SPRING DIEBACK OF YELLOW BIRCH IN NORTH AMERICA:

HISTORICAL EXAMINATION OF WEATHER AND FROST HARDINESS

By

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ABSTRACT

Existing process-based models (Birch Dieback Model, ForHyMII) were used to simulate impacts of winter thaws and recurring frost events on shoot and root hardiness, and the potential for frost-induced tissue damage in yellow birch (*Betula alleghaniensis* Britt.). ForHyMII was used to calculate soil moisture, soil temperature and soil frost from daily weather records for air temperature, snow and rain. The Birch Dieback Model was used to track shoot and root hardiness in terms of growing degree-days. Normally, no frost-induced damage should occur when tissue temperatures are higher than the corresponding frost hardiness temperatures. With the dieback model, % tissue damage is related to number of degrees (ºC) that air and soil temperatures drop below the shoot and root hardiness temperatures, respectively.

A *Weather Reader* algorithm was used to analyze daily weather records from all existing Canadian and American weather stations of the study area, from 1930 onward. Specifically, the *Weather Reader* was used to compile daily precipitation and daily minimum, mean and maximum air temperatures, and was used to calculate accumulated degree-days for each event, from start to end. In addition, an annual summary was prepared for each station showing the number of defined thaw events that occurred, and the maximum accumulation of degree-days of the most severe thaw event for each year. The compiled data were mapped to display the geographic patterns of the most severe thaw events, and these maps were then compared with the timing and extent of historically observed birch decline episodes. It was found that the years of 1936, 1944, 1945 and 1981 were particularly anomalous in terms of region-wide winter thaw extremes, and also in terms of observed birch decline events. This coincidence was tested with the Birch Dieback Model, to confirm that tissue damage on account of reduced frost hardiness in root and shoots should have occurrence in the years that dieback was noticed, and to confirmed lack of potential for major frost-induced damage in other years.

Since there are considerable efforts in modeling future weather based on varying climate-change scenarios, it is suggested that the newly developed *Weather Reader* algorithm and the process-based hydrology and frost hardiness models could become important tools to asses the future of yellow birch (and other hardwoods) under various climate change scenarios, over time, and across North America.

Key words: yellow birch (*Betula alleganiensis* Britt), shoot dieback, winter climate, thaw-freeze events, Geographic Information Systems (GIS), geostatistics, freezing injury, process-oriented model, Forest Hydrology Model, Birch Dieback Model.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

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CHAPTER 1

THESIS INTRODUCTION

Dieback of yellow birch (*Betula alleghaniensis* Britt.) and paper birch (*Betula papyrifera* Marsh.) trees has been a problem in eastern North America (Balch 1944; Sinclair 1952; Pomerleau 1953, 1991; Walker et al. 1990; Ward and Stephens 1997). Widespread decline of birch exhibited as branch dieback and mortality was first recorded during the 1930's in central and southern New Brunswick, Canada. Since then, severe birch dieback has been noted from the Maritime region (Pomerleau, 1953) to eastern Ontario (Sinclair 1952; Walker 1990). Birch decline has lead to a 19% loss of the 368 x 10^6 m^3 growing stock of yellow birch in North America (Ward and Stephens 1997). The estimated value of timber volume loss during the 1935-1955 period would be 60 billion dollars (current value), as of 1987 (LRTAP Workshop No.6).

Evidence suggests that mean global surface temperatures have risen by 0.6 ^oC (0.4-0.8 ^oC) during the last century, with a greater increase in winter than in summer (McElroy 1994; IPCC 2001). With General Circulation Models, it has been predicted, that there will be future increases in mean global surface temperatures (1.4 to 5.8 ^oC over the period 1990 to 2100), and that these will be greater within the land masses at northern latitudes. Increased global temperature should lead to longer, more frequent, winter thaws than at present in certain regions such as the Maritimes. This in turn could have a greater effect on forest vegetation than slight changes in mean temperature (Cox and Malcolm 1997). In contrast, increased emissions of particulates from industrial sources may cause atmospheric cooling, thereby offsetting overall warming trends to the same extent (Charlson et al. 1987; Wigley 1989).

Prolonged winter thaws followed by sharp freezing have been recognized as an important mechanism to incite shoot dieback in northern hardwood species (Auclair 1987; Pomerleau 1991; Auclair et al. 1992, 1996, 1997). For example, soil freezing (Hepting 1971), winter root thaw-freeze events and late spring frosts (Braathe 1957, 1995; Auclair et al. 1996; Cox and Malcolm 1997; Zhu et al. 2000, 2001, 2002) have all been found to be inciting factors for dieback in yellow and white birch. Accumulated effects of winter cavitation, - i.e. winter-induced xylem embolism in *Betula papyrifera* var. *cordifolia* Regel Fern (Sperry 1993), *Betula occidentalis* Hook (Sperry et al. 1994) and *Betula alleghaniensis* (Zhu et al. 2000, 2001, 2002a, b) - has also been considered to be a factor in birch dieback due to potential disruption of water transport in affected trees. A field investigation on *Fagus grandifolia* Rhrh. demonstrated that residual winter cavitation causes considerable crown dieback (Sperry 1993).

Winter thaw-freeze cycles have been connected to increases in residual xylem cavitation. For example, potted white and yellow birch subjected to experimentally induced winter thaws showed correlations between branch dieback, relative xylem conductivity (relative to maximum) xylem and thaw durations (Braathe 1995, 1996; Cox and Malcolm 1997; Zhu et al. 2000, 2001, 2002a, b). When xylem sap freezes, dissolved air forms bubbles in the ice. In turn, these bubbles may nucleate cavitation as negative pressure develops in vessels during thawing (Hammel 1967; Sperry and Sullivan 1992; Langan et al. 1997; Robson et al. 1998). Once air bubbles grow large enough and disrupt the cohesion of water, water columns retreat, and vessels become air-filled (embolised) (Tyree and Dixon 1986; Sperry et al. 1988; Jarbeau et al. 1995).

Pomerleau (1991) reported evidence of a link between birch decline and root depth. Trees with diffuse–porous wood anatomy, such as birch, generally refill winter-induced xylem cavitation by generating positive root pressure in spring before leaf-out (Sperry et al. 1987; Hache and Sauter 1996). Sperry et al. (1994) observed that when root pressure in birch was artificially suppressed by overlapping cuts across the stem, existing embolisms were not refilled and shoot dieback was extensive.

The shallow root systems of birch are likely susceptible to thaw-freeze-induced injuries. Such injuries are particularly frequent when snow cover is temporarily lost as a result of extended thaws during winter. The subsequent damage by re-freezing of de-hardened roots was shown to lead to weak root pressure development during the following spring (Cox and Malcolm 1997).

Freezing injury to shoots has been reported to impede the springtime xylem refilling in woody plants (Ameglio et al. 2001) because freezing injuries to parenchyma cells in the xylem of young twigs led to irreversible damage (George and Burke 1986). Cold hardiness of yellow birch has been found to be just sufficient to prevent freezing injuries at normal winter temperatures in the Maritimes (Calme et al. 1994). Any significant reduction in cold hardiness due to increased thaw duration may render yellow birch twigs susceptible to freezing injuries. Mid-winter thaws are common in eastern Canada (Canavan 1996).

In New Brunswick, extensive xylem cavitation was documented in birch with crown dieback (Greenidge 1951), this however, was not attributed to winter thaw-freeze cycles at first. Sperry et al. (1994) determined that, in the two diffuse porous species, more than 90% of vessels have cavitated by the end of the winter. Auclair (1993) noted (i) the long interval between winter embolism formation and the development of symptoms, (ii) high variations in spring refill make it difficult to recognize the cause of dieback.

The continuing increase in greenhouse gas concentration in the atmosphere (mainly CO_2), is expected to result in more frequent winter thaw-freeze cycles and longer thaw duration. Since 1750, atmospheric CO_2 concentration increased by 31 ± 4%. This may exceed the adaptive limits of some northern hardwood species, thereby placing tree species at risk. With the aid of a modeling approach, I aim to assess the magnitude of dieback events in yellow birch and test if dieback relates to differing historical winter climate records. Yellow birch was chosen because it had the highest rate of mortality (Walker et al. 1990) in declining birch stands for the 1930-1960 period.

Objectives

The objectives of this thesis are to:

1. Develop a method to determine to what extent past birch decline events may have been affected by anomalous thaw-freeze events in northeastern North America.
2. Analyze the applicability of this method by comparing historical birch decline events with extent of birch decline as projected with the method, based on past weather records.
3. Demonstrate how this method could be used to assess future occurrence of birch decline in the same region, based on potential climate change scenarios, as afforded by the output of global circulation models.

Specifically, this is done by:

1. Summarizing historical birch dieback chronology and locations in eastern Canada (Chapter 2).

2. Using historical weather data from northeastern North America to develop past patterns of anomalous thaw-freeze events in eastern Canada since 1930 (Chapter 3).

3. Using a forest hydrology model to simulate snow pack depth and soil moisture, soil temperature, and extent of soil frost in the rooting zone of yellow birch, for select years and select locations for which anomalous thaw-freeze events occurred (Chapters 4).

4. Combining the simulated soil temperature output with the systematic assessment of shoot and root frost hardiness in yellow birch, to specifically locate when frost-induced shoot and/or root injuries may have actually occurred for select locations (Chapter 5).

5. Demonstrating how the method can be used to evaluate the recurrence of potential birch decline events for the climate change model for eastern Canada (Canadian Global Coupled Model CGCM1, Chapter 6).

A chapter-by-chapter overview of this Thesis is presented in Figure 1.1.

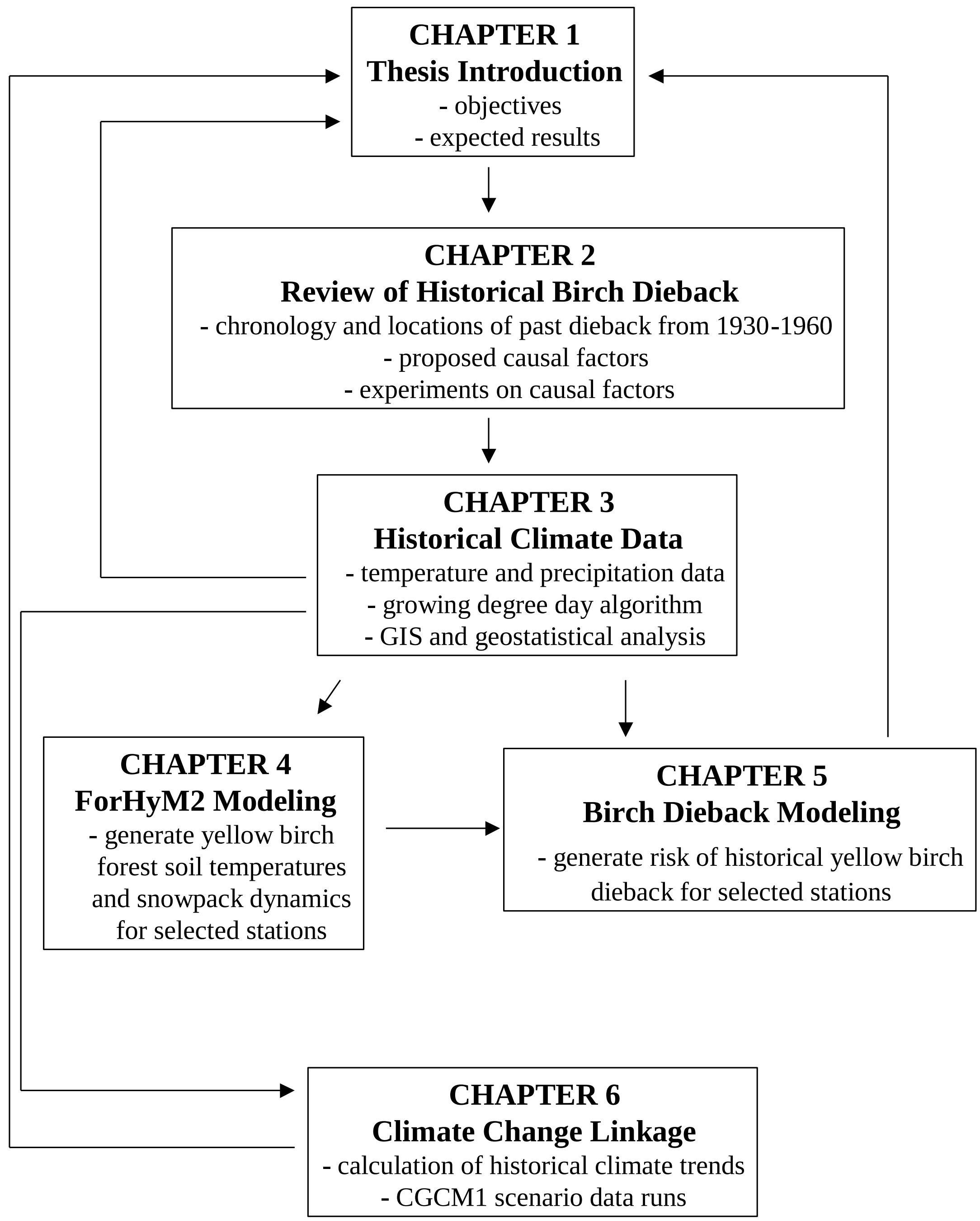


Figure 1.1. Flowchart of thesis outline and modeling efforts.

CHAPTER 2

REVIEW OF YELLOW BIRCH DIEBACK IN EASTERN CANADA FROM 1930-1960

Yellow Birch Habitat

Yellow birch is said to be one of the most valuable of the native birches (Burns and Honkala 1990): it is an important source of hardwood lumber and a good browse plant for deer and moose. Other wildlife feeds on the buds and seeds. In the forest, it is easily recognized by its exfoliating bark with its distinct yellowish-bronze color. The inner bark is aromatic and has a flavor of wintergreen. Yellow birch is generally slow-growing but long-lived, and is usually found in association with other tolerant hardwoods and conifers on moist, well-drained soils.

Native Range

Yellow birch is wide-spread across northeastern North America. In Canada, it occurs in Newfoundland, Nova Scotia, New Brunswick, throughout southern Quebec and Ontario to southeastern Manitoba. In the USA, yellow birch ranges east to west from New England to Minnesota, northeastern Iowa, and east to northern Illinois, Ohio, and from the Canadian border to south in the Appalachian Mountains to eastern Tennessee and northeastern Georgia. In the south, yellow birch generally grows at high elevations, and is restricted to moist gorges above 910 m. The largest concentrations of timber-size yellow birch are found in Quebec, Ontario, Maine, Upper Michigan, New York, and New Brunswick (Quigley and Babcock 1969). About 50 percent of the growing stock of yellow birch in North America is in Quebec.

