CLIMATIC SETTING AND PHENOLOGY OF *Braya longii* AND *B. fernaldii* ON THE LIMESTONE BARRENS OF NORTHWESTERN NEWFOUNDLAND

EDWARD J. DONATO

Climatic Setting and Phenology of *Braya longii* and *B. fernaldii* on the Limestone Barrens of Northwestern Newfoundland.

By

Edward J. Donato

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Abstract

The endangered *Braya longii* and threatened *Braya fernaldii* are endemic to the Limestone Barrens of the Great Northern Peninsula of Newfoundland. This project determines the regional climate variability and change of the Great Northern Peninsula, and the phenology of both species of braya in response to the microclimate of the Limestone Barrens. Although mean air temperature decreases with increasing latitude along the Northern Peninsula, a consistent linear trend is not achieved. Summer and winter air temperature has been on the rise throughout the past decade (1991 to 2002). Mean winter air temperature since 1995 has been warmer than the time period from 1972 to 1995 but not as warm as the time period from 1951 to 1971. During the last 33 years, two periods of below average temperature and two periods of above average temperature can be attributed to a positive and negative NAO index respectively. The flowering phenologies of *Braya fernaldii* and *Braya longii* were significantly influenced by the date of snowmelt. Mean ground temperature was an indicator of first fruit for *Braya fernaldii,* but in natural substrate only. Latitude had a small influence on flowering and fruiting times of *Braya fernaldii*. Anthropogenically-modified substrate types favoured germination success. The results of this study provide guidance for the potential conservation management of both species of braya.

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I would like to dedicate this thesis to my Cousin, and my Grandmother - both recently passed away. Thanks Nona for your love and support. Thanks to my Uncle John for his encouragement.

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Introduction and Overview

Mean annual temperatures are predicted to increase by 2 to 4 °C in Atlantic Canada (Moore et al., 1999). With them will be a corresponding lengthening of the annual period of above-zero temperatures (Taylor and Garbary, 2003). Changes in growing season temperature and length may have a substantial effect on the life cycle of arctic and alpine plants (Totland, 2002). Early-flowering species are believed to be vulnerable to climate change, particularly because of an increased risk of frost damage due to earlier snowmelt (snowmelt provides an insulating blanket), while late-flowering species may respond to climate change because they currently experience stressful environmental conditions such as low temperatures (Molau, 1993). In experimental studies, a lengthening of the growing season can have direct negative effects on growth and vigour (Molau, 1996; 1997). Climate change is predicted to have its greatest effects at high elevations and latitudes and may strongly impact the terrestrial vegetation of these regions (Dunne, 2003). Thorhallsdottir (1998) found that arctic plants are predicted to respond quickly to warmer spring and early summer temperatures.

The Great Northern Peninsula of the Island of Newfoundland, 49 °N to 52 °N and 55 °W to 58 °W, belongs to a larger region known as the northwest Atlantic (Figure 1.1). Two rare sub-arctic plants, Long's Braya (*Braya longii*) and Fernald's Braya (*Braya fernaldii*), inhabit the northern section of the Great Northern Peninsula known as the Limestone Barrens (Meades, 1996 a; b). The phenology of these sub-arctic alpine plants is influenced by the parameters of climate in this subregion of Newfoundland.

Climate

The Great Northern Peninsula is of climatological interest as it is part of the northwest Atlantic, its climate has differed from that of western and southern Canada (Banfield and Jacobs, 1998; Zhang et al. 2000). Regional climate differences exist within the Great Northern Peninsula; the southern section has a climate capable of supporting a mixed forest, whereas the extreme northern shores have a near–arctic climate (Hare, 1952). Hare (1952) acknowledges the fact that nowhere else on earth does the Arctic extend so far into the mid-latitudes.

The climate of Newfoundland is a product of Northern Hemisphere mid-latitude atmospheric circulation, the location of the province in relation to the mainland of Canada, and the cold surface waters of the Atlantic Ocean that surround the province (Banfield, 1983). The Great Northern Peninsula is affected by these cold Atlantic waters, but more so by the Gulf of St. Lawrence because of the west winds that prevail in this region throughout most of the year. Southwesterly airflows can carry the characteristics of the gulf and deliver them to the region (Banfield, 1983). These westerly air flows can create drier conditions for locations in the 'rain shadow' east of the Long Range Mountains (Banfield, 1983). The cold Atlantic waters, accompanied by the cold Labrador Current, result in a long ice season around the Great Northern Peninsula. Waters west of the peninsula can be 40 percent ice covered into April, while waters to the east can remain 40 percent ice covered well into May (Banfield, 1983).

Ecoregions and Climatic Zones of the Great Northern Peninsula

The Great Northern Peninsula is made up of two distinct ecoregions: (i) the Strait of Belle Isle and (ii) the Northern Peninsula Forest (Figure 1.1) (Damman, 1983). The Strait of Belle Isle region is characterized by rocky coastal barrens. In the Northern Peninsula Forest, the most important tree is the balsam fir (*Abies balsamea*) followed by the black spruce (*Picea mariana*) at higher elevations; several trees such as white pine (*Pinus strobus*), yellow birch (*Betula alleghaniensis*), and aspen (*Populus tremuloides*) reach their northern limit near the southern boundary of the ecoregion (Damman, 1983).

For the purpose of this study two major climatic zones make up the Great Northern Peninsula (Banfield, 1983): (i) the East Coast and Hinterlands, and (ii) the Northern Peninsula (Figure 1.1). Banfield (1983) describes the East Coast and Hinterlands climate as consisting of cold winters (50 to 70 % precipitation falling as snow) and generally warm and fairly sunny summers. Annual precipitation is 1000 to 1500 mm and cool late springs allow sea ice to persist until mid-May. The Northern Peninsula climate has short cool summers (high average cloudiness with occasional warm days of 25°C) and long cold winters (continuous snow cover duration up to 3 months) (Banfield, 1983). Annual precipitation is 900 to 950 mm near the coast, except 760 to 900 mm near the Strait of Belle Isle. The average annual temperature becomes progressively lower from south to north along the peninsula (Banfield 1983). Extreme temperature can reach as high as 30°C in the summer and as low as –37.5°C in the winter. The average frost-free season is 120 days with the last spring frost occurring around June 10 (Banfield, 1983).

Study Species

Braya longii and *B. fernaldii* are two sub-arctic alpine plants that belong to the (Mustard) family (*Brassicaceae)* (Meades, 1996 a; b). Both species contain few populations and are endemic to a narrow strip of limestone barrens along the Great Northern Peninsula of Newfoundland (Figure 2.1). Two Harvard botanists, M. L. Fernald and Bayard Long, discovered *Braya longii* and *B. fernaldii* on the Great Northern Peninsula in 1924 and 1925 (Meades, 1996 a; b). Meades (1996 a; b) reports that at the time of discovery, *B. longii* was found along a 6 km stretch of coastline from Yankee Point to Sandy Cove and *B. fernaldii* was found along a 120 km stretch from St. Barbe to Burnt Cape (Figure 2.1). At the present time, the range for Long's braya remains around 6 km while Fernald's braya has increased to over 150 km (Parsons, 2002); a small population of Fernald's braya has also been found at Port au Choix (Figure 2.1). In 1997, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated *B. longii* as endangered and *B. fernaldii* as threatened (Hermanutz, 1998). The status of each species was re-affirmed in 2000 (Hermanutz and Parsons, 2003). As of summer 2000, *Braya longii* occurred in only four sites, whereas *Braya fernaldii* was found in 14 sites (Hermanutz et al., 2002).

Habitat

The Limestone Barrens are located within the Strait of Belle Isle Ecoregion (Figure 1.1) which is characterized by tundra-like vegetation (Damman, 1983) and a cool, moist climate (Banfield, 1983). Both braya species are calciphiles, restricted to shallow soils (Hermanutz et al., 2002). Braya are pioneering plants (Grime, 1979) that grow in disturbed and exposed alkaline soil and calcareous gravel; braya are the first to colonize the gaps created in the landscape by soil frost activities (Noel, 2000). Both species of braya are concentrated in areas of moderate to high substrate disturbance and are adapted to this environment (Noel, 2000). Naturally disturbed habitats for braya are defined as areas with natural small-scale disturbances such as wind erosion, frost heave and soil movement, whereas anthropogenic disturbances are areas of human activity such as quarrying for roads (Noel, 2000).

Conservation Effort

The present distribution of both species has been influenced by the loss of habitat from limestone quarrying, road construction and community development (Meades, 1996 a; b). There has also been increasing concern regarding non-native and native insect herbivores threatening the survival and reproduction potential of both species of braya (Hermanutz and Parsons, 2002; Hermanutz, 2002). In 1998 the Braya Recovery Team was created to assess the present distribution and population dynamics of braya plants and their habitat (Hermanutz, 1998). The main goal of the Recovery Team at the present time is to secure the long-term survival of both species of braya. Six primary strategies are in effect at the present time to achieve this goal: scientific research, population monitoring, critical habitat assessment and protection, *ex situ* conservation, education and stewardship, as well as restoration and species reintroduction (Hermanutz, 2002). Objectives related to climate change are: (i) to determine the current climate sensitivity of rare plants using braya as an indicator species, (ii) to assess future vulnerability of braya, and (iii) to formulate future management strategies that integrate rare plant vulnerability to climate change (Bell et al., 2003). With respect to reintroduction, it is recommended that potential habitat sites must be based on climatic and geomorphological characteristics that most closely mimic natural sites that are currently occupied by braya (Hermanutz and Parsons, 2002).

This study addresses the goals of the Braya Recovery Team by providing an understanding of the regional climate of the Great Northern Peninsula and the microclimate characteristics of braya habitat along the Limestone Barrens. This study also examines the phenology of *Braya fernaldii* and *Braya longii* in the context of microclimatic characteristics.

Broad Study Themes

Two separate chapters will address the objectives of this study. Chapter 1 describes the climate of the Great Northern Peninsula of Newfoundland with respect to spatial variation and seasonal/interannual climate variability, and examines long term temperature and precipitation trends. Temperature trends are correlated against indices of atmospheric circulation and sea ice extent. Chapter 2 analyzes the microclimate of braya substrates along the Limestone Barrens with specific emphasis on soil temperature, and correlates the timing of the phenological events of germination, flowering, and fruiting with environmental indicators of soil temperature and snowmelt.

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Co-Authorship Statement

All manuscripts in this thesis were co-authored with Trevor Bell and John Jacobs. In all instances I was the principal contributor to the project design and proposal, implementation of the field research component, analysis of the data, and manuscript preparation.

Chapter 1. Spatial and Temporal Patterns of Temperature and Precipitation on the Great Northern Peninsula, Newfoundland.

1.1 Introduction

This paper examines the spatial and temporal variability in climates of the Great Northern Peninsula of the Island of Newfoundland. Understanding regional patterns of temperature and precipitation requires an effort to piece together spatial and long-term trends and to relate these trends to large scale regional climate and atmospheric circulation. Banfield and Jacobs (1998) state that the historical variation of the climate of a local area is related to events on spatial scales ranging from global through hemispheric to regional.

The Great Northern Peninsula, between 49° and 52°N and 55° and 58°W, belongs to a larger region known as the northwest Atlantic (Figure 1.1). It is this area of the Atlantic where two dominant ocean currents, the cold Labrador Current and the warm Gulf Stream-North Atlantic Drift, contribute to a cool marine climate (Banfield and Jacobs, 1998). The Great Northern Peninsula occupies the extreme northwest portion of the Island, an area which is greatly influenced by the cold Labrador Current (Hare, 1952).

General Climate

The spatial and temporal variability of climate along the Great Northern Peninsula can be attributed to factors such as latitude, sea surface temperatures, sea ice conditions, and local topography (Hare, 1952; Banfield, 1981, 1983). Seasonal variations in temperature, precipitation, and wind on the Great Northern Peninsula are largely the

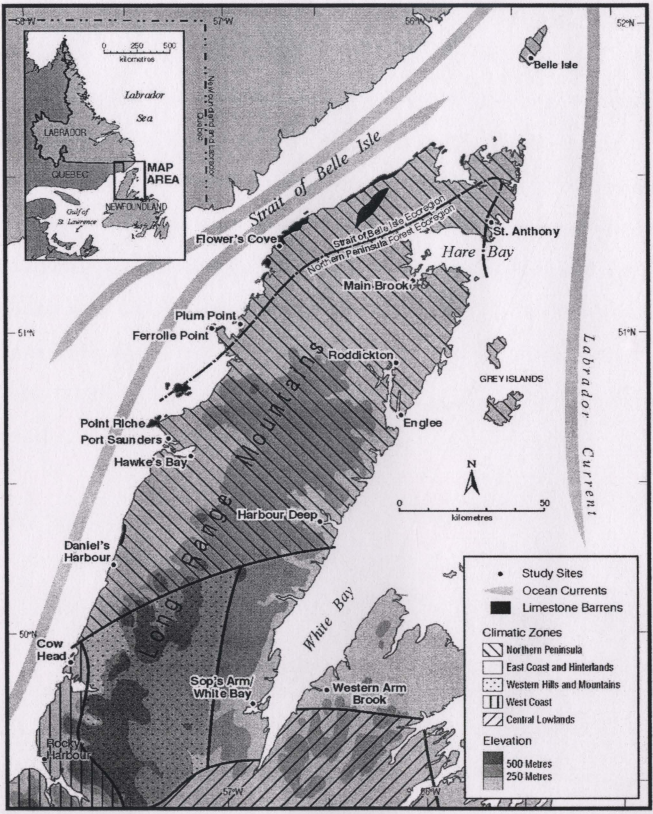

Figure 1.1
Great Northern Peninsula study region in northwest Newfoundland illustrating study sites (climate stations), ecoregions, climatic zones, and elevation. The Limestone Barrens (black) are restricted to a narrow coastal strip along the Strait of Belle Isle.

result of general air circulation patterns (pressure differences) and sea surface temperatures (Hare and Thomas, 1979; Banfield, 1983; Banfield, 1993; Banfield and Jacobs, 1998). Three quasi-permanent pressure systems, the Icelandic low, the Bermudan high, and the central-northern Canadian high, influence seasonal climate characteristics of the Northern Peninsula (Hare and Thomas, 1979; Banfield, 1983; Banfield, 1993; Banfield and Jacobs, 1998). These pressure systems determine the frequency of storms during the winter, draw icebergs south in the spring as a result of north winds, maintain a primary storm track north of Newfoundland in the summer, and produce consistent westerly winds during the fall (Hare and Thomas, 1979; Banfield, 1993). Banfield and Jacobs (1998) concluded that monthly and seasonal near-shore sea surface temperatures correlated strongly with seasonal air temperatures at all Newfoundland stations.

