REGIONAL AND LOCAL CLIMATOLOGY OF A SUBARCTIC ALPINE TREELINE, MEALY MOUNTAINS, LABRADOR

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Regional and Local Climatology of a Subarctic Alpine Treeline, Mealy Mountains, Labrador.

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Abstract

This thesis investigates climatological aspects of a subarctic alpine treeline site in the Mealy Mountains, Labrador. The first of two manuscripts looks at a method of regional climate modeling (statistical downscaling) to produce temperature scenarios for the future and to assess the applicability of large-scale models (global climate models) for regions of complex topography. Both the GCM and statistically downscaled models predict warming for the study site, especially for winter months. However, the output of GCMs was determined to not capture the local climatic influences of this region, and thus produces scenarios that smooth over the signal of future climate change. The second manuscript produces a descriptive climatology of the study site and also investigates the relationship of the treeline with the climate. It was determined that the current climate regime of the Mealy Mountains is not a limiting factor to tree growth beyond its current elevation; however, recent changes and future climate predictions may encourage the recruitment and establishment of spruce trees above their current position.

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List of Abbreviations

a.s.l.	above sea-level
CGCM3	Coupled Global Climate Model 3
CW	Cartwright
FT	freeze-thaw
GB	Goose Bay
GCM	global climate model
GDD	growing degree days
GrADS	Grid Analysis and Display System
IPCC	Intergovernmental Panel on Climate Change
MM	Mealy Mountains
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NCEP	National Centre for Environmental Prediction
NDVI	normalized difference vegetation index
POT	peaks over threshold
RH	relative humidity
RMSE	root mean square error
SAT	surface air temperature
SD	statistical downscaling
SDSM	Statistical Downscaling Model
SE	standard error
SWE	snow-water equivalent
VP	vapour pressure
VPD	vapour pressure deficit

Chapter 1: Introduction

Research Context

Global warming has resulted in an average increase in surface air temperatures of 0.7˚C in the last century, according to the latest IPCC report (2007). Despite improved methods for producing global climate models (GCM) and other model simulations, they still generally fail to address climatic change in mountainous regions (Christensen et al. 2007; IPCC 2007); for example, their coarse resolution does not take into account land coverage, topography and other localized physical features and influences. Impact models, used for ecological and agricultural purposes for instance, require output and information at much smaller scales than the output of GCMs (Dibike et al. 2007).

Mountain regions provide a unique study region for the detection of climate change, and therefore also for the assessment of possible impacts under climate scenarios. Alpine ecosystems are especially sensitive to climatic variability and change, and are key areas to investigate the impacts of the predicted warming. Climate changes considerably with altitude within short stretches of territory, and therefore so does vegetation cover and hydrology (Whiteman 2000). Plant life is highly constrained by temperature, and different vegetative communities can be found along this altitudinal gradient. Therefore, warming would cause an upward shift of these communities, resulting in lost habitat for the summit vegetation (Körner 1998). Further, sub-arctic and arctic mountain ranges are subject to permafrost degradation and changes in snow cover which can amplify the effects of climatic change (Cannone et al. 2007). In order to understand the potential changes in mountain ecosystems due to global warming, the climate system must necessarily be well understood (ACIA 2004). The relationships within biophysical environments are often investigated in long-term ecosystem monitoring studies to assess the vulnerability of ecosystems in a changing climate.

The Mealy Mountains, located in Labrador, is the region of interest for both manuscripts included in this thesis; the Mealys have recently been declared Canada's next National Park (Figure 1.1). Ecological impact studies are ongoing at this site, exploring the effects of climate change on tundra and boreal ecosystems, which globally cover 15 % of ice-free terrestrial land (Saugier et al. 2001). These studies aim to predict what changes might happen in the future, particularly with respect to the alpine treeline. To provide these impact studies with realistic conditions for the current climate, a comprehensive assessment of the climatology of these study sites is required.

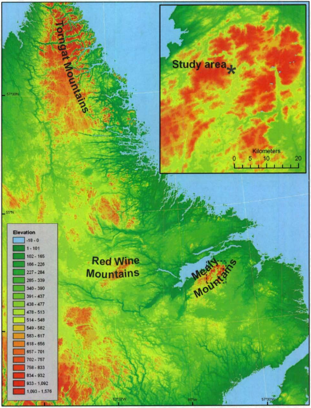

Figure 1.1: Relief Map of Labrador (elevations are in metres above sea-level).

Thesis Structure and Objectives

The structure of the thesis is made up of this introductory chapter, which includes a general literature review that covers topics relevant to the focus of the thesis. Chapters 2 and 3 are manuscript style stand-alone papers, followed by the final chapter which provides a summary of the conclusions drawn from the two manuscripts, a discussion of the limitations of the research and a direction for future developments and studies.

This MSc thesis will focus on the climatological aspects of the Mealy Mountains in Labrador. The approach includes the construction and analysis of a regional climatology for the alpine study area, for which there has been ongoing data collection since 2001. Also, a commonly used method to produce climate models for the localized study site will be employed (statistical downscaling). Results of the climatological studies will be useful for local stakeholders in the region; this includes local governments interested in natural resources or protecting the land, and also other researchers who will benefit from the analysis for their own study purposes. If the methods of the statistical downscaling are successful for this isolated highland site, it would be a significant methodological contribution for ecological studies in alpine regions, as well as providing valuable climate forecasting and scenarios for policy makers.

The objectives are identified as follows:

- To establish statistical relationships between temperature and large-scale circulation patterns for statistical downscaling of a regional climate model (Paper I);

- To evaluate the reliability of reanalysis data for use in the regional climate modeling of data-sparse, high-latitude alpine areas (Paper I);
- To construct a regional climatology of a study site in the Mealy Mountains; a remote highland range (Paper II).

The Mealy Mountains were selected for the regional climatology because there was an adequate existing observational record, as well as extended regional networks of climate data available for the construction of the climatology. The statistical downscaling was performed for this region of complex topography to be able to compare its results with those of GCMs.

Literature Review

To complete this thesis, a literature review spanning relevant topics was conducted in order to have a good understanding of the different systems involved in the climatology of the region, and also of the analytical tools to be used. For regional modeling, not only is a grasp of the technology required, but also of the physical processes guiding atmospheric behaviour in alpine and high latitude regions. This chapter covers basic climatological processes particular to alpine and high latitude regions, and introduces the methodology used.

Mountain Climates

Mountains are key areas to detect climatic changes due to their distinct vegetation transition zones. Mountain, or highland, climatology is subject to complex climatic patterns and processes. There are variable contrasts over short extents of distance due to topographic influences and the different moisture and energy fluctuations with altitude. Alpine regions, which cover almost one quarter of the earth's continental areas (Beniston 2003), experience much heterogeneity in space and time, but there are predictable patterns - temperature decline with elevation - to be found within these systems. The main themes to be considered in this overview of mountain climates are their particular climatic features and controls, including atmospheric systems in relation to orography, bioclimatic considerations, and finally a brief introduction to changes in mountain climates with respect to global climate change.

Mountainous regions are influenced by their nearby regional climate, such as prevailing wind patterns, ocean currents, and also by their altitudinal and latitudinal positions. In terms of latitudinal position, just like any other location, the mountain range is influenced by the global circulation system; between 40-70° of latitude, the atmospheric pressure system brings a polar front and subpolar lows, meaning Westerly winds and a band of significant precipitation compared to regions of subtropical and polar highs. Altitude is the most important feature unique to mountain climatology, as changes in elevation cause reduced air density, changes in vapor pressure, and lower temperatures (Barry 1992). Peaks and valleys also influence wind, providing barriers or funneling effects to increase their velocities. Other perturbations to upper-air circulation are caused by mountains, frequently causing increased cloud formation and precipitation (Chater and Sturman 1998). Further, there is a phenomenon called the orographic effect which can increase precipitation on the windward side of a mountain; this happens when wind carrying moist air comes perpendicular to a mountain range, forcing this mass of air upwards and cooling it until its dew point is reached, causing condensation, and therefore clouds and rain (Barry 2008). Conversely, the leeward side may get significantly less precipitation because the air descending has already lost much of its moisture.

Temperature changes with elevation are one of the most well understood physical processes in alpine research. The decrease of temperature with altitude in the troposphere is called the lapse rate, and is typically 6-7° C/km (Gardner et al. 2009), but this figure is variable in space and time. Also, diurnal temperature patterns in mountains are more variable than those at sea level (i.e. the range of daily maximum and minimum temperatures is greater at altitude). Temperature inversions, when there is a temperature increase with altitude, occur when a warmer and less dense air mass moves over one that is cooler and more dense, and prevents convection.

Climatic and biophysical relationships in highland areas are interesting to study because they change rapidly with altitude. The relationships that plants and animals have with temperature gradients are more obvious in the mountains. For example, a change in elevation of just a few hundred meters will affect the number of growing degree days enough that the flora at the bottom of a mountain would not be able to grow at the top, where it is cooler. In other words, there is a distinct altitudinal gradient for species distribution even in smaller mountain ranges (Trivedi et al. 2008). The aspect of a mountain side also affects the amount of solar radiation it receives; depending on whether the slope is south or north facing, the amount of insolation can be quite variable, leading to differences in temperature and productivity of plant systems. Another factor affecting temperatures in mountain ranges is that valleys have a distinct diurnal influence, where there is nocturnal cooling and enhanced daytime heating (Barry 1992).

As previously mentioned, because alpine systems are highly susceptible to climatic change, they provide a good area to study the detection and signals of change for climatic, hydrological and ecological purposes. A warmer climate will intensify the hydrological cycle, which will increase evapotranspiration and the ratio of rain to snow precipitation (Beniston 2003). In turn, this means that there will be more surface runoff, increased soil moisture and groundwater reserves. However, as complex topography is not generally well represented in modeling studies, it is difficult to have accurate predictions of changes in precipitation as a result of global warming. Also, cryospheric processes will be very vulnerable to changes in temperature and precipitation; for example, for every 1 °C increase, the snowline in mountainous regions is expected to rise by 150 m (Beniston 2003). Further, in temperate mountains, the snowpack temperature is often close to its melting point, so minor increases in temperature will have notable effects. With observed and predicted increases in temperature, plant species will migrate upwards along the shifting altitudinal gradient (Cannone et al. 2007; Loffler 2007; Trivedi et al. 2008), and the once coldest ecozones at the peaks will decrease in area or disappear completely (Beniston 2003).

High Latitude Climates

High latitude ecosystems and the physical processes of this region have an influential role in the global climate; they are therefore a key area to study in the context of global climate change. The last IPCC report concluded that the arctic is 'very likely' to warm and surpass the mean global warming temperature (Christensen et al. 2007). This is in agreement with the many reports which show that already some of the largest environmental changes have been seen at high latitudes (Turner et al. 2007). Further, sub-arctic and arctic ecosystems are important indicators in the context of global warming because they are particularly susceptible to the impacts of modest changes in the climate. For example, arctic species are adapted to the low temperatures and short growing seasons, but slight increases in surface air temperature may cause invasive species to live further north or on higher ground (Forbes et al. 2001). Tundra and boreal ecosystems account for 15% of ice-free terrestrial systems, an expanse larger than both the temperate or tropical regions (Saugier et al. 2001). Though the polar region is important in global climatic processes, the extent of its role is not fully understood. Some processes are well understood – such as the transport of energy from the tropics to higher latitudes, which has an important role in atmospheric circulation – however there remains much uncertainty as to how global warming could affect them (McGuire et al. 2006). Another knowledge gap in current model predictions is that sea ice and atmospheric-oceanic teleconnections, such as the North Atlantic Oscillation, are not well represented in GCMs; these processes are complex and attached to much uncertainty. Climatic variability on multi-decadal and interannual scales and across different regions of the arctic make regional considerations all the more valuable.

The changes along latitudes provide climatic and ecological transition zones. These are evident in temperature isotherms; latitudinal bands of ecotypes; solar radiation differences; and seasonal effects. The boreal forest and tundra ecozones are important carbon sinks or storage areas; these northern ecosystems hold significant amounts of global soil carbon, which is vulnerable to climate change (McGuire et al. 2002). Though the processes controlling climate are such as the cryosphere; the seasonal presence of sea ice; and other feedbacks within the northern physical environment (Christensen et al. 2007).

Surface temperatures in the Arctic have been warming nearly twice as fast than the global average, a phenomenon referred to as 'Arctic amplification' (Graversen 2006). In the past few decades, the Arctic has seen a distinct warming trend at a rate approaching 1 °C per decade (Overland et al. 2004), though some of this could be attributed to natural fluctuations in the climate. This enhanced warming in the North has largely been attributed to the albedo feedback system. This positive feedback system, generated by warmer conditions melting more ice and snow, reduces the area of Earth's surface that reflects incoming solar radiation, in turn further warming land and ocean surfaces. Some researchers also associate warming trends with atmospheric phenomena such as the North Atlantic and Arctic Oscillations (Cohen and Barlow 2005). Another recent theory is that changes in the vertical structure of atmospheric circulation in the troposphere may be related to the warming trend in arctic surface air temperatures (Graversen 2006; Graversen et al. 2008).

The GCMs used in the last IPCC report projects an annual warming in the Arctic of 5 ºC (Christensen et al. 2007). The warming trend in the north is often attributed to increased warm air advection from lower latitudes (Turner et al. 2007). With warming, the atmosphere of lower latitudes is able to hold more water vapour, which results in additional moisture and accompanying heat transported to the Arctic (McGuire et al. 2006). As water vapour is the greatest contributor to the greenhouse gas effect, this positive feedback system is another factor in the amplification of warming in the polar regions. An increase in water vapour can also result in an increase in cloudiness, further enhancing the greenhouse gas effect (Varvus 2004).

Of note for this study, a period of slight cooling was observed over eastern Canada and Greenland in the 1980s and 1990s, which has been linked to a prolonged positive phase of the North Atlantic Oscillation (or the Arctic Oscillation) (Banfield and Jacobs 1998; Feldstein 2002); the positive phase NAO causes enhanced subpolar westerlies which cools the eastern Arctic (Thompson and Wallace 2001). This positive phase has since returned to a more neutral pattern, and accordingly resulted in an end to the anomalous cooling pattern.

There are many implications of warming surface temperatures. With northern latitude heating documented over the instrumental period of the past 100 years (Hansen et al. 2006), growing seasons are becoming longer, starting 5 to 13 days earlier, and there has been an increase in boreal insect disturbance (Bunn et al. 2007). Warmer temperatures allow the atmosphere to hold more moisture; this subjects boreal and tundra vegetation to an increased evaporative demand - a stress on the relatively low-productivity ecosystems. With earlier snowmelt, there is a change in albedo resulting in increased springtime energy absorption, therefore altering ecosystem processes. Experimental warming on small-scale plots has shown that an increase in surface air temperature of only 1 °C over the summer months can lead to increased shrub growth in the tundra within a decade (Chapin III et al. 2005).