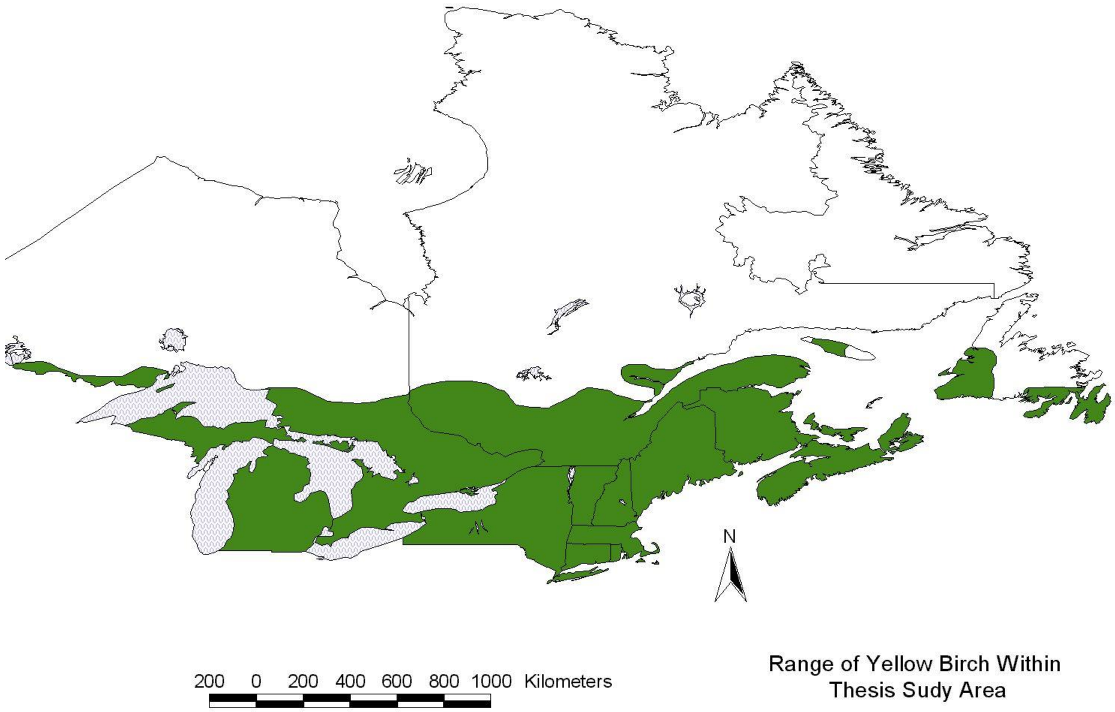


Figure 2.1. Map illustrating native range of yellow birch within study area.

Climate

Yellow birch grows in cool areas with abundant precipitation. Its northern limit coincides with the 2 °C average annual temperature isotherm, and its southern and western limits coincide with the 30 °C maximum temperature isotherm (Dansereau and Pageau 1966). Although the average annual temperature is about 7 °C within its range, temperature extremes range from –40 °C to 38 °C. Annual precipitation ranges from about 1270 mm in the east to 640 mm at its western limit. More than half of the precipitation may be snow. Snowfall ranges from 152 to 356 cm, and averages 229 cm in the north. The growing season ranges from 60 to 150 days and averages about 120 days.

Soils and Topography

Yellow birch grows over a large area with diverse geology, topography, and soil and moisture conditions. It is found on glacial tills, outwash sands, lacustrine deposits, shallow loess deposits, and residual soils derived from sandstone, limestone, and igneous and metamorphic rock (Post et al. 1969). Soils derived from granites, schists, and shales all occur in parts of its range. Growth of yellow birch is affected by soil texture, drainage, rooting depth, stone content in the rooting zone, elevation, aspect, and soil fertility. Yellow birch grows best on well-drained, fertile loams and moderately well-drained sandy loams and on flats and lower slopes (Gilbert 1965). Rootlet development is profuse in loam but poor in sand. In the Lake States, birch grows best on well- and moderately well-drained soils and on lacustrine soils capped with loess. Its growth is poor on poorly-drained lacustrine soils, shallow soils over limestone, and coarse-textured sandy loams without profile development (Post et al. 1969). Site index between the best and poorest sites differs by more than 9 m at 50 years. Although growth is poor on soils with restricted drainage, yellow birch is often abundant on such soils because competition from other species is less severe.

In the Green Mountains of Vermont, birch grows on unstratified glacial till at elevations up to 792 m (Siccama 1974). Thickness of the upper soil horizon - as influenced by elevation and aspect - has been used to estimate the site index of yellow birch. In general, yellow birch was found to grow best at low elevations with northeast aspects.

Associated Forest Cover

Yellow birch is present in all stages of forest succession. Second-growth stands contain about the same proportion (12 %) of birch as virgin stands. Yellow birch is usually found singly or in small groups in mixtures with other species. Since yellow birch is seldom found in pure stands, it is generally not recognized as a separate stand type. Instead, yellow birch is a major component of three forest cover types: (1) Hemlock-Yellow Birch, (2) Sugar Maple-Beech-Yellow Birch, and (3) Red Spruce-Yellow Birch (Eyre, 1980). Hemlock-Yellow Birch is considered a long-lasting sub-climax type. On moist sites, Red Spruce-Yellow Birch is the climax type (Kujawski and Lemon 1969).

Chronology and Locations of Past Yellow Birch Dieback 1930-1960

Dieback on yellow birch in the 1930's and 1940's was spectacular in rapidity and severity when compared to that of any other eastern hardwood species (Sinclair et al. 1987). Figure 2.2 illustrates a generalized summary of incidence and severity of dieback in eastern Canada, having an "active" phase from 1937 to 1949, and a "latent" phase from 1950-1960 (Auclair 1987). Historical observations are anecdotal, but still provide the best available information on birch dieback.

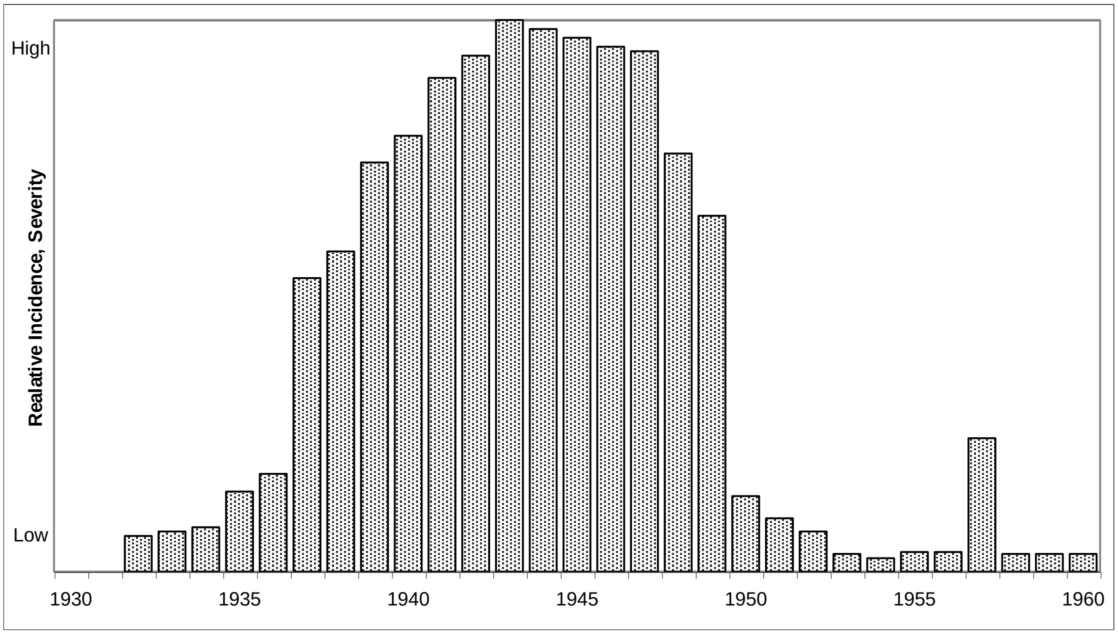


Figure 2.2. The relative incidence/severity of crown dieback of yellow and white birch in northern hardwoods of eastern Canada (after Auclair 1987, Auclair et al. 1997).

Dieback in yellow birch was first observed between 1932 and 1935 in central and southern New Brunswick, although there had been a downward trend in radial increment since 1925 (Balch 1953; Hawbolt and Skolko 1948). Ten percent of birches were reported dead or dying in 1938, and by 1940, 25% mortality was reported in central and southern New Brunswick. At this time, no important damage was found in the northern part of the province (Balch 1953). Fifty to 90% of birches were reported dead or dying in southern New Brunswick by 1943, and dieback had increased in northern New Brunswick (Canadian Forestry Service 1943). The following year, 75% of birches were reported dead or dying in northern New Brunswick. The dieback was widespread in Cumberland and Colchester and noticeable in Pictou County, Nova Scotia (Balch 1944; Canadian Forestry Service 1944).

In 1946, although 48 to 91% of birch were dead or dying throughout New Brunswick, there was some indication that the rate of dieback was decreasing (Canadian Forestry Service 1946). In Nova Scotia, dieback on birch was heavy to severe in Colchester and Cumberland and negligible to moderate elsewhere (Canadian Forestry Service 1946). Dieback on yellow birch was common in 1944. By 1946, many stands reached an advanced stage of dieback, becoming severe by 1947 (Balch 1944; Canadian Forestry Service 1946, 1947). Light dieback was reported on Cape Breton Island in 1947 (Canadian Forestry Service 1947). This dieback of yellow birch became progressively more severe in 1949 and 1950, but was less evident by 1952 (Canadian Forestry Service 1949, 1950, 1952). Lightly injured trees continued to show signs of improvement in New Brunswick, but injury was still moderate to severe in Nova Scotia in 1947 (Canadian Forestry Service 1947). This recovery of birch continued from 1949 through 1952 (Canadian Forestry Service 1949, 1950, 1951, 1952). By 1950, an improvement of less severely injured trees was also reported in Nova Scotia, continuing until 1952 (Canadian Forestry Service 1950, 1951, 1952). Trees in some localities in the Maritimes were still reported suffering in 1954. There were no reports of yellow birch dieback in the Maritimes from 1954 to 1960 (Canadian Forestry Service, 1954).

Yellow birch dieback in Quebec was first observed in the late 1930's. Pomerleau (1953) reported on yellow birch dieback at St. Donat, North of Montreal in 1937, Davidault (1953) first noted dieback in the Matapedia Valley of the Gaspé region in 1939. Between 1940 and 1942, dieback was found in most inhabited areas of Quebec (Canadian Forestry Service 1951; Pomerleau 1953). During 1943-1944, dieback was well distributed south of the St. Lawrence River east of Rimouski and north of the St. Lawrence River in the Laurentide Park (Davidault 1953). By 1945, birch dieback was found as far west as the St. Maurice Valley (Canadian Forestry Service 1945). In 1946, dieback was reported north of Montreal, in the Gatineau, and at St. Maurice. Improvements were first reported from the Gaspé region at Matapedia (Canadian Forestry Service 1946). By 1947, almost all merchantable birch were dead or dying in the area east of Rimouski. Young trees however, not too severely affected, were regaining vigor (Canadian Forestry Service 1948, 1949, 1950). In the Lake St. John Districts, 4% of trees improved from 1948 to 1951, but dieback continued to progress on 85% of the trees (Martineau 1953). The percentage of trees with injured crowns decreased from 40% in 1950 to 30% in 1952. Signs of improvement of birch were observed before two seasons of hot weather in 1951 and 1952. Thereafter, renewed decline was noted in northern forests (Canadian Forestry Service 1954). Similarly, renewed decline developed after two months of dry, hot weather in 1955 (Canadian Forestry Service 1955). No appreciable change was noted in 1956, but improvements were noted in 1957, except in Abitibi County, where crown deterioration had increased since 1954 (Canadian Forestry Service 1956, 1957). By 1958, the health of yellow birch in Quebec was very good except for a new case of decline in Montmorency County that began in 1956 (Canadian Forestry Service 1958).

Dieback was last reported in Quebec in 1981 (Benoit et al. 1981). Figure 2.3 illustrates that an anomalous winter thaw and a late spring frost occurred in Southern Quebec in that year, within the region of decline (Lennoxville, QC, 7024280).

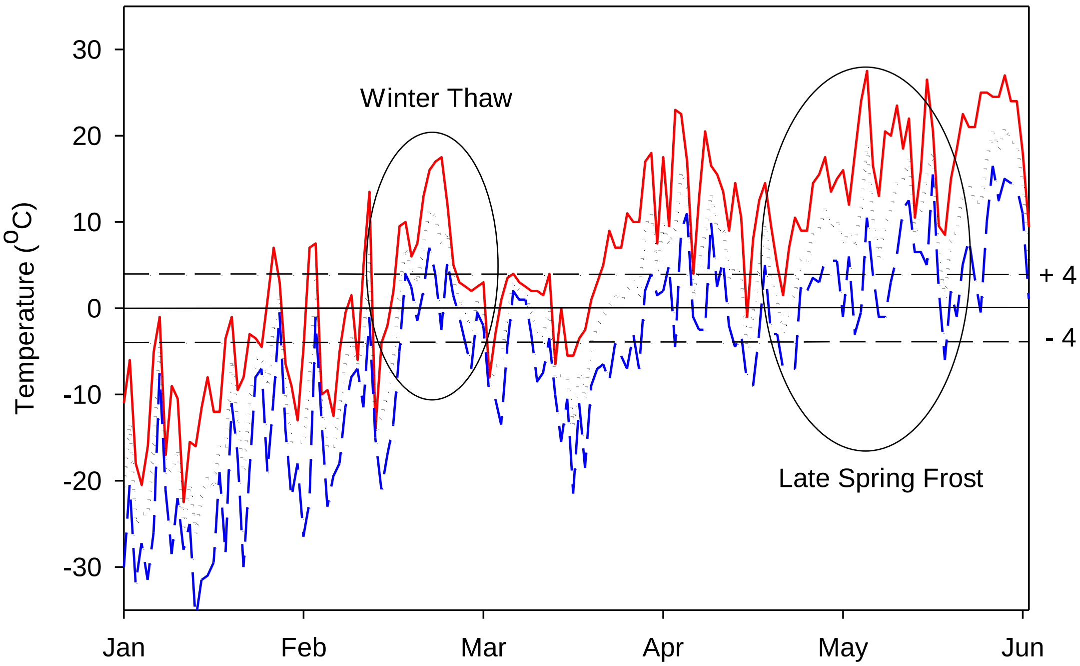


Figure 2.3. Air temperature time series for Lennoxville, QC showing maximum (solid red), mean (black dots) and minimum (blue dashed) daily air temperatures for the winter and spring of 1981. The winter thaw should contribute to an early de-hardening process and increased xylem cavitation. The late spring frost should contribute to tree injuries directly.