Long Term Trends

Long term temperature trends for Newfoundland and eastern Canada do not follow global trends or those experienced by central and northwestern Canada (Banfield and Jacobs, 1998; Zhang et al., 2000).

Banfield and Jacobs (1998) found no significant warming or cooling trend for summer or winter in Newfoundland, using the St. Anthony/Belle Isle and St. John's records from 1895 to 1995. Banfield and Jacobs (1998) did, however, find five noticeable periods (epochs) of mean temperature variability in the long-term average: a near-normal period from 1895 to 1919, a cold period from 1920 to 1935, a near-normal period from 1936 to 1950, a warm period from 1951 to 1971, and a cold period from 1972 to 1995.

Within the province of Newfoundland and Labrador, Banfield and Jacobs (1998) found temperature trends of different sub-regions to be highly correlated.

Precipitation records in Newfoundland and Labrador have not followed the trend in southern Canada and the eastern United States (Zhang et al., 2000; Joyce, 2002). Banfield and Jacobs (1998) found no significant trends in the precipitation record for St. John's, Newfoundland, during the past century, while there has been a significant increase in winter precipitation in the eastern United States of 0.67 cm/century (Joyce, 2002). Zhang et al. (2000) found a significant annual increase in precipitation for southern Canada of 12 percent over the past century.

Climate Indices and Sea Ice

The North Atlantic Oscillation (NAO) is a quasiperiodic variation in the north-south pressure gradient over the North Atlantic (Barnston and Livesey, 1987). It has been shown to be correlated with variability of climate in the North Atlantic region. Atlantic (Eastern) Canada is influenced by the NAO during the winter months (Hurrell, 1995; Banfield and Jacobs, 1998; Bonsal et al., 2001; Wettstein and Mearns, 2002). Hurrell (1995) describes how the positive phase of the NAO in winter increases the northerly flow of air over eastern Canada, bringing with it cooler temperatures.

Other indices have been used to study the climate of the North Atlantic. A positive Baffin Island-West Atlantic Index (BWA) from 1947 to 1969 was associated with warmer winter temperatures for the east coast of Canada, while a negative BWA index from 1970 to 1995 resulted in a cooling trend for the same region (Shabbar et al., 1997). In contrast to the NAO, the BWA index has a positive correlation with winter temperatures (Shabbar et al., 1997). Wettstein and Mearns (2002) studied the North Atlantic–Arctic Oscillations for the northeastern United States and Canada. They found that during the winter the warm phase of the Arctic Oscillation (AO) resulted in cooler temperatures for eastern Canada (Wettstein and Mearns, 2002). The effects of El Nino–Southern Oscillation (ENSO) are more evident over western and central Canada hardly affecting eastern Canada (Bonsal et al., 2001).

Sea ice extent in the northeast Atlantic has fluctuated in the past. The repeated failure of Europeans to find the Northwest Passage during the 19th century was likely the result of a greater sea ice extent and cooler summertime temperatures (Alt, 1985). Sea ice in the Cabot Strait has shown a high degree of interannual variability in the last two centuries with the most extensive ice occurring in 1923 and an increase in sea ice during the 1960s and 1990s (Hill et al., 2002). Research has found that sea ice extent has been linked with the North Atlantic Oscillation (NAO) (Deser et al., 2000; Kvamsto et al., 2004). The positive phase of NAO was associated with an extensive ice cover in the Labrador Sea, while the negative phase of the NAO was associated with a reduced ice cover in the Labrador Sea (Deser et al. 2000). Deser et al. (2000) and Banfield and Jacobs (1998) found that the extent of sea ice was related to cooler sea surface temperatures.

This paper presents regional patterns and long term trends for temperature and precipitation for the Great Northern Peninsula of Newfoundland. The spatial and temporal variability of climate is examined and discussed.

Specific study objectives are:

1. to create a regional climatology for the Great Northern Peninsula.
2. to determine the spatial variability of temperature and precipitation along the Great Northern Peninsula.
3. to examine the regional temperature and precipitation records.
4. to extend the long-term regional temperature record (Vincent, 1998).
5. to examine temperature trends in the St. Anthony/Belle Isle record for the time periods of 1896 to 2002, 1948 to 2002, and 1991 to 2002.
6. to examine the relationship between the winter North Atlantic Oscillation (NAO) index and mean winter temperatures for St. Anthony/Belle Isle.
7. to compare the record of sea ice extent to winter temperature at St. Anthony/Belle Isle.

1.2 Methods

This section outlines the process of record selection for stations along the Great Northern Peninsula and the approach to data analysis.

Selection of Records

Suitable climate records were selected to represent the overall geographical area and subregions of the Great Northern Peninsula (Figure 1.1). Fifteen Environment Canada climate stations are located on the Great Northern Peninsula (Figure 1.1). For all stations, with the exception of St. Anthony/Belle Isle, data were downloaded from the Environment Canada website (2003). Data for St. Anthony/Belle Isle, which combines the records from Belle Isle (1895 to 1969) and St. Anthony (1949 to 1995), was produced as part of a historical series by Vincent (1998). Western Arm Brook and Point Riche, both located on the west coast of the peninsula, were eliminated from the study because of incomplete records and a short data set, respectively. Of the remaining thirteen stations, eleven had complete precipitation records. The precipitation records for Englee and Ferolle Point were incomplete and eliminated from the study. Table 1.1 provides a summary of station information used for the study. All data were quality checked by Environment Canada. All climate data from Environment Canada can be found in Appendix 1.1.

Air temperature patterns were defined by seven stations on the west coast [Flowers Cove, Plum Point, Port Saunders, Hawke's Bay, Daniel's Harbour, Cow Head, and Ferolle Point], five on the east coast [Main Brook, Roddickton, Englee, Harbour Deep, and Sop's Arm/White Bay], and one [St. Anthony/Belle Isle] on the north coast of the peninsula (Figure 1.1). Precipitation patterns were defined by six records on the west coast [Flowers Cove, Plum Point, Port Saunders, Hawke's Bay, Daniel's Harbour, and Cow Head], four on the east coast [Main Brook, Roddickton, Harbour Deep, and Sop's Arm/White Bay], and one [St. Anthony/Belle Isle] on the north coast. Only two records, Daniel's Harbour and St. Anthony/Belle Isle, had temperature and precipitation records back to 1972, but only Daniel's Harbour had quality-checked data up to and including 1999. Main Brook, Hawke's Bay, and Roddickton were considered to be inland stations since they were located at least one km inland.

Table 1.1
Climate stations on the Great Northern Peninsula selected for the study. Refer to Figure 1.1 for locations.

Station (Abbreviation)	ID	Lat. and Long.	Altitude (m)	Length of Record	Exposure	Distance from Ocean (m)
Belle Isle (BI)	8500500	51° 52'N 55° 22'W	130	1896 - 1944	n.a.	250 south
St. Anthony (SA)	8403400	51° 22'N 55° 35'W	17	1949 - 1995	100m south to St. Anthony Harbour. Forest cover 150m north and 150m west.	2400 east
Flowers Cove (FC)	8401582	51° 18'N 56° 44'W	9	1972 - 2002	Forest cover 400m to the north. Low forest cover 30m southeast.	250 west
	8401583	51° 20'N 56° 41'W	9	1980 - 2002	Small pond and bog 30m south.	
Plum Point (PP)	8402958	51° 04'N 56° 53'W	6	1973 - 2003	Forest cover 40m to the east.Buildings and homes within 25m to the north, south, and east.	100 west
Ferolle Point (FP)	8401565	51° 01'N 57° 06'W	6	1996 - 2003	Nearest forest 3km east.	100 south
Port Saunders (PS)	8403040	50° 39'N 57° 12'W	91	1980 - 2001	Forest cover 30m east and south and 48m north. Hawke's Bay located 3km south.	6750 west
Hawke's Bay (HB)	8402078	50° 36'N 57° 11'W	11	1985 - 2002	Forest cover begins 250m east. Hawke's Bay located 200m northwest.	10750 west
Daniel's Harbour (DH)	8401400	50° 14'N 57° 34'W	19	1947 - 1995	Pond 170m north. Mostly marsh and low shrubs, some trees 10km east.	1000 west
Cow Head (CH)	8401335	49° 54'N 57° 47'W	15	1983 - 2002	Protection on north and east by a garage. Forest across the street. Wetland 1km west.	60 west
Main Brook (MB)	840KE88	51° 10'N 56° 01'W	14	1984 - 2002	Salmon Bay located 1km north. Wetland 700m north and a pond 50m west.	19000 east

Station (Abbreviation)	ID	Lat. and Long.	Altitude (m)	Length of Record	Exposure	Distance from Ocean (m)
Roddickton (RN)	8403098	50° 52'N 56° 07'W	12	1972 - 1990	Forested to the east, north, and south. Chimney Bay located 50m west.	11250 southeast
Roddickton (North)	840L0R9	50° 52'N 56° 07'W	12	1991 - 1999		11250 southeast
Englee (EN)	8401538	50° 43'N 56° 07'W	30	1994 - 2003	Low shrubs with trees up to 10 m high. Englee Harbour located 600m east.	100 south
Harbour Deep (HD)	8402073	50° 22'N 56° 31'W	30	1991 - 2002	No trees within 50m radius. Pigeonniere Arm located 600m north.	6250 southeast
Sop's Arm/ White Bay (SW)	8403690	49° 46'N 56° 52'W	17	1981 - 2003	Scattered tall trees. Hilly terrain.	350 southeast

Climate Data

Daily air temperature and precipitation records were available from Environment Canada (2003) in spreadsheet form. Monthly records were extracted from the data for the following variables: maximum temperature, minimum temperature, mean temperature, total rainfall, total snowfall, and total precipitation (all variables were not available at all stations). All climate data can be found in Appendix 1.1.

Monthly data were used to create seasonal records of mean air temperature, total precipitation, and snowfall for each year of each station. Winter mean air temperature for a given year was calculated as the average of monthly means for December (of the previous year), January, and February (Joyce, 2002; Zhang et al. 2000). The remaining seasons were defined by monthly dates as follows: March to May for spring, June to August for summer, and September to November for fall (Joyce, 2002; Zhang et al. 2000). The same time periods were used for seasonal precipitation and snowfall. The winter and summer seasons for the study of long-term air temperature trends at St. Anthony/Belle Isle followed the procedures of Banfield and Jacobs (1998): December (of the previous year), January, February, and March for winter, and June, July, August, and September for summer (Banfield and Jacobs, 1998).

Subregional and Seasonal Climate Variability

Climate normals (1971 – 2000) available from Environment Canada (2004a) were used to illustrate the latitudinal variation of summer mean temperatures from south to north along the west coast of the Great Northern Peninsula. The stations ranged from Rocky Harbour (49.56°N) to St. Anthony (51.36°N) (Figure 1.1).

Six stations - Cow Head, Hawke's Bay, Plum Point, Sop's Arm/White Bay, Harbour Deep, and Main Brook - were used to examine the spatial variation and interannual variability in air temperature, total precipitation, and snowfall for the Great Northern Peninsula. These six stations, three each on the east and west coasts, were chosen since they had the greatest homogeneity of records for the time period from 1991 to 2001. These six stations also best represented the southern (Cow Head and Sop's Arm/White Bay), central (Hawke's Bay and Harbour Deep), and northern (Plum Point and Main Brook) parts of the peninsula (Figure 1.1).

Long Term Trends

Before analyzing long term climate trends, the degree of spatial homogeneity between all climate stations on the Great Northern Peninsula was tested since only St. Anthony/Belle Isle had a long term record spanning the past century. Therefore, the St. Anthony/Belle Isle record was used to represent all climate stations along the northern peninsula. The close proximity of the station at Main Brook allowed for an extension of the St. Anthony/Belle Isle temperature record to include seven additional years from 1995 to 2002 (since the station had closed down in 1995). The extension was calculated using the difference method of adjusting climatological means (Thom, 1971).

Long term winter, summer, and annual temperature trends for the St. Anthony/Belle Isle record were examined on these timescales: the past century (1896 to

2002), the second half of the century [1948 to 2002, based on departures from the 1951 to 1980 averages (Environment Canada, 2004b)], and the last decade (1991 to 2002).

Climate Indices and Sea Ice

The North Atlantic Oscillation (NAO) index series from Jones (Climate Research Unit, 2004) was correlated with the St. Anthony/Belle Isle temperature record from 1900 to 2002 to examine the relationship between the NAO and winter temperature on the Great Northern Peninsula. A correlation analysis was also conducted on a five-year running mean for both data sets.

The NAO index series was compared with Hills' record of ice extent off the east coast of Newfoundland from 1868 to 2000 (Hill, 2004). The ice record was also correlated with the St. Anthony/Belle Isle temperature record to examine the relationship between ice extent off the east coast of Newfoundland and winter land temperature from 1896 to 2002. NAO data and sea ice can be found in Appendix 1.1.