While precipitation generally is more locally variable than temperature, the record presented in the latest IPCC Report shows a net increase over the Arctic (Christensen et al. 2007). Whether or not this is an indication of a trend is uncertain, especially as the unusual positive phase of the NAO in the last few decades of the 20^{th} century is tied to increased moisture transport into the Arctic, and therefore more precipitation (Dickson et al. 2000). One study concluded that there has been a significant increase in freshwater input to the Arctic Ocean from river discharge; it concluded that the only realistic explanation of this 7% increase could be an increase in precipitation (McClelland et al. 2004). On the other hand, the past few decades have seen a decrease in snow cover in the Northern Hemisphere (Strack et al. 2004); this has been coupled to increases in air temperature in modeling studies (Euskirchen et al. 2006). The IPCC Report assimilated the results of 21 global models, and for the Arctic region projected an increase in precipitation for all seasons by the end of the 21^{st} century. The predicted increases in precipitation were much larger in the Arctic, compared to regions closer to the equator.

The presence of sea ice and its seasonality in the northern polar region has an obvious effect on the climate of the surrounding land. A recent study used the Community Climate System Model to demonstrate how the rapid melting of sea ice produced accelerated warming over land by factor of 3.5 (Lawrence et al. 2008). The warming trend was noticed up to 1500 km inland, a significant distance from the immediate effects that coastal lands are subject to. This model also found that the increased warming over land due to the disappearance of sea ice increased the degradation of permafrost. The Arctic Climate Impact Assessment also found that temperature scenarios are closely associated with projected changes in sea-ice (ACIA 2004).

If permafrost were to thaw it would be a largely irreversible process. The persistence of permafrost depends on frozen water to maintain its structure. As summer months exceed the 10 °C mean threshold that defines regions as 'arctic', permafrost temperatures are approaching 0 °C and tundra is being overtaken by shrubs and wetlands. These warmer temperatures and changes in vegetation do not promote the preservation of permafrost (Sturm et al. 2005; Turner et al. 2007). In addition, active layers are directly linked to summer air temperatures (Zhang et al. 1997). Warmer temperatures could increase the thickness of active layers, therefore allowing more water to be stored in the soil. If areas of permafrost experience more freeze/thaw cycles due to warmer air temperatures, this would cause terrain disturbance and thermokarst action. Another effect of a changing climate is that changes in the thickness of snow cover over tundra affect the ground thermal regime of the underlying soil and permafrost. A study concluded that decreasing/increasing the snow depth resulted in decreasing/increasing the maximum ground temperature up to a depth of 30 cm (Ling and Zhang 2007).

High latitude climates are complex with many linear and non-linear interactions within the global climate system. The arctic is an important driver of climate systems that affect lower latitudes, and will be influential in climatic change with positive and negative feedbacks. As observational systems are more sparse than in lower latitudes, there is still much to be learned about the climate of high latitudes. Research is required for predictions of changes and impacts, and to better distinguish between climate variability and change.

Overview of Climate Change and Modeling

In the last few years, GCMs have made improvements to their resolution, and are now able to better capture large-scale circulation patterns and seasonal variability, while decreasing the error in several climatic parameters, such as precipitation and surface air temperature (Randall et al. 2007). GCMs typically have a horizontal resolution of 400 to 125 km (Christensen et al. 2007), and while recent modeling efforts show considerable confidence in predicting the climate at large scales, they are inadequate for regional impact studies.

The role of regional climate models is not to decrease uncertainty of global models, but to add spatial and temporal detail to the simulation. RCMs have demonstrated relative strength compared to GCMs at timescales of a few years to multiple decades (ACIA 2004), in part because they capture mesoscale climatic processes more realistically (Giorgi and Hewitson 2001). Regional modeling is especially useful for regions of varied topography or land coverage, such as mountainous areas or urban centers (Leung et al. 2003). Alternative types of modeling have come out of the need for results at a more localized scale; among them are statistical and dynamical downscaling. Both of these use statistical relationships between large-scale circulation patterns (provided by GCMs) and local observed climate data. Downscaling efforts have been occurring for over two decades, and have provided results for spatial resolutions of 10-30 km.

Recent studies have looked at the performance of GCMs and regional models in northern Canada (Bonsal and Prowse 2006; Gachon and Dibike 2007). Bonsal and Prowse found that GCMs had an intermediate accuracy for temperature in all sub-regions of Canada, whereas the only region for significantly accurate precipitation was over northern Quebec and Labrador. Model simulations typically show strong correlation between warming temperatures and increased precipitation (Christensen et al. 2007). With respect to uncertainty in RCMs, temperature has consistently been better simulated than precipitation (Déqué et al. 2005).

For northern latitudes, results of GCMs are likely subject to significant biases from lower latitudes because those regions generally have more complete and dense observational systems and historical records. This highlights the importance of regional simulations through statistical linkages for areas where there is an adequate observational database. Overall, the results of GCMs for the arctic and northern latitudes predict greater warming in the winter and spring seasons, with a less pronounced warming trend for the summer and fall (McGuire et al. 2006).

Gridded Data

In the past, climate datasets have been incomplete and inadequate to properly assess long-term trends and patterns; this constrained models and predictions with short and spatially sparse records. Since the 1990s, there has been a move to homogenize observed data to make it more useful in climatology, and the product of this effort has been gridded datasets, or reanalysis data (Kalnay et al. 1996). A gridded dataset is a collection of climatological observations compiled with standardized spatial and temporal scales. These evenly-spaced and geo-referenced datasets are often more useful than the limited data from irregularly spaced climate stations (Milewska et al. 2005). The list of observations that may be used includes, but is not limited to: surface and sea temperatures, pressure, humidity, precipitation and upper air station (rawinsonde) data (Kistler et al. 2001). Several institutions and universities independently produce their own gridded datasets, but the process of doing so is generally similar for all. Data is retrieved from many sources (land climate stations, buoys at sea, satellite, historical ship data, etc.) across political borders to create large-scale regional or global output. Atmospheric and oceanic observations are assimilated with supercomputers using "state-of-the-art" models (Kalnay et al. 1996). This involves a rigorous quality control aspect that will omit significant outliers and interpolate for missing values. The end product results in a homogeneous (in space and time) set of observations that are geo-referenced to a standardized grid cell. Each grid then has a two- or three- dimensional set of values specific to certain climatological elements. Gridded data is usually referenced using latitude/longitude, and is on a daily, monthly or yearly time series. Several institutions have made their reanalysis data publicly available for download and are updated at least yearly for the most up to date analysis of climate conditions.

The National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) are two well-respected American institutions that conduct leading research on climate science. Together, they produced one of the first gridded data sets in the mid-1990s that reanalyzed observations covering the globe from 1948 to the present (Kalnay et al. 1996). They used a fixed model to avoid gaps in the data produced by changes in operational methods (i.e. advances in instrumentation and data recording capabilities). This model also overcame the problems associated with changes in spatial resolution of land and ocean data sources. For example, since the 1990s, there has been a decrease in the number of land observation stations in Canada, down from around 2900 in 1991 to 2200 in 2000 (Milewska and Hogg 2002). Further, assimilation of data is continuously updated as historical records are found and gradually digitized (Peterson and Vose 1997). The NCEP-NCAR reanalysis project included data assimilated from: upper air radiosonde observations of temperature, wind, specific humidity, vertical temperature from NOAA, cloud coverage from satellites, aircraft observations of temperature, land surface reports of atmospheric pressure, and oceanic reports of sea-level pressure, temperature, wind and humidity (Kistler et al. 2001). After models are ran through supercomputers in the assimilation process, the output is in the form of gridded variables of the aforementioned meteorological parameters. NCEP-NCAR has made their reanalysis data available for public download through the standardized gridded data format, GRIB, on their website (NCEP-NCAR).

As in all disciplines of scientific research, there is continuous evolution and improvement in technology and methodology, and as the use of gridded data is still a relatively recent development in climatology, this is of course a consideration in its application.

Statistical Downscaling

Two techniques are widely used to derive the local climate conditions from the low-resolution predictors used in GCMs: statistical downscaling (SD) and regional climate models. Statistical downscaling is based on the idea that the regional climate is driven by the large-scale climate state and its regional features, such as topography (ACIA 2004). It involves combining observed data (predictands) with large-scale climatic factors (predictors) to make a statistical model that relates these two, increasing the resolution and knowledge of local information. This derived local information is dependent on the accuracy of the large-scale models from which they are 'driven' (Mitchell and Hulme 1999), which is why improvements in reanalysis data is a key factor in the continued use and success of statistical downscaling.

There are three main types of downscaling - dynamical, stochastic weather generation, and regression (Wilby et al. 2004) - which have been subject to much comparison to determine which method has the most skill. The most straightforward type is regression, which relies on deriving statistically significant relationships between the predictors and predictands. This is achieved through multiple or single regression models; canonical correlation; or principle component analysis.

Statistical downscaling as a tool in modern climatological techniques has its advantages and disadvantages. In regions of complex topography, SD has a reputation for being useful as long as there exists an adequate amount of 'predictand' data to produce a realistic climatology. On the other hand, when there are no 'on-the-ground' observations to calibrate the predictors with, SD is not possible. Other advantages of SD are its low-cost, rapid development of site-specific models, and the availability of open-source software for analysis. Statistical DownScaling Model (SDSM) is a decision support tool for modeling local climate change impact using a robust statistical method (Wilby et al. 2002). SDSM, the first available open-source software of its kind (Wilby and Dawson 2007), is useful whenever GCM and RCM simulations are at too coarse a grid for realistic assessments at the spatial and temporal scales of interest.

The statistical power of SD has greatly improved with developments in gridded reanalysis data. The available observed data is not spatially and temporally dense enough for GCMs to produce output that would be considered fine-resolution. However, as grid-boxes decrease in size (or increase in density) when it is required to interpolate and re-grid the datasets to increase statistical power, the predictor-predictand relationship correspondingly increases in power (Wilby and Wigley 2000). Also, with developments in reanalyses, regression-based downscaling has benefited from more standardized sets of data (Karl et al. 1990); standard deviations for gridded observational data have decreased with more robust and quality-controlled data assimilations. Essentially, with more realistic gridded data sets, SD modeling benefits from greater calibration (in space and time) between observed and large-scale data.

The skill of downscaling is as important for hindcasting as it is in forecasting the future climate. A recent paper by Cheng *et al* (2008) used gridded and historical climate data from south-central Canada to downscale output from GCMs on an hourly and daily scale. They used data from the NCEP-NCAR reanalysis, as well as observational data from Environment Canada climate stations. They used different regression methods depending on the climatic variable they were analyzing (temperature, wind speed, surface pressure or cloud cover): either multiple regression or principal component analysis. Their results give credibility to the ability of SD, in that over 95% of the total variance of most examined variables was explained by the downscaling; in other words, a strong relationship was found between the GCM predictors and the observed predictands.

Several studies use SD to evaluate the skill of predictor-predictand relationships, to decide on the best combination of predictors that are able to minimize sources of variation and capture the local climate. Cavazos and Hewitson (Cavazos and Hewitson 2005) use the NCEP-NCAR reanalysis to assess atmospheric variables as predictors for daily precipitation for grid cells covering a wide range of climate profiles. In all locations, mid-tropospheric humidity and geopotential height were the most significant predictors of daily precipitation across all seasons. The major difference in the analysis of different locations is that the predictors showed poorer performance in the subtropical or tropical regions. This may be due to deficiencies in the reanalysis data near equatorial regions, and highlights the importance of high-resolution, standardized gridded data in statistical downscaling.

Downscaling is useful both for climate research and for impact assessment studies. Many downscaling results are used for agricultural purposes, to see what the impacts of a changing climate would have on crops; the output of GCMs would fail to capture this. It is also important for paleoclimatic studies to be able to couple the results of downscaling to sensitive climate reconstructions, such as tree rings. Finally, statistical downscaling can be useful to construct climatologies for regions that have sparse observational records.

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Co-Authorship Statement

For all chapters of this thesis I was the lead author, with the guidance and input of my academic supervisor, Dr. John Jacobs. Dr. Jacobs, is co-author on both manuscripts.

My role in the production of this thesis included outlining the scope of the research questions, gathering and synthesizing the relevant literature, analysis of the data, drafting the text, and completing final revisions. Dr. Jacobs planned and established the field observational program on which much of this thesis is based. He was involved in the development of the methodology and the concepts explored, contributed to data analysis, and provided final reviews of the prepared manuscripts.

Field work and data collection was performed by both myself and Dr. Jacobs.

Chapter 2: An approach to regional climate modeling of a data-limited, subarctic alpine site: statistical downscaling in the Mealy Mountains, Labrador.

Abstract

The low resolution of global climate models (GCMs) fails to capture the climate regimes of areas of complex topography, where historical climate records are often sparse and the climate is distinct from its surrounding regions. These large scale models are not sensitive to local climatic influences of particular regions, such as those at high latitudes or with large bodies of water that are ignored in GCMs. However, various regional modeling efforts are being conducted to better predict the future climate change scenarios of these regions by providing models at a finer scale. This study investigates the use of statistical downscaling, a method of regional climate modeling, for the subarctic-alpine region of the Mealy Mountains, Labrador. The study site has been part of climatic and biological studies since 2001, and has a corresponding nine-year climate record. As this record is relatively short, two nearby, long-term stations are used for the downscaling (Goose Bay and Cartwright), and these results are then used as predictors in a multiple linear regression to forecast the temperatures in the Mealy Mountains. Two emissions scenarios (A1B and A2) from the CGCM3 model are downscaled, and in general, the results indicate that the region will experience greater warming than is predicted by the raw GCM data. Further, both the downscaling process and the multiple regression demonstrate a high level of statistical significance, indicating that the methodology, including the extension of the predictions using short-term climate records, is a valid procedure to extend climate predictions for remote, data-limited regions. Finally, in comparing the gridded data sets used in climate modeling to actual temperature observations, we find that the gridded data smooth over the climate extremes, demonstrating the shortcomings in making local predictions from low-resolution models.

Keywords: statistical downscaling, regional climate modeling, Labrador, Mealy Mountains

Introduction

Climate change will have a significant effect on biological and physical systems, and the impacts are likely to be even more pronounced at higher latitudes, where the climate system is especially sensitive to change (Serreze and Francis 2006). Climate change scenarios are important for any impact study, and global climate models (GCM) are used to provide predictions of future climates at a global scale. However, the coarse resolution of GCMs is insufficient at producing reliable climate change predictions at a regional or site-specific scale, especially in regions of complex topography, unique meso-climates and minimal historical data. Thus, climate change scenarios need to be developed at finer resolutions to more realistically describe the predicted impacts at a site-specific, or even regional, scale (Wilby et al. 2002). The use of regional climate models is increasing, however these are still limiting in the areas and time periods that they cover.

Sub-arctic and arctic alpine regions are characterized by often extreme and variable climates that provide habitat for distinct flora and fauna, commonly for species at the edge of their range. These areas are particularly vulnerable to climate change because their ecosystems are highly controlled by altitudinal climatic gradients. For example, an increase in average surface air temperatures would cause an upslope shift in temperature regimes. Climatological research in alpine regions is complicated by a paucity of observational data at a sufficient spatial and temporal scale, and also by the difficulties in representing complex topography in modeling efforts (Beniston et al. 1997). The scale of impacts that climate change will have on the alpine sub-arctic study area is below the scale of a GCM, which produce scenarios at a typical resolution of 200-500 km (Leung et al. 2003). It has previously been found that GCMs typically overestimate warming for northern regions (Barrow et al. 2004). Further, large biases exist in GCM output, especially for regions that are somewhat close to grids that have significant influences from oceanic processes (Bonsal and Prowse 2006, Gachon et al. 2005). The highland from oceanic processes (Bonsal and Prowse 2006, Gachon et al. 2005). The highland regions in Labrador are thus susceptible to modeling errors due to both their alpine and northern components.