Dieback of yellow birch in Ontario had occurred since at least 1944. In that year, dieback was reported in eastern Ontario, and light to moderate dieback levels were found in the Algonquin, Haliburton, and Huron regions (Canadian Forestry Service 1944). From 1947 to 1951, Sinclair and Hill (1953) reported that the condition of birch was serious, but the rate of deterioration decreased, and the condition of some trees was improving. Between 1948 and 1952, only 13% of trees examined showed decline in crown condition of some trees. The bulk of this decline was either light or moderate. Mortality was minor (Sinclair 1952). The average rate of decline over the 1950-1952 period was not serious (Canadian Forestry Service 1953). Data from an Ontario survey, for 1949-1954, did not show wide variations in severity of damage. Also, an increase in the number of trees showing either a cessation of decline or an improvement in crown condition was found (Hill and Sinclair 1954). Decline was more apparent during the 1953-1955 period than the 1951-1953 period in the Sault Ste. Marie, North Bay, Parry Sound, Lake Simcoe and Lake Erie Districts (Canadian Forestry Service 1957). A map adapted from Auclair (1987) in Braathe (1995), shows the observed accumulated dieback for the 1930 to1960 period (Figure 2.4).

Sugar maple showed a slight decline during the 1930 to1960 period, but this decline was less marked than what occurs with yellow birch. Pomerleau (1953) mentioned that the sugar maple decline had continuously increased in intensity on birch since about 1937, but was highest from 1940 to 1950. From 1946 to 1949, beech, maple, elm, cherry and poplar were similarly damaged. Even conifers were affected, although at a reduced level.

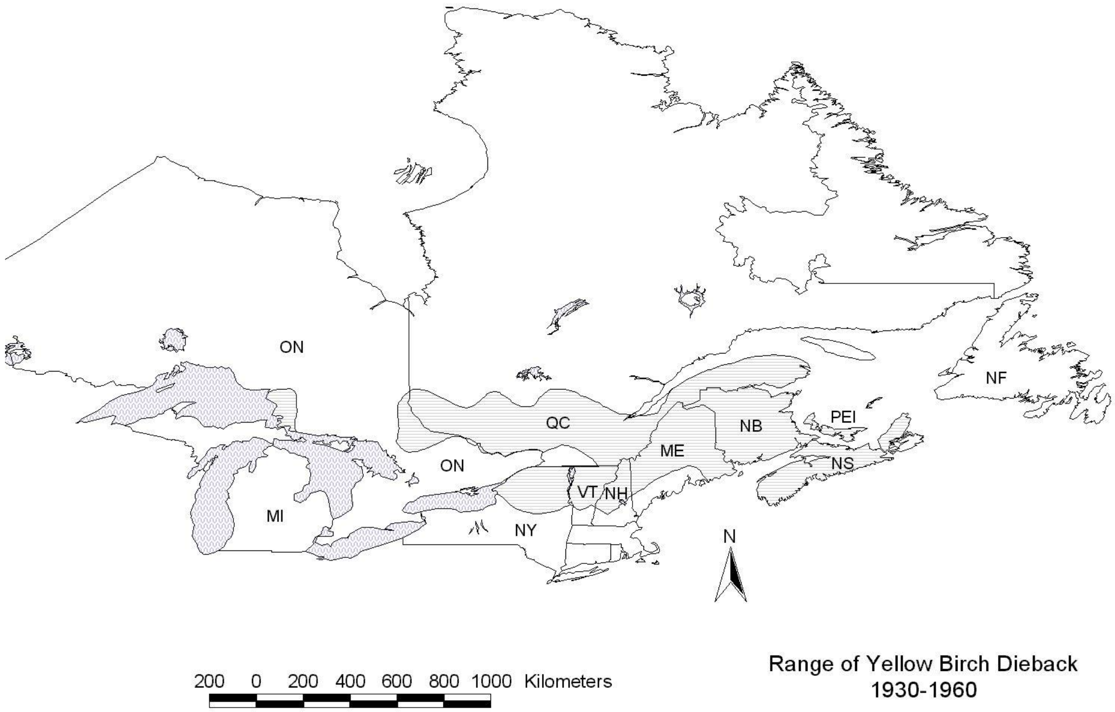


Figure 2.4. Map showing a summary of accumulated birch dieback for the period of 1930-1960. Shaded area identifies the maximum occurrence of yellow birch dieback reported in a symposium on birch dieback in 1952 (Canada Department of Agriculture, 1953) and in the forest decline workshop (LRTAP, Workshop No. 6, 1986; adapted after P. Braathe, 1995).

Potential Causal Factors

Both biotic and abiotic factors have been suggested as causes for the decline of yellow birch. The bronze birch borer was found to be associated with yellow birch dieback, but researchers concluded that the borers were not the primary cause, but only a factor contributing to the decline (Canadian Forestry Service 1943, 1944, 1946, 1947; Balch 1944; Hawbolt 1947; Pomerleau 1953b). Organisms such as fungi, bacteria, and insects were found to be of insufficient virulence to initiate birch dieback (Bier 1953). Therefore, like the bronze birch borer, they too require circumstances of weakness to invade yellow birch effectively, and to produce mortality in twigs and branches

(Hawbolt 1947; Hawbolt 1952; Hansborough 1953; Hill and Sinclair 1954; Redmond 1957). A causal relationship between a virus and birch dieback symptoms was never found (Hansborough 1953). Climatic analysis showed no evidence of spatial or chronological pattern in the occurrence of water deficiencies to account for the geographic distribution of the observed dieback (Clark and Hare 1953). Dieback symptoms were found in the crown when large proportions of the rootlets were killed (Pomerleau 1953). Braathe (1957, 1995) suggested a correlation between birch dieback, the thaw of March 1936, and the late spring frosts in 1944 and 1945. Similarly, Benoit et al. (1981) suggested that an "unusual" thaw in February and periods of severe cold in March, 1981, provoked a decline of yellow birch in Quebec. Frost and drought have also been put forth as possible factors initiating dieback (Canadian Forestry Service 1953, 1955, 1966, 1967, 1984).

Summary of Experiments on Causal Mechanisms

Early studies focused on bronze birch borer as the possible cause of yellow birch dieback (Balch and Prebble 1940), until it was shown that dieback was occurring on trees without insect damage. A variety of statistical approaches were used to identify climatic factors triggering dieback in birch. These included: temperature and precipitation correlations with changes in radial growth increments (Hawbolt 1947, 1952; Hawbolt and Skolko 1948; Clark and Hare 1953); and crown dieback or radial growth observations in relation to soil moisture (Greenidge 1953; Fraser 1953; Fraser and Mawson 1953; Pomerleau 1959) and soil temperature (Redmond 1955). Specific events such as sudden spring flooding, intense cold winters without complete snow cover (Pomerleau 1944), and the effect of deep soil frost (Pomerleau 1991) were also observed to coincide with yellow birch dieback. Cumulative results of injections studies, root excavations, and an extended survey of the trends in soil moisture distribution over a prolonged period suggested that the locus of action for birch decline was in the roots (Greenidge 1953).

Thaw-freeze experiments in 1988, 1989, and 1994 reproduced dieback symptoms, i.e., small chlorotic and curled leaves, failure of bud growth and progressive dying back of twigs from the ends (Braathe 1995). Such symptoms appeared after a frost of –5 ^{o}C at bud-burst, i.e., a stage where green tips of leaves were visible. In March and early April, at least 100 degree-days are needed to attain this stage (base temperature 4 ^{o}C), whereas about 50 degree-days are needed to attain this stage in late April and May.

Pomerleau (1991) reported evidence of a link between birch decline and rooting depth. He also linked birch decline with winter thaws. These thaws can degrade snow pack, thereby rendering the roots subject to deep soil frost.

Extensive xylem cavitation was documented in birches showing crown dieback in New Brunswick (Greenidge 1951). However, at the time, dieback was not attributed to winter thaw-freeze cycles. Sperry et al. (1992) determined that, in diffuse-porous species, more than 90 % of vessels embolise by the end of the winter. Auclair (1993) noted the long time interval between winter embolism and the development of symptoms has made it difficult to recognize the cause of the dieback.

Cox and Malcolm (1997) subjected two-year old paper birch to simulated winter thaws of various durations in climate-controlled chambers. The simulated thaws and subsequent frosts induced dieback in the shoots of the treated plants. Although stem thaw treatments did not significantly increase dieback, there were significant correlations between growing degree-days (GDD), shoot dieback, and percent reduction in conductive xylem. All trees that received a > 60 GDD treatment died to some extent. Plants in the root and stem thaw treatment that received more than 60 GDDs of thaw before frost showed a significant increase in dieback, and a significant loss of conducting xylem after a period of growth recovery. Furthermore, correlations of higher significance were found between increased GDD, extent of dieback, and loss in conductive xylem than for trees subject to root + stem thaw than for trees subject to stem thaw only. The occurrence of dieback in response to thaws cycles, and its close correlation with residual xylem conductivity, support the hypothesis that root injuries may be a key factor in initiating birch dieback and decline.

Zhu et al. (2000) measured shoot dieback, shoot growth, stem xylem cavitation, stem and root freezing injury and root pressure in two-year old, cold-hardened, potted yellow birch seedlings. These seedlings were subjected to a simulated winter thaw for 0, 5, 10, 19, or 27 days followed by 10 weeks of air and soil temperatures at –10 ^{o}C. Thaw duration was significantly correlated ($P<0.05$) with all previously mentioned decline symptoms. In particular, shoot dieback was positively correlated with: (i) stem xylem cavitation ($P<0.001$), (ii) residual stem xylem cavitation (after spring refilling) ($P<0.01$), and (iii) root freezing injury (electrolyte leakage or TTC reduction) ($P<0.01$), (iv) but only weakly correlated with stem freezing damage ($P<0.05$). Freezing damage to roots was negatively correlated with root pressure ($P<0.05$), which-in-turn was positively correlated with residual stem xylem embolism. In stems, there was no correlation between freezing damage and xylem cavitation. These authors concluded that long periods of winter thaw followed by freezing resulted in freezing injury to roots concomitant with a reduction in spring-time root pressures, thus leading to poor refilling of accumulated winter xylem embolism. Zhu et al. (2001) also concluded that stem xylem cavitation was unlikely the primary cause of stem freezing injury. They also found that root freezing injury and residual xylem cavitation are the most reliable parameters for predicting dieback of yellow birch seedlings, however, both root and shoot freezing injuries are also well related with the re-growth of new shoots.

Zhu et al. (2002) exposed one-year-old, cold hardened, container-grown birch seedlings (*Betula alleghaniensis*) to cold treatments at 2, -4, -10, -16, -22, -28, -34 and –40 ^{o}C after being pre-treated with 0, 3, 6, 9 and 12 days of a simulated winter thaw. Freezing injury to roots and shoots, and growth characteristics were determined after 60 days in greenhouse conditions. It was determined that thawed roots became increasingly damaged with decreasing cold temperatures. Plants pre-treated with thaws showed significantly lower stem increment, shoot length, and leaf area in response to cold temperatures than unthawed plants. Variations in growth were significantly correlated ($P<0.05$) with root and shoot freezing injuries. Cold hardiness was related to the highest freezing temperature ("critical temperature") that caused significant injury. For seedlings without thaw pre-treatment, shoot and root critical temperatures were estimated to be at -52 and -23.8 ^{o}C, respectively. Following 12 days of thaw, these temperatures increased to –24^{o}C for shoots, and to –13^{o}C for roots. After twelve days of thaw, or 66 growing degree-days, roots and shoots of yellow birch were sufficiently de-hardened, to render them susceptible to freezing damage at temperatures that are commonly encountered in the Maritimes. It was also observed that root pressure declined significantly with increased root freezing injury.

CHAPTER 3

ANAMOLOUS THAWS AND SPRING FROSTS IN EASTERN CANADA

Introduction

This chapter focuses on using several techniques to define, to quantify and to spatially and temporally track biologically significant thaw events during the period of the 1930 to 1960's birch decline. These techniques refer to: (i) using historical weather records from 400+ weather stations in northeastern North America, (ii) using Geographic Information Systems (GIS) technology and geostatistics to display the spatial extent of historical thaws and spring frost events.

Methods

The daily weather data contained daily minimum, mean, maximum air temperatures (^{o}C), and precipitation (mm). These data were obtained from Environment Canada (Atlantic Climate Center) and from the online National Climatic Data Center (USA).

Two definitions of thaw-freeze events were developed and are expressed as accumulated degree-days (DD) during early thaw-freeze event as follows:

A vegetative response thaw that is considered to be biologically significant to yellow birch (Braathe 1995; Cox and Malcolm 1997; and Zhu et al. 2000, 2001, 2002) is defined to start when the daily maximum temperature reaches +4 ^{0}C. Cumulative degree-days (GDD) are subsequently calculated based on the mean daily temperature values above 4 ^{0}C. The thaw event ends when the daily minimum temperature reaches a value of -4 ^{0}C.

The cumulative degree-days (GDD) for that event is given by

$$GDD = {}^{n}\Sigma_{i=1}[(Tmax + Tmin)/2 - 4]$$

A "snowpack degradation response" thaw (SDD) occurs when degree-days are accumulated based on mean daily temperature values above 0 ^{0}C, i.e.,

$$SDD = {}^{n}\Sigma_{i=1}[(Tmax + Tmin)/2]$$

A *Weather Reader* algorithm (Appendix I) was developed to convert American daily weather records into metric units, to join the Canadian and American data sets, and to calculate:

1. daily accumulated degree-days from start to end of each thaw-freeze event until the end for each weather station;
2. an annual summary of the number of thaw-freeze events for thaws of greater than 4 days in length (annual frequency);
3. maximum accumulation of degree-days for the greatest single thaw-freeze event per station, per year.

The results of the algorithm were then imported as a geo-referenced spreadsheet into GIS (ArcView 3.1™), based on the geographic location of each weather station recording data for a given year. Maps of annual summaries for the greatest degree-day accumulations per year, and number of thaw events per station per year were categorized and are displayed below in the form of graduated color dots. From these maps, years and areas which contained biologically significant thaw-freeze events were selected for further analysis.

Quality control of the daily weather record data was performed by checking for missing data. Shown in Figure 3.1 is an example of minimum, mean, and maximum for Fredericton, NB, for 1930 to 1960. A method was developed to determine if a thaw is anomalous in nature (Figure 3.2). This was done by daily weather comparison to the 30-year temperature normals for each of the selected stations, i.e., difference from daily normal (^{o}C) = Mean daily 1936 value - 30 year average of means for that day.

Once the anomalous thaw events were determined, files for daily accumulation of GDD and SDD per thaw event were exported from GIS as *.dbf files into GS+ for Windows^{TM}, to calculate geostatistics. Geostatistics refer to a spatial interpolation technique known as kriging. Kriging is a weighted moving average method for estimation based on known values (Appendix II). The main difference between kriging and a simple distance-weighted average is that kriging allows flexibility in defining the spatial interpolation model, and takes into account the model of the spatial process, i.e., the variogram. Since the estimation variances can be mapped, confidence placed on the estimates can also be calculated and mapped.

Kriging of daily cumulative degree-day calculations was done in two steps:

1. The sample variance was used to estimate the shape of the variogram (a curve that represents the variance as a function of distance), i.e., the variogram describes the spatial relationship between the daily weather parameters.
2. The estimated variance function was used to determine the weights needed to define the contribution of each climate station value to the interpolation between two known station GDD values. Climate stations close to the point for which an estimated value is to be generated contribute the most to the interpolation (refer to Appendix II for details on kriging)

Daily accumulated (GDD) files for each Julian day (1-152) and year were then exported from GS+ for Windows ™ as ASCII grid files (152 rows, and 78 columns) into ArcView 3.1™. For spatial mapping and tracking of individual thaw-freeze events through time, each grid cell size was 20 km.