Statistical Analysis

The spatial variation in temperature, total precipitation, and snowfall for the six stations of Cow Head, Hawke's Bay, Plum Point, Sop's Arm/White Bay, Harbour Deep, and Main Brook was examined with a one way ANOVA (Sokal and Rohlf, 1995); the interannual variability was calculated using standard deviation (Banfield and Jacobs, 1998). The General Linear Model was used to examine the trends in temperature for the St. Anthony/Belle Isle record (Sokal and Rohlf, 1995). Alpha was set at 0.05 for significance for all statistical tests (Sokal and Rohlf, 1995).

1.3 Results

This section presents the results of the analysis of station data with respect to the regional climate of the Great Northern Peninsula, and its long term variability using the St. Anthony/Belle Isle record. The time series of the North Atlantic Oscillation (NAO) index is compared with the winter temperature series for the St. Anthony/Belle Isle record and the record of sea ice extent off the east coast of Newfoundland.

General Climate

Table 1.2 provides mean values for temperature, precipitation, and snowfall for each station. Mean annual temperature ranged from a high of 3.7°C at Cow Head to a low of 0.6°C at St. Anthony/Belle Isle. Hawke's Bay recorded the highest mean summer temperature of 14.0°C. Roddickton North, Main Brook, and Hawke's Bay, stations located furthest inland (Figure 1.1), recorded the highest annual temperature ranges - 22.4, 22.8, and 22.5°C, respectively. St. Anthony/Belle Isle and Main Brook, the two northernmost stations, received the most precipitation on average - 1259 and 1238 mm, respectively. Thirty-six percent of the annual precipitation at Main Brook fell as snow compared with 22% and 26% at the two southern stations of Harbour Deep (east coast) and Cow Head (west coast), respectively. Two stations located on the east coast of the peninsula, Roddickton North and Sop's Arm/White Bay, recorded the least amount of annual precipitation – 970 and 995 mm, respectively.

Table 1.2

Mean seasonal temperatures (Deg C), precipitation [total (mm), snowfall (cm)], and standard deviation at selected climate stations (Environment Canada, 2004a). Missing data represented by n.a.

Station (period of record)		Temperature Summer	Winter	Fall	Spring	Year	Precipitation Summer	Winter	Fall	Spring	Year	Snowfall Annual
Daniel's Harbour	mean	12.8	-6.8	6.1	0.2	3.1	302.4	294.0	301.2	218.3	1115.9	371
(1947 - 1995)	S.D	0.8	2.4	0.8	1.5		68.3	98.6	76.3	69.3		
Port Saunders	mean	12.4	-8.4	5.2	-0.1	2.3	317.2	303.8	292.1	207.6	1120.6	409
(1980 - 2000)	S.D	0.8	2.1	1.0	1.7		69.1	97.0	70.9	63.9		
Plum Point	mean	12.7	-8.8	5.4	-0.5	2.2	328.4	313.7	326.8	255.5	1224.3	416
(1973 - 2002)	S.D	0.9	1.9	0.8	1.5		63.8	61.3	58.3	54.5		
Hawke's Bay	mean	14.0	-8.5	5.8	0.5	3.0	273.3	285.3	279.5	180.4	1018.5	369
1985 - 2002)	S.D	1.0	1.9	1.0	1.5		46.0	55.2	48.0	69.0		
Harbour Deep	mean	12.8	-8.2	5.7	-0.1	2.6	318.5	252.0	331.1	221.2	1122.8	247
(1991 - 2002)	S.D	1.3	2.0	1.1	1.5		55.8	105.3	100.2	71.3		
Flowers Cove	mean	11.4	-9.3	4.5	-1.0	1.4	314.2	249.0	282.9	200.4	1046.5	288
(1972 - 2000)	S.D	1.0	2.0	0.8	1.7		75.7	97.3	75.6	51.9		
St. Anthony/Belle Isle	mean	10.4	-9.6	3.6	-2.0	0.6	305.5	344.3	331.3	278.7	1259.9	n.a.
(1896 - 2002)	S.D	1.0	1.9	0.8	1.2		99.3	101.2	95.5	79.2		
Cow Head	mean	13.6	-6.4	6.7	1.0	3.7	324.6	325.3	326.3	233.2	1209.5	319
(1983 - 2002)	S.D	1.0	1.5	0.9	1.5		60.8	71.9	46.5	62.8		
Main Brook	mean	12.9	-9.9	4.8	-0.6	1.8	301.1	401.2	299.5	236.3	1238.1	525
1984 - 2002)	S.D	1.0	1.8	0.9	1.4		65.3	130.8	81.0	63.8		
Roddickton North	mean	13.1	-9.3	4.8	-0.4	2.1	258.8	259.6	269.2	183.3	970.9	312
(1972 - 1999)	S.D	1.0	2.0	0.9	1.8		58.1	92.7	105.8	45.9		
Sop's Arm/White Bay	mean	13.9	-6.9	6.1	1.1	3.6	265.0	239.8	288.1	203.8	996.8	279
(1981 - 2003)	S.D	1.3	1.6	0.9	1.3		75.0	77.4	85.7	64.1		
Ferolle Point	mean	12.3	-7.4	5.7	-0.8	2.5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
(1996 - 2003)	S.D	0.7	1.1	0.8	1.7		n.a.	n.a.	n.a.	n.a.	n.a.	
Englee	mean	12.2	-7.1	5.8	-0.2	2.7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
(1994 - 2003)	S.D	0.8	1.1	1.1	1.5		n.a.	n.a.	n.a.	n.a.	n.a.	

Subregional and Seasonal Climate Variability

Temperature (1991 to 2001)

Latitudinal temperature variations are evident along the west coast of the Northern Peninsula; as latitude increases, mean temperature decreases. Figure 1.2 illustrates this decrease using mean summer temperature ($r^2=0.75$), from the Canadian Climate Normals 1971 – 2000 (Environment Canada, 2004a). The graph shows a slight latitudinal decrease in mean air temperature south of 50.2°N, no change from 50.2°N to 51.1°N, and a sharp decrease north of 51.1°N.

An examination of mean seasonal temperatures for the 1991 to 2001 period, using the stations at Cow Head, Hawke's Bay, Plum Point, Sop's Arm/White Bay, Harbour Deep, and Main Brook (Figure 1.3) indicated a consistent south to north decrease in mean seasonal temperature along the Great Northern Peninsula for fall ($p<0.001$), winter ($p<0.001$), and spring ($p=0.01$). This decrease in mean seasonal temperatures was not as evident for the summer months ($p=0.06$). The east and west coasts of the peninsula were also examined for seasonal temperature differences. For three of the four seasons, there was no noticeable difference in mean temperatures between stations on the east and west coasts [winter ($p=0.36$), spring ($p=0.54$), summer ($p=0.65$)]; however, the east coast was slightly warmer during the fall ($p=0.06$).

The greatest interannual variability in seasonal mean temperature was experienced during the winter months (the mean of the standard deviations for all six stations = 2.1°C) (Table 1.3). Cow Head and Hawke's Bay recorded the lowest

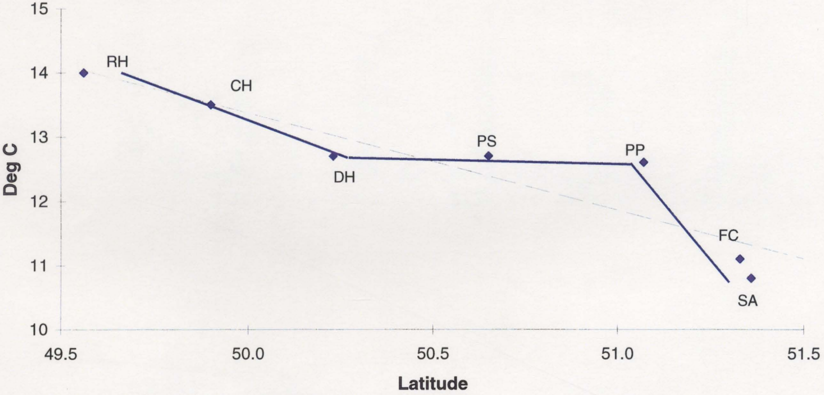

Figure 1.2
Mean summer air temperature plotted against latitude along the west coast of the Great Northern Peninsula (Blue) from Rocky Harbour to St. Anthony [climate normals 1971-2000, Environment Canada 2004a] Solid blue lines represent trends at various latitudes. Linear trend line is shown as a dashed black line.

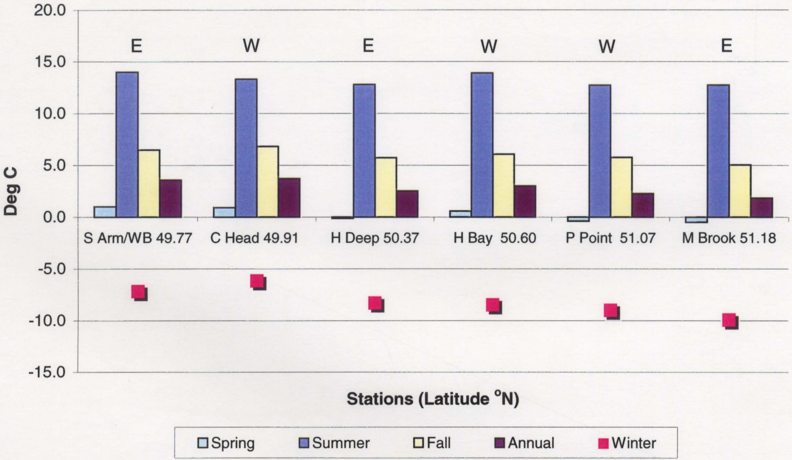

Figure 1.3
Mean annual and mean seasonal air temperature along the Great Northern Peninsula (1991-2001).
West coast stations (W): Cow Head, Hawke's Bay, and Plum Point.
East coast stations (E): Sop's Arm/White Bay, Harbour Deep, and Main Brook.

Table 1.3

Variability of seasonal mean temperature, total precipitation, and snowfall, 1991 to 2001.

	Temperature: standard deviation °C				Total Precipitation: standard deviation mm				Snowfall: standard deviation cm		
	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
Sop's Arm/White Bay	0.7	1.9	1.6	1.4	63.8	69.6	60.9	45.7	11.3	64.1	22.7
Harbour Deep	1.1	2.1	1.6	1.3	100.2	110.1	72.5	58.3	9.2	48.0	37.4
Main Brook	0.7	2.1	1.6	1.3	63.9	52.7	78.9	69.4	18.3	70.3	54.4
Plum Point	0.7	2.3	1.6	1.3	39.6	67.4	55.1	64.8	13.8	40.1	42.4
Cow Head	0.8	1.8	1.4	1.2	47.7	84.1	75.5	42.8	21.4	49.4	43.8
Hawke's Bay	0.9	2.3	1.7	1.2	38.5	61.4	70.8	44.9	9.9	70.9	72.7
Mean S.D.	0.8	2.1	1.6	1.3	59.0	74.2	69.0	54.3	14.0	57.2	45.6

interannual seasonal variability in temperature during the summer (the mean of the standard deviations for all six stations = 1.3°C) (Table 1.3).

Precipitation (1991 to 2001)

Total precipitation did not vary with latitude on either coast along the Northern Peninsula between 1991 and 2001 (Figure 1.4). Mean annual precipitation was highest for the most southerly station on the west coast (Cow Head) and the most northerly station on the east coast (Main Brook). Mean total precipitation during spring was the lowest of all seasons for all stations. There was a large difference in snowfall amounts with respect to latitude between 1991 and 2002 (Figure 1.5). Main Brook and Plum Point, the two most northern stations, had higher snowfall totals compared to the four stations located further south for the fall, winter, and spring seasons. There was no significant difference in mean total precipitation or snowfall between the east and west coast during any season [total precipitation: fall ($p=0.91$), winter ($p=0.21$), spring ($p=0.67$), summer ($p=0.99$)]. The greatest interannual seasonal variability in mean total precipitation was experienced during the winter months (the mean of the standard deviations for all six stations = 74.16 mm) (Table 1.3).

In summary, there was a significant south to north latitudinal temperature decrease for fall, winter, and spring. There was no significant difference between the east and west coasts with respect to mean temperature, total precipitation, and snowfall; there were, however, slightly warmer temperatures experienced on the east coast during fall.

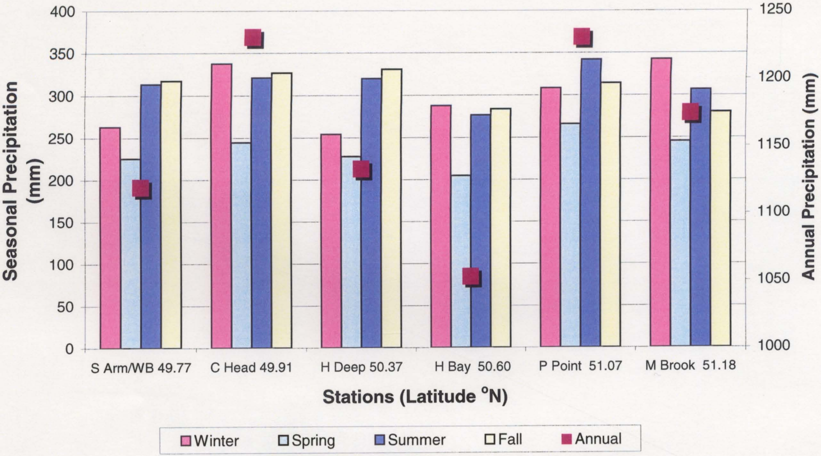

Figure 1.4

Mean annual and mean seasonal precipitation along the Great Northern Peninsula (1991-2001).
West coast stations: Cow Head, Hawke's Bay, and Plum Point.
East coast stations: Sop's Arm/White Bay, Harbour Deep, and Main Brook.