Beyond the limitations of GCMs for local-scale climate or impact studies, it is also important to consider the source of data that climate regional and global models are built on. The description of climate, its mean state and recent changes are often at a coarse spatial scale, and thus the data that is used to construct models is at a similar scale. Spatio-temporal modeling at a finer resolution is usually based on coarse resolution datasets, which are often incomplete. Reanalysis data aims to provide a quality-controlled, global datasets of analyzed data (Serreze and Hurst 1999) that are as spatially and temporally continuous as possible. Recently, gridded reanalysis data and modeling efforts have greatly improved in resolution and in spatial and temporal consistency, however there remains the need for finer, or even point, scale observations for impact studies, especially for those with heterogeneous topography and climate (Wilby et al. 2004). Further, there is still a lack of validation with *in situ* observations, especially for remote areas where large observational networks are non-existent, and where many topographical features are not captured. A certain level of validation of gridded data would thus improve the credibility of regional modeling efforts, which rely partially on these data sources. The recent improvements in reanalysis data and its widespread availability has allowed for comparisons between the gridded datasets and surface observations (Cavazos and Hewitson 2005).

To overcome the limitations of GCMs and produce future scenarios that are more representative and accurate for smaller regions, a method to develop finer resolution models has been developed called statistical downscaling (SD). SD establishes statistical relationships between large-scale climate variables from reanalysis datasets and GCMs (predictors) and local climate station observations and in some cases proxy data sources (predictands). Once a statistical model is produced, it can be used with current GCM output to provide future climate scenarios that are more site-specific. It has been shown that the SDSM software is relatively successful in producing the main characteristics of a climate regime, but is not as accurate in capturing the variability, especially in precipitation (Gachon et al. 2005).

The objectives of this study are twofold: (1) to describe the climate change predictions for an alpine site in Labrador using the SDSM model for statistical downscaling, and (2) to provide an evaluation of the gridded data sets for use in regional modeling efforts. Together, the aim of these objectives is to investigate the reliability of statistical downscaling in producing temperature predictions using spatially and temporally limited observational datasets for a topographically complex location. In a review of the literature, it was found that a number of studies have used the statistical downscaling methodology to generate regional models that are more applicable for ecological and agricultural projects (Leung et al. 2003). There have also been studies looking at and evaluating temperature downscaling in northern Canada, however these have mostly used climate records from long standing automated stations (Gachon and

Dibike 2007), and have not tried to bridge the gap between a short term, geographically isolated site with those of the surrounding region.

The results of this study will be useful for climate change impact studies, including a concurrent study on treeline ecology and climatic change. One of the deliverables of this study is temperature climate scenarios for the future of the Mealy Mountains, which can in turn be used in predicting changes in vegetation cover through modeling efforts. Further, the climate modeling is important to give an indication of the change in the extremes of temperature, which could have significant effects on the composition and health of an ecosystem. Climatic extremes (and extreme events) play an important role in ecology and are a source of disturbance to an ecosystem (Easterling et al. 2000, Katz et al. 2005). Though ecosystems have a large degree of resiliency, some species' range or distribution may reach a type of tipping point once a certain threshold is exceeded, and rapid changes can follow (Chapin III et al. 2004).

The study site for this paper is a valley in the Mealy Mountains, Labrador (53° 36.9' N and 58° 50.2' W); a subarctic alpine region which sustains an altitudinal spruce, fir and larch treeline, and has recently been declared part of a new Canadian national park. The distinct ecotone of the site, which transitions from boreal forest to alpine tundra, are assumed to be largely climatically driven and are therefore of particular interest considering recent warming trends in the region. The climate of the Mealy Mountains study site is characterized by strong seasonal contrasts; its proximity to the Labrador Sea to the east yields a strong maritime influence at certain times of the year, while a significant continental influence has been found for other times of the year.

Several recent studies have looked at the northward and upward movement of treelines (Payette 2007; Grace et al. 2002), thus the results of this modeling exercise will be relevant to other ongoing research at the site looking at the treeline.

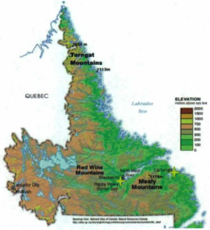

Figure 2.1: Topographic map of Labrador. The yellow stars denote the location of the Goose Bay and Cartwright climate stations. (Map source: Natural Resources Canada).

Climatological and ecological research has been in progress at this site since 2001, which allows for broad and significant collaboration of data collection and analysis, and the study has most recently been a site of International Polar Year projects. To date there has not been a published review of the current climatic regime in the Mealy Mountains, nor has a regional climate modeling effort yet been published. This is therefore the first look at the possible future climatic outlook at the local scale.

This chapter is organized into the following sections, subsequent to this introduction. Section 2 describes the data used, including the observational network, gridded reanalysis data, and data from GCMs that is used in the statistical downscaling process. Section 3 describes the methodology, which includes a summary of the downscaling process, as well as an overview of the method for analyzing the gridded datasets. Section 4 presents and discusses the results from the two aforementioned objectives, as well as a comparison of the downscaling results to GCM model output. Finally, section 5 provides a brief summary of the main conclusions of this study.

Data

Data from a number of different sources were used throughout the modeling exercise and this paper. They are described as follows:

1. Climate station observations (predictands). Automatic climate stations were operated in the Mealy Mountains study area and were recording atmospheric data from 2001 to 2009. The 'Base' station, located at the research basecamp, was operated from 2005 to 2009; located at 600 m.a.s.l., it is considered representative of the climate at the upper tree limit in this area. In addition, the climate records from two nearby Environment Canada stations (Goose Bay and Cartwright) are used in the modeling process (Table 2.1).

Table 2.1: Coordinates of observational stations used in this study.

Station	Latitude (°N)	Longitude (°W)	Elevation (m.a.s.l.)
Mealy Mountains	53.63	58.87	600
Cartwright	53.71	57.04	14
Goose Bay	53.32	60.42	49

2. Large-scale atmospheric variables (predictors). These are developed from the National Centre for Environmental Prediction (NCEP) reanalysis data (Kistler et al. 2001). These variables, interpolated onto the Coupled Global Climate Model (CGCM3) grid, are available at a daily interval on a grid size of 3.75° longitude x 3.75° latitude. These are the latest data available for downscaling from the Data Access Integration Portal (DAI CGCM3 Predictors 2010).

3. GCM data. Daily data from the CGCM3, produced by the Canadian Centre for Climate Modelling and Analysis, were used for simulation of the present and future climate. The predictors of this model cover the period of 1961 to 2000 for the 'current' period, and 2001-2100 for the 'future'. There are two datasets for the future period simulations, driven by IPCC SRES scenario emissions A1B and A2; both are used in the downscaling process. The A1 family of scenarios is one of rapid economic development, low population growth and more efficient technologies spread across the world, with the A1B subset emphasizing balanced use of energy resources. The A2 scenario describes a more heterogeneous world,

with slower development, resulting in higher CO_2 output than the A1B scenario. The choice of GCM model was guided by CGCM3 having predictors available for current and future periods, on grids that have been matched to NCEP predictors; these are also the most recent data made available, and have not knowingly been previously used in downscaling studies in Labrador.

4. Gridded Reanalysis data. These extensive datasets are a product of the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR), and incorporate climatological observations and numerical weather prediction for a number of climatic parameters dating back to 1948. The data are a valuable tool for climatological studies and modeling. In this study, besides being used directly in the statistical downscaling process, they are used as an additional tool to explore their utility and value for a remote location (the study site) with variable climatic patterns and sparse local historical observations.

Methodology

Statistical Downscaling Methodology

The method of statistical downscaling used for this study is the regression-based model developed by Wilby and Dawson (Wilby and Dawson 2007) called SDSM. SDSM is a decision support tool that allows the user to assess the regional climate impacts from global warming at a more local spatial scale than that produced by the driving GCMs. The windows-based software, currently version 4.2.2, allows the formulation of statistical relationships between local observed climate data (predictands) and regional scale predictors, which are then used to model current and future climate. The modeling procedure is achieved through a number of steps which include: quality control and data transformation; predictor variables screening; model calibration; weather generation; statistical analyses; scenario generation; and graphing model output. The process and a detailed description of the procedure can be found in the *User's Manual for SDSM* (Wilby and Dawson, 2007), as well a flow diagram has been included in the Appendix.

The first step is the preparation of the predictor and predictand data, which the user of SDSM must supply in the appropriate data format. The quality control step counts the number of values and ensures that there are no missing data. The next step is the selection of the predictors, which is perhaps the most complex step in the downscaling process. All of the predictors are screened against the predictand using the SDSM software, which produces a correlation matrix and the explained variance for each predictor. It is suggested that the final group of predictors used includes variables for atmospheric circulation, thickness, and moisture content (Wilby et al. 2002). The predictors provided by NCEP for this study include 10 atmospheric variables at three different height levels (surface, 500 hPa and 850 hPa; see Appendix), and at the outset are all treated as potential predictors for use in the model. The predictors with the highest correlation are used to train and validate the multiple regression model that would be used to calibrate and then generate the model used to predict future variables. After choosing the candidate predictor set, SDSM provides the user with those which have a predictor-predictand relationship that are statistically significant to a chosen confidence level ($p<0.05$). The NCEP dataset corresponds to the grid of the local study site, and also the predictors used by the circulation model for future scenario generation.

Model Evaluation and Generation

The SDSM software has built in functions to evaluate the model output, from the calibration process through to the uncertainty of the scenario output. To be sure that the downscaling model will produce a future climate regime derived from GCM output, the model's ability to reproduce the current climate is a necessary analysis. As the lengths of the observational records used in this study are sufficient to allow the withholding of data during the calibration process, these 'independent' data can then be used to validate the model. There are both visual and statistical approaches to evaluate the performance of the regression model. This includes the root mean square error (RMSE), which is computed over monthly and annual periods from the observed and simulated climates, and gives a statistic for estimating the relative error. As well, we look at the goodness of fit of the regression models in the form of the coefficient of determination (R^2); this gives a measure of the explained variance.

Once the calibration model is validated, the final step is the generation of scenarios, which produces the future climate conditions for the local site of the predictand, using the calibrated regression model and the selected GCM data.

Scenario building for the Mealy Mountains

Finally, to produce the scenario for the MM site, we ran a multiple linear regression to predict the future climate at the upper limit of the treeline in the MM; the independent variable was the MM observational data, with the corresponding years of the long-term records from Goose Bay and Cartwright (2001 – 2006) as the independent variables. For this, we ran twelve different regressions using the daily data to get regression coefficients on a monthly basis; this was done to minimize the effects of autocorrelation in the time series. We then used these monthly regression coefficients to forecast the temperatures of the MM using the scenario data generated from the statistical downscaling, for the corresponding minimum, maximum and mean temperatures.

The use of gridded data for further validation

As this study involves looking at data from a remote area of complex topography, the gridded reanalysis data (from NCEP-NCAR) was used as a further method of validation of the predictand file to be used in the statistical downscaling procedure. Graphical and numerical comparisons between the reanalysis data and the local observational record of the study site for a similar time period were examined to see how accurately the NCEP-NCAR data represents the climate of the Mealy Mountains.

Bioclimatic Indicators from the Modeling

The results of the modeling of the future climate can be further investigated to provide some insight into how bioclimatic indicators are predicted to change. The extremes are often investigated by the frequency of a certain climate variable going beyond a given range, or threshold. Peaks over threshold (POT) are a common way to look at a certain tail of a distribution to quantify the number of values at an extreme; POTs can be above or below a threshold. With an increase in global mean temperatures, we would expect an increase in the upper tail (warmer) of temperatures. It has been found that there has been stronger warming in minimum temperatures than maximum (Easterling et al. 1997). In this study, we will look for changes in maximum temperatures in the shoulder seasons (spring and autumn) at a threshold of 0 °C, which is important for freeze-thaw events. As well, we will also look at POTs over the course of the year for temperatures above 25 °C. As the modeling effort produces the climate over a tridecade period, we can compare the different time periods and quantify the potential for change.

Results and Discussion

The SD modeling was performed for Cartwright and Goose Bay, for minimum, maximum and mean temperatures on a monthly basis. Models were run for the present period for calibration (1961-1975) and validation (1976-2003) of the downscaling, as well as for three tri-decade periods in the future: 2011-2040, 2041-2070 and 2071-2100 (hereafter referred to as 2020s, 2050s and 2080s respectively). The downscaling was performed for both the A1B and A2 scenarios, however the presented results focus on the A1B scenario; results of all models are available in the appendix.

Selection of predictors for this study

After analysis of all predictors for each station, a common set of predictors was selected for use for both Cartwright and Goose Bay. This was decided for a number of reasons. Firstly, geopotential height and wind predictors (vorticity) are frequently seen in downscaling studies (e.g. Souvignet et al. 2010). Secondly, the combination of upper atmospheric circulation variables and temperature predictors has been successful in a number of other studies (Gachon et al. 2005, Huth 2004). Finally, with the previously mentioned maritime and continental influences on the climate, it is important to include upper atmospheric variables which would capture the synoptic, macro-scale processes and events of the greater region. The final seven predictors selected are: mean sea level pressure, zonal and meridional vorticities (surface level), specific humidity (surface level and 850 hPa), geopotential height (500 hPa) and surface temperature.

Table 2.2 shows the skill in downscaling temperatures using the selected predictors, and the explained variance (from 0.60 to 0.73) is relatively high in comparison to other studies (such as Gachon et al. 2005, where downscaling of temperature was performed in northern Canada).

Gachon and Dibike's study (2007), which looked at downscaling results in northern Canada, did not use surface temperature as a predictor in their model because they found that it did not reproduce the present climate adequately, but they recommended exploring the use of more surface predictors. In our study, we did include surface temperature as a predictor, and as demonstrated by the skill level of the model, its use appears successful. One possible explanation for this is due to improvements in the updated GCM (the third CGCM versus the CGCM2, used by Gachon and Dibike).

Table 2.2: Explained variance (R^2) in surface air temperature for the generic set of 7 predictors used in the calibration of the downscaling model, for each of the two stations used.

Station	Min	Max	Mean
Cartwright	0.61	0.62	0.69
Goose Bay	0.60	0.66	0.73

Model validation

Using the SDSM software, we are able to produce synthetic (i.e. simulated) daily weather series with predictors from NCEP data, in order to validate the use of the regression model weights, which will subsequently be used to generate model output for the future using GCM predictors. Figures 2.2 and 2.3 shows the results of this process, and indicate that the NCEP predictors do quite well in capturing the observed values. The difference is never greater than half a degree, and on an annual basis the discrepancy is only 0.09 °C; this difference is not significant at a 95% confidence level (t-test). The season with the largest difference is autumn, where the NCEP results consistently underestimate the temperature for Sept. – Nov.