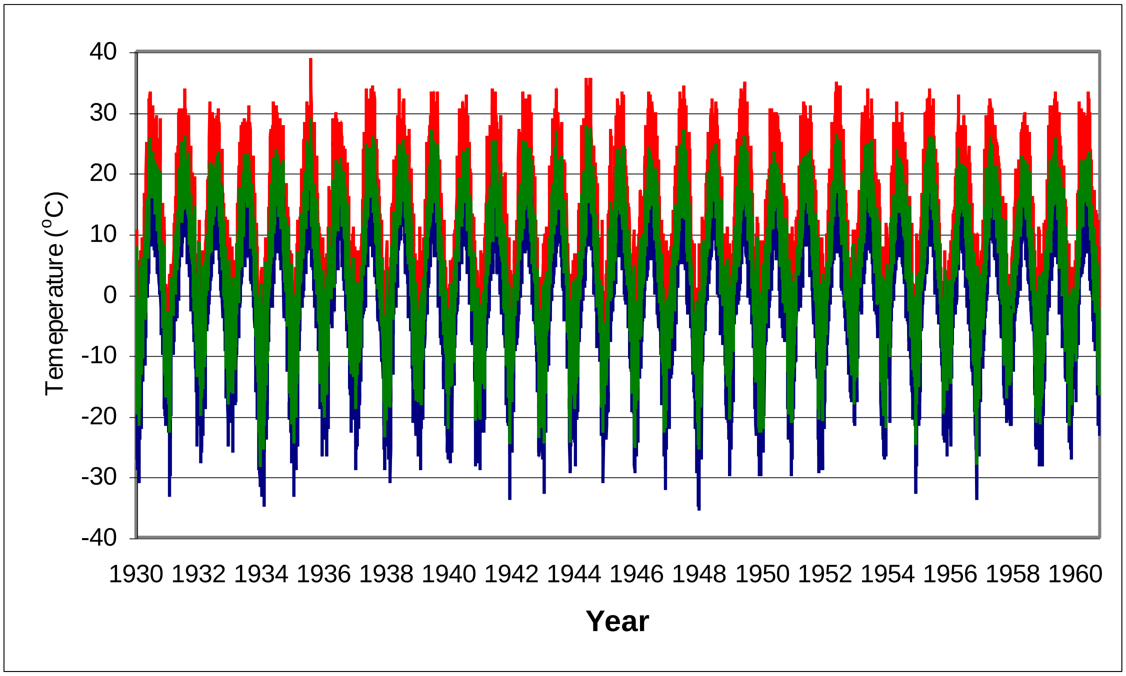


Figure 3.1. Illustration of maximum (red), mean (green), and minimum (blue) air temperatures for Fredericton, NB for 1930 – 1960. Gaps in the data are easily located. This is an example where gaps do not appear in the data.

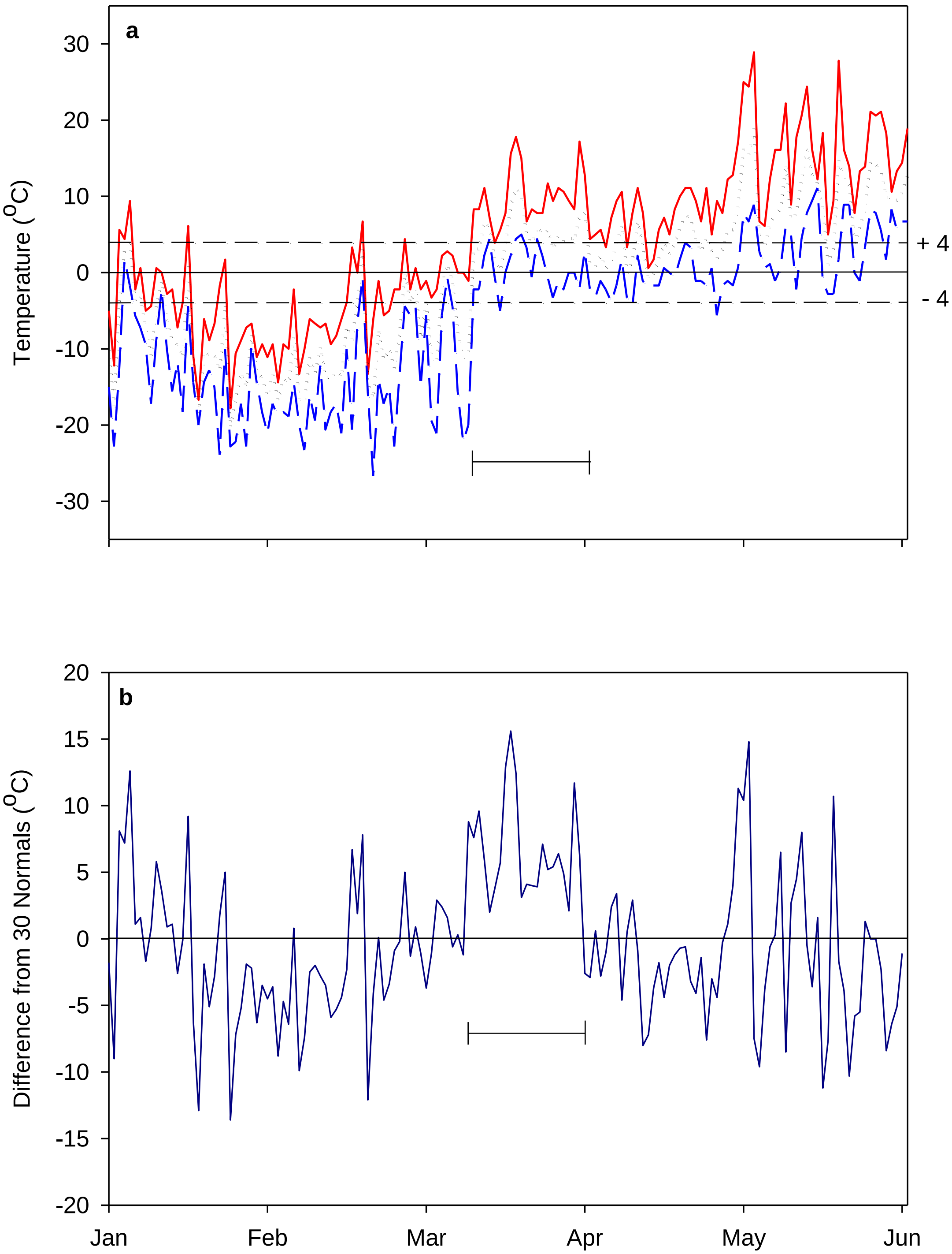


Figure 3.2 (a) Illustration of daily maximum (red), mean (green) and minimum (blue) air temperatures for Fredericton, NB from January 1 to May 1, 1936, and (b**)** daily mean temperature differences from 30-year temperature normals. The anomalous period is indicated with bars.

Results and Discussion

A summary of 1930 to 1990 average annual maximum thaw GDD calculations, for the greatest single thaw-freeze events per year is shown in Figure 3.3 for the entire study area. The years 1936, 1945, 1957, 1981 1986 and 1987 have "peaks" in comparison with other years.

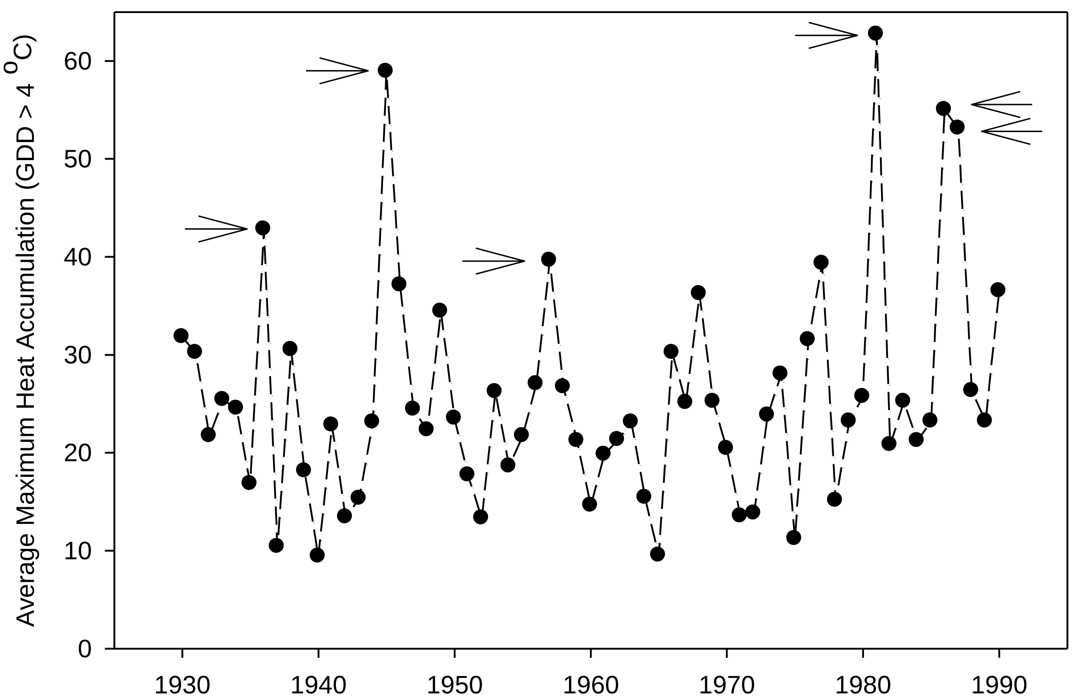
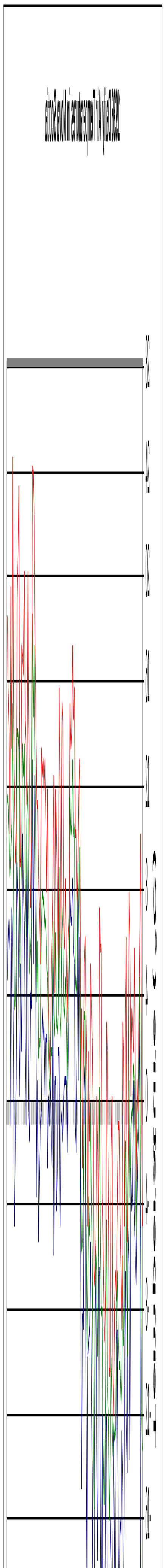


Figure 3.3. Graph showing average yearly maximum degree-day accumulations (heat sums during thaw) per year from 1930 – 1990 for all stations within the study area. Some peaks are marked by arrows.

Suspect years include 1936, 1944, and 1945. A later, well-documented 1981 winter-thaw and late spring frost in southern Quebec and part of Atlantic Canada was also investigated. The projection used for mapping is the Lambert Conformal Conic (WGS 84). Decimal degrees are converted to meters, with a Central Meridian of –75.



The 1936 thaw events for a station in eastern Nova Scotia in Colchester County, are shown in Figure. 3.4.

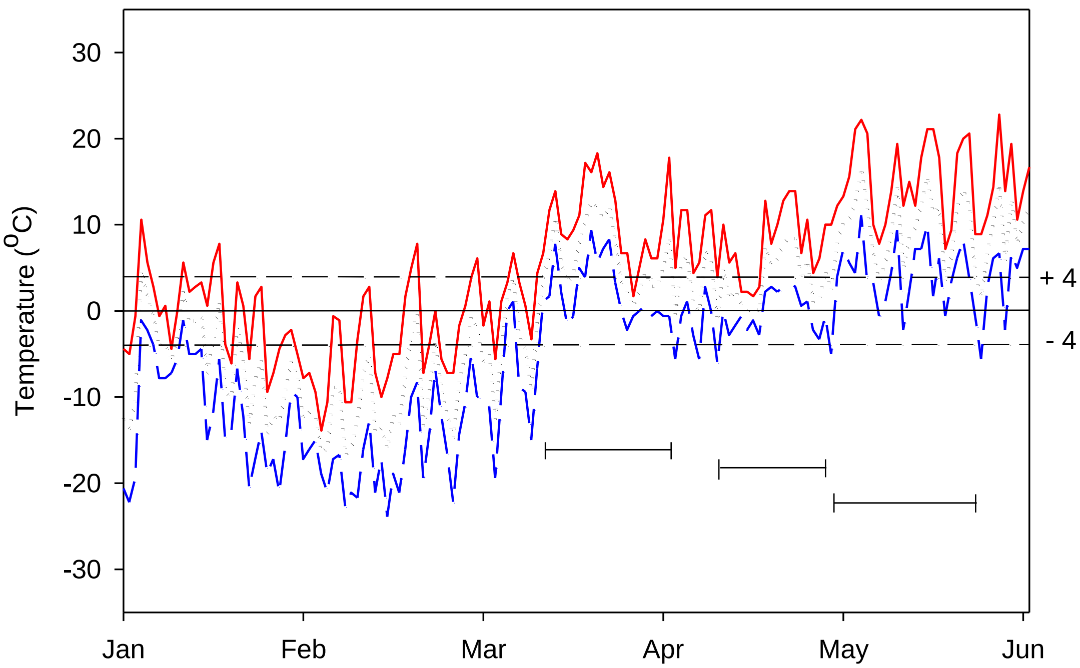
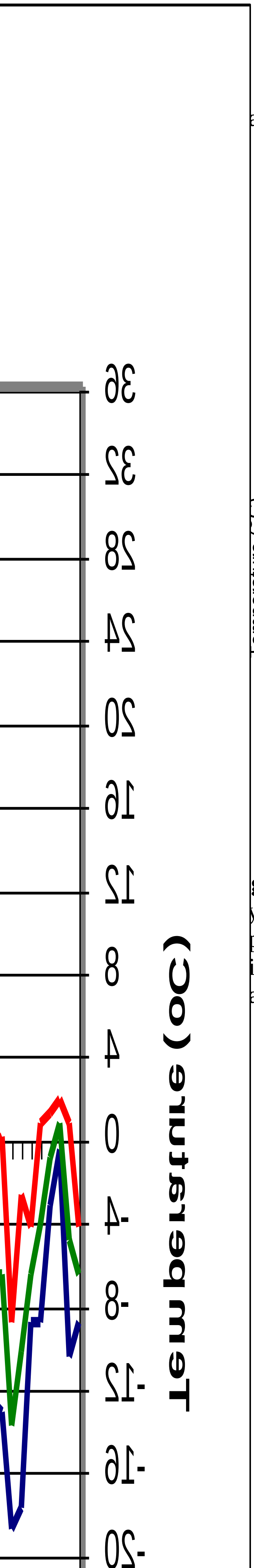
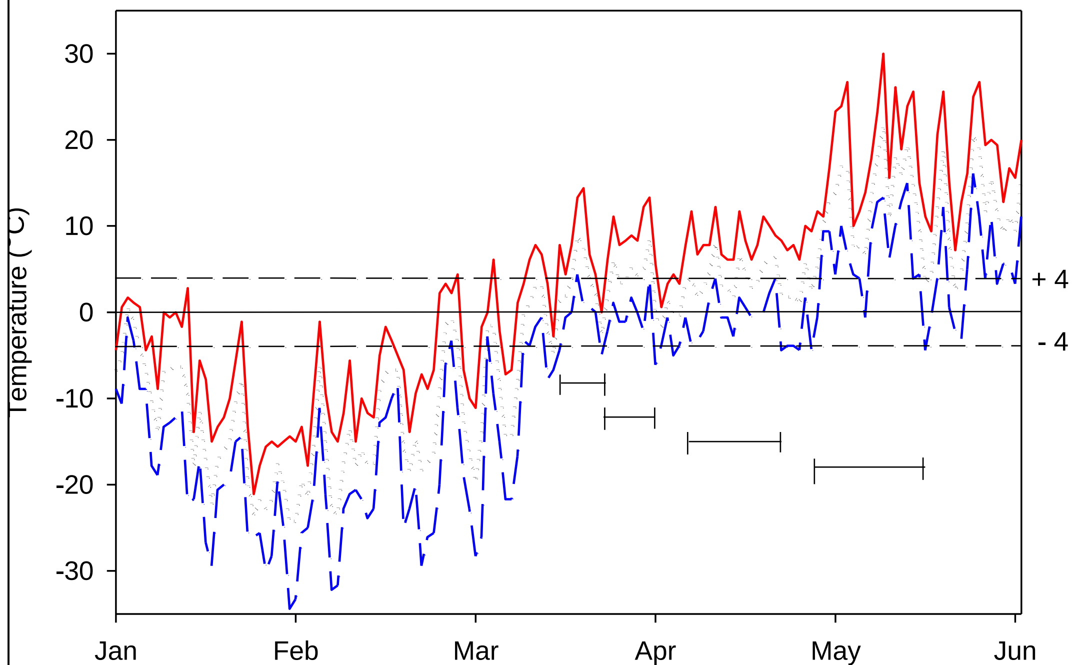