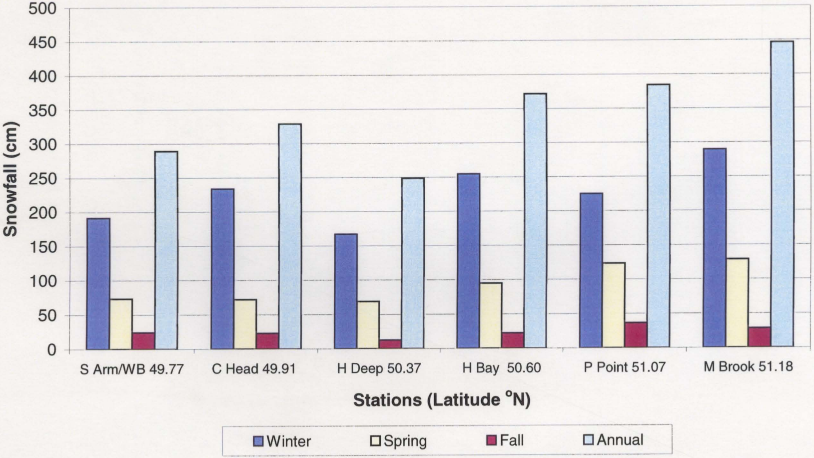

Figure 1.5
Mean annual and mean seasonal snowfall along the Great Northern Peninsula (1991-2001).
West coast stations: Cow Head, Hawke's Bay, and Plum Point.
East coast stations: Sop's Arm/White Bay, Harbour Deep, and Main Brook.

Snowfall totals were higher for more northerly stations. The greatest interannual variability for temperature and total precipitation occurred during the winter.

Long Term Trends

Temperature

Homogeneity of records was necessary for assuming the same long term trend for all stations. Analysis of the thirteen stations' records for average seasonal temperature indicated a strong regional homogeneity among stations for all seasons [286 of 300 (95%) paired correlations were significant at the $p=0.05$ level; 85% of p-values < 0.01]. The strongest regional homogeneity occurred during the winter - all stations were significantly correlated (all r^2 values greater than 0.8; all p-values <0.05) - whereas the weaker homogeneity occurred during the fall and summer. As an example, Figure 1.6 illustrates the homogeneity of records for mean winter temperature. The records show two similar warming trends from 1973 to 1980 and 1993 to 2000. There were rapid cooling trends from 1969 to 1973 and from 1981 to 1989.

The St. Anthony/Belle Isle record, extended from the Main Brook station for the time period 1896 to 2002, was used to study long term temperature trends since this record contained a century of data. Figures 1.7 and 1.8 illustrate the long term summer (JJAS) and winter (DJFM) temperature trends, respectively. Analysis of the summer temperature record showed a weak warming trend ($r^2=0.1$, $p=0.001$) (Figure 1.7), while the winter record for the same time period showed no similar trend ($r^2=0.01$, $p=0.37$) (Figure 1.8).

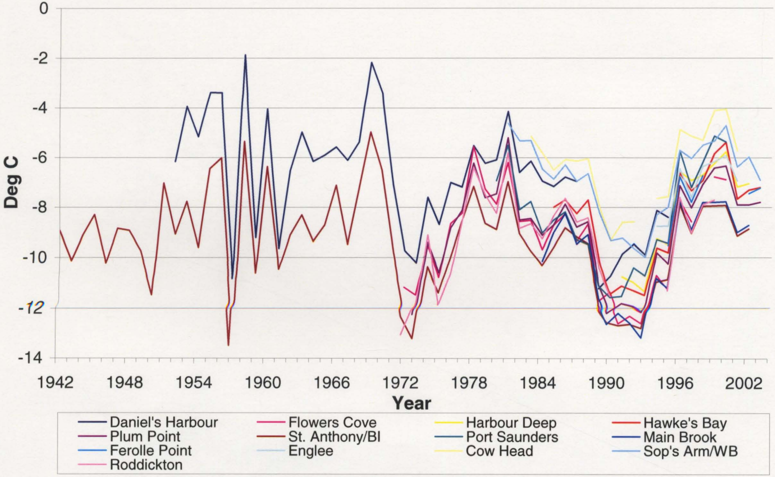

Figure 1.6
Mean winter (DJF) temperature for stations along the Great Northern Peninsula.

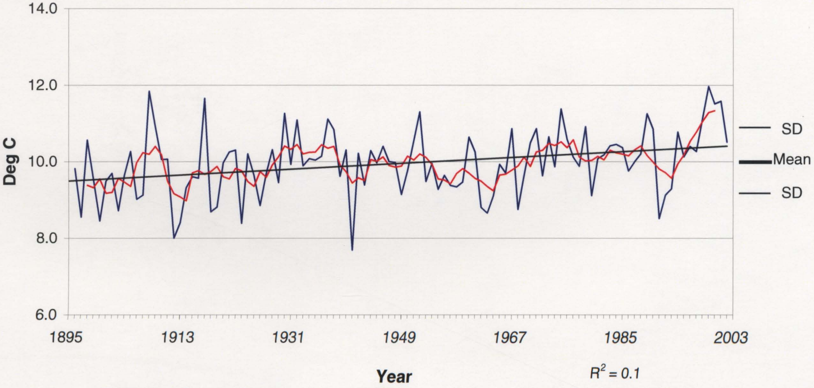

Figure 1.7
Historical record of mean summer (JJAS) air temperature for St. Anthony/Belle Isle, 1896-2002. Five-year moving average shown in red. Historical trend shown with thin black line.
Mean and Standard Deviation (SD) based on 1951 to 1980 averages (Environment Canada, 2004b).

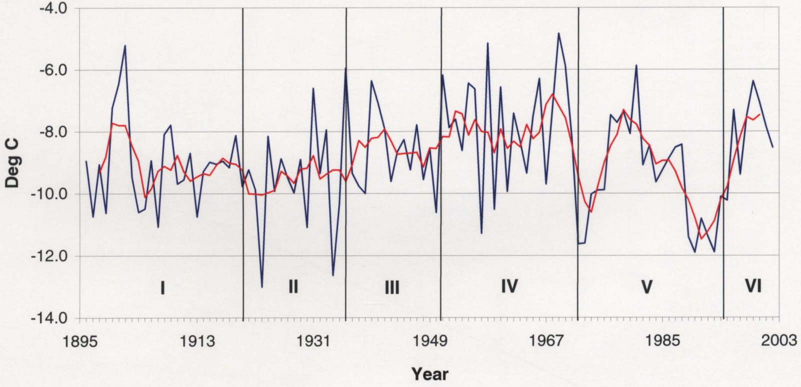

Figure 1.8
Historical record of mean winter (DJFM) air temperature for St. Anthony/Belle Isle, 1896-2002, including the five time periods (epochs) found by Banfield and Jacobs (1998) and the additional of epoch VI. Five-year moving average shown in red.

The second half of the last hundred years (1948 to 2002) was examined for summer, winter, and annual temperature trends in the St. Anthony/Belle Isle record. The trends were based on departures from the 1951 to 1980 averages (Environment Canada, 2004b). There was a significant warming trend of 0.8°C from 1948 to 2002 for summer temperature ($r^2=0.1$, $p<0.01$) and although the winter months did have a cooling trend of 0.6°C it was not significant ($r^2=0.05$, $p=0.17$). As for annual temperatures, there was no noticeable trend from 1948 to 2002 ($r^2<0.001$, $p=0.88$). Analysis of the last decade (1991 to 2002) indicated warming trends for both summer (2.6°C increase, $r^2=0.7$, $p=0.001$) and winter (4.2°C increase, $r^2=0.6$, $p=0.002$). Figure 1.9 illustrates the warming trend for mean summer and winter temperatures at St. Anthony/Belle Isle.

The time period from 1996 to 2002 was used to represent a sixth period (epoch) of warmer temperatures in the long term St. Anthony/Belle Isle record (1896 to 2002); Banfield and Jacobs (1998) ended their fifth period (epoch) in 1995 (Figure 1.8). The average (DJFM) temperature for the sixth epoch was 1.1°C warmer than the overall mean temperature of the entire length of record. The mean temperature of the sixth epoch was significantly warmer than the fifth epoch [2.1°C ($p=0.01$, $df=29$)]. The fourth and sixth epochs were equally warm; there was no significant difference in mean temperature between the fourth epoch and the sixth epoch [temperature difference = 0.02°C ($p=0.98$, $df=27$)].

Contrary to the periods (epochs) identified by Banfield and Jacobs (1998), general trends from 1969 to 2003 can be further divided into four separate epochs of cyclic warming and cooling (Figure 1.10). Periods of continuous temperature decrease or

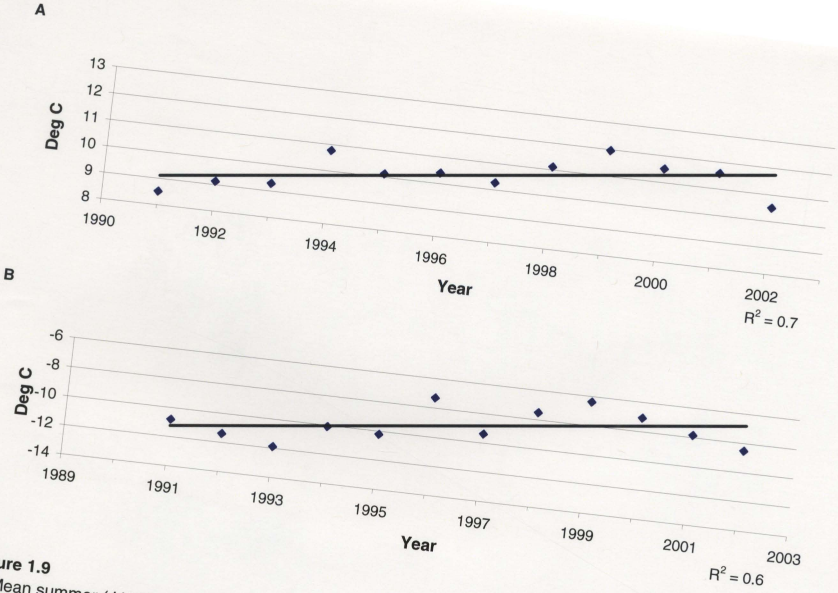

Figure 1.9
A) Mean summer (JJAS) air temperature for St. Anthony/Belle Isle, 1991-2002.
B) Mean winter (DJFM) air temperature for St. Anthony/Belle Isle, 1991-2002.
Trend shown in heavier black line.

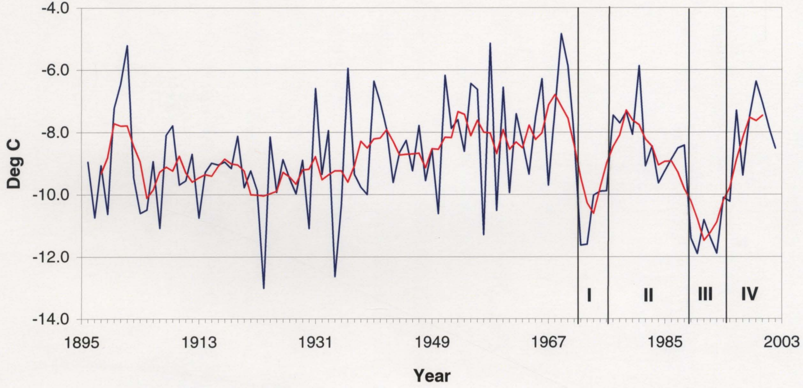

Figure 1.10
Historical record of mean winter (DJFM) air temperature for St. Anthony/Belle Isle, 1896-2002, including four new epochs of cooler and warmer temperatures during the last 33 years.

cooling lasted from 1969 to 1973 and 1979 to 1991. The warming trends occur from 1974 to 1979 and 1991 to 1998. As a result of these warming and cooling trends, the last 33 years can be divided into two epochs of below average temperature from 1972 to 1976 and 1989 to 1994, and two epochs of 'above average' temperature during the late 1970s to mid 1980s and during the late1990s.

Precipitation

Analysis of nine precipitation records indicated a weak regional homogeneity between all stations for all seasons [92 of 215 (43%) paired correlations were significant at the p=0.05 level]. The greatest regional differences occurred during the winter (30% of paired correlations were significant at the p=0.05 level). Despite a weak correlation, the strongest regional homogeneity occurred during the fall and summer. Four stations - Daniels Harbour, Plum Point, Flowers Cove, and Port Saunders - showed strong homogeneity during the fall (all r^2 values greater than 0.5; all p-values <0.05). Daniel's Harbour, Flowers Cove, Cow Head, and Port Saunders displayed strong homogeneity during the summer (Figure 1.11) (all r^2 values greater than 0.5; all p-values <0.05). Data based solely on the Daniel's Harbour record indicated a weak increasing trend for total summer precipitation since 1948 (r^2=0.12).

In summary, temperature records for all stations on the Great Northern Peninsula indicated a greater regional homogeneity than precipitation records. There has been a significant warming trend for summer and winter temperatures during the last decade and

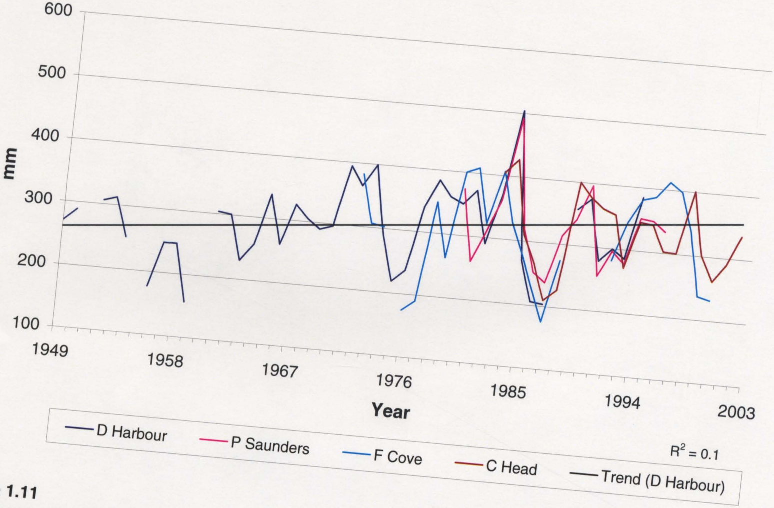

Figure 1.11
Mean summer (JJA) precipitation for stations along the Great Northern Peninsula. Trend line (black) calculated for the Daniel's Harbour station record only.

for summer only during the last 50 and 100 years. The last 33 years have seen two cyclic periods of cooling and warming.