Before the actual results for the future periods are analyzed, it is necessary to verify the results of the calibration procedure. Observations from the homogenized data set are compared to 'hindcasted' data produced by the SDSM software, which are modeled using NCEP predictors. The selected calibration period was 1961 – 1975, thus the remaining years of the predictor set (up until 2003) are used to independently validate the modeling process. Table 2.3 shows the RMSE for all three of the SDSM models on a monthly and annual basis. Higher RMSEs are seen in the winter months (December, January and February), while the general pattern is smoother with mean temperatures than for minimum and maximum temperatures; this same pattern has been seen in other SD studies in northern Canada (Gachon et al., 2005).

Table 2.4 shows absolute values of the difference between observed and modeled temperatures (1976-2003). Figures 2.2 and 2.3 show the observed mean temperatures at both sites compared to the simulated values from NCEP predictors (the mean of 20 ensembles). Visually, it is evident from these graphs that the simulated values are well reproduced; similar agreements are seen for minimum and maximum temperatures.

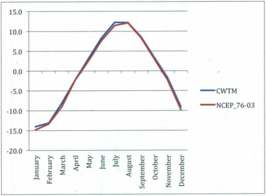

Figure 2.2: Monthly mean temperatures for observed Cartwright (blue line) and downscaled hindcasted (red line) temperatures using NCEP predictors (1976-2003).

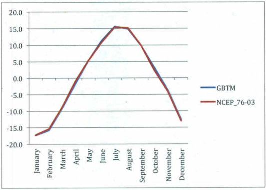

Figure 2.3: Same as Figure 2.2, for Goose Bay.

Table 2.3: RMSE (°C) for monthly and annual minimum, maximum and mean temperatures for the calibration of the statistical downscaling models of both Cartwright and Goose Bay.

	Min		Max		Mean	
	CW	GB	CW	GB	CW	GB
Jan	4.7	4.1	4.5	4.1	4.0	3.6
Feb	5.1	4.9	4.3	4.4	4.1	4.0
Mar	4.2	4.1	3.6	3.5	3.3	3.2
Apr	3.2	3.1	2.5	2.8	2.3	2.4
May	2.1	2.2	3.2	3.3	2.1	2.2
Jun	2.2	2.4	4.1	3.9	2.6	2.6
Jul	2.2	2.4	4.2	3.4	2.7	2.4
Aug	2.0	2.2	3.4	2.7	2.2	1.9
Sep	2.0	2.2	2.9	2.9	2.0	2.1
Oct	1.9	2.6	2.5	2.7	1.8	2.2
Nov	2.7	3.5	2.4	2.6	2.1	2.6
Dec	4.1	4.4	3.7	4.2	3.3	3.8
Yearly	3.0	3.2	3.4	3.4	2.7	2.8

The mean differences, observed minus simulated, are reported in Table 2.4 for minimum, maximum and mean temperatures. For Goose Bay, the simulated values are cooler than observed values in the late fall, by 2 °C or less, but are warmer in the early spring by the same amount. Interestingly, when the differences between the monthly values are averaged over the year, there is no difference (0.0 °C) between the observed and simulated values. For Cartwright, the simulated values are even more in agreement with the observations for minimum temperatures, with the highest deviation seen in March (1.3 °C colder than observed), and a yearly average of less than 0.5 °C colder.

Table 2.4: Differences between observations and simulated values from the same period, produced from NCEP predictors using the statistical downscaling method.

	Cartwright			Goose Bay		
	Min	Max	Mean	Min	Max	Mean
January	0.6	1.1	0.8	0.2	0.2	0.0
February	0.1	0.2	0.2	-1.2	-0.5	-0.4
March	1.3	0.7	1.0	-1.5	-0.6	-0.3
April	0.1	0.0	0.0	-2.1	-0.5	-0.7
May	0.4	0.7	0.6	-1.1	0.2	-0.1
June	0.6	0.4	0.7	-0.7	0.5	0.5
July	0.6	1.1	0.8	-0.3	0.2	0.2
August	-0.1	0.1	0.1	0.4	-0.3	-0.3
September	0.2	0.3	0.3	0.8	-0.1	0.0
October	0.5	0.3	0.4	2.1	0.3	0.8
November	0.3	0.6	0.5	1.9	0.4	0.4
December	0.5	1.4	0.8	1.8	0.4	0.4
Annual	0.4	0.6	0.5	0.0	0.0	0.0

Scenario Results

The results of both the GCM output and the downscaling models (A1B scenario) are shown in Tables 2.5 and 2.6 for Cartwright and Goose Bay, respectively. These present the differences between the present and modeled temperatures for the 2050s period (2011-2040) on an annual and seasonal basis.

Annually in Cartwright, the mean and minimum temperatures are in better agreement than for maximum temperatures, where the difference between the GCM and SD predicted temperatures reaches almost 5 degrees. Seasonally, the results are variable, with the most consistent agreement in the winter months, where the SD results are 1–2 °C warmer than the GCM. The largest consistent difference occurs in the fall, where the SD temperatures for the 2050s are predicted to be between 2 and 7 °C warmer than what the GCM predicts, with mean temperatures at the higher extreme of this range. Some cooling is also seen in these SD predicted temperatures, predominantly in the spring and summer periods, and to a greater extent in the GCM predictions.

Previous downscaling studies in northern Canada have concluded that the temperature change signal of the future is less than what is seen in the GCM output, and also that the SD output is more smoothly distributed (Gachon and Dibike 2007). Our results, however, show more warming in the SD results than in the GCM output. This is especially the case for Goose Bay, where max/min/mean temperatures see more warming from the SD for all seasons, looking at the 2041-2070 period. Further, the greater winter warming that our modeling predicts is consistent with other findings for higher latitudes, including statistical downscaling and raw GCM output (Barrow et al., 2004, Gachon and Dibike, 2007). Those projections are largely attributed to feedback effects of changes in surface conditions, such as snow and sea-ice cover. Prior statistical downscaling of minimum temperatures has projected a cooling trend at Cartwright, but warming for Goose Bay (Lines et al. 2006).

Table 2.5: Comparison of the differences between present observational period (1961 – 2003) and the CGCM3 and SDSM modeled temperatures (2050s) for the A1B emissions scenario for Cartwright.

	Mean		Min		Max	
	GCM	SDSM	GCM	SDSM	GCM	SDSM
DJF	7.7	8.5	10.4	9.6	5.4	7.5
MAM	3.0	-0.6	-1.6	-0.6	-3.9	-0.2
JJA	6.0	-0.8	-2.3	-0.6	-8.9	-0.7
SON	-1.6	5.5	3.6	5.4	0.0	5.5
Annual	3.8	3.1	2.5	3.4	-1.9	3.0

Table 2.6: Same as Table 2.5, but for Goose Bay.

	Mean		Min		Max	
	GCM	SDSM	GCM	SDSM	GCM	SDSM
DJF	2.1	5.7	2.2	5.6	1.2	5.2
MAM	-4.0	0.9	-3.1	2.2	-3.8	0.8
JJA	-4.7	1.1	-3.1	1.3	-5.2	1.4
SON	-0.6	4.5	-0.9	3.1	-0.9	5.0
Annual	-1.8	3.0	-1.3	3.0	-2.2	3.1

Minimum Temperatures

The results for the modeling of minimum temperatures were variable for both CW and GB. The observations display an expected seasonal pattern of minimums over the course of the year (see Figures 2.4 and 2.5), however both the SD and raw GCM output for the 2050s period show deviations from this pattern, most notably in the winter months. The modeled minimums at Cartwright are notably warmer beginning in the fall through the winter (by up to 10 °C). The degree of these deviations is such that they look questionable, even considering enhanced moderating effects of changing ocean currents. However multiple runs of the SD model with adjusted and the same parameters yield similar results, and further the GCM raw output has comparable divergences. The spring and summer simulations actually show a slight cooling trend in both the SD (< 1 °C) and GCM (<2 °C) modeling efforts; this trend persists through to the 2080s for the GCM but not for the SD. Goose Bay sees warmer minimum temperatures across all seasons from the SD results, with the highest increase for the winter months. On the other hand, the raw GCM predictions see only the winters experiencing warmer minimums, with all other seasons experiencing a cooling trend.

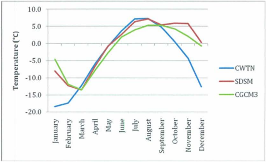

Figure 2.4: Minimum temperatures for Cartwright – observations from the present period (1961 – 2001; blue), statistically downscaled predictions for the 2050s (red) and predictions from CGCM3 for the 2050s (green). Modeled minimum temperatures are for the A1B emissions scenario.

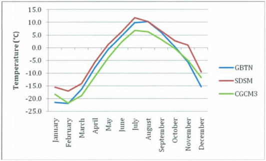

Figure 2.5: Same as Fig. 2.4, for Goose Bay.

Maximum Temperatures

For Cartwright, the SD model predicts increasing maximum temperatures for the 2050s on an annual basis, however as with minimum temperatures, this is not a trend that is prevalent throughout the year (Figure 2.6). The largest increase in maximums occurs over the autumn and winter months, with very little change in the spring and summer. The GCM, however, predicts a cooling trend for Cartwright for the 2050s, with an annual mean maximum temperature that is 2 degrees cooler than the present observation period. This trend persists, though to a decreasing degree, throughout the century. The GCM displays a greater shift in the lag, which is likely caused by oceanic moderating effects than the SD model; the lag in the GCM maximum temperatures persists through March. The warmest month is still July for the SD temperatures, which is the same as present day observations, however the GCM scenario's warmest month is also shifted further into the year, with August and September having the warmest months. The warmer autumns are expected with a warmer ocean and the later onset of freeze-up for sea-ice.

In Goose Bay, the results of the two models are quite different from one another (Figure 2.7). The overall trend produced by the statistical downscaling shows warming in all months of the year, resulting in an annual 3 °C projected increase by the 2050s. The GCM predicts an overall annual cooling trend (by 2 °C), with warming only in the late fall and early winter months. The sharp increase in maximum temperatures, most pronounced in the winter, could be a result of decreased sea-ice which the GCM would reveal in its oceanic component. As Gachon (2007) discusses, the oceanic component of GCMs strongly influences the temperatures that are simulated by the model. Further, a large-scale model will likely overlook the seasonal effects of inland, but significant, bodies of water, such as Lake Melville and its effects on Goose Bay.

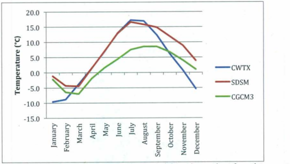

Figure 2.6: Maximum temperatures for Cartwright – observations from the present period (1961 – 2001; blue), statistically downscaled predictions for the 2050s (red) and predictions from CGCM3 for the 2050s (green). Modeled temperatures are for the A1B emissions scenario.

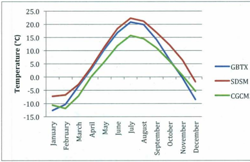

Figure 2.7: Same as Fig. 5, for Goose Bay.

Change in temperature thresholds

Results for the peaks over threshold are presented in Tables 2.7 and 2.8, for 25 °C and 0 °C respectively. For the 25 °C threshold (maximum daily temperature over 25 °C), the general trend for both Cartwright and Goose Bay is an increase over the modeled 30-year time slices. Summer is the season of interest for the peaks surpassing 25 °C, where Goose Bay sees a significant increase, from 16 in present observations to 27 by the 2080s. The change in POTs at Cartwright is negligible; the difference with Goose Bay being the maritime/continental distinct influences of the two sites. The increase in POTs could have several effects on the ecosystem, including an increased number of growing degree days, but also on evapotranspiration rates, a potential stress on plants.

Maximum temperature peaks above 0 °C show a significant increase at both Goose Bay and Cartwright, which is not surprising given the predicted warming. Though the largest increase occurs in the winter season, which is to be expected, the spring and autumn also see an increase, indicating warming throughout the year. For both sites, the number of maximum temperature events that surpass 0 °C per winter doubles by the 2050s. This increase in thaw events has many implications, including affecting areas of discontinuous permafrost, lengthening of the growing season, frost-heaving, and an increase in snow-melt and freeze-thaw events (Sharratt 1993).

Table 2.7: Yearly observed and predicted (for downscaled scenario A1B) peaks over threshold (> 25 °C) compared for observations, and the three modeled tri-decade periods.

	Cartwright				Goose Bay			
>25 °C	1971-00	2020s	2050s	2080s	1971-00	2020s	2050s	2080s
Winter	0	0	0	0	0	0	0	0
Spring	0	0	0	0	0	0	1	1
Summer	7	4	6	8	16	17	23	27
Autumn	0	0	0	1	1	1	2	3
Annual	7	4	6	8	17	18	26	32

Table 2.8: Yearly observed and predicted (for downscaled scenario A1B) peaks above threshold (>0 °C) compared for observations, and the three modeled tri-decade periods.

	Cartwright				Goose Bay			
>0 °C	1971-00	2020s	2050s	2080s	1971-00	2020s	2050s	2080s
Winter	15	41	46	54	11	19	24	29
Spring	55	51	55	63	61	58	63	68
Summer	92	91	91	91	92	92	92	92
Autumn	81	90	91	91	77	86	88	88
Annual	243	273	284	299	242	256	266	278

Regression to Mealy Mountains

The next step involves the multiple regression analysis to subsequently produce temperature predictions for the Mealy Mountains. The regression shows a strong linear relationship between the MM and the two independent variables (CW and GB), demonstrated by the high R values and low standard error of the estimate (Table 2.9).

The Durbin-Watson statistics were all between 1 and 2, indicating that there is minimal autocorrelation. The range of standard error (SE) for minimum temperatures is 0.10 °C to 1.38 °C, and for maximum temperatures is 0.15 °C to 1.88 °C. The SEs for minimums and maximums do not exceed 2 and are as low as 0.1, suggesting we can predict a monthly temperature within 2 degrees, with the highest for both occurring in May.

Table 2.9: Pearson correlation coefficient (R) and standard error of the estimate reported for the regression model used to synthesize the MM climate from Goose Bay and Cartwright.

	Min		Max	
	R	SE	R	SE
Jan	0.999	0.12	0.993	0.33
Feb	0.988	0.65	0.985	0.58
Mar	0.999	0.34	0.993	0.62
Apr	0.959	1.08	0.971	0.71
May	0.956	1.38	0.941	1.88
Jun	0.995	0.14	0.998	0.15
Jul	0.980	0.32	0.950	0.38
Aug	0.995	0.13	0.971	0.43
Sep	0.903	0.73	0.963	0.74
Oct	0.993	0.15	0.987	0.15
Nov	0.997	0.10	0.928	0.69
Dec	0.987	0.76	0.998	0.17

Tables 2.10 and 2.11 show the observational record from the MM, and the projected change per tridecade for the two emissions scenarios, for maximum and minimum temperatures. On an annual basis, both scenarios predict a warming trend, however this is not a general pattern throughout the seasons. Both spring and summer, at least for the 2020s, will see some cooling. The winter and autumn will experience consistent and increasing warming through all modeled periods.