Figure 3.4. Air temperature time series for a typical station in eastern Nova Scotia (Truro, NS, # 8206000) from January 1 to May 31 1936. The solid red line represents maximum, dotted black represents mean, and dashed blue represents minimum daily temperatures. The thaw events greater than 4 days in duration are marked with bars. Note maximum daily temperature must be +4 ^{o}C in order to commence a thaw event and the event ends when a minimum daily temperature of –4 ^{o}C is reached.

This particular station received three thaws; a March thaw, a mid to late April thaw, and a late frost in May. This pattern occurred throughout Nova Scotia. Some stations did not receive the last frost of at least –4 ^{0}C, but were just slightly above -4 ^{0}C. Southern New Brunswick had much the same pattern, but not as pronounced. Most of northern New Brunswick and the Gaspé Peninsula had a less pronounced March thaw than Nova Scotia, and had accumulated GDD levels just below 50 prior to the late spring frost in May. In southern Quebec, the March thaw was even less pronounced an in the Maritimes, but did undergo significant late frost events in May, as illustrated

Figure. 3.5.





gure 3.5. Air temperature time series for a typical station in southern Quebec (St. yacinthe, QC # 7027360) from January 1 to May 31 1936. The solid red line presents maximum, dotted black represents mean, and dashed blue represents inimum daily temperatures. The thaw events greater than 4 days in duration are arked with bars.

Figure 3.6a illustrates the number of thaw events per station, and Figure 3.6b illustrates the maximum heat accumulation per station for the greatest single thaw-freeze event during the period of January 1 to May 31 in 1936. Calculations for this year involved weather records from 198 stations. As can be seen in Figure 3.6a, all but one station in Nova Scotia recorded at least 1 thaw, with a maximum number of 5 thaw events greater than four days in duration. The map surface of maximum heat accumulations per station (Figure 3.6b) shows that some stations in eastern Nova Scotia accumulate thaw GDDs greater than 100 and less than 200. These high accumulations occur prior to the late frost event, or during the March thaw-freeze event. Accumulations for New Brunswick stations are representative of the March thaw as well, except for a few stations along the Maine - New Brunswick border, where GDD values are highest prior to the last frost in May. Stations in southern Quebec and the St. Lawrence, also reached the highest levels of accumulated GDDs, prior to the late frost in May. Other station accumulation values can be attributed to the second thaw-freeze event in April.

a

b

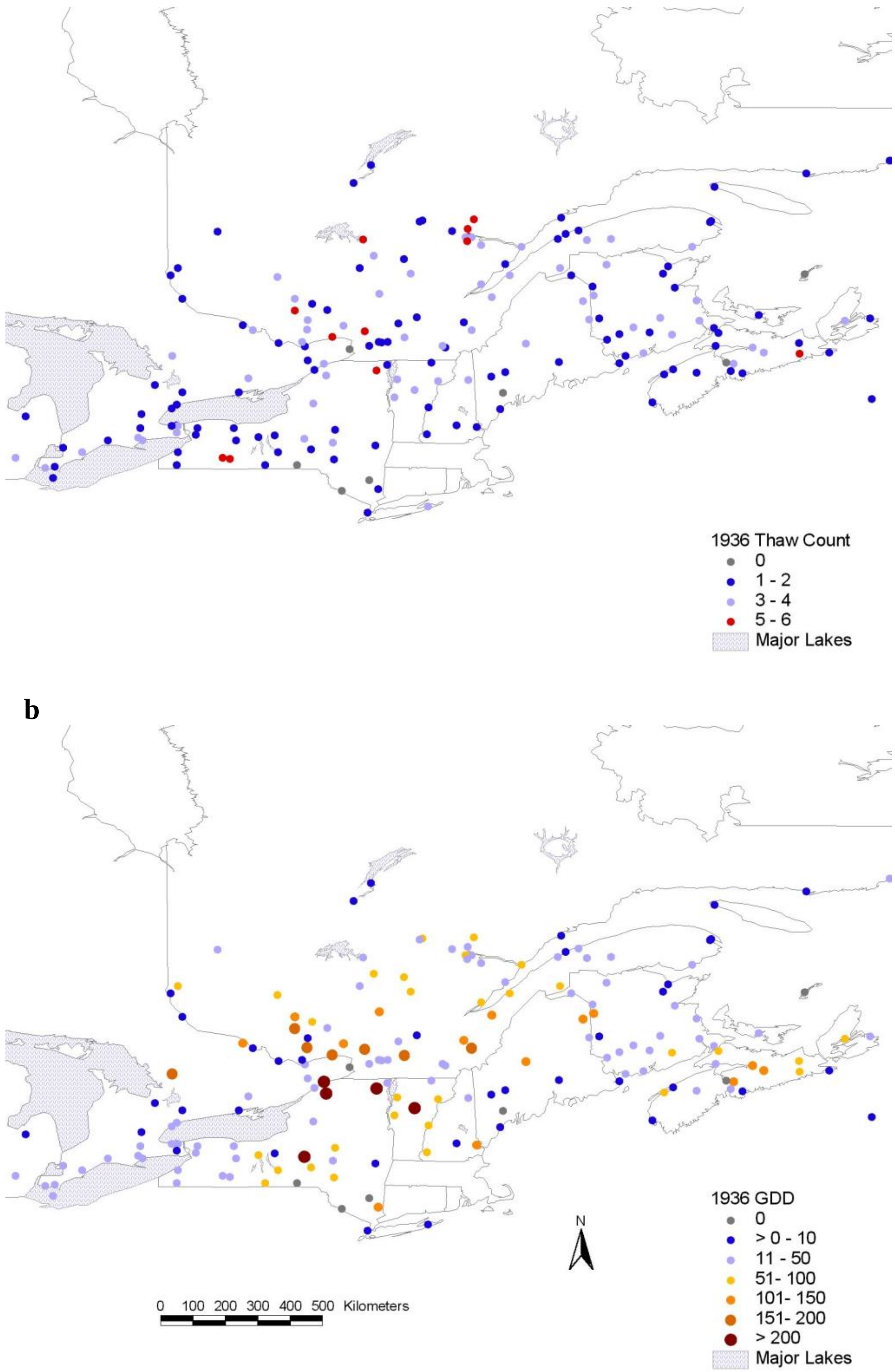


Figure 3.6. Map showing the distribution of climate stations (198) and (a) number of thaws events greater than four days in duration, and (b) the maximum degree-day accumulations for the greatest single event per station in northeastern United States and eastern Canada for 1936.

As shown in Figure 3.7, the 1944 thaw shows a "normal" progression to spring and undergoes a late frost on May 17. The area that received the late frost was mostly in Quebec, including the Gaspé Peninsula and some areas of northern New Brunswick. As shown in Figure 3.8, thaw counts for eastern Canada were limited to 1 or 2 events. Figure 3.8b shows the late frost area in southern Quebec and Gaspé regions, with most areas having received greater than 50 to 200 GDDs before the last frost in May. For the same time, heat units accumulated were negligible in the rest of New Brunswick, Prince Edward Island, and Nova Scotia (<10 GDD).

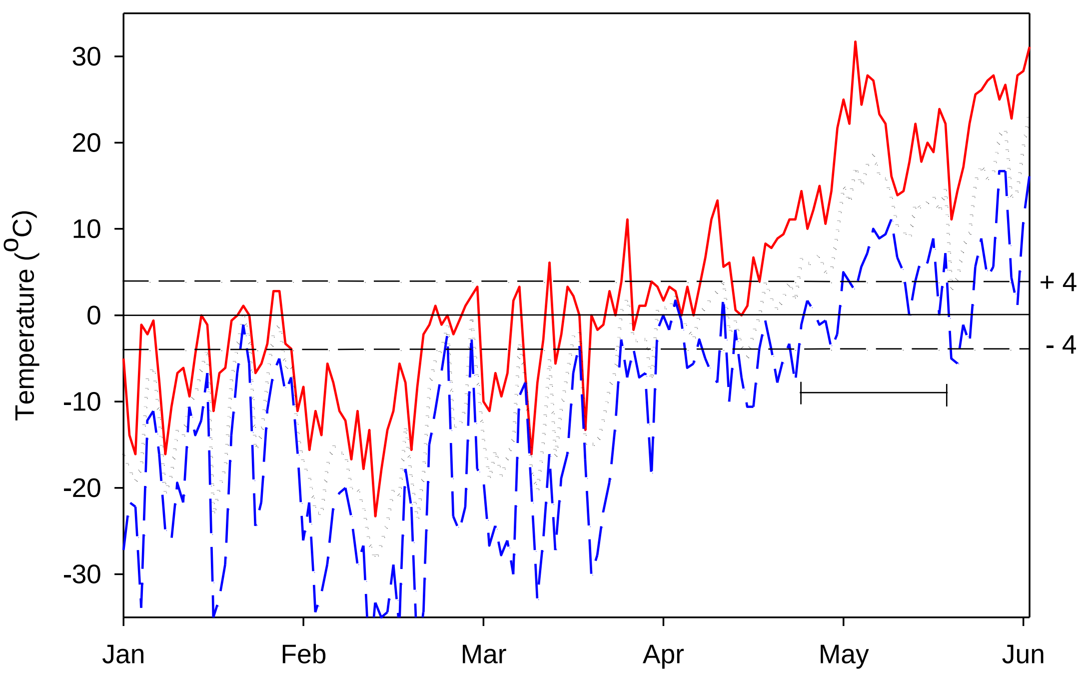
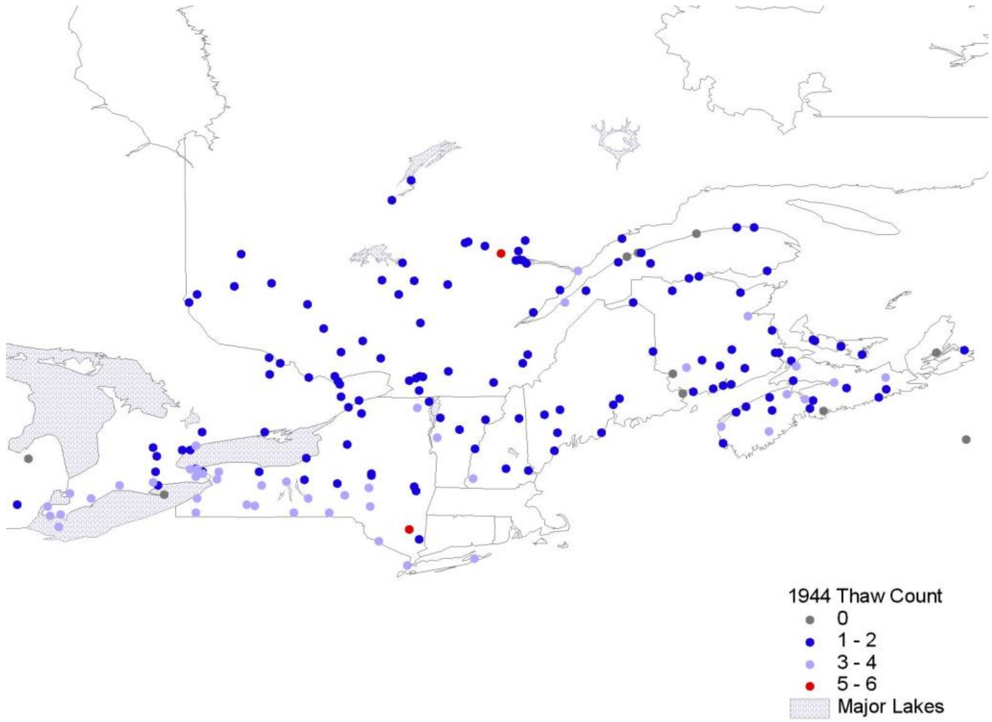


Figure 3.7. Air temperature time for a typical station in southern Quebec (Nominingue, QC, # 7035520) from January 1 to May 31, 1944. The solid red line represents maximum, dotted black represents mean, and dashed blue represents minimum daily temperatures. The thaw event greater than 4 days in duration is marked with bars.