Climate Indices and Sea Ice

A significant negative correlation was found between the winter NAO index and the St. Anthony/Belle Isle winter temperature record from 1900 to 2002 ($p=0.001$, $r^2=-0.32$) (Figure 1.12). The significance level increased when the correlation was applied to five year moving averages for each record ($p<0.001$, $r^2 = -0.72$). There was little response in temperature to a large fluctuation of the NAO from 1917 to 1920 and from 1960 to 1971, while a high positive NAO around 1976 and 1993 led to a large temperature decrease. A significant positive correlation was found between the winter NAO index and sea ice extent off the east coast of Newfoundland from 1868 to 2000 ($p<0.001$, $r^2=0.42$) (Figure 1.13). The two records deviate from each other prior to the 1920s, but since the 1920s there appears to be a close correspondence between the NAO and sea ice extent. Ice extent had a significant negative correlation with the winter temperature record for St. Anthony/Belle Isle from 1896 to 2002 ($p<0.001$, $r^2=-0.68$).

1.4 Discussion

The following section attempts to provide possible explanations for the results. This section discusses the regional climatology of the Great Northern Peninsula of Newfoundland, and its long term variability. The North Atlantic Oscillation (NAO) and its relationship to temperature and sea ice extent will also be discussed.

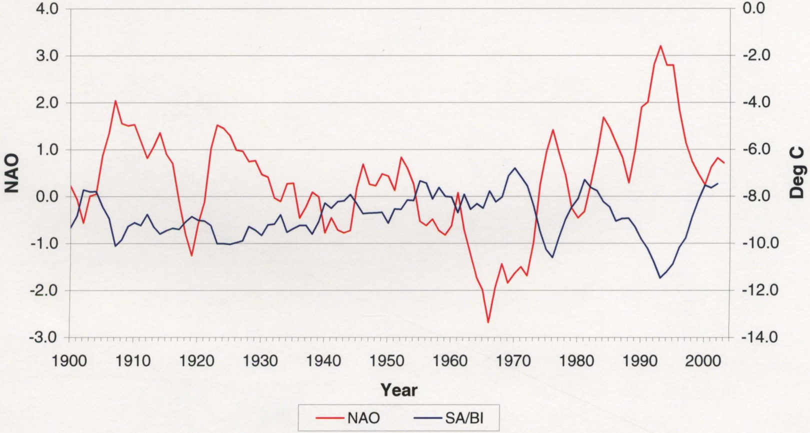

Figure 1.12

Five-year moving averages for winter NAO index and winter (DJFM) air temperature at St. Anthony/Belle Isle, *1900 to 2002.*

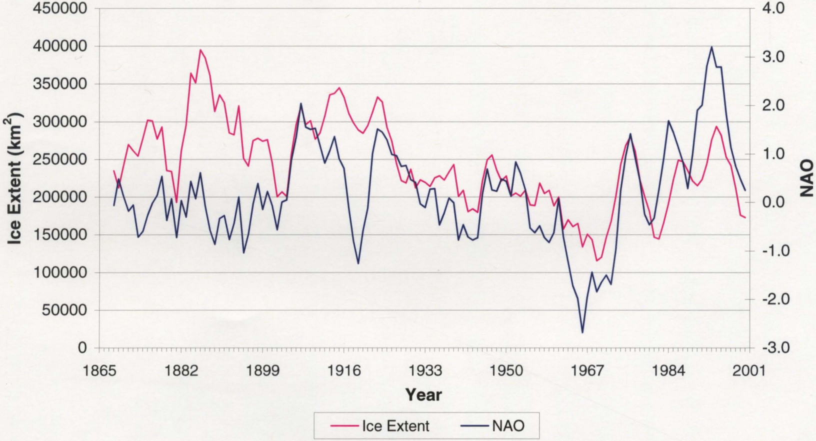

Figure 1.13
Five-year moving averages for winter NAO index and ice extent off the east coast of Newfoundland, 1968 to 2000.

Subregional and Seasonal Climate Variability

Temperature decreases with increasing latitude along the west coast of the Great Northern Peninsula during all seasons. These results agree with the results found by Banfield (1983). Figure 1.2 illustrates this decrease in mean summer temperature (JJA) with latitude for selected stations along the peninsula. Sea ice extent and cooler ocean surface waters in northern sections contribute to the decrease in temperature from south to north. Solar radiation intensity decreases with increasing latitude. The latitudinal extent of the Great Northern Peninsula is large enough for temperatures to vary from south to north (Banfield, 1983; Hidore and Oliver, 1993). Between the latitudes of 50.2°N to 51.1°N there appears to be no change in temperature with latitude, which suggests that some other factor is responsible for the relatively high temperatures at Port Saunders and Plum Point. The sharp decrease in mean summer temperature north of 51.1°N (1.8°C drop in temperature with a 0.3 degree increase in latitude) can be attributed to cold water from the Labrador Current affecting the northern sections of the Great Northern Peninsula more strongly than the southern parts. Also, sea ice can persist around the northern sections of the peninsula into late spring (Markham, 1980; Banfield, 1983).

Temperature (1991 to 2001)

According to the seasonal analysis using the 1991 to 2001 records for Cow Head, Hawke's Bay, Plum Point, Sop's Arm/White Bay, Harbour Deep, and Main Brook, the general decline in temperature with increasing latitude was significant during the fall, winter, and spring (Figure 1.3). This latitudinal pattern was not significant for the summer months, although the p-value of 0.06 was very close to a significant value. The six stations did not cover the entire latitudinal range of the Northern Peninsula and therefore did not represent the extent of mean summer temperatures along the peninsula. Also, Hawke's Bay recorded a high summer average temperature for its latitude possibly because it is the furthest inland station on the west coast of the Northern Peninsula and is ice free earlier than locations at the same latitude on the east coast (Banfield, 1983). The west coast station of Cow Head, which has the least amount of ice cover throughout the winter (Banfield, 1983), recorded a higher mean winter temperature than Sop's Arm/White Bay, located farther south on the east coast (Figure 1.1).

The greater interannual variability (standard deviation) of temperatures during the winter months (Table 1.3) can be related to the effects of ice cover (Banfield, 1983; Banfield and Jacobs, 1998). Around the Great Northern Peninsula, ice coverage varies from month to month. The standard deviation of winter temperature at Cow Head, a station that has the least amount of ice cover throughout the winter, was the lowest of all stations during 1991 to 2001. Fall was the period of least interannual variability when the lag of warm waters around the peninsula after summer has a considerable moderating effect. Cow Head and Hawke's Bay had the lowest standard deviation for the summer months probably due to the prevailing southwest winds from an extensive Bermuda high (Hare and Thomas, 1979; Banfield, 1993). These winds have a marine fetch across the Gulf of St. Lawrence, which reduces the interannual variability in temperature (Banfield and Jacobs, 1998). Sop's Arm/White Bay, a station on the east coast of the peninsula, has the least marine effect from predominant southwest winds in the summer and therefore had the highest interannual variability.

Precipitation (1991 to 2001)

Annual total precipitation did not vary with latitude or coast during the time period of 1991 to 2001 (Figure 1.4). Although not statistically significant, there were greater amounts of total precipitation and snowfall during the winter months for the west coast of the peninsula. This increased precipitation (mostly snowfall), can be attributed to cold northwest air outbreaks from Quebec and Labrador picking up moisture from the warmer waters of the Gulf of St. Lawrence (Banfield and Jacobs, 1998; Banfield, 1993). A greater amount of snowfall occurred at the two most northerly stations (Figure 1.5) which would have a greater percentage of precipitation falling as snow during the winter months as a result of cooler temperatures. Spring was the season with the lowest mean total precipitation, possibly resulting from consistent north winds associated with a stationary Icelandic low and the eastward migration of the central Canadian high (Hare and Thomas, 1979; Banfield, 1993), and an extended period of sea ice (Hare, 1952; Banfield, 1983).

The greatest interannual variability in mean total precipitation and snowfall occurred during the winter. In this season the Great Northern Peninsula lies in the track of major storms (Banfield, 1993) which greatly influences the amount of snow or rain received. During the summer, when interannual variability of precipitation is low, the track of major storms lies to the north.

Long Term Trends

The greatest homogeneity of records for stations on the Great Northern Peninsula for mean temperature occurred during the winter. Banfield and Jacobs (1998) also found winter temperature to be the most consistent between stations throughout Newfoundland and Labrador. Banfield and Jacobs (1998) found that precipitation during most of the year in Newfoundland is most frequently associated with the passage of frontal cyclones; convective or conditional instability, however, can increase precipitation over interior stations during the summer and increase precipitation during fall and winter over stations located close to large open waters. Therefore, the seasonal inconsistency of type and amount of precipitation resulted in a very low homogeneity of records for stations on the Great Northern Peninsula compared to mean seasonal temperature.

Temperature

The linear trend of summer warming found for the St. Anthony/Belle Isle record from 1896 to 2002 (Figure 1.7) was not evident for the same record from 1896 to 1995 (Banfield and Jacobs, 1998). The relatively abrupt increase in mean summer temperatures by more than 2 degrees from 1991 to 2002 (Figure 1.9) was a significant departure from the pattern found by Banfield and Jacobs (1998) through 1995. The summer warming trend appears as a late-20th century event (particularly the last decade). Other than 1908 and 1917, the summers of 1999, 2000, and 2001 were the warmest on record; the warmest mean summer temperature was recorded in 1999 (Figure 1.7).

The trends for St. Anthony/Belle Isle did not agree with the national trends for Canada. Nationally, particularly warm temperatures did not occur from 1999 to 2001 and the warmest year on record from 1948 to 2002 was 1998, followed by a sharp decrease over the next two years (Environment Canada, 2004b). Globally, Mann et al. (1998) indicates that the annual temperature of the Northern Hemisphere in the twentieth century has warmed at a greater rate than any time in the last 600 years. According to Mann et al. (1998), three years in the 1990s were warmer than any other year since 1400.

Consistent with Banfield and Jacobs (1998), there were no warming or cooling trends for the winter St. Anthony/Bell Isle record (Figure 1.8). The shorter sixth epoch (1996 to 2002) was noticeably warmer than the previous fifth epoch (1972 to 1995) of Banfield and Jacobs (1998). The criteria for epoch length, set out by Banfield and Jacobs (1998), stated that a temporal change had to persist for a decade or more. Although the sixth epoch had been warmer, the last four years displayed a constant cooling trend. If this cooling trend continues for the next three years, the sixth epoch may not be noticeably warmer than the fifth epoch and therefore, may be considered a stationary period in temperature trends. Nationally, the winter of 1997 was the warmest during the sixth epoch, compared to 1999 being the warmest at St. Anthony/Belle Isle (Environment Canada, 2004b). Nationally there has been an increase in winter temperatures since 2001 (Environment Canada, 2004b). During the last 33 years, the two epochs of below average temperature (Figure 1.10) from 1972 to 1976 and 1989 to 1994 can be attributed to the highly positive NAO around 1976 and 1993 (Figure 1.12). The two epochs of warmer temperature during the late 1970s to mid 1980s and during the late1990s can be attributed to lower NAO values during those periods.

Climate Indices and Sea Ice

The North Atlantic Oscillation (NAO) was associated with both winter temperature and sea ice extent in the northwest Atlantic. A negative correlation was found between the winter NAO index and winter temperatures for the St. Anthony/Belle Isle record (Figure 1.12), while a positive correlation was found between the winter NAO index and the extent of sea ice off the east coast of Newfoundland (Figure 1.13). Hurrell (1995) explained how a positive NAO during the winter increased the northerly flow of air over eastern Canada which would bring cooler temperatures to Newfoundland. The cooler sea surface temperature, as a result of cooler air temperature, increases the extent of sea ice (Banfield and Jacobs, 1998). Ice extent would also be increased from pack ice drifts pushing farther south with the north wind. During the heaviest periods of ice from winter to spring, a northwesterly to northerly wind results from the migration of the central Canadian high pressure area and a stationary Icelandic low pressure area (Hare and Thomas, 1979; Banfield, 1993). This flow of air would push the pack ice southeast off the east coast of Newfoundland and southwest as it approaches the southern limits of the Island (Hare, 1952). North winds also would push pack ice into the Gulf of St. Lawrence via the Strait of Belle Isle (Hare, 1952). The pack ice would increase the ice extent and therefore be linked to a positive NAO during the winter.

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Chapter 2. Microclimate and Phenology of *Braya fernaldii* and *Braya longii* on the Limestone Barrens of the Great Northern Peninsula of Newfoundland.

2.1 Introduction

The purpose of this study is to relate the phenological events of two sub-arctic alpine plants, Long's braya (*Braya longii*) and Fernald's braya (*Braya fernaldii*), to their present and past microclimates on the Great Northern Peninsula (Figure 2.1).

Plant phenology is the seasonal timing of the life cycle of plants. Events such as germination, flowering, and fruiting, are examples of phenological events critical to plant survival and reproduction (Rathcke and Lacey, 1985). In arctic and alpine environments, the short growing season influences the initiation, timing, and duration of phenological events (Stenstrom and Molau, 1992; Totland, 1997; Thorhallsdottir, 1998). For most arctic and alpine plants, flowering occurs early as a result of the short time available to complete the phenological stages (Totland, 1997).