Looking closely at the seasonal results presented in Tables 2.10 and 2.11, there are a few noteworthy observations to report. Firstly, the annual increase in temperatures is similar for minimums and maximums as far ahead as the 2080s, however the increase of minimum temperatures is greater at the beginning of the century (2020s tridecade) than for maximums; in other words, the minimums warm faster than the maximums. Secondly, looking at the seasonal trends, the warming for both temperature indicators is much greater in the winters and autumns. Summers are actually predicted to see some cooling, until the 2080s, however the degree of cooling in the 2050s is less than 1 standard error (SE), therefore it could be a result of the statistical noise. Finally, of significance to the credibility of the statistical downscaling model, the A2 scenario, described to have a higher greenhouse gas output than the A1B scenario, predicts greater warming in the MM towards the end of the century (2080s), which indicates that the SD captures the signal of the driving GCM. By the middle of the century, the predicted temperature increases for minimums and maximums exceeds 1 SE.

Table 2.10: Observational record from the MM (2005-2009), and the projected change per tri-decade for the two emissions scenarios, for maximum temperatures.

		A1B			A2		
Tmax	MM (2005-9)	20s	50s	80s	20s	50s	80s
Winter	-11.5	3.0	5.3	7.4	2.3	4.7	9.3
Spring	0.1	-0.5	0.4	1.7	0.1	1.3	2.8
Summer	15.6	-1.6	-0.3	0.7	-1.8	-0.4	1.9
Autumn	3.9	1.3	2.4	4.7	1.0	3.0	7.0
Annual	2.0	0.5	2.0	3.6	0.4	2.1	5.2

Table 2.11: Same as Table 2.10, for minimum temperatures.

		A1B			A2		
Tmin	MM (2005-9)	20s	50s	80s	20s	50s	80s
Winter	-20.0	5.3	7.3	9.5	4.5	7.0	11.6
Spring	-8.7	-0.5	0.6	1.9	0.1	1.0	3.1
Summer	6.6	-1.5	-1.5	0.6	-1.5	-0.3	1.5
Autumn	-3.1	2.6	2.6	4.0	2.6	3.2	4.5
Annual	-6.3	1.5	1.5	4.0	1.4	2.7	5.2

Table 2.12: Same as Table 2.10, for mean temperatures.

		A1B			A2		
Tmean	MM (2005-9)	20s	50s	80s	20s	50s	80s
Winter	-15.7	5.5	7.4	9.3	4.7	7.0	11.3
Spring	-4.4	-2.1	-0.9	0.7	-1.2	-0.5	2.2
Summer	11.1	-3.2	-2.1	-1.4	-3.3	-2.2	-0.3
Autumn	0.5	4.5	5.4	6.5	4.5	5.3	7.3
Annual	-2.1	1.2	2.4	3.8	1.2	2.4	5.1

Present period: Comparison of observational data with reanalysis and modeled

Gridded data sets from NCEP-NCAR, the basis of modeled scenarios, are displayed graphically to compare the mean average surface temperatures of the study region to on the ground observations; the reanalysis data is assimilated by a process of statistical interpolation (Kalnay et al. 1996). Figure 2.7 shows the mean temperature for the period 1961 – 2003, which is the overlapping period used in the statistical downscaling process. There is a single temperature for each grid cell, and the cells cover a 2.5° x 2.5° (latitude by longitude) area. Thus, the map seen in Figure 2.7, showing most of Quebec and Labrador, is represented by only 48 grid cells, and therefore 48 different temperature points. Given the smoothness of the contours, virtually all topographic detail, including relatively large water bodies, is absent. In other words, the gridded data is insensitive to the scale of ecological studies. In a seasonal analysis of the reanalysis data, we compared the MM Upper Station and the two nearby Environment Canada stations (Goose Bay and Cartwright). Table 2.13 presents the temperature differences between the station and reanalysis data; the reanalysis temperatures were taken from the actual coordinates of the climate stations, using the GrADS software application, which allows the user to extract a spatially precise interpolated temperature reading from the dataset for a chosen time period. This comparison indicates that, over the three stations, the reanalysis consistently does not capture the warmth of the spring/summer/fall, and also underestimates the winter cold (i.e. the reanalysis is warmer in the winter than observations). This is to be expected considering the nature of the reanalysis interpolations and how their large resolution is often at odds with the heterogeneity of the localized predictand in comparison.

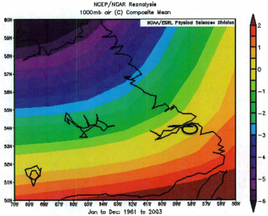

Figure 2.8: Map of surface temperature (at 1000 mb) produced using NCEP-NCAR gridded data. The period of analysis corresponds to the Mealy Mountains observational record that was used in this study for the statistical downscaling modeling. The black circle denotes the MM site, in the -0.5 °C to +0.5 °C range.

Table 2.13: Temperature differences between the three climate stations and NCEP/NCAR reanalysis, on a seasonal basis (averaged over 1961 – 2003). The winter months in the reanalysis data are warmer than the actual observations, which demonstrate that the reanalysis has underestimated the region's cold winter temperatures. In the summer months, the reanalysis is cooler than the actual observations. *The MM station is adjusted to sea level using the observed seasonal lapse rate.

	Goose Bay	Cart-wright	Mealy Mtns*
SPRING	3.2	0.6	3.0
SUMMER	4.0	0.9	2.1
FALL	3.0	1.4	3.1
WINTER	-1.0	-0.8	-2.4

Conclusion

In comparing the observational temperatures with the NCEP data, the gridded reanalysis data smooth over the temperature record and fail to accurately capture the conditions observed from the three climate stations used in this study (Goose Bay, Cartwright and the Mealy Mountains). This indicates that there are distinct limits to the value and usefulness of the coarse gridded sets, and these limitations are relevant when it comes to analyses for the current period (e.g. in using exclusively gridded data in studies that have a significant climatic component), but also for their use in future scenarios, as they are a fundamental component of GCMs. Moreover, the discrepancy between these two sources of temperature data is particularly relevant for the main study site, which can lead us to infer that the inaccuracy of gridded data is enhanced when it comes to elevated or topographically complex regions. Figure 2.9 demonstrates this, as the average yearly temperature (from -0.5 °C to +0.5 °C) over the Mealy Mountains region is uniform throughout the region, which covers a range of 1000 m in elevation, as well as being adjacent to a large body of water, Lake Melville (which the gridded data describes as having the same average temperature as the adjacent land area).

Overall, the regression-based modeling efforts in this paper, for both the synthesis of the Mealy Mountains record and for the statistical downscaling, show a relatively high skill-level. This indicates that these methods have some validity in the modeling of future temperature projections, and that they offer an alternative to coarse-scale GCM output. The GCMs, as seen in our results when compared to the regionally downscaled model, underestimate the summer warming for this highland region. The methods explored are especially beneficial for areas of complex topography with limited observational records, which is common for northern studies involving some aspect of climatology or ecological research.

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Chapter 3: Climatology of the forest-tundra ecotone at a subarctic alpine site in Labrador.

Abstract
High latitude regions are especially susceptible to climatic change as a result of global warming and warrant close monitoring and research of the physical and biological features of their diverse ecosystems. The Mealy Mountains, Labrador, is a geographically isolated subarctic-alpine ecozone, and thus an important ecological resource and region, as well as having cultural and potentially economic significance. In 2001, Memorial University researchers set up a study site for ecological and climatological studies. The site covers a valley where a network of three automatic climate stations covering an altitudinal gradient of 600 m has been collecting climatological data since 2001. As the site is home to an altitudinal treeline, it is a good location to analyze the relationships between the climate and the ecosystem. The analysis in this paper is twofold; first, it offers a descriptive climatology of the study site, and second provides bioclimatic interpretations between climatic and biotic (specifically towards the treeline) factors. The analysis of the climate observational record, (such as air and ground temperatures, precipitation, vapour pressure deficit and growing degree days) indicates that the physical environment is suitable for tree growth. The primary conclusion is that the current climate regime provides no limiting factor to the upward movement of the treeline; however further investigations into the contributions of snow and wind to limiting tree growth and establishment are recommended.

Keywords: climatology, subarctic-alpine, treeline, Mealy Mountains, Labrador

Introduction

There is general agreement within the scientific community that climatic change will have far-reaching consequences for the environment and human activities (Parry et al. 2007). Though there are constant advances in modeling climate projections for the future, it is equally important to adequately document the present climate state at the regional and landscape scales to accurately assess potential impacts, as well as for monitoring purposes. Highland regions typically lack a well-established, representative climatological record, and therefore baseline information for researchers and stakeholders is scarce. Further, highland ecosystems may act as indicators for systemic responses to global warming due to their sensitivity to altitudinal climatic gradients (Cannone et al. 2007).

Climate models predict that northern high latitudes are to experience stronger temperature warming than lower latitudes. The expansion of the boreal forest ecosystem northward, and upwards for alpine treeline areas, is therefore of particular significance. Previous studies indicate that summer temperatures control the position of an altitudinal treeline (Gehrig-Fasel et al. 2008; MacDonald et al. 2008). Vegetation changes that are likely to occur in a warming climate are especially important in the forest-tundra transition zone because they will have significant climate feedbacks; for example, with changes in albedo and carbon storage (Chapin III et al. 2000). In order to predict the responses of biotic systems, there is a need for knowledge of the recent and current climate, and its spatial and temporal variability at the regional and landscape scales.

The climate of a highland area is dependent on latitude, continentality and topography, and is generally complex due to many influencing factors (Barry 2008). The most reliable way to realistically characterize the climate of a highland region, where climate stations are typically in lowland sites if at all, is by the collection of field measurements (Richardson et al. 2004).

Ongoing multidisciplinary research at a site within the Mealy Mountains (53° 36.9' N and 58° 50.2' W; Figure 3.1) began in 2001, and includes studies of the vegetation as well as the climate (Jacobs et al. 2005). With an extensive record of the main climatic variables - temperature and precipitation - the climate regime can be adequately characterized and documented. Where data have been collected along an altitudinal gradient, particular attention can be placed on the differences between upper and lower sites, which would be useful for distinguishing between the climatic factors that influence vegetation patterns, and therefore aid in a predictive capacity. The 8 years of data collection to 2009 allow for a comprehensive summary of climatological data, and are also useful for ecological monitoring and making links between microclimate and vegetation.

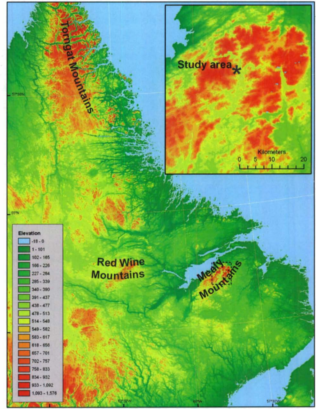


Figure 3.1: Map of Labrador showing elevation, with the three major mountain ranges labeled, and the inset showing the Mealy Mountains.

The predicted changes in climate lead ecologists and climatologists to question the response of ecosystems that are particularly at risk, such as the alpine treeline of the Mealy Mountains. The objectives of this paper are twofold. First, in the synthesis and analysis of the record of the study site, the aim is to determine whether the climate of this highland region is behaving comparably with the surrounding lowland regions. According to regional records, the current climate regime of the large-scale area is in a period of change and likely not representative of the last climatic normals. With this knowledge, we intend to establish whether the climate regime of the Mealy Mountains is in unison with the patterns of the adjacent areas, despite having distinct topographical and geographical features. Second, the objective is to determine whether the current climate of the alpine study site is a limiting factor to vegetation and ecosystem change; this will be determined by analyzing relevant biolclimatic indicators. Specifically, the intent is to determine whether the climate at higher altitudes is limiting the growth or colonization of black spruce trees, considering the discrete changes in ecotones with elevation.

Study Site

The Mealy Mountains, south-central Labrador, is a sub-arctic alpine region that is of ecological, cultural and economic importance (Bell et al. 2008; Hollett 2006; Keith 2001) and is home to a diversity of landscapes, including alpine tundra, boreal forest and wetlands. A large part of the Mealy Mountains has recently been declared the site of a national park, which will represent the East Coast Boreal Region under the Parks Canada Natural Regions. Rising from the southern shores of the saltwater Lake Melville, the mountains vary in topography and ecozones, ranging from closed canopy forest to alpine tundra with bare summits and exposed bedrock. Vegetation in the higher regions and summits is characteristic of arctic-alpine areas, with many plant species typical of more northerly environments. The maritime influence, from Lake Melville and the Labrador Sea and its cold ocean currents, provides a minor moderation effect, keeping the climate moist, with winters that are cold and long, and summers relatively short and cool (Keith 2001). Late lying snowbeds throughout the summer provide a unique habitat for plant growth, as well as relief for woodland caribou.

The areas above treeline are the southernmost outliers of the High Subarctic Tundra Ecoregion (Meades 2007), and the mountains fall within a region of sporadic discontinuous permafrost (Smith and Riseborough 2002). The change in elevation, from sea-level to 1,100 m. above sea level (a.s.l.), is a main factor in determining vegetation transition zones, and the gradient goes from closed-canopy forest up to sub-arctic alpine tundra at the higher levels. Analogous highland areas in the region include the Red Wine Mountains to the west, as well as sites in northern Labrador.

Approach and Methodology

The project is largely based on climatological observations over the extent of the study period, starting in July 2001. The main study area within the Mealy Mountains is an east-facing valley, Moraine Valley[1], 9 km long and up to 2.5 km wide, with the highest summit at 1057 m to the northwest (Figure 3.2). Three automatic climate stations were installed in the study area, providing data that spans over 400 m in elevation, and transitions from open boreal woodland to subarctic alpine tundra (Table 3.1). In addition

[1] "Moraine Valley" is an unofficial name for the study site.

to these long-term stations, short-term or seasonal data were collected in various locations in the valley, including soil temperature and moisture, air temperature and humidity, and snow cover. The observational program was designed to maximize spatial and temporal resolution of quantitative measurements, within the limits of available research resources.

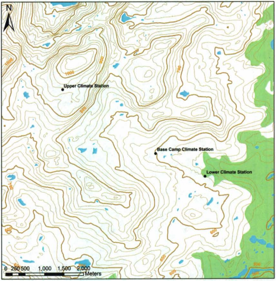


Figure 3.2: Map of Moraine Valley, and location of three main climate stations.

Table 3.1: Location and record length of Mealy Mountains climate stations

STATION	Lat	Long	UTM	Elev (GPS)	Start	End
				m a.s.l.		
Mealy Lower (Forest-transition)	N 53° 36.64'	W 58°49.03'	21U 0379782 5941517	570	17-Jul-2001	28-Nov-2006
Mealy Base (Forest-transition)	N 53° 36.9'	W 58° 50.2'	21 U 0378513 5942093	600	25-Jun-2005	3 Feb 2010
Mealy Upper (Tundra)	N 53° 37.77'	W 58°52.39'	21U 0376127 5943716	995	18-Jul-2001	17-Jul-2009

The data collected directly from the study site cover a relatively short time period for an adequate analysis of trends or to investigate the effects of large-scale climatic controls, such as the signal of the North Atlantic Oscillation (NAO). Therefore, to supplement the observational data, historical records from nearby climate stations have been used to construct a longer climatology. A statistical model was established between the Goose Bay and Cartwright climate data and that of Moraine Valley in order to extend the length of the alpine record. Moraine Valley monthly temperature records were reconstructed back to 1942 using multiple linear regression. Statistical analyses for the regression and throughout the study were performed using SPSS. This record that spans multiple decades is used as a basis for our climatological analysis. The dataset that was used to extend the short-term record of the study site was from the Adjusted Historical Canadian Climate Data from Environment Canada (Environment Canada 2008). This data set has already been corrected and adjusted for changes in instrumentation, station location and accuracy over the years of the record (Vincent et al. 2002).