a



b

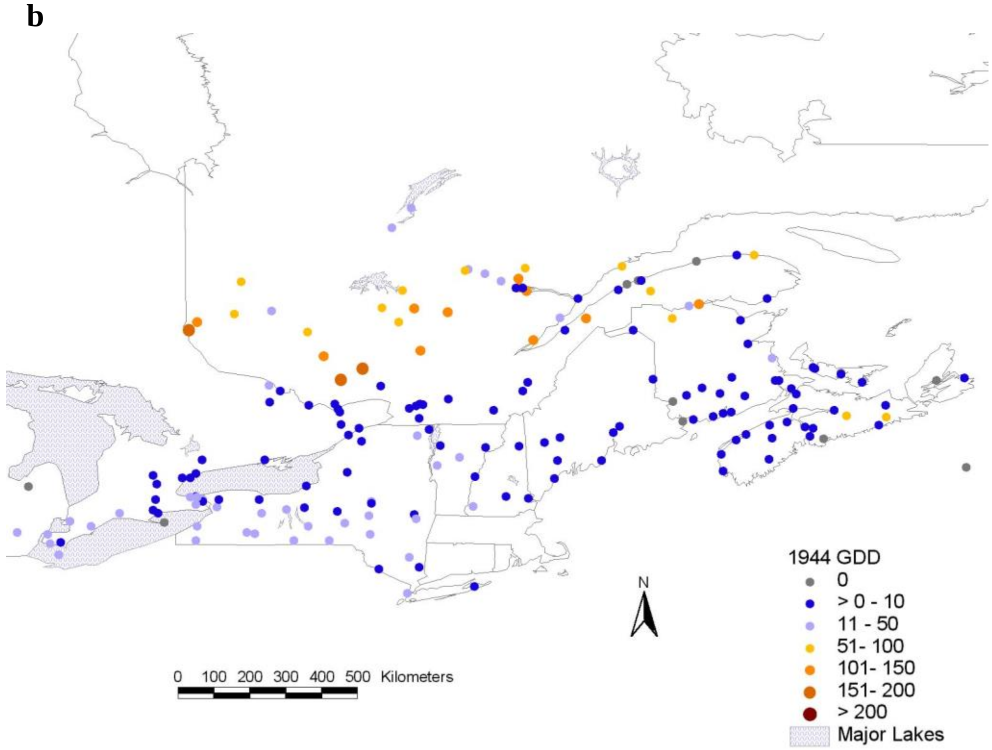
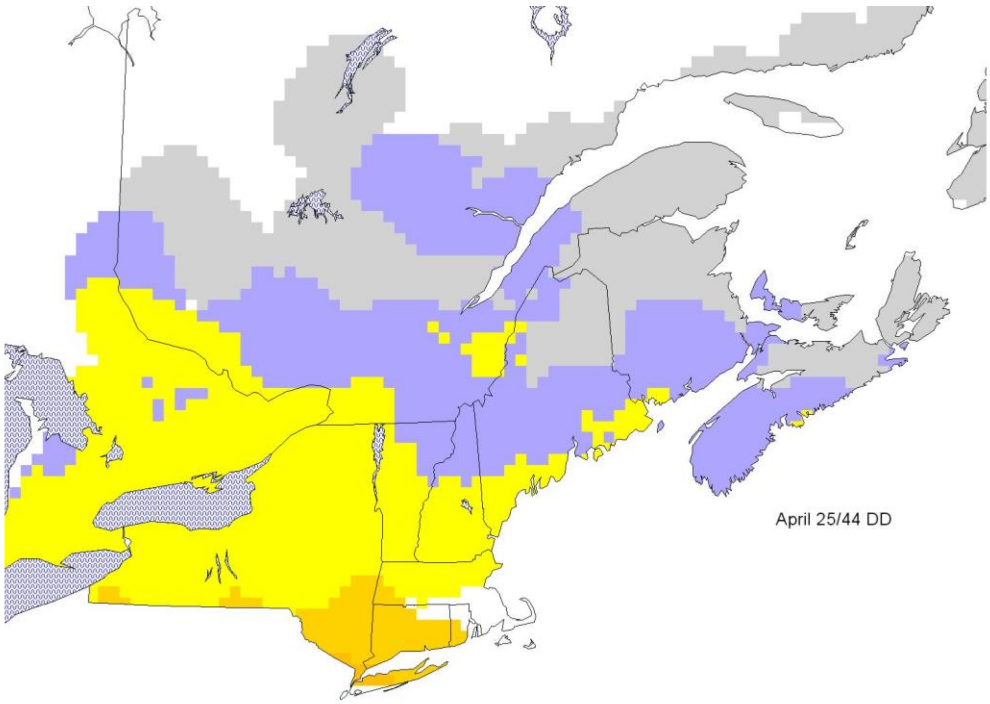


Figure 3.8. Map showing the distribution of climate stations (213) and (a) number of thaws events greater than four days in duration, and (b) the maximum degree-day accumulations for the greatest single event per station in northeastern United States and eastern Canada for 1944.

In addition to the preceding dot maps, geographic extent of thaw anomalies were presented in terms of “kriged” surfaces (Appendix II). In these surfaces, thaw degree-days are represented at a 20 km grid cell resolution, using 16 nearest neighbors all within a distance of 100 km for purpose of geospatial interpolation. The result of so doing is illustrated in Figure 3.9 for the spring of 1944. In this winter, thaws began on April 23, and ended on May 19. Figure 3.9a shows the accumulation levels and thaw locations 2 days after the previous value of –4 ^{o}C (April 25), with the rest of the figures providing a “snapshot” of the progression at May 13, May 17, May 18 (start of frosts) and May 19. This figure also illustrates the rest of eastern Canada continuing with a normal progression into summer.

a



b

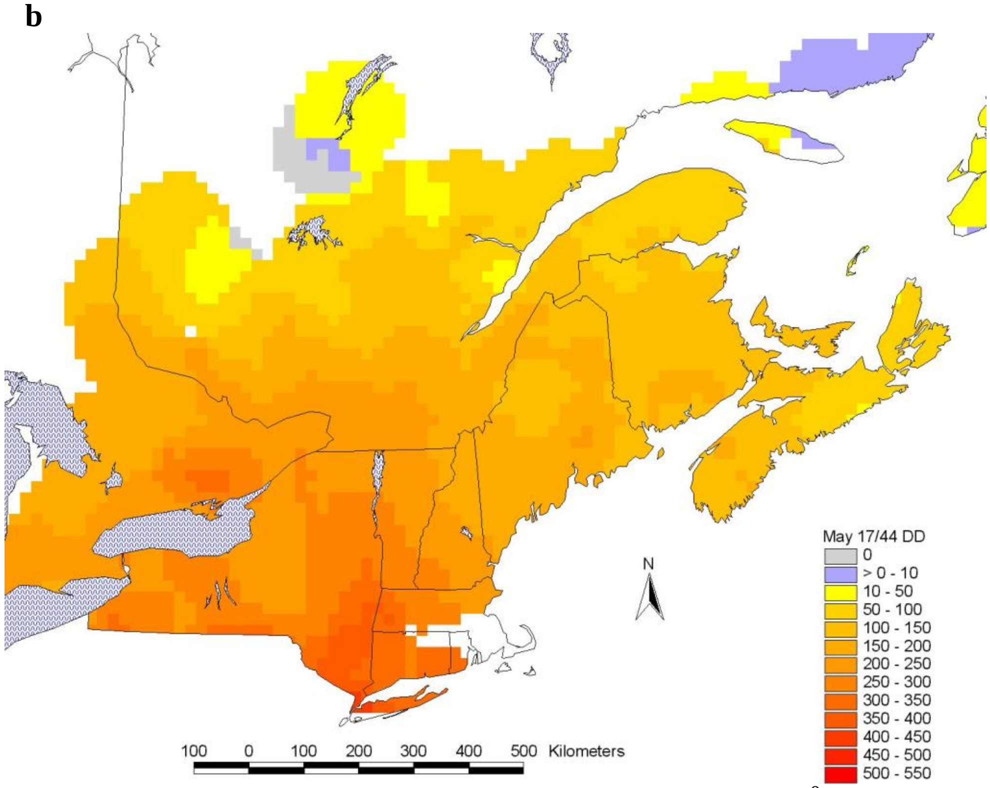


Figure 3.9. Map showing the accumulated degree-days (base 4 ^{0}C) during thaw at different times in 1944. (a) two days after thaw commencement, (b) at the height of accumulation, (c) at the start of last frost, and (d) total area affected by the last frost.

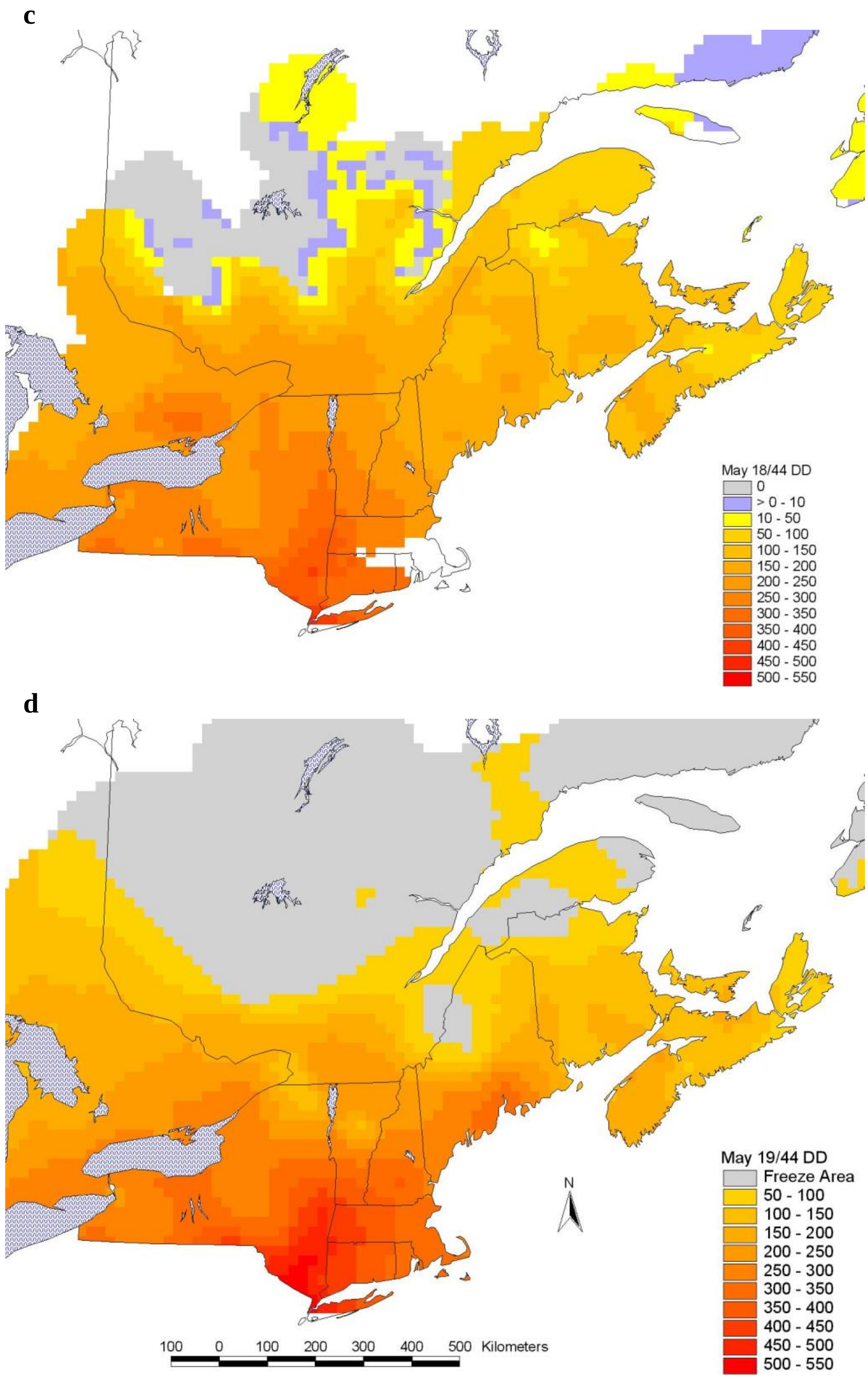


Figure 3.9. cont'd.

The year 1945 had an extraordinary warm spring (record spring temperatures), with a subsequent freeze to $-7^{o}C$ in the middle of April, as can be seen in Figure 3.10. Nova Scotia and areas within Atlantic Canada did not accumulate degree-days during thaw from the middle of March until the middle of April. This was also the case in southern Quebec.

Figure 3.11 illustrates the distribution and number of thaw events per station, and the maximum heat accumulation for a single thaw event during the period of January 1 to May 31 in 1945. The 1945 event covered nearly all the areas struck by the 1936 and 1944 events, and also affected additional areas. The early spring thaw was widespread across eastern Canada, with high GDD values before recurring frosts of $-4^{o}C$. Figure 3.12 illustrates a series of spatial progression of this main thaw-freeze event from March 12 to April 16. This freeze event was particularly widespread, with variable amounts of accumulated degree-days of 10-200 before the last freeze.