Environmental climatic variables have been studied to ascertain their effects on germination (Ratchke and Lacey, 1985) and the timing of flowering and fruiting (Molau, 1993; Kudo, 1993; Totland, 2002; Dunne et al., 2003; Inouye et al., 2003). The reproductive period of flowering plants is determined by external environmental constraints and physiological adaptations to those constraints (Daubenmire, 1974). Ratchke and Lacey (1985) found that temperature, photoperiod, and rainfall were the three environmental factors that triggered flowering, whereas only temperature triggered fruiting. A study by Thorhallsdottir (1998) in the central highland of Iceland, found that air temperature and

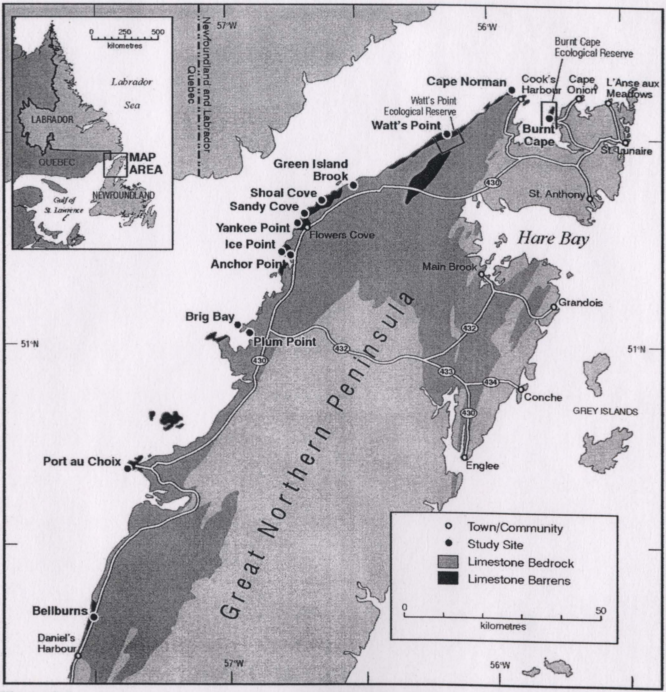


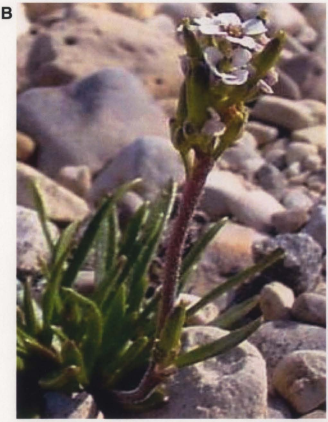
Figure 2.1
Great Northern Peninsula study region in northwest Newfoundland with selected study sites. The Limestone Barrens (black) are restricted to a narrow coastal strip of along the Strait of Belle Isle.

cumulative degree days above zero were correlated with the number of species in flower by the first week of July. Recent studies have shown that the date of snowmelt has a large influence on the date of first flower (Kudo, 1993; Molau, 1996; Dunne et al., 2003; Inouye et al., 2003). Environmental cues for germination included temperature and soil moisture (Karssen, 1982).

Study Species and Phenology

The two study species, Fernald's braya (*Braya fernaldii*) and Long's braya (*Braya longii*), are very similar in appearance, but each has distinguishing features (Figure 2.2 a, b). Long's braya has sparsely hairy siliques (fruit), white flowers, and can grow to an average height of 10 cm, whereas Fernald's braya has very pubescent siliques, purple flowers, and grows to an average height of 7 cm (Meades, 1996 a,b). There has been an increased interest in the timing of the phenological events of flowering and fruiting for *Braya fernaldii* and *Braya longii* on the Limestone Barrens. Parsons (2002) observed that both species began flowering towards the middle of June and started producing fruit in mid to late August. There were local variations. Noel (2000) found that substrate type influenced the recruitment and persistence of braya seedlings; anthropogenic disturbances promoted high seedling recruitment and low persistence, whereas natural disturbances promoted low seedling recruitment and long term persistence. Anthropogenically-modified populations contained dense stands of braya which contained 64% seedlings, whereas natural populations contained well dispersed populations of braya with only 6% seedlings (Noel, 2000).

(John Maunder)



(John Maunder)

Figure 2.2
Braya with flowers and fruit on the Limestone Barrens. A) *Braya fernaldii.* B) *Braya longii.*

Freedman et al. (1982) provided evidence of high seedling densities in natural, undisturbed conditions in arctic alpine landscapes; however, high seedling densities were also found in disturbed alpine conditions (Chambers et al., 1987; Schlag and Erschbamer, 2000) and undisturbed arctic-alpine conditions (Welling and Laine, 2000).

Substrate Microclimate

Studies have shown that ground temperature varies over small distances within patterned and non patterned ground (Anderson and Bliss, 1998; Thorn et al., 2002). Patterned ground on the Limestone Barrens consists of sorted diamicton (Greene, 2002) and sorted limestone gravel. Greene (2002) characterized braya substrate on the Limestone Barrens as either diamicton (sorted or nonsorted), or anthropogenically-modified substrate (Figure 2.3 a ,b, c). Diamicton is characterized by angular to sub-rounded boulders, cobbles, and pebbles in a muddy matrix (Greene, 2002). Nonsorted diamicton lacked textural sorting but did experience frost-heave (Greene, 2002). Sorted diamicton takes the form of sorted circles and polygons on level ground, and nets on moderate slopes (Washburn, 1956; Anderson and Bliss, 1998). The central zone of the sorted circle consisted of relatively stone-free, fine-grained sediment and was surrounded by a zone of cobble to boulder clast-supported diamicton (Greene, 2002). Nonsorted and sorted diamicton together are referred to as natural substrate. Anthropogenically-modified substrate consisted of bulldozed natural substrate and shattered bedrock, introduced for road and runway building. Often it is gravel from elsewhere on the peninsula (Greene, 2002).

Figure 2.3

Examples of typical substrate where braya populations have been found on the Limestone Barrens. A) Nonsorted diamicton; frost shattered limestone bedrock in a muddy matrix. B) Sorted Circle; frost heaves out shattered limestone bedrock forming sorted circles with muddy matrix in the centre. C) Anthropogenically-modified; quarried and graded gravel that has been brought to the site.*Slope for sites is near-horizontal.

This paper presents an analysis of the microclimate and phenology of *Braya fernaldii* and *Braya longii* on the Limestone Barrens of the Great Northern Peninsula of Newfoundland. Specific study objectives are:

1. to determine whether significant ground temperature differences occur between natural and anthropogenically-modified substrate types.
2. to determine whether there is a significant difference in germination success in braya populations growing on natural and anthropogenically-modified substrates.
3. to determine whether germination success in braya populations is associated with ground temperature in natural and anthropogenically-modified substrate.
4. to assess which microclimatic variables have the strongest association with the date of first flower.
5. to determine if there is an association between mean ground temperature and the length of the flowering period, the date 100% of the plants are in flower and the date of first fruit.
6. to reconstruct a proxy record of the date of first flower for both species.

2.2 Methods

This section outlines the methodology for obtaining microclimate and phenological data for the study species. Study sites and descriptions are presented in Table 2.1.

For the purpose of this study, the climate day began and ended at 2:30 am Newfoundland Standard Time (Environment Canada, 2004). In the data recovery process,

Table 2.1

Study sites on the Limestone Barrens for climate monitoring and braya phenology. (n.a. represents sites with no braya present) *Slope for sites is near-horizontal.

Location	ID	Substrate	Species	Climate Monitoring (number in brackets indicates the number of sensors at the location)	Lat. and Long.	Elev (m)	Site Exposure	Distance from Ocean (m)
Cape Norman	CN	Natural nonsorted	*B. fernaldii*	Air 1.5cm (1) Ground 10cm (1)	51° 38' N 55° 54' W	14	Entire area is barren with scattered low vegetation patches.	400
Burnt Cape	BC	Anthropogenically modified	*B. longii*	Air 1.5cm Ground 10cm (2)	51° 35' N 55° 44' W	65	Small stunted forest patches > 50m from site.	550
Watt's Point	WP	Anthropogenically modified	n.a.	Air 1.5cm (1) Ground 10cm (1)	51° 28' N 56° 19' W	9	Stunted forest > 100m from the site.	200
Green Island Brook	GB	Anthropogenically modified	*B. fernaldii*	Air 1.5cm (1) Ground 10cm (1)	51° 24' N 56° 32' W	14	Small vegetation patch 15m south of the site.	350
Shoal Cove	SH	Anthropogenically modified	*B. longii*	Air 1.5cm (1) Ground 10cm (1)	51° 22' N 56° 38' W	14	Small vegetation patches scattered throughout.	300
Sandy Cove (Crusher Site)	SC-C	Anthropogenically modified	*B. longii*	Air 1.5cm (1) Ground 10cm (1)	51° 21' N 56° 40' W	18	Small vegetation patches scattered throughout.	200
		Natural nonsorted	*B. longii*	Ground 10cm (1)	51° 21' N 56° 40' W	18	Small vegetation patches scattered throughout.	200
Sandy Cove (Airstrip)	SC-A	Anthropogenically modified	*B. longii*	Ground 10cm (5)	51° 21' N 56° 41' W	16	Stunted forest 100m to 250m from sites.	250

Location	ID	Substrate	Species	Climate Monitoring (number in brackets indicates the number of sensors at the location)	Lat. and Long.	Elev (m)	Site Exposure	Distance from Ocean (m)
Sandy Cove (Airstrip)	SC-A	Natural nonsorted	*B. longii*	Air 1.5 m (1) Ground 10cm (3)	51° 21' N 56° 41' W	15	Stunted forest 100m to 250m from sites.	250
Sandy Cove (Airstrip)		Natural sorted	*B. longii*	Ground 10cm (1)	51° 21' N 56° 41' W	15	Stunted forest 100m to 250m from sites.	250
Sandy Cove (Tuck Away)	SC-T	Natural sorted	n.a.	Ground 10cm (5)	51° 21' N 56° 41' W	16	Stunted forest 10m from site.	400
Yankee Point	YP	Anthropogenically modified	*B. longii*	Air 1.5cm (1) Ground 10cm (1)	51° 20' N 56° 43' W	22	Area surrounded by stunted forest, 10m to 20m from site.	250
Anchor Point	AP	Natural sorted	*B. fernaldii*	Air 1.5cm (1) Ground 10cm (1)	51° 14' N 56° 48' W	20	Surrounded by boreal forest 10m to 20m from sites.	1000
		Natural nonsorted	*B. fernaldii*	Ground 10cm (5)	51° 14' N 56° 48' W	20		1000
Ice Point	IP	Natural nonsorted	n.a.	Ground 10cm (1)	51° 14' N 56° 49' W	13	Small vegetation patches scattered throughout.	100
Plum Point	PP	Grass	n.a.	Air 1.5cm (1)	51° 04' N 56° 54' W	11	Observers backyard. Houses and forested area 10m to 20m from site.	750
Brig Bay	BrB	Natural sorted	n.a.	Air 1.5cm (1) Ground 10cm (1)	51° 03' N 56° 55' W	11	Small vegetation patches scattered throughout.	150

Location	ID	Substrate	Species	Climate Monitoring (number in brackets indicates the number of sensors at the location)	Lat. and Long.	Elev (m)	Site Exposure	Distance from Ocean (m)
Port au Choix	PAC	Natural nonsorted	*B. fernaldii*	Air 1.5cm (1) Ground 10cm (3)	50° 42' N 57° 22' W	20	Small vegetation patches. <100m from Gargamelle Cove	550
Bellburns	BLB	Anthropogenically modified	n.a.	Air 1.5cm (1)	50° 21' N 57° 32' W	34	Small vegetation patches scattered throughout.	150

notations for temperature are as follows: daily maximum temperature (maxT) = the maximum temperature recorded during the climate day, daily minimum temperature (minT) = the minimum temperature recorded during the climate day, mean daily temperature (meanT) = [(maxtT + minT)/2], and growing degree day above 5°C or 0°C = (meanT – 5°C or 0°C) (Environment Canada, 2004). Mean monthly and seasonal temperature, and growing degree days were calculated for designated time periods.

Equipment

Air temperature was measured inside radiation shields at 1.5 m above ground level using data loggers from the Onset Computer Corp. Miniature subsurface (ground) temperature loggers measured ground temperature at 10 cm depth. Temperature data were recorded at 1 hour intervals. Soil moisture was measured using standard gypsum blocks. For logger type, identification, resolution and uncertainty, see Appendix 2.1. For logger data and history see Appendix 2.1.

Ground temperature data loggers were inserted in hand-dug excavations at a depth of 10 cm during the summer field seasons of 2001 and 2002 at sites from Port au Choix to Cape Norman (Figure 2.1). The loggers were placed in three types of substrate: nonsorted diamicton, sorted diamicton, and anthropogenically-modified substrate. The study of soil moisture was attempted during the summer of 2002 and 2003 but was cancelled due to the failure of gypsum blocks to provide consistent readings in the field and in experiments in the laboratory (Appendix 2.2).

Before temperature variability between substrate types could be assessed, the level of variation in ground temperature within substrates was determined. This was carried out by logging ground temperatures at four locations within Xm^2 area in a single substrate type. This exercise was repeated simultaneously in the three main substrate types between June and September 2003.

Twenty-four ground temperature sensors were used to study variation between natural and anthropogenically-modified substrate types during the month of September 2003. Sixteen loggers were placed in natural substrates (SC-C, SC-A, SC-T, AP, IP), whereas eight were located in anthropogenically-modified substrate (SC-C, SC-A, YP) (Table 2.1, Figure 2.1).

Phenology

A total of 11 sites, 6 in anthropogenically-modified substrate (BC, GB, SH, SC-C, SC-A, YP) and 5 in natural substrate (CN, SC-C, SC-A, AP, PAC), were chosen to study germination, flower and fruit phenology from May to August, 2003 (Figure 2.1).

Germination Phenology

A sample of 30 plants at each of the 11 sites was chosen to study germination at one week intervals from June to August 2003. A 25 cm by 25 cm quadrat was placed around each plant and the number of germinates was counted within the quadrat (Tilley, 2003). Each plant chosen for the study had at least two rosettes to ensure that the plants were producers of germinates in the past (Luise Hermanutz, Biology Department, Memorial University of Newfoundland, pers. comm., 2003). The average number of germinates observed per site was calculated at weekly intervals.

