (eds.). New York: Springer. pp. 21-46.

Molau, U. 1993. Relationships between floweing phenology and life history strategies in tundra plants. Arctic and Alpine Research. 25:391-402.

Molau, U. 1997. Phenology and reproductive success in arctic plants: susceptibility to climate change. In: Global Change and Arctic Terrestrial Ecosystems. Oechel, W.C., Callaghan, T., Gilmanov, T., Holten, J.I., Maxwell, B., Molau, U. and Sveinbjörnsson, B. (eds.). New York: Springer. pp. 143-170.

Molau, U. and Mølgaard, P. 1996. ITEX Manual, Second Edition, Danish Polar Centre.

Muc, M., Freedman, B. and Svoboda, J. 1989. Vascular plant communities of a polar oasis at Alexandra Fiord, Ellesmere Island. Canadian Journal of Botany. 67: 1126-1136.

Murray, C. and Miller, P.C. 1982. Phenological observations of major plant growth forms and species in montane and *Eriophorum vaginatum* tussock tundra. Holarctic Ecology. 5: 109-116.

Myeni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G. and Nemani, R.R. 1997. Increased plant growth in the northern high latitudes from 1981 – 1991. Nature, 386: 698-702.

Outcrop. 1990. Northwest Territories Data Book 1990/91. Outcrop Ltd. 238 p.

Paterson, W. S. B. and Reeh, N. 2001. Thinning of the ice sheet in northwest Greenland over the past forty years Nature. 414: 60 - 62.

Raillard, M. and Svoboda, J. 2000. High Grazing Impact, Selectivity, and Local Density of Muskoxen in Central Ellesmere Island, Canadian High Arctic. Arctic, Antarctic and Alpine Research, 32: 278-285.

Serreze, M.C., Walsh, J.E., Chapin, F.S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T. and Barry, R.G. 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change. 46:159-207.

Shaver, G.R. and Kummerow, J. 1992. Phenology, resource allocation, and growth of arctic vascular plants. In: Arctic Ecosystems in a Chaning Climate: An Ecophysiological Perspective. Chapin III, F.S., Jefferies, R.L., Reynolds, J.F., Shaver, G.R. and Svoboda, J. (eds.), Academic Press, pp. 193-211.

Stirling, I., Lunn, N.J., and Iacozza, J. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climate change Arctic 52 (3): 294-306.

Stott, P.A., Tett, S.F., Jones, G.S. et al. 2001. Attribution of twentieth century temperature change to natural and anthropogenic causes. Climate Dynamics 17:1-21.

Svoboda, J. and Freedman, B. (eds.). 1994. Ecology of a Polar Oasis. Toronto: Captus Press.

Tynan, C. and McMaster, D. 1997. Observations and predictions of Arctic climate change: potential effects on marine mammals. Arctic, 50: 308-322.

Wadhams, P. 1995. Arctic sea-ice extent and thickness. Philosophical Transactions of the Royal Society of London. Series A – Mathematical and Engineering Sciences, 352(1699): 301-319.

Zasada, , J.C., Sharik, T.L. and Nygren, M. 1992. The reproductive process in boreal forest trees. in: A Systems Analysis of the Global Boreal Forest. Shugart, H.H., Leemans, R., and Bonan, G.B. (eds.). Cambridge: Cambridge University Press, pp. 85-125.