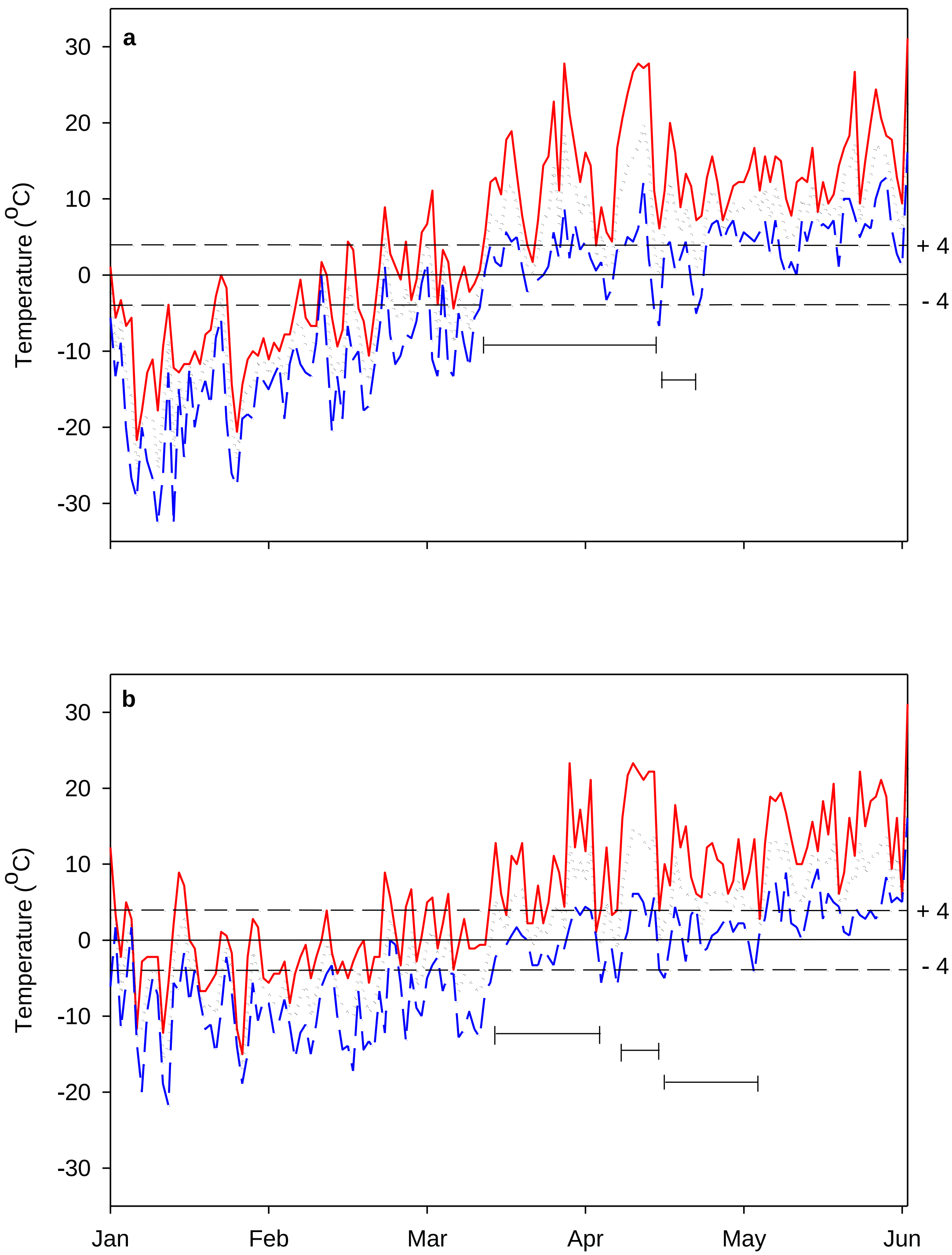
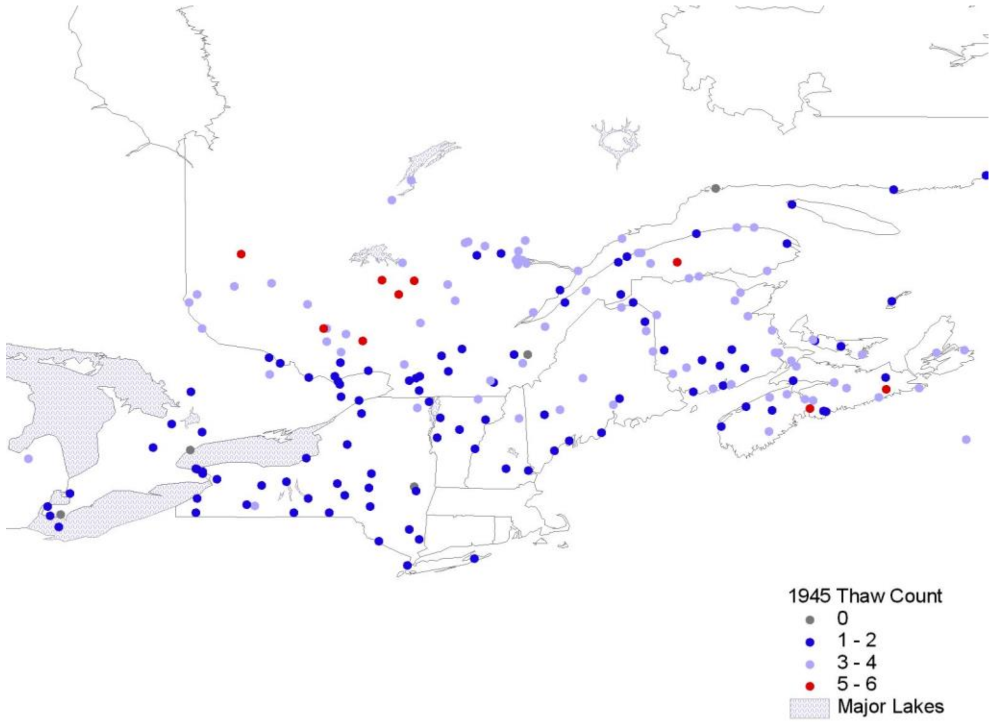


Figure 3.10. Air temperature times series for a typical station in (a) southern Quebec (Ste Clothilde, QC, # 7027040) and (b) Nova Scotia (Springfield, # 8205200)from January 1 to May 31 1945. The solid red line represents maximum, dotted black represents mean, and dashed blue represents minimum daily temperatures. The thaw events greater than 4 days in duration are marked with bars.

a



b

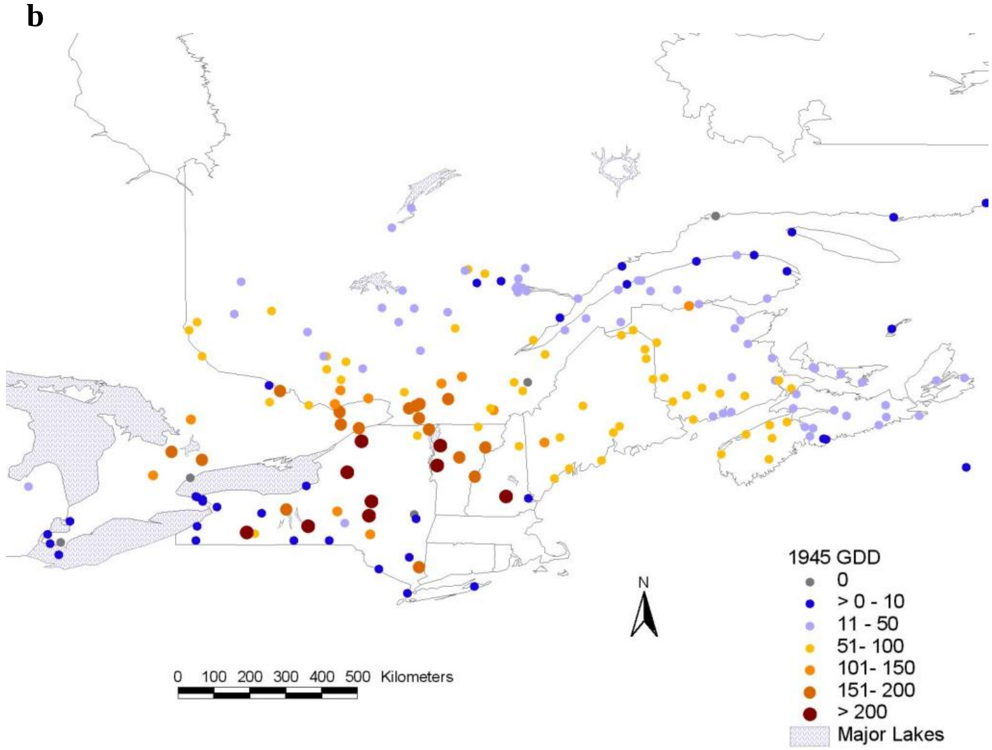
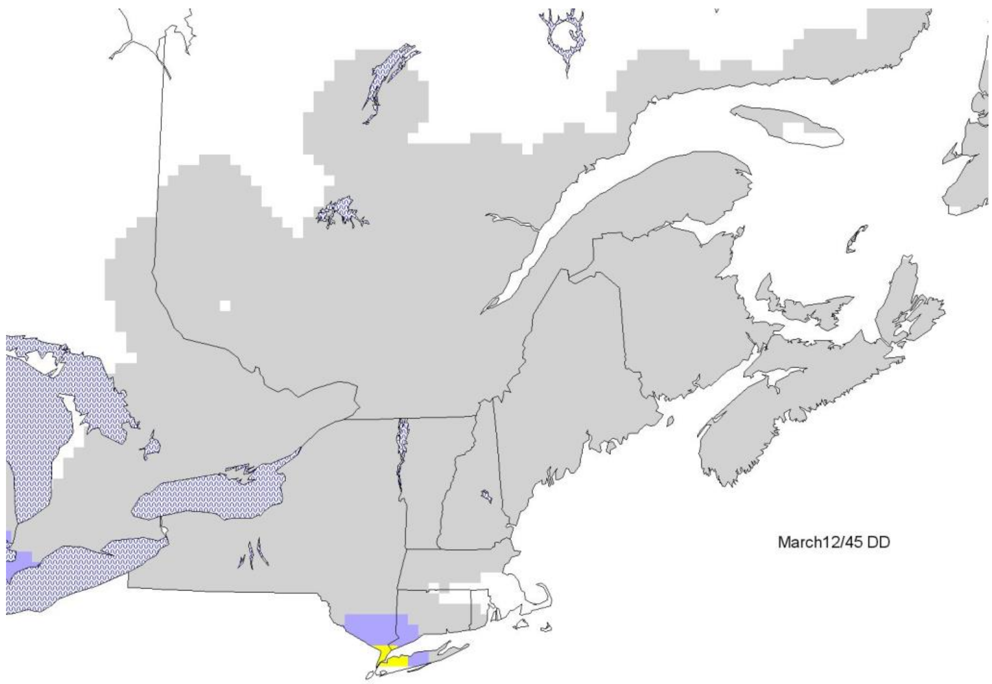


Figure 3.11. Map showing the distribution of climate stations and (a) number of thaws events greater than four days in duration, and (b) the maximum degree-day accumulations for the greatest single event per station in northeastern United States and eastern Canada for 1945.

a



b

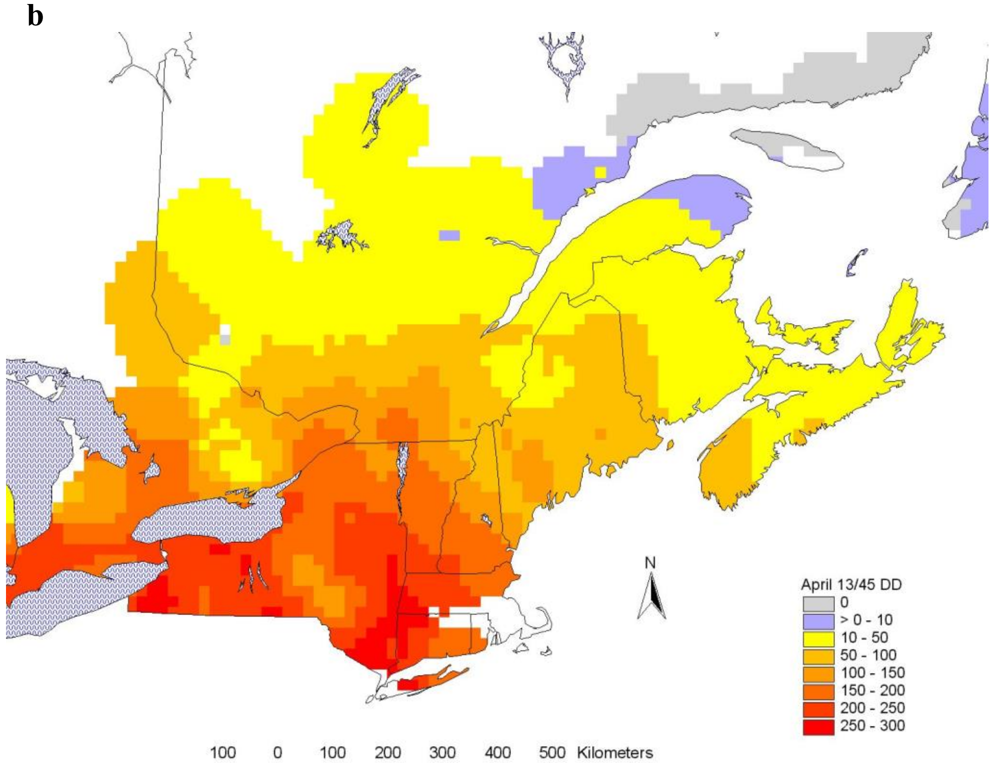
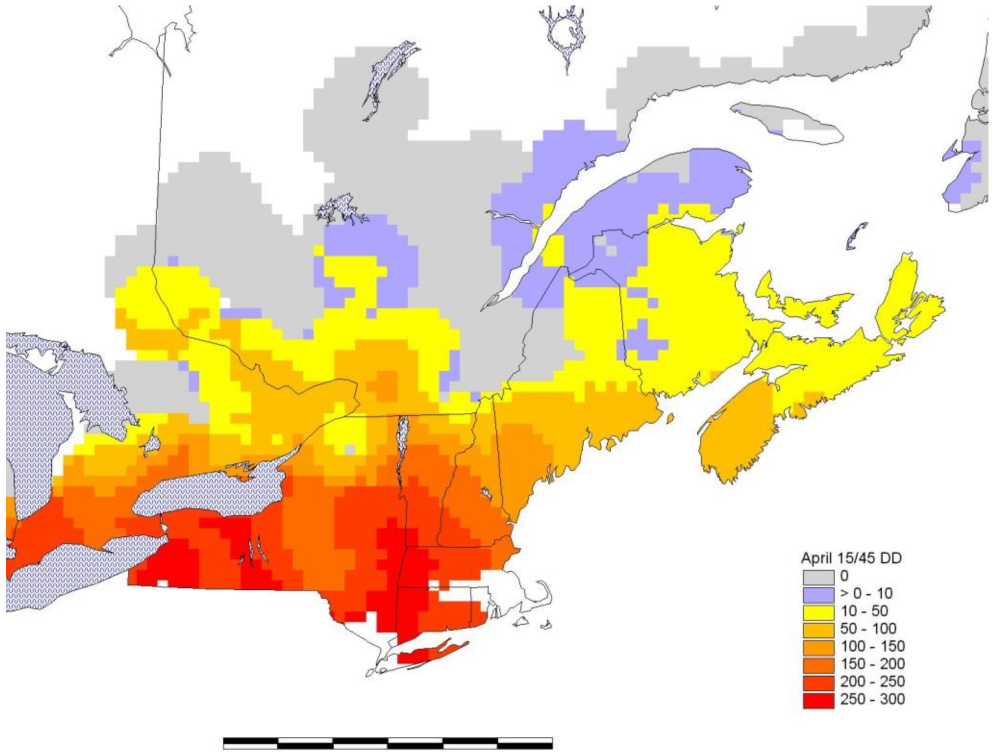


Figure 3.12. Map showing the accumulated degree-days (base 4^0C) during thaw at different time frames in 1945. (a) on the day of thaw commencement, (b) at the height of accumulation, (c) at the start of last frost, and (d) total area struck by last frost.

c



d

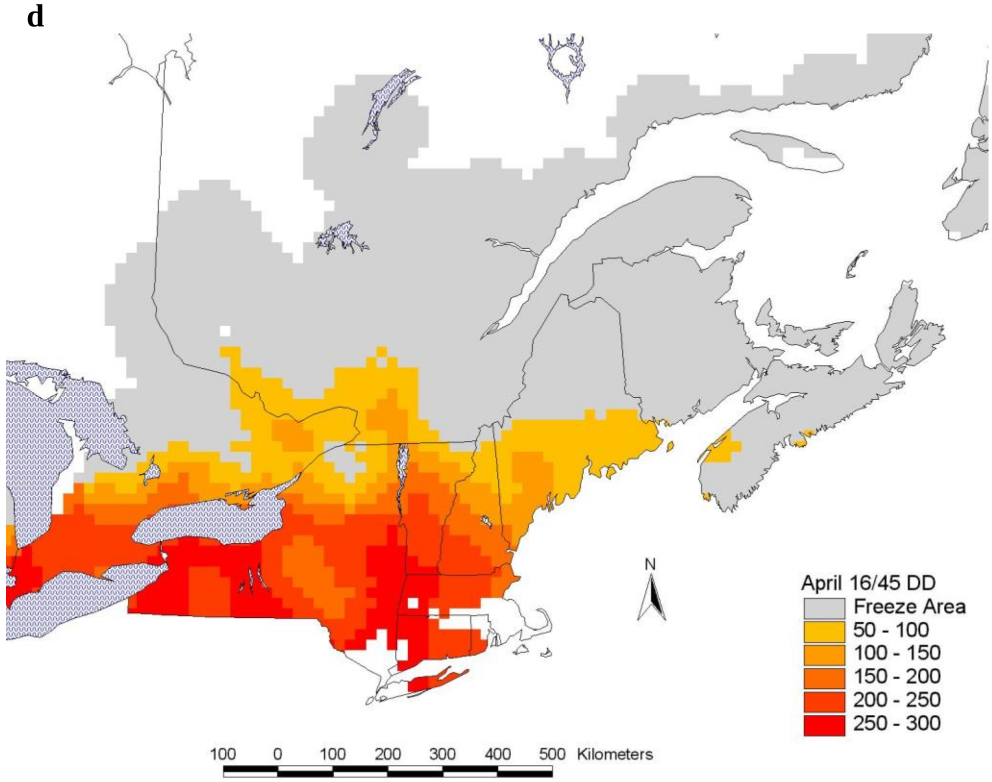


Figure 3.12. cont'd.