Flowering Phenology

At each site 100 flowering plants were randomly selected to determine the percentage of plants in flower. A flowering plant was defined as one having buds (Luise Hermanutz, Biology Department, Memorial University of Newfoundland, pers. comm., 2003). The beginning of the flowering period was defined as the opening of the first flower and the end was defined as the wilting of the last flower (Stenstrom and Molau, 1992). A flower was considered open when the stigmas were visible and the petals were bent outward (Inouye et al., 2003; Stenstrom and Molau, 1992). Wilting was indicated by the disappearance of the last petals (Stenstrom and Molau, 1992).

Six sites were chosen to study the association between the date of first flower and selected microclimatic variables [SC-C (natural), SC-A (natural), SC-A (anthropogenically-modified), YP, AP, PAC]. These six sites had ground temperature monitoring available before the snowmelt in the spring of 2003. The date of snow melt was calculated as the day the ground temperature (at 10 cm) reached and remained above 1°C (Dunne et al., 2003).

Four sites with *Braya fernaldii* (CN, GB, AP, PAC) and six sites with *Braya longii* in natural and anthropogenically-modified substrate [SH, SC-C (natural and anthropogenically-modified), SC-A (natural and anthropogenically-modified), YP] were selected to examine the association between ground temperature and the date of 100%

flower (the date on which all plants had at least one flower) and the length of the flowering period.

Fruit Phenology

At each site 100 randomly chosen flowering plants were examined to determine the percentage of plants in fruit. A plant was considered in fruit when the stigma turned from yellow to brown and the siliques (fruit) extended beyond the petals (Luise Hermanutz, Biology Department, Memorial University of Newfoundland, pers. comm., 2003). Four sites for *Braya fernaldii* (CN, GB, AP, PAC) and six sites for *Braya longii* in natural and anthropogenically-modified substrate [SH, SC-C (natural and anthropogenically-modified), SC-A (natural and anthropogenically-modified), YP] were selected to examine the association between ground temperature and the date of first fruit.

Spring Temperature and Snowmelt Date

A HOBO XT logger was installed inside the radiation shield of the Environment Canada climate station at Plum Point (PP) (Figure 2.1) to test the accuracy and constancy of the Onset temperature loggers used for the microclimate study. The logger record overlapped with the Environment Canada station record from June 2002 to January 2003. A correlation analysis (Sokal and Rohlf, 1995) was used to assess the degree of consistency between the two records. Once a statistically significant correlation was verified, the Plum Point station could then be used as a source of historical climate data for nearby braya populations. For example, the Plum Point data were used to study historical snowmelt dates on the Limestone Barrens from 1974 to 2002 (Environment Canada, 2003). The Julian date of snowmelt (the first date in spring when 0 cm snow depth was recorded) was correlated with spring air temperature (March – April) at Plum Point to determine the relationship between the two variables over the 28 year period.

Statistical Analysis

A one way ANOVA (Sokal & Rohlf, 1995) was used to examine the variation in ground temperature within and between substrate types, and to determine if there was a difference in the average number of germinates between substrate types. The general linear model (Sokal & Rohlf, 1995) was used to test for relationships between the phenological stages of flowering and fruiting and ground temperature.

2.3 Results

Ground Temperature

Mean daily air and ground temperature from July 2002 to July 2003 at the Shoal Cove anthropogenically-modified site is illustrated in Figure 2.4 to represent the annual temperature cycle for the Limestone Barrens. The highest temperature recorded for both air and ground throughout the record was 18°C. The biggest temperature differences between the air and ground occurred with the presence of snow during the winter months. During the winter the air temperature reached a low of -20°C whereas ground temperature only reached a low of -2°C.

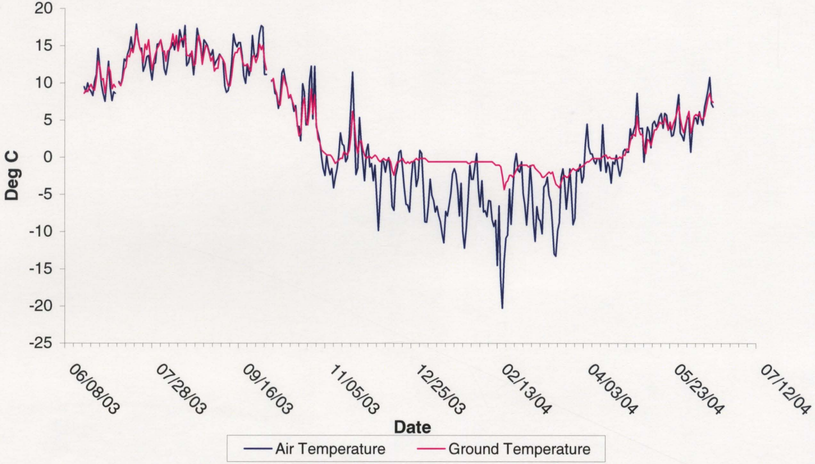


Figure 2.4

Mean Daily Air temperature at 1.5 m and ground temperature at 10 cm from June 2003 to July 2004 at the Shoal Cove anthropogenically-modified site.

Ground Temperature Variation Within Substrate Type

The variation in ground temperature in a single substrate site was least for natural substrate and most for anthropogenically-modified substrate. At the Tuck Away site there was no difference in meanT ($p=0.75$), maxT ($p=0.08$), or minT ($p=0.73$) in sorted natural substrate. At Anchor Point there was no noticeable difference in minT ($p=0.64$); however, a statistically significant difference in meanT ($p=0.02$) and maxT ($p<0.001$) was recorded in non-sorted natural substrates. The anthropogenically-modified site of Sandy Cove Airstrip experienced the greatest statistically significant variation for meanT, maxT, and min T (all p values < 0.001).

Ground Temperature Variation Between Substrate Type

On the basis of 24 ground temperature records, anthropogenically-modified substrate on average experienced a higher meanT, maxT, and minT than natural substrates. There was no statistically significant difference in meanT ($p=0.17$, difference of 0.2^{o}C) or maxT ($p=0.97$, difference $<0.1^{o}$C), between natural and anthropogenically-modified substrate, but there was for minT ($p=0.01$, difference of 0.3^{o}C).

Phenology

Table 2.2 details the phenology of *Braya fernaldii* and *Braya longii,* mean summer ground temperature, and snowmelt date (June to August 2003) at each site. Germination totals and flowering and fruiting times are also summarized there.

Table 2.2

Phenology of *Braya fernaldii* and *Braya longii*, summer soil temperature, and snowmelt dates at sites along the Limestone Barrens. Summer field season 2003. Missing data represented by n.a.

Site	Substrate	Species	Date of First Flower	Date of 100% Flowering	Length of Flowering (Days)	Date of First Fruit	Mean # of Germinates	Soil Temp (JJA) °C	Snowmelt Date (April)
Cape Norman	Natural	*B. fernaldii*	June 26th	July 19th	54	July 12th	7	11.5	
Burnt Cape	Anthropogenic	*B. longii*	June 14th	July 12th	n.a	June 26th	78	n.a.	
Green Island Brook	Anthropogenic	*B. fernaldii*	June 10th	June 28th	32	June 22nd	10	13.2	
Shoal Cove	Anthropogenic	*B. longii*	June 12th	July 12th	56	July 5th	154	11.9	
Sandy Cove Crusher	Natural	*B. longii*	June 16th	July 15th	58	July 5th	12	12.0	26
	Anthropogenic	*B. longii*	June 18th	July 15th	n.a	July 5th	200	n.a.	
Sandy Cove Airstrip	Natural	*B. longii*	June 14th	July 16th	60	July 7th	23	12.3	24
	Anthropogenic	*B. longii*	June 9th	July 5th	65	July 5th	238	13.1	22
Yankee Point	Anthropogenic	*B. longii*	June 8th	June 27th	66	June 22nd	286	12.3	24
Anchor Point	Natural	*B. fernaldii*	June 13th	July 13th	68	June 27th	5	13.4	25
Port au Choix	Natural	*B. fernaldii*	June 6th	June 24th	31	June 16th	13	14.9	22

Germination success in anthropogenically-modified substrate was noticeably higher than in natural substrate (Figure 2.5). The average number of germinates observed for 30 plants in anthropogenically-modified substrate from June to Aug 2002 was 179 compared with 12 in natural substrate. Yankee Point had the highest average number of germinates for anthropogenically-modified substrate with 286, whereas the airstrip site at Sandy Cove had the highest average number of germinates for natural substrate with 23 (Table 2.2).

Figure 2.6 plots the date of snowmelt against the date of first flower for *Braya fernaldii* and *Braya longii* in natural and anthropogenically-modified substrate during the spring of 2003. *Braya fernaldii* at the most southern location of Port au Choix was first to flower, whereas *Braya longii* at the most northern location of Sandy Cove was the last to flower. *Braya longii* at the Sandy Cove Airstrip and Yankee Point sites flowered earlier than *Braya fernaldii* at the more southern location of Anchor Point.

There was a statistically significant relationship between snowmelt and the date of first flower for both species (p=0.04, df=5) (Table 2.3). There was no relationship between June meanT and the date of 100% flowering (p=0.16, df=3) or the length of the flowering period (p=0.62, df=3) for *Braya fernaldii* (Table 2.4). For *Braya fernaldii* in natural substrate only, there was a weak relationship between June meanT and the date of 100% flowering (p=0.06, df=2) (Table 2.5). With respect to *Braya longii*, there was no noticeable relationship between June meanT and the date of 100% flower (p=0.48, df=4) or the length of the flowering period (p=0.14, df=4).

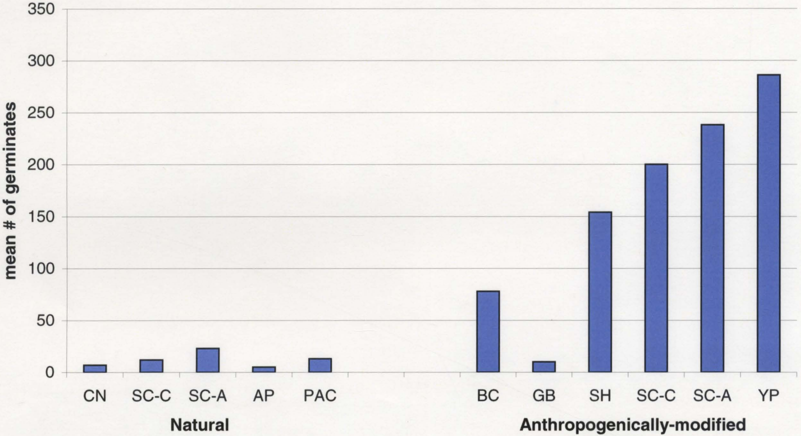


Figure 2.5
Mean number of germinates in natural and anthropogenically-modified substrate, summer 2003.

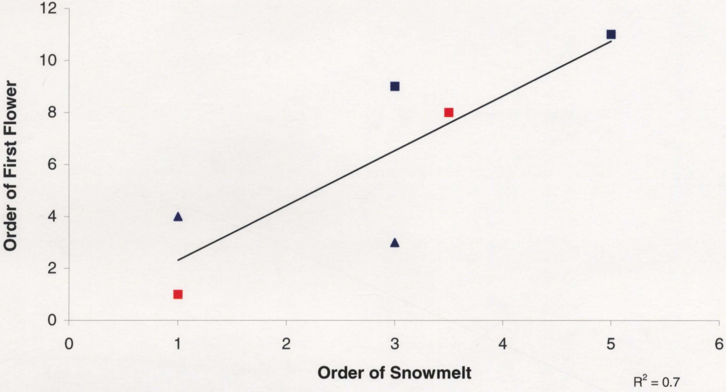


Figure 2.6
Date of first flower vs. the snowmelt date for *Braya fernaldii* (red) and *Braya longii* (blue).
Blue triangles represent *Braya longii* in anthropogenically-modified substrate.
Line of best fit for all data is indicated.

Table 2.3

F-ratio, degrees of freedom, and significance level from a one way ANOVA on the effects of environmental variables on the date of first flower for *B. fernaldii* and *B. longii.* DD indicates growing degree days.

Env. Variable	df	F-ratio	P
May minT	5	1.69	0.264
May maxT	5	1.88	0.242
May meanT	5	1.84	0.246
DDs>0°C	5	1.80	0.251
snowmelt date	**5**	**9.01**	**0.04**

Table 2.4

F-ratio, degrees of freedom, and significance level from a one way ANOVA on the influence of June mean ground temperature on the phenological stages of *B. fernaldii* in natural and anthropogenically-modified substrate.
100% represents the day 100 percent of the sampled plants were in flower, **Length** represents the length of the flowering period, and **Ffruit** represents the first day a plant in the sample was observed to be fruiting.

	df	F-ratio	P
100%	3	4.68	0.163
Length	3	0.34	0.619
Ffruit	**3**	**8.63**	**0.099**

Table 2.5

F-ratio, degrees of freedom, and significance level from a one way ANOVA on the influence of June mean ground temperature on the phenological stages of *B. fernaldii* in natural substrate.
100% represents the day 100 percent of the sampled plants were in flower, **Length** represents the length of the flowering period, and **Ffruit** represents the first day a plant in the sample was observed to be fruiting.

	df	F-ratio	P
100%	2	97.49	0.064
Length	2	0.41	0.639
Ffruit	**2**	**2760.33**	**0.012**

There was a weak relationship between June meanT and the date of first fruit (p=0.1, df=3) for *Braya fernaldii* (Table 2.4). Figure 2.7 illustrates the relationship between June meanT and the date of first fruit for both *Braya fernaldii* and *Braya longii* in natural and anthropogenically-modified substrate. *Braya fernaldii* at the most southern location of Port au Choix was the first to fruit, whereas *Braya fernaldii* at the most northern location of Cape Norman was last to fruit. With the exception of *Braya longii* at Yankee Point, *Braya longii* at Burnt Cape were in fruit before *Braya longii* at locations farther south. With respect to *Braya fernaldii* in natural substrate only, there was a strong relationship between June meanT and the date of first fruit (p=0.01, df=2) (Table 2.5). With respect to *Braya longii*, there was no relationship between June meanT and the date of first fruit (p>0.9, df=4).