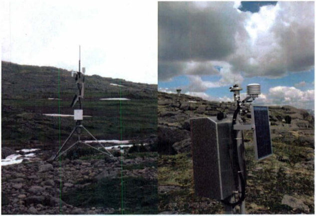


Figure 3.3: Base Station (left photo), elevation 600 m asl; and the Upper Climate Station (right photo) at the summit of Moraine Valley (995 m asl). Note bulk precipitation gauge in the background at the Upper Station.

The climate stations at the study site are all solar-powered and record data using dataloggers that are downloaded and inspected yearly (Figure 3.3). Details of the climate stations, their instrumentation, accuracy and the variables they record are given in Tables 3.2 and 3.3. The temperature sensors were placed in ventilated, non-aspirated radiation shields. The ground temperature sensors at the upper and lower stations were placed at 1.0 m and 0.7 m depth, respectively. The Base station has three ground probes at 0.1, 0.3 and 0.6 m depth. The bulk precipitation gauges at the lower and upper sites, which give a minimum estimate of annual precipitation, are visited at the start and end of each summer field season when the depth of precipitation is measured and the gauges recharged with antifreeze and oil. The precipitation data are enhanced during field seasons by twice-daily observations at the Base camp site using manual plastic gauges. These observations are also used to compare precipitation events in the Mealy Mountains to those at the nearby Environment Canada climate stations in Goose Bay and Cartwright. In order to estimate the contribution of snowfall to the annual precipitation, snow surveys were conducted in mid-March for the years 2008 and 2009 in Moraine Valley (Leblanc et al. 2009). Sample sizes and the sites varied between the two years (Table 3.4), but data from both years cover the same altitudinal gradient as the climate stations.

Table 3.2: Instrumentation details for Upper and Lower climate stations installed in the Mealy Mountains. N.B. All stations are equipped with instruments obtained from Campbell Scientific (**www.campbellsci.ca**) and/or Onset Corp. (www.onsetcomp.com). Note: The readings for the Temperature and Relative Humidity sensors of different brands are within the manufacturers specifications. The set-up of the different instruments was replicated, with similar exposure, and passive, wind-ventilated shields of the same design.

Variable	Equipment	Accuracy	Notes
Air Temperature (°C) and Relative Humidity (%)	CS500 temperature and humidity sensor in Gill-type shield	Relative Humidity probe: between ±3% RH (for 10 to 90% RH) and ±6% RH (for 90 to 100% RH) Temperature Sensor: ±0.6°C for temperatures of -10°C to +30°C	Operating Range of -40°C to +60°C
Ground Temperature (°C)	107B ground temperature probe (thermistor) at 1 m (Upper Station) and 0.7 m (Lower Station)	±0.4°C over the range of -24° to 48°C	Range of -35°C to +50°C. Probes are at 1 m (Upper Station) and 0.7 m (Lower Station)
Solar Radiation (kW m^{-2})	LI200S Pyranometer	Absolute error in natural daylight is ±5% maximum; ±3% typical	
Data Logger	Campbell Scientific Extended Low-temperature CR510 datalogger with S4M storage module		Operating range of -55°C to +85°C
Precipitation	Rain Gauge: Bulk storage collector, with antifreeze and mineral oil deposited into the gauges to prevent evaporation	Unknown	Provides uncorrected minimum estimate of annual precipitation.

Table 3.3: Instrumentation details for Base climate station installed in the Mealy Mountains

Variable	Equipment	Accuracy	Notes
Air Temperature (°C) and Relative Humidity (%)	HMP 35C T/RH Sensor	Relative Humidity probe: between ±3% RH (for 10 to 90% RH) and ±6% RH (for 90 to 100% RH) Temperature Sensor: ±0.6°C for temperatures of -10°C to +30°C	Operating Range of -40°C to +60°C
Ground Temperature (°C)	107B ground temperature probes (thermistor) at 10, 30 and 57 cm depth	±0.4°C over the range of -24° to 48°C	Range of -35°C to +50°C. Probes are at 1 m (Upper Station) and 0.7 m (Lower Station)
Wind Speed and Direction	RM Young Anemometer	Wind Speed: ±0.3m/s Direction: ±3°	Wind Speed Range: 0 – 100 m/s
Tipping Bucket Rain Gauge	Texas Electronics Tipping Bucket Rain Gauge	1.0% up to 50 mm/hr	Summer months only

Table 3.4: Snow survey sites and sample size. (Data from LeBlanc et al, 2009).

Site Name	Easting	Northing	2008	2009
			Sample Size	
Wrong valley	375578	5939650	69	
T1A	380165	5940925	93	
Lower Climate	379809	5941645	74	40
Base Camp	378532	5942284	72	40
Upper Climate Station	376166	5943920	41	40
Wet Meadow	377434	5943410	48	40
Forest	384436	5940167	58	40
New site 1 (forest)	381832	5934866		40
New site 2	370968	5948694		40

Surface air temperature (SAT), defined as the temperature indicated by a standardized thermometer exposed to the air but shielded from direct sunlight, is central to both climatological and ecological research. Temperatures in the Mealy Mountains are seasonally and spatially variable due to differences in elevation, topography and its geographical location. The analysis of SAT will examine the variability of surface air temperature across the altitudinal transect for which data have been collected.

As an extension to the SAT analysis, we also explored the freeze-thaw (FT) cycles from this same data. The FT cycles of an environment have important implications for many physical and biological phenomena. These cycles affect permafrost, active layer depths, terrestrial carbon storage and soil nutrient cycling. For this study's purpose, we define a cycle as when the surface air temperature falls below 0 °C and returns above that threshold, or when it starts below freezing, rises and returns to below 0 °C all within the 24 hour period of a day (Baker and Ruschy 1995).

All three climate stations have at least one ground temperature probe, which gives us a substantial collection of data to make some inferences about the ground temperature regime. At the Base site, the three thermistors are located in a region of typical subarctic alpine vegetation, with the probe closest to the surface in the root zone (at 10 cm depth), followed by one at 0.30 m and finally one at 0.57 m, which is as deep as it could go before hitting large rocks. The Upper Station's single thermistor is at a depth of 1 m, and the Lower Station's is at 0.7 m. The length of record is the same as the rest of the climate station data, as shown in Table 3.1.

The definition of a growing season is variable, and to an extent subjective, depending on location, vegetation type and on the discretion of the author. Generally, the beginning of the season is associated with the photosynthetic period, increased solar radiation, thawing ground and increasing air temperatures, and ends as temperatures, photosynthesis and light availability decrease (Euskirchen et al. 2006). In reviewing the literature for high latitude and treeline related studies, it was found that the parameters defining a growing season are also quite variable. Thus for this study, we have selected two thresholds for either ground or air temperatures that are commonly used in treeline and vegetation studies. Both soil and air temperatures are of relevance while looking at the growing period because the onset of photosynthesis is controlled by both factors. Firstly, we used 5 °C (from May through October) as a threshold to calculate growing degree days (GDD), which is a conventional threshold used in many ecological studies, including ones on high-altitude black spruce treeline (Sirois 2000; Sirois et al. 1999). Secondly, we used a paper by Kőrner and Paulsen (2004) that studied altitudinal treelines on a global scale as a reference to define the growing season. This paper looked at two ground temperature thresholds (0 °C and 3.2 °C) at a depth of 10 cm; the justification being that root-zone temperatures are strongly correlated to tree-canopy temperatures, and both are important physiological criteria for trees. The 3.2 °C threshold was the ground temperature in springtime that Kőrner and Paulsen (2004) found best corresponded to a weekly mean canopy temperature of 0 °C.

Humidity measurements at the three climate stations include hourly values of relative humidity (RH), vapor pressure (VP), and vapor pressure deficit (VPD). VPD is an important environmental factor for the exchange of water vapour between plants and the atmosphere. VPD, coupled with temperature, are both good predictors for stomatal conductance to water vapour and net photosynthesis. Stomatal conductance decreases when VPD increases (Dang et al. 1997); in other words, a plant is more water stressed with higher VPD.

Solar flux (i.e. total solar irradiance on a horizontal surface) was measured at both the Upper and Lower climate stations, which allows for a comparison between the two sites of different elevations. A post-field comparison of the two pyranometers used showed systematic differences in hourly flux measurements to be neglible, at less than 0.010 W m^{-2}.

Wind patterns are a contributing factor to an area's climate and ecology, having implications for seed and pollen dispersal, the spread of forest fires, as well as a role in directing evapotranspiration. The MM study site anemometer was placed at the Base climate station and has been recording wind speed and direction on an hourly and daily (peak gust) basis since the summer of 2005.

Results

In this section, the results are presented by climatic or bioclimatic parameter and are subsequently further analyzed in the discussion section. This section largely comprises a summary of data collected from field observations.

Air Temperature

Averaged over the 2001-2009 period, mean temperatures for July, consistently the warmest month, were 13.3 °C and 10.2 °C, respectively from the Lower (570 m), and Upper (995 m) climate stations. Over the 8 years of data collected from a full July record, there is a positive linear trend in temperature (Figure 3.4), however it is noted that this length of record is too short to determine a conclusive warming trend and natural climate variability could be a part of this. It is of note that there has been a regional pattern of warming coming out of the late 20th century and into the present period. For their Northeastern Forest ecoregion, which includes southcentral Labrador, Environment Canada has reported an increase in mean annual temperature of 0.8 °C from 1948 to the present (Environment Canada 2010). Mean monthly air temperatures are displayed in Figure 3.5.

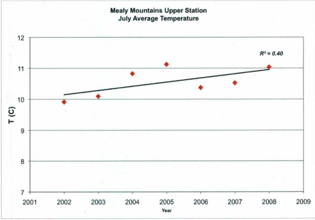


Figure 3.4: July temperature trend from Upper Station (2002 – 2008).

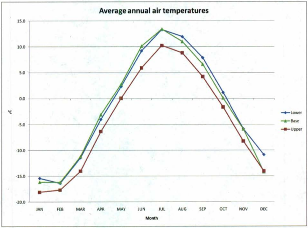


Figure 3.5: Mean Monthly Air Temperatures (2001 to 2006), Mealy Mountains study area.

The freeze-thaw of air temperatures were calculated and compared for the three climate stations (Figure 3.6). The Base station experiences more FT cycles in the early spring than the Upper site, which is expected as it would remain colder (below 0 °C) longer at higher elevation. The Upper site also experiences more cycles into the summer than both the Lower and Base sites, which is indicative of warmer temperatures reaching the summit later in the year; only the Upper site had FT cycles in July, and only one such event was observed in August.

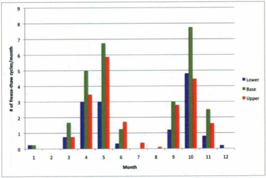


Figure 3.6: Yearly average of freeze-thaw cycles compared across the three stations. Lower and Base have 4 years of data, and the Upper station has 7 years.

The average yearly elevational gradient of surface air temperature (SAT), calculated using daily data, was -0.51 °C/100 m (range -0.24 to -0.65 °C/100m, with a standard deviation of 0.12 °C/100m) reported in Table 3.5, and displayed in Figure 3.7.

Table 3.5: Monthly averages of elevational gradients (°C/100 m), for maximum (LR_TX), minimum (LR_TN) and average (LR_TAVG) temperatures between the Upper and Base sites, 2005 – 2009.

MONTH	LR_TX	LR_TN	LR_TAVG
1	-0.30	-0.12	-0.24
2	-0.43	-0.29	-0.39
3	-0.57	-0.41	-0.49
4	-0.77	-0.45	-0.56
5	-0.73	-0.37	-0.56
6	-0.74	-0.38	-0.57
7	-0.73	-0.38	-0.62
8	-0.76	-0.40	-0.61
9	-0.78	-0.46	-0.65
10	-0.58	-0.46	-0.55
11	-0.48	-0.40	-0.48
12	-0.41	-0.28	-0.40
ANNUAL	-0.61	-0.37	-0.51
St.Dev	0.17	0.097	0.12

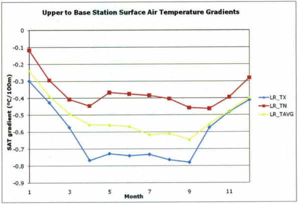


Figure 3.7: Elevational gradient of SAT for minimum (LR_TN), maximum (LR_TX) and average (LR_AVG) temperatures between Upper and Base Stations, 2005-2008.

Ground Temperatures

Summary data is presented in Table 3.6 for the average yearly ground temperatures for full-year records. As expected, the Lower site has a higher average temperature (0.2 °C) than the Upper (-1.8 °C). The Upper site recorded the lowest average ground temperature at -1.1 °C, whereas the others averaged above freezing. Figure 3.8 presents the record of the Base ground temperature data (2006-9), displaying minimum, maximum and average temperatures by depth. Here, the expected pattern of ground temperature variability and amplitude is observed, with the deepest ground temperature being the least variable (i.e. it is the warmest of the three when the air temperature is lowest, and the coldest when the air temperature is highest in summer).

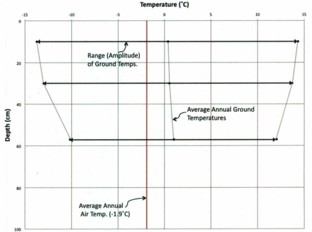


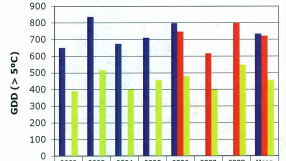
Figure 3.8: Average, minimum and maximum ground temperatures from three thermistors at the Base station (2006 – 2009).

Table 3.6: Summary of ground temperature data for entire length of climate station records.

Site	# of yrs.	Avg. air temp. (°C)	Avg. ground temp. (°C)
Lower (2002-06)	5	-0.6	0.2
Base (2006-08) 0.57 m	3	-2	1.0
Base (2006-08) 0.3 m	3	-2	0.5
Base (2006-08) 0.1 m	3	-2	0.4
Upper (2002-08)	7	-4.2	-1.8

Growing Season and Growing Degree-days

Using the conventional growing degree days calculated for days of mean daily temperatures above 5 °C, the results are reported in Figure 3.9 for the three climate stations. The mean annual GDD values for the years on record are 732.7, 719.9 and 454.8, respectively from low to high elevation. The Lower to Upper growing season temperatures (June – September; months with a significant number of GDD) are on average 10.6 °C, 10.3 °C and 7.3 °C. The warmest monthly temperatures are consistently recorded in July, and are on average 13.3 °C, 13.4 °C and 10.2 °C from Lower to Upper. The start and end dates of the growing season, as defined by Kőrner's thresholds presented earlier, are presented in Table 3.7.



	2002	2003	2004	2005	2006	2007	2008	Mean
Lower	648.7	835.7	673.5	708.2	797.5			732.7
Base					746.2	616.2	797.2	719.9
Upper	390	514.2	398.3	455.9	477.7	400.4	547.3	454.8

Figure 3.9: Growing Degree Days record for Lower, Base and Upper sites.