The well-documented winter thaw for the winter of 1980/81 in southern Quebec is illustrated in Figure 3.13a. Lachance (1988) described snow cover for the winters of 1981 and 1982 as noticeably low, while temperatures of December 1980 and January 1981 were the coldest ever recorded in southern Quebec. In addition, this region sustained the warmest and longest winter thaw recorded since 1900: all snow covering the ground melted from February 14 to February 28, 1981. The winter thaw was followed by a cold spell in mid-March. There was also a late spring frost throughout most of southern Quebec, the Gaspé Peninsula and northern New Brunswick. Stations in central and southern New Brunswick and Nova Scotia underwent an early spring thaw, but did not receive the February thaw or the late spring frost event that occurred in the northern locations of the study area. An example of these temperatures is provided in Figure 3.13b for Fredericton, NB.

Figure 3.14 illustrates that most of eastern Nova Scotia received a thaw event of 50-100 GDD during March and April. Stations in southern Quebec and the Lac St Jean region received a late frost in the middle of May, and had much higher accumulations of degree-days before the last frost (50-200 GDD).

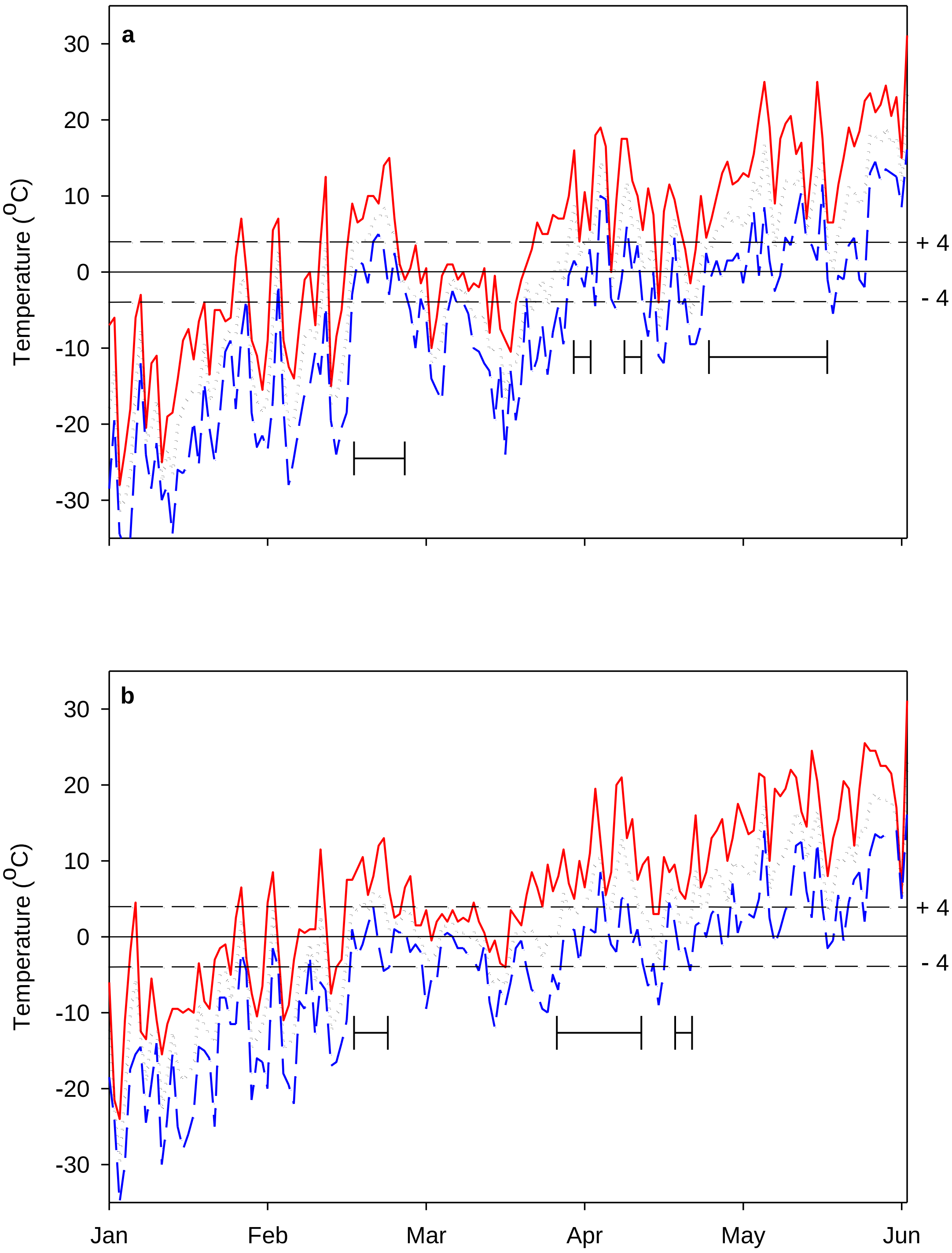
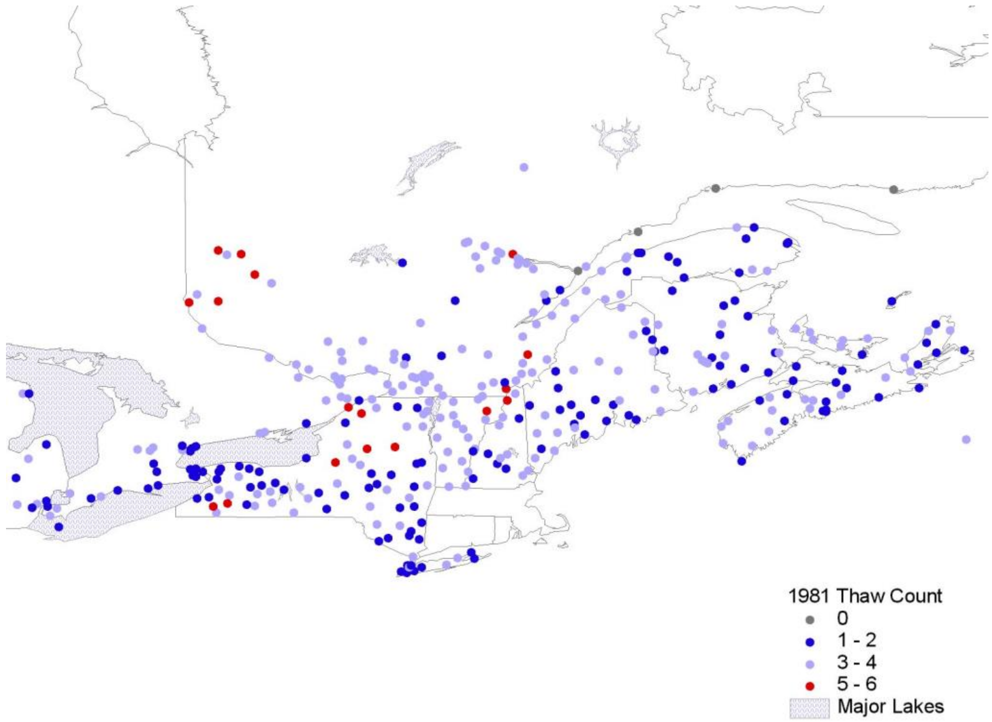


Figure 3.13. Air temperature times series for a typical station in (a) southern Quebec (Milan, QC # 7024920) and (b) south-central New Brunswick (Fredericton, NB, # 8101600) from January 1 to May 31 1981. The solid red line represents maximum, dotted black represents mean, and dashed blue represents minimum daily temperatures. The thaw events greater than 4 days in duration are marked with bars.

a



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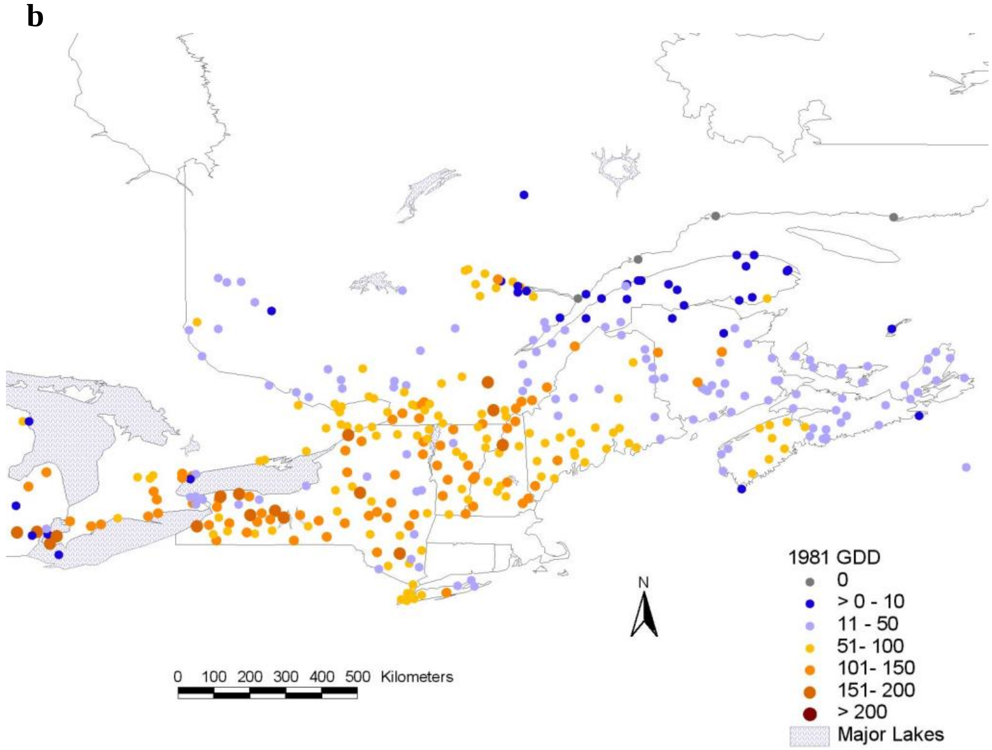


Figure 3.14. Map showing the distribution of climate stations (424) and (a) number of thaws events greater than four days in duration, and (b) the maximum degree-day accumulations for the greatest single event per station in northeastern United States and eastern Canada for 1981.

The following kriged surfaces are again represented with a 20 km grid cell resolution (Appendix II). The first winter thaw from February 14 to 28 is illustrated in Figure 3.21. A second early spring freeze-thaw event from March 28 to April 17 in 1981 is illustrated in Figure 3.15. Also illustrated in Figure 3.16 is a late spring frost that occurred throughout most of southern Quebec and the Gaspé Peninsula.

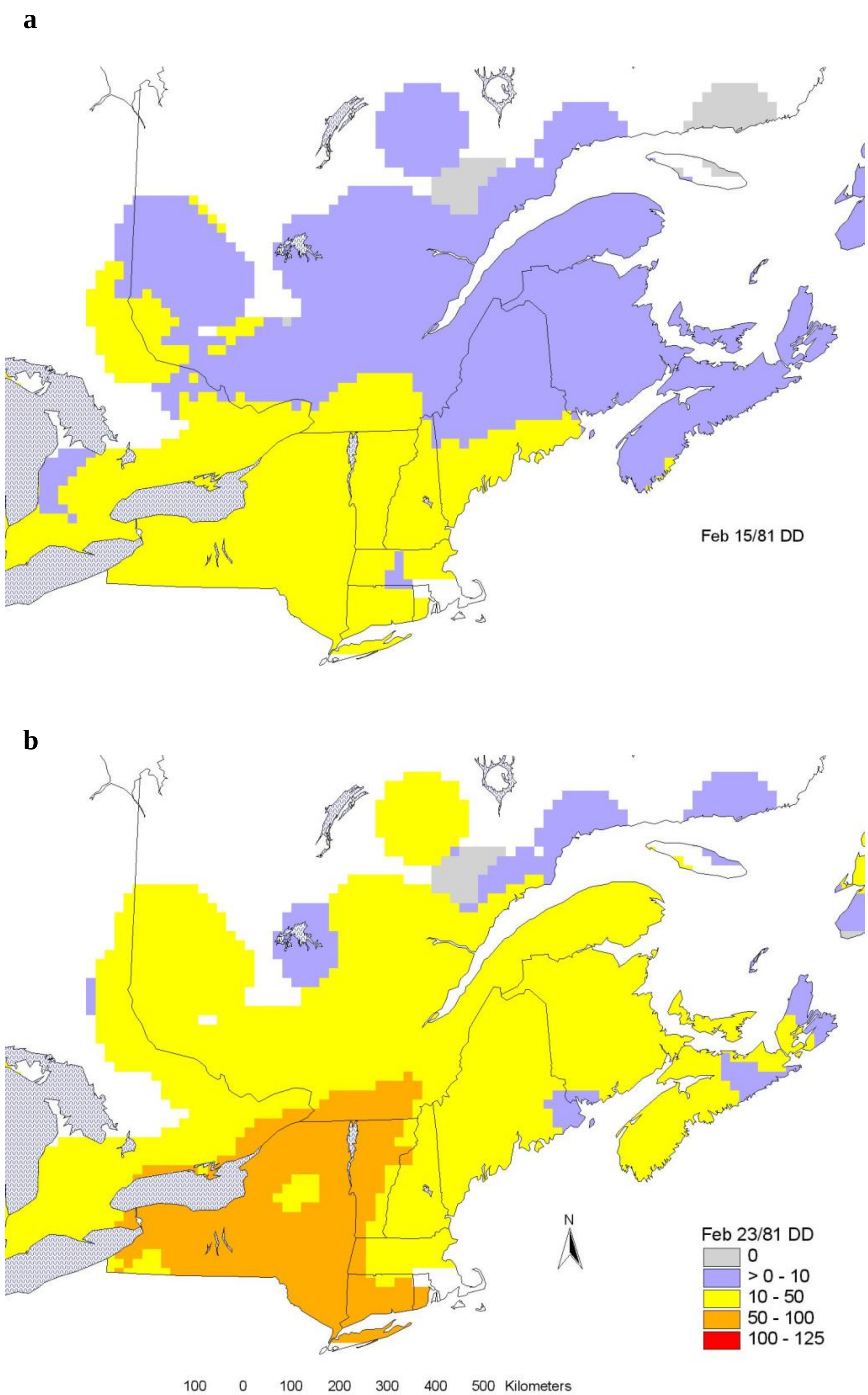