Spring Temperature and Snowmelt Date

A strong correlation was found between the Onset temperature logger record (meanT = 5.1°C) and the Environment Canada climate station record (meanT = 4.8°C) with respect to mean air temperature at Plum Point (r^2 value = 0.99). There was no statistically significant difference between the two records for meanT (p=0.71), minT (p=0.83), and maxT (p=0.38). The date of snowmelt was strongly correlated with mean spring temperature at the Plum Point station (p<0.001, r^2 value = -0.770). Figure 2.8 illustrates the Julian date of snowmelt and mean spring air temperature at Plum Point from 1974 to 2002. A low spring air temperature produces a late snowmelt date, whereas a high spring air temperature produces an early snowmelt date. The lowest spring air

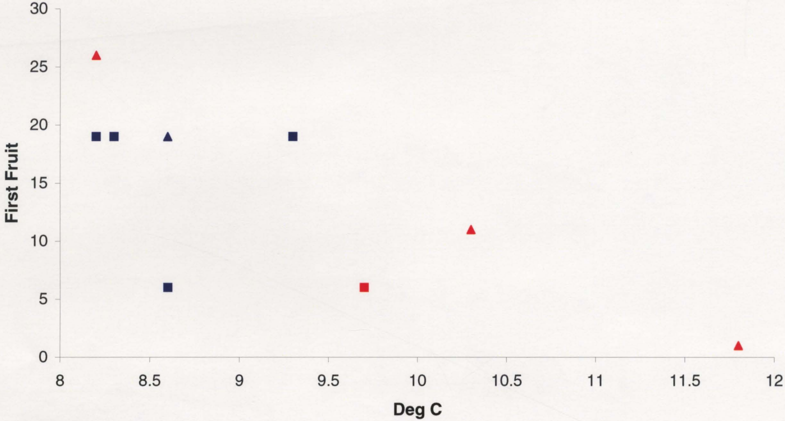


Figure 2.7

June mean ground temperature vs. the date of first fruit for *Braya fernaldii (red)* and *Braya longii (blue)* in natural substrate (triangle) and anthropogenically-modified substrate (square), summer 2003.

The value of 1 on the Y axis represents the first site to fruit, whereas the value of 26 on the Y axis represents the last site to fruit.

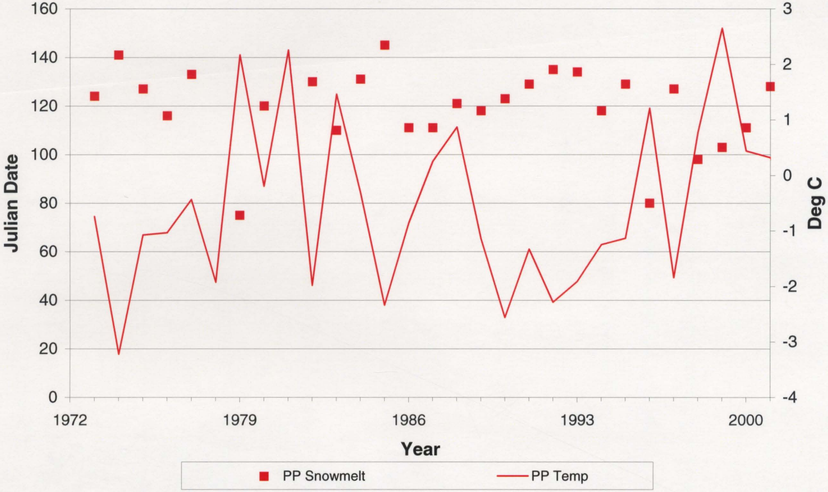


Figure 2.8
Julian date of snowmelt for Plum Point (PP). Mean spring temperature (March, April, May) for Plum Point is illustrated with a solid red line. Snowmelt dates are missing for 1978 and 1981.

temperature of -3°C recorded in 1974 produced one of the latest snowmelt dates at Julian Day 140.

2.4 Discussion

This study relates the phenological events of two sub-arctic alpine plants, Long's braya (*Braya longii*) and Fernald's braya (*Braya fernaldii*), to their present microclimate on the Great Northern Peninsula. This section discusses the main phenological dates for both braya species, substrate microclimate, the relationship between microclimate and phenology, and the historical record of snowmelt.

Microclimates and Phenology Relationships

Substrate type had an influence on germination and flowering. Germination success in anthropogenically-modified substrate was noticeably greater than in natural substrate. Braya in anthropogenically-modified substrate flowered earlier than those in natural substrate. There was no significant difference in ground temperature between natural and anthropogenically-modified substrate. The observed difference in ground temperature was 0.3°C, which was less than the specified accuracy of the sensor (Appendix 2.1).

Anthropogenically-modified substrate at Yankee Point and natural substrate at the Sandy Cove airstrip had identical mean summer ground temperature; however, germination was significantly greater at Yankee Point (Figure 2.5). Plants at Yankee Point (anthropogenically-modified substrate), with a mean ground temperature in May of

6.2°C, flowered earlier than those at the Sandy Cove Airstrip (anthropogenically-modified substrate) and Anchor Point (natural substrate) with mean ground temperatures in May of 7.7°C and 8.0°C respectively. Therefore, on the basis of the 2003 ground temperature data set it appears that neither braya germination nor flowering times are strongly linked to the ground temperature regime.

Ground temperature did have an effect on fruiting times. June meanT was an indicator of first fruit for *Braya fernaldii* on natural substrate (Table 2.4; Figure 2.7). As June meanT increased, the Julian date of first fruit decreased. With respect to *Braya longii*, the first day of fruit happened on the same day at four sites (Table 2.2); statistical analysis indicated no relationship between June meanT and the date of first fruit for *Braya longii*. Ratchke and Lacey (1985) noted that environmental cues seldom stimulate the onset of fruit ripening; instead, it was determined primarily by internal factors that control the rate of fruit development.

The date of snowmelt was an important indicator of the date of first flower. Ratchke and Lacey (1985) stated that photoperiod and precipitation are important cues to flowering. Also, if critical temperatures initiate flowering (Thorhallsdottir, 1998), the critical ground temperatures cannot be achieved without the disappearance of snow. Snowmelt was an important environmental indicator of flowering in previous studies by Kudo (1993), Inouye et al. (2003), and Dunne et al. (2003).

There were no significant relationships between ground temperature and the date of 100% flowering and the length of the flowering period for either species. The Sandy Cove Airstrip site reached 100% flowering 19 days after the Yankee Point site, even though the summer mean ground temperature (June to August) was the same for both sites (Table 2.2). There was, however, a weak relationship between June meanT and the date of 100% flowering for *Braya fernaldii* in natural substrate (Table 2.5). Since most *Braya longii* sites contained anthropogenically-modified substrate, ground temperature did not have an effect on flowering.

Braya longii had a higher number of germinates than *Braya fernaldii*. *Braya fernaldii* in anthropogenically-modified substrate at Green Island Brook had the lowest germination success when compared to *Braya longii* in the same substrate type, whereas *Braya longii* at the Sandy Cove Airstrip had the greatest germination success when compared to *Braya fernaldii* in the same substrate type (Figure 2.5). There was not enough phenological information by species to determine whether flowering and fruiting differed by species type.

Latitude had a small influence on flowering and fruiting times. With respect to *Braya fernaldii*, the Julian date of first flower increased as latitude increased. *Braya fernaldii* at the most southern location of Port au Choix was first to flower whereas *Braya fernaldii* at the most northern location of Cape Norman was the last to flower (Table 2.2). *Braya longii* at the Sandy Cove Airstrip and Yankee Point sites flowered earlier than *Braya fernaldii* at the more southern site of Anchor Point. *Braya fernaldii* at the most southern location of Port au Choix was the first to fruit whereas *Braya fernaldii* at the most northern location of Cape Norman was last to fruit. With the exception of *Braya longii* at Yankee Point, *Braya longii* at Burnt Cape flowered before all locations farther south.

Spring Temperature and Snowmelt Date

For *Braya longii* and *Braya fernaldii*, flowering occurred between 45 and 55 days following the date of snowmelt. If flowering is triggered by the date of snowmelt, it may have occurred as early as mid-April in 1996 at Port au Choix and as late as mid July in 1982 at Anchor Point (Figure 2.8). The years from 1973 to 1977 and 1988 to 1995 may have been periods of late flowering for *Braya fernaldii* and *Braya longii*, correlating with years of cooler spring temperatures (Figure 2.8). As the average spring temperature (March, April, May) increased, the Julian date of first flower decreased. If the period of warmer spring temperatures observed since 1997 continues, the date of first flower for braya may occur progressively earlier in the calendar year.

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Summary and Conclusions

Chapter 1 analyzed the spatial and temporal trends of climates on the Great Northern Peninsula of Newfoundland and attempted to link the trends to large scale regional climate and atmospheric circulation patterns. Mean air temperature decreases with increasing latitude along the peninsula, but does not display a consistent linear trend. Although not statistically significant, the greater amount of total precipitation experienced on the west coast of the peninsula may be attributed to cold air outbreaks from Quebec and Labrador over the Gulf of St. Lawrence during the winter. Northern stations experience more snowfall throughout the year as a result of cooler temperatures. The greater interannual variability of air temperature during the winter has been associated with a higher degree of continentality from sea ice extent, whereas the greater interannual variability of precipitation during the winter can been associated with increased synoptic activity.

The trend of increasing mean summer air temperatures for St. Anthony/Belle Isle since 1896 was attributed to the warmer temperatures experienced in the latter part of the 20th century. Other than 1908 and 1917, the summers of 1999, 2000, and 2001 were the warmest on record. Annually, for the same time period, air temperature has been increasing in southern Canada but particularly warm temperatures did not occur from 1999 to 2001, whilst the warmest year on record from 1948 to 2002 was 1998. This trend of increasing mean temperatures was evident during summer and winter for the last ten years of the record. Mean winter air temperature, post-1995, has been warmer than in the period from 1972 to 1995 but not as warm as in the period from 1951 to 1971. During the last 33 years, periods of below average temperature from 1972 to 1976 and 1989 to 1994 were attributed to the highly positive NAO index whereas periods of warmer temperature during the late 1970s to mid 1980s and during the late 1990s were attributed to lower NAO index values. The positive winter NAO index is associated with stronger than normal northerly flow of air over eastern Canada. With it there has been a corresponding increase in the extent of sea ice as a result of cooler temperatures and the southerly movement of pack ice.

Chapter 2 analyzed the microclimate of braya substrate types along the Limestone Barrens with respect to temperature and soil moisture, and determined the timing of the phenological events of germination, flowering, and fruiting with respect to environmental indicators of temperature, soil moisture, and snowmelt. The flowering phenology of *Braya fernaldii* and *Braya longii* was significantly influenced by the date of snowmelt. Mean ground temperature was associated with the fruiting phenology of *Braya fernaldii,* but in natural substrate only. Since the mean ground temperature of anthropogenically-modified substrate was highly variable within a small area of substrate it was difficult to determine if temperature was of great importance for the phenological responses of both species of braya in that substrate. Latitude had a small influence on flowering and fruiting times. With respect to *Braya fernaldii*, the Julian date of first flower increased as latitude increased. Anthropogenically-modified substrate types did favour germination success. The maximum ground temperature of anthropogenically-modified substrate was higher than that of natural substrate, but the difference was not statistically significant. This small temperature difference may have been enough to initiate germination in both species of braya but a larger sample would be needed to confirm this. Other variables such as light and moisture may have favoured germinations.

Climate models have predicted that greenhouse gases should cause an average global temperature increase of 1 to 6°C over the next century (Inouye et al., 2003) and an anticipated increase in mean annual temperatures by 2 to 4°C in Atlantic Canada (Moore et al., 1999). The increase in greenhouse gases will also affect precipitation patterns, soil moisture, and snow and ice cover (Inouye et al., 2003; IPCC, 2001). Since 1996, both springtime temperature and the Julian date of snowmelt have been increasing on the Limestone Barrens of the Great Northern Peninsula. Martin (2004) examined snow cover trends on the Big Level Summit Plateau (49.7°N, 57.8°W, 795 m a.s.l.) of the Great Northern Peninsula for the period 1963 to 1999 and found a significant trend toward earlier snowmelt for that period. If these trends continue, earlier flowering dates may be observed for both species of braya as a result of earlier snowmelt, and earlier fruiting may be observed for *Braya fernaldii* as a result of warmer ground temperatures. Molau (1997) found that the reproductive success of two tundra plant species increased with increasing temperature. In addition, germination success may increase for both species of braya as a result of increasing maximum ground temperatures.

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Appendices

Appendices for both chapters can be found on the CD titled Appendices.

Appendix 1.1

All individual climate station records, NAO index, and sea ice records can be found in the folder entitled Climate. Each record was placed into Microsoft Excel. The raw data, monthly temperature and precipitation, and annual temperature and precipitation can be found for each climate station record.

Appendix 2.1

Appendix 2.1 is divided into two folders: Logger Data and Logger Records. The Logger Data folder contains information on the type of logger, the identification #, and the resolution and uncertainty. The identification # was the code given to each logger at the time of installation. For example; the temperature logger at Cape Norman (CN), which measures air temperature at 1.5 m above the surface and ground temperature at 10 cm below the surface, was identified as LBE 19. The climate record for each logger is found in the Logger Records File. The files are listed with identification #s that correspond to the information in the Logger Data folder. For example; the logger record for Cape Norman can be found in the file LBE 19.

Appendix 2.2

The soil moisture study attempted during the summer of 2002 and 2003 can be found in the folder titled Soil Moisture Study.