Table 3.7: Growing season start/end dates for Forest/Transition and Tundra zones, using Kőrner and Paulsen's 3.2 °C ground temperature threshold. Significant difference between the zones found for the end of the growing season, but not for the beginning.

	Forest/Transition	Tundra
Start	20-Jun	15-Jun
End	09-Oct	28-Sep

Precipitation

Precipitation at the study site is quite variable, both between the Upper and Lower stations, where bulk rain gauges record annual precipitation, and also between the years of data collection (Table 3.8). The yearly record ranges from 954 – 4293 mm per year.

Table 3.8: Precipitation bulk gauge record for the Lower and Upper sites (measurement units are in mm).

Year	Lower	Upper
2001-02	n.d.	n.d.
2002-03	2272	2367
2003-04	2214	2181
2004-05	3654	1413
2005-06	3312	954
2006-07	4293	1008
2007-08	3843	1872
2008-09	3447	1116

Data collected from the snow surveys show that mean snow depth varied over the two years from a minimum of 37.6 cm at an area of krummholz 600 m.a.s.l., to a maximum of 223.4 cm at the Lower Climate Station site (Figure 3.10). The snowpack density shows less variability between and within sites than for snow depth (Figure 3.11). It is lowest in forested areas, and slightly higher in exposed areas, such as the Base Camp and Upper Climate Station sites. It is also noted that between the two sampling years, there is not much of a difference, with an average density of 0.38 and 0.42 kg/L, and standard deviations of 0.040 and 0.045, in 2008 and 2009 respectively. The snow water equivalent (SWE; Figure 3.12) across the sample sites is quite variable, ranging from 13.6 cm at the krummholz site to 68.4 cm at the Lower Climate Station in 2008.

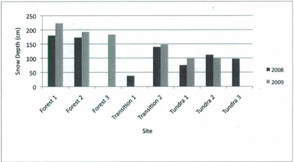


Figure 3.10: Average snow depth for the two years of surveys.

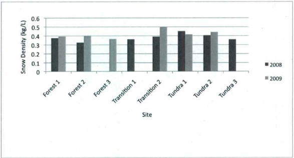


Figure 3.11: Average snow density across sites.

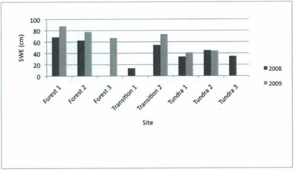


Figure 3.12: Snow Water Equivalent (cm) across sites.

Humidity

The average relative humidity increases with elevation (75, 78 and 88% from Lower to Upper, respectively). At the Upper station, RH was greater than 80% for over 90% of the observations, based on the hourly data (Figure 3.13).

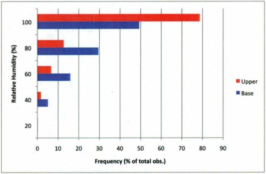


Figure 3.13: Histogram of the frequency distribution of hourly relative humidity observations for daytime hours (0600-1800) at the Base and Upper climate stations in the Mealy Mountains. The mean for the Base is 77.5% (n=35461, s.d.=17.1) and for the Upper station is 88.3% (n=61394, s.d.=16.0).

Figure 3.14 displays the average monthly VPDs as well as the monthly average temperatures. The month with the highest VPD is July (mean VPD of 0.496 kPa), which is also the warmest month.

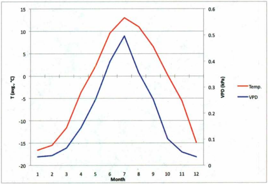


Figure 3.14: Vapor Pressure Deficit at Base Climate Station, monthly average from 2005-2009 (blue), with average monthly temperatures for the same period (red).

Solar Radiation

Annually, the Lower site receives significantly more solar radiation than the Upper site (Student's t-test, $p \leq 0.000$), with the difference more noted from February to April (Figure 3.15). The average bright sunshine hours for the growing period (June – Sept.) was compared for the Lower and Upper stations (using the WMO threshold for bright sunshine of 0.12 kW/m^2), and the results are displayed in Table 3.7. There are no observed significant differences between the two sites for the number of bright sunshine hours.

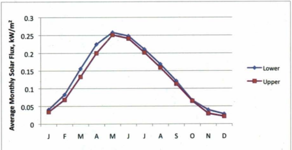


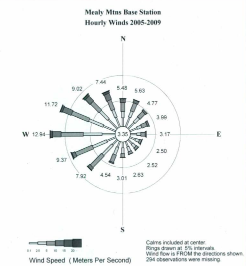
Figure 3.15: Average monthly solar radiation at Lower and Upper sites (2001-2006). The Lower site, an annual basis, receives close to 9% more solar radiation than the Upper site.

Table 3.9: Bright sunshine data (in kW/m^2) for Lower and Upper stations for May – Sept.

	Lower	Upper
	average/hr	average/hr
2002	0.42	0.43
2003	0.45	0.44
2004	0.41	0.41
2005	0.46	0.44
2006	0.43	0.44
Average	0.434	0.432
St. Dev.	0.0	0.0

Wind Speed and Direction

Figure 3.16 shows the monthly average speeds over the four years of data (2005 – 2009). On an annual basis, the prevailing winds are clearly westerlies, with more than 40% coming from the westerly quadrant with speed most frequently in the range 5 to 10 m/s. Figure 3.17 shows the windrose for daytime and nighttime hours, where the daytime was defined as 0600 to 1800 hrs. Though the prevailing directions are quite similar, the nighttime hours see slightly stronger winds with a more northerly component. Wind speeds are lower in the summer months consistently by about 5 m/s, and start to increase in speed at the beginning of autumn (Figure 3.18). Seasonal plots (Figure 3.19) show a slight increase in frequency of northerly through northeasterly easterly winds in winter and spring.



PERCENT OCCURRENCE: Wind Speed (Meters Per Second)
LOWER BOUND OF CATEGORY

DIR	0.1	2.5	5	10	15	20
N	1.69	1.22	1.75	0.70	0.11	0.01
NNE	2.07	1.25	1.68	0.55	0.08	0.00
NE	1.67	1.28	1.43	0.37	0.02	0.00
ENE	1.54	0.94	1.11	0.38	0.02	0.01
E	1.27	0.80	0.86	0.22	0.03	0.00
ESE	1.19	0.77	0.42	0.11	0.01	0.00
SE	1.11	0.86	0.48	0.07	0.00	0.00
SSE	1.12	0.96	0.50	0.06	0.00	0.00

TOTAL OBS = 35438 MISSING OBS = 294

PERCENT OCCURRENCE: Wind Speed (Meters Per Second)
LOWER BOUND OF CATEGORY

DIR	0.1	2.5	5	10	15	20
S	1.13	1.11	0.73	0.04	0.00	0.00
SSW	1.19	1.56	1.52	0.26	0.00	0.00
SW	1.38	2.68	3.18	0.58	0.09	0.00
WSW	1.90	3.01	3.63	0.65	0.16	0.02
W	2.61	3.72	4.42	1.65	0.50	0.05
WNW	2.68	3.04	3.66	1.86	0.43	0.05
NW	2.57	2.23	2.40	1.33	0.39	0.10
NNW	2.03	1.55	2.04	1.31	0.42	0.08

CALM OBS = 1188 PERCENT CALM = 3.35

Figure 3.16: Windrose and frequency table for annual hourly winds, 2005-2009. (UAI Environmental software used for above). Wind direction refers to the direction the wind is from. Frequency of calms is shown in the centre.

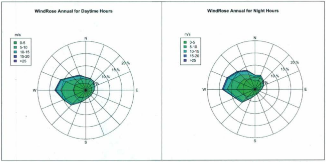


Figure 3.17: Windroses (in polar diagram form) for Daytime (left) and Nighttime (right) hours, for all months of the year. ('R' Project for Statistical Computing used for this figure).

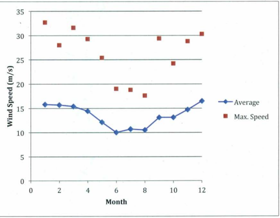


Figure 3.18: Average monthly wind speed and maximum gusts over the period 2005-2009.

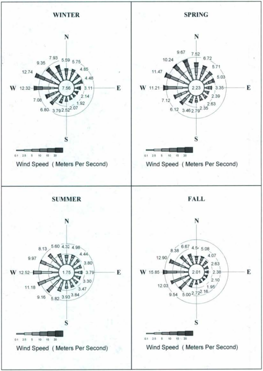


Figure 3.19: Seasonal windroses for hourly winds (2005-2009).

Discussion

Previous studies have explored the extent of the relationship between growing season (or July) temperatures and the altitudinal treeline (e.g. Grace et al. 2002), and how past changes in climate regimes have affected the location of the treeline. The relationships explored in this study have shown that indicators and conditions commonly used to evaluate the location of the treeline are experienced in this Mealy Mountains study.

Steeper temperature elevational gradients (as in greater decreases in temperature with elevation) occurred in summer months, especially for maximum temperatures, and were also more variable than winter monthly gradients. As Figure 3.7 demonstrates, there is a distinct seasonality of maximum, minimum and average monthly elevational SAT gradients. The more variable pattern of minimum temperature gradients, with the notable dip in the spring, is consistent with nighttime inversions (positive temperature change with altitude), which often occur after warm, clear-sky days during the summer and fall (Blandford et al. 2008).

Though the lower site saw warmer ground temperatures than the Upper, this elevational relationship is not found between the Lower and the Base site's data, where the Base's deepest thermistor (at 0.57 m) saw an average of 1.0 °C, almost a full degree higher than what was recorded at 0.7 m of depth at a slightly lower altitude. As the length of the full records is variable, we turn to look at a year where all three stations overlap with quality data (2005-6) to further compare. Still, the Base site recorded slightly warmer ground temperatures than at the Lower site, although with a colder average air temperature. This discrepancy may be due to two factors. Firstly, the thermistors might be buried in different substrates in which the conductance of heat might be different, and secondly, the different snow coverage patterns would affect the ground temperature regimes.

We can infer from the average temperatures that the Upper site is in an area of sporadic permafrost, with mean air and ground temperatures below 0 °C. The Base site air temperature roughly corresponds to a commonly used threshold of mean annual air temperature of -1.0 °C used to infer the presence of permafrost (Smith and Riseborough 2002). At the Lower site, though the mean annual air temperature is just slightly below freezing, the ground at 0.7 m of depth is well below 0 °C for much of the year, with a DJF average of -7.4 °C, and MAM average of -3.8 °C. As seen in previous maps of permafrost distribution (Rekacewicz 2005; Smith and Riseborough 2002), the data we have collected corresponds to sporadic, or sporadic discontinuous permafrost for our study site.

Soil temperatures, especially in the root-zone, have phenological implications for tree growth and development (Cheng 2009; Repo et al. 2004), and when they decrease to a certain (cold) threshold may limit important physiological processes and therefore the establishment of trees. Cheng (2009) found that the average low soil temperature threshold for most physiological processes in black spruce trees to be 14.0 °C. The June - August average ground temperature at 10 cm depth (i.e. in the root-zone) is 12.5 °C, slightly cooler than the threshold Cheng concluded to be phenologically significant.

At 10 cm depth, the ground sees both the coldest temperatures (December – February) and the warmest (June – August; Figure 8). This is expected as the amplitude of ground temperatures at the surface is comparable to that of the surface air temperature.

The deepest thermistor, at 57 cm, is the least variable in its ground temperature over the course of the year, which is also expected as the effects of solar radiation warming the ground decrease with depth.

As presented in the results, growing seasons differed significantly depending on elevation at the study site. These seasonal temperatures, however, were consistent with what Kőrner and Paulsen (2004) presented as correlating with treeline position, at around 5 to 6 °C. Between the Lower and Upper sites, there are significant differences in GDDs (independent sample t-test, $t = 19.25$, $df = 4$, $p<0.00$). This is not unexpected given the over 400 m difference in altitude and the vegetation differences between sites. At the two subarctic (Scandinavia) sites in Kőrner and Paulsen's study, average GDDs were reported to be 169 – 181, which is well below the number of GDD calculated for all three MM sites.

Kőrner and Paulsen (2004) defined the growing season length by the number of days that have an average ground temperature above 3.2 °C. They found the seasons to be 102 and 106 days long for their northern subarctic sites. Using these same parameters for defining and calculating the season length based on 10 cm depth ground temperature, the MM Base station season average was calculated to be 145 (s.d.=17) days. For the 975 m tundra site in the Mealy Mountains, the length of the 2008 season (the only complete year of 10 cm ground temperature data we collected from the temporary installation of ground loggers), which was a typical year in our overall record, was found to be 110 days. This is slightly above what Kőrner and Paulsen reported, but over a month shorter than what was found at the Base site. While they conclude that season length is not significantly correlated to global treeline positions, their meta-analysis did not show season lengths shorter than three months.

Other studies (Bunn et al. 2007) have found growing seasons in the northern boreal forests lasting from May to August using NDVI data for photosynthetic activity. Our results in comparison to these two referenced papers indicate that at least the Base station, located at the upper limit of the transition zone and 200 m below the highest found conifer, has an adequately long season to support tree growth. In our study area, the presence of isolated small erect conifers up to 200 m above the nominal 600 m a.s.l. forest limit indicates a somewhat extended forest-tundra transition zone, likely a result of microclimatic variability not captured by the three stations. In terms of summer temperatures, GDDs, and growing season length, the upper climate station record defines a distinct break with conditions in the transition zone below. Finally, the observed absence of any conifers above ca. 800 m is evidence that the long-term climate at the Upper station site has been too severe to support tree species. However that said, the growing season temperatures of the most recent decade are not outside the limits for tree growth, as indicated by previous studies of alpine treelines.

Based on our climate station records, there are no significant differences between the forest transition zone, represented by the two lower stations, and the tundra for the starting date of the growing season (when the temperatures go over the 3.2 °C threshold). However, there are significant differences for the date of the end of the growing seasons between the forest transition and tundra, defined as when the ground temperatures go below 3.2 °C (t-test: $p < 0.001$). Given the temperature-elevation relationship, it would be expected that the growing season would begin later in the year at higher altitudes.

However, when one takes into account other physical features of the area, there are reasons that can explain this. For example, the tundra site is more wind blown, therefore the snow is blown off the ground surface may have an earlier exposure to solar heating. Based on three years of late winter visits, we would expect both the base and upper sites to be exposed at similar times. Site visits indicate considerable variability at both sites, and a tendency for snow to be blown off at the upper site. The June air temperatures for the start of the growing season, on the other hand, do indicate that there is a significant difference between the two zones (the Base 2007 - 2009 average is 8.9 °C, whereas the Upper average is 6.9 °C).

As it is difficult to accurately record precipitation amounts at a remote study site that is typically only visited in the summer, the most accurate precipitation observations occur over the field season. With these daily observations, comparisons and relationships can be drawn from Goose Bay and Cartwright, which both have Environment Canada stations recording precipitation. Table 3.10 compares the summer precipitation of the MM with Goose Bay and Cartwright. As Figure 3.20 demonstrates, there are some precipitation events in the Mealys that are comparable to those in Goose Bay and Cartwright, however this is not always the case.

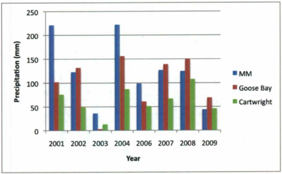


Figure 3.20: Rainfall record comparison for summer field observations (no data collected from 2005). The field observations from the Mealy Mountains (blue) are compared to Environment Canada's record in Goose Bay (red) and Cartwright (green).

Table 3.10: Mealy Mountain summer precipitation observations compared to those from Goose Bay and Cartwright (2001 - 2009).

	Goose Bay	Cartwright	Both
Simultaneous events with MM	75	65	55
Correlation (r), all observations (n = 191)	0.2	0.4	
Correlation (r), events >1mm only	-0.02	0.24	
Precipitation Ratio Average (MM:Site)	2.6	2.1	

To examine the extent of the relationship between precipitation across the three sites, an analysis comparing these locations was performed for the eight years of summer observations that were collected, which amounted to 191 total daily observations. Precipitation ratios were calculated for the summer field season observation period (Figure 3.21). For the eight year record, the ratio of precipitation for the MM to Goose

Bay (1.2 for all observations) is generally lower than for that of the MM to Cartwright (2.0), with 2003 being an anomaly with a ratio of 12 for MM:Goose Bay. This very high ratio is likely explained by a single rainfall event of 33 mm observed in the Mealy Mountains, at which time 2 mm was recorded in Goose Bay.

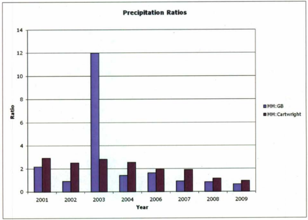


Figure 3.21: Summer precipitation ratios (MM – Mealy Mountains, GB – Goose Bay) for the observed field season record to the Environment Canada records, 2001 – 2009. Mean MM:GB ratio is 2.6 (s.d. = 3.8) and 2.1 (s.d. = 0.7) for MM:Cartwright.

The bulk precipitation gauge records from the Lower and Upper sites were also compared to the corresponding records of total annual precipitation at Goose Bay and Cartwright (Figure 3.22). As previously stated, the Lower site recorded on average significantly more precipitation than the Upper site, while both of the MM gauges recorded on average more than Goose Bay and Cartwright. Undercatch of precipitation, in particular snowfall, is common due to wind effects (Goodison et al. 1998), thus the bulk gauges undoubtedly underestimate total yearly precipitation. Further, undercatch at the upper station would be greater due to windier conditions at the summit compared with lower in the valley.

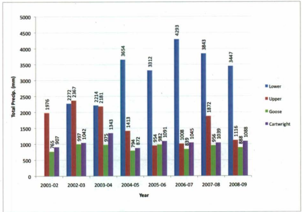


Figure 3.22: Bulk precipitation gauges at Lower and Upper sites compared to corresponding annual totals of precipitation from Goose Bay and Cartwright. A leak was found at the Lower site in the summer of 2002 resulting in loss of data for that year. Mean annual values (excluding Lower 2001-02 data) are 3291 mm for Lower, 1611 mm for Upper, 900 mm for Goose Bay and 1053 mm for Cartwright.

In both years, the Lower Climate Station site recorded the greatest snow depth of all sites surveyed. The snow depth between sites is quite variable (Figure 3.10), with a high standard deviation of 47.4 and 48.3 cm for 2008 and 2009, respectively. For a site such as the krummholz one, with an average depth of 37.6 cm and a standard deviation of

37.0, this is indicative of the high variability of snow cover, and of the topographic and vegetation influence on collection of snow. The snow maps (Environment Canada 2010), which are based on coarse scale satellite data, show that in the central Mealy Mountains area for the corresponding dates of the survey there was an approximate depth of 100 cm for both 2008 and 2009, with a maximum depth reading of 212 cm.

A high level of variability while measuring snow is expected due to the differences between sites, such as exposed versus forested areas, and also due to snow drifts caused by wind. The large variability in snow depth, a factor that influences vegetation, can be attributed to these topographic and site factors, as well as random sampling. Over the two-year period of data collection, the level of inter-annual difference is to be expected with a broad range of vegetation cover and density at the study site. Comparing the snow survey data with the Environment Canada maps indicates that the maps give a minimum indication of snow depth, but fail to capture the variability of a region, especially at their coarse scale of 1 km^2 resolution. It is worth noting, however, that the 2009 maximum depth of 212 cm for the period of the snow survey found on the map is within comparable range to the maximum survey depth of 223 cm, though the precise location of the map's maximum is difficult to determine.

The observed increase of RH with elevation, as presented in the results, can be attributed to more frequent cloud cover and fog with altitude, as confirmed by observations during the field season, when frequently the summit of the valley is under cloud or fog. Higher levels of VPD are seen during the summer months; there is a clear correlation between monthly average temperatures and VPD (Figure 3.14). A number of studies have looked at VPD and its effects on black and white spruce. Pepin et al (2002) found that when VPD went from 0.75 to 4.0 kPa, stomatal conductance decreased by 40%. Further, Dang et al. (Dang et al. 1997) found that net photosynthesis decreased by 18% in black spruce when VPD was at 2.0 kPa compared to 1.0 kPa. At the Base Station, the JJA average over four summers of records is 0.417 kPa and looking at the frequency distribution of hourly summer VPD values, 87% of the readings fall between 0 and 0.5 kPa. (Figure 3.23); these results are indicative of a low moisture deficit and therefore not a limiting stress for black spruce. From the five years of record at the Base site (2005 – 2009), there is not much variability observed in July VPD (average = 0.5 kPa, st. dev. = 0.04), which is the month that sees the highest VPD. Further, only six days over the five summers had VPD events that were greater than 2.0 kPa, all which occurred in the mid-afternoon and none of which occurred one after the other. These results indicate that in our years of data collection there has not been a summer that has been subject to moisture stress.

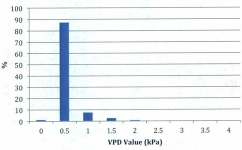


Figure 3.23: Vapor Pressure Deficit frequency distribution of summer (JJA) hourly data (2005-2009).

Another indication of the summit being under more frequent cloud cover than lower down in the valley is the fact that annually the Lower site sees less solar radiation than the Upper site. A study in the Appalachian mountains by Markus et al. (1991) found that elevations between 900 – 1300 m asl were more likely to experience low-level cloud cover than elevations higher or lower than this range. Although in a different region, this finding fits with the pattern in the Mealy Mountains. On the other hand, the bright sunshine data show that the summer months (May – Sept.) see a similar amount of solar radiation between the Upper and Lower site.

Although there is no general altitude-wind relationship that is directly known to be ecologically relevant (Kőrner 2007), wind is still an important factor that may affect the location of the treeline or stands of trees (Richardson et al. 2004). From the Base station anemometer, the diurnal variation of wind speed and direction is not significant (see Figure 3.17); the night hours see slightly stronger winds from a more northerly direction, but overall these periods are both dominated by westerlies. The slight diurnal pattern is in agreement with the valley wind theory, which predicts more downslope winds at night (katabatic), and upslope during the day when a positive radiation balance is more likely. Though the maximum recorded gusts do not show the same smooth pattern as average speeds, the three lowest data points are also found in the summer months. Winter and spring have their prevailing winds coming from the W and WNW, whereas the summer and fall have more W-SW prevailing winds. The changes in direction over the course of the year suggest that the topography does not play a dominating role in determining the surface winds, despite the data being collected in a valley.

Conclusion

The vegetation, location and topography of the subarctic Mealy Mountains, Labrador, provide a good opportunity to study relationships between climate and distinct ecosystems, which are susceptible to change with a shift in the current climate regime. Although the Mealy Mountains are a relatively low-lying mountain range, their location, vegetation and topographical features offer a desirable site for long-term ecological monitoring as well as for studies that link the physical with the biological.

This paper presented a synthesis of the climate data that has been collected over several years of fieldwork, and in doing so provides a general description of the current state of the climate for ecological monitoring purposes as well as supplement the many biological studies ongoing at the same site. Further, in combining knowledge of the physical limitations of treelines, specifically for spruce species, we were able to determine that the Mealy Mountains treeline is not immediately limited by the region's current climate regime. This is apparent in the length of the growing season that Moraine Valley has, growing season temperatures, as well as in bioclimatic indicators such as vapour pressure deficit, which is not a limiting factor for spruce trees at this site. Previous studies have indicated that the treeline is fairly dynamic in that it can respond to a shift in climate fairly rapidly in terms of recruitment and establishment, and further, that increasing the length of the growing season, moister conditions and warmer temperatures are all factors that can contribute to the advancement of a treeline (MacDonald et al. 2008).

From a climatic perspective, the altitudinal treeline of Moraine Valley is not limited by the current climate regime, though it may be lagging when considering the recent warming of the late 20^{th} century and into the 21^{st}. That is to say, the climate of the Mealy Mountains described by this analysis reflects conditions that have been warmer than much of the previous century. To make predictions for the future changes in the treeline, a comprehensive understanding of the biological limitations of this treeline ecosystem is required in conjunction with the findings of this study.

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Chapter 4: Summary

The objectives of this thesis were to investigate climatological aspects within a larger multidisciplinary study based in the Mealy Mountains. Since 2001, ongoing research at the study site has looked at various ecological and physical features, including treeline ecology, sub-arctic and alpine vegetation, and climate.

The first manuscript investigated a method of regional climate modeling for a data-limited and remote alpine site, using a combination of statistical downscaling for the modeling, as well as multiple regression techniques. The latest available model data (CGCM3) was used for the purpose of statistical downscaling, and two emissions scenarios were modeled this way. The downscaling methodology was successful in reproducing the current and recent past climate regime, which is an indication that the modeling of the future climate, using the same method, is also completed with a similarly high skill level. Three future tri-decade periods were modeled, covering up until the end of the current century. All scenarios point to a greater degree of warming than is predicted by the raw GCM output. This result is in agreement with a number of other regional modeling efforts, especially for high-latitude regions, which conclude that GCMs tend to underestimate the magnitude of future warming.

To further investigate the validity of GCM output for small-scale regional studies, we considered the source of the data that forms the baseline for most modeling efforts. These gridded data sets were compared with observational data for a corresponding time period, and the analysis demonstrates that the gridded data smoothes over the extremes (minimums and maximums). These deviations from actual observations are thus propelled into the future scenarios, and are a shortcoming of low-resolution models for small-scale studies. Despite the discrepancies between gridded data and actual observations, the combined modeling effort (regional downscaling and statistical modeling) produced plausible scenarios, and these results should be more useful to researchers investigating local climate change impacts.

The second manuscript's primary objective was to provide a descriptive climatology of the study site; this was done primarily from observations that were acquired on site. Three automated climate stations collected data across an altitudinal gradient that traversed closed canopy forest to tundra; this approach enabled an examination of various physical factors that have a role in controlling the extend of the different ecozones. This leads to the second objective of the manuscript, which was to provide an analysis of the bioclimatic controls over subarctic-alpine treelines, for black spruce trees in particular. It was concluded that the current state of the climate of the study area and associated variables, including indicators such as ground temperature, the length of the growing season, and moisture stress, pose no significant restraints on tree growth at the coldest (highest in elevation) site, which is above the treeline. Therefore, there must be other environmental or ecological factors, beyond those that were investigated in this paper, that are involved in limiting tree growth beyond the current treeline. Further research might address other factors that may be involved in limiting the establishment of black spruce trees, such as winter icing conditions, which have been noted at the summit of the study site. The substantial presence of krummholz and the scarcity of seedlings are both possible indicators that harsh winter conditions may be connected to the lack of establishment of trees.

Each manuscript has its particular objectives, but they also complement one another. The first explores the application of climate modeling to a regional study, and produces future scenarios for the Mealy Mountains study site. The second paper offers a look at the current climatic environment in relation to an ecological indicator: the altitude of the alpine treeline. Researchers will be able to use the current climatology and its future scenarios for climate change impact assessments of the vegetation and ecology of the site. An increasing interest in climate modeling applications at regional and local scales, especially for northern areas, will likely promote further modeling efforts, as well as collaborative research with ecologists and others with an interest in areas such as the Mealy Mountains.

Appendix

Table 1: The predictors provided by NCEP for this study include 10 atmospheric variables at three different height levels.

Predictor	Nomenclature		
	Surface level	500 hPa	850 hPa
Mean sea level pressure	mslp		
Mean temperature at 2 m	temp		
Specific Humidity	shum	s500	s850
Geopotential Height		p500	p850
Zonal Vorticity	p__u	p5_u	p8_u
Meridional Vorticity	p__v	p5_v	p8_v
Vorticity	p__z	p5_z	p8_z
Wind Direction	p_th	p5th	p8th
Wind Speed	p__f	p5_f	p8_f
Divergence	p_zh	p5zh	p8zh

Tables 2 – 5 present predicted temperature changes for two emission scenarios (A1B and A2; using CGCM3.1 predictors) for Cartwright and Goose Bay. Results are given for the GCM predictions and the statistically downscaled model (SDSM predictions) for comparison. Changes are presented as the difference between the Future period (2050s) and the present climate.

Table 2: Cartwright, GCM predictions.

Future (2050s) - present						
	Mean		Min		Max	
	A1B	A2	A1B	A2	A1B	A2
DJF	-7.7	-8.1	10.4	10.7	5.4	5.6
MAM	3.0	2.6	-1.6	-1.2	-3.9	-3.7
JJA	6.0	5.8	-2.3	-2.4	-8.9	-8.7
SON	-1.6	-1.7	3.6	3.7	0.0	0.1
Annual	0.0	-0.3	2.5	2.7	-1.9	-1.7

Table 3: Cartwright, SDSM predictions.

Future (2050s) - present						
	Mean		Min		Max	
	A1B	A2	A1B	A2	A1B	A2
DJF	8.5	8.1	9.6	9.2	7.5	7.1
MAM	-0.6	-0.2	-0.6	-0.3	-0.2	0.2
JJA	-0.8	-0.8	-0.6	-0.6	-0.7	-0.8
SON	5.5	5.4	5.4	5.3	5.5	5.4
Annual	3.1	3.1	3.4	3.4	3.0	3.0

Table 4: Goose Bay, GCM predictions.

Future (2050s) - present						
	Mean		Min		Max	
	A1B	A2	A1B	A2	A1B	A2
DJF	2.1	2.5	2.2	2.6	1.2	1.5
MAM	-4.0	-3.8	-3.1	-2.8	-3.8	-3.5
JJA	-4.7	-4.5	-3.1	-2.8	-5.2	-4.9
SON	-0.6	-0.4	-0.9	-0.8	-0.9	-0.8
Annual	-1.8	-1.6	-1.3	-1.0	-2.2	-1.9

Table 5: Goose Bay, SDSM predictions.

Future (2050s) - present						
	Mean		Min		Max	
	A1B	A2	A1B	A2	A1B	A2
DJF	5.7	5.3	5.6	5.1	5.2	4.8
MAM	0.9	1.5	2.2	2.6	0.8	1.5
JJA	1.1	1.0	1.3	1.3	1.4	1.2
SON	4.5	4.3	3.1	3.0	5.0	4.7
Annual	3.0	3.0	3.0	3.0	3.1	3.1

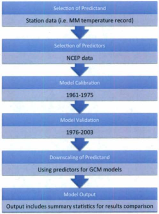

Figure 1: Flow chart of statistical downscaling methodology (Chapter 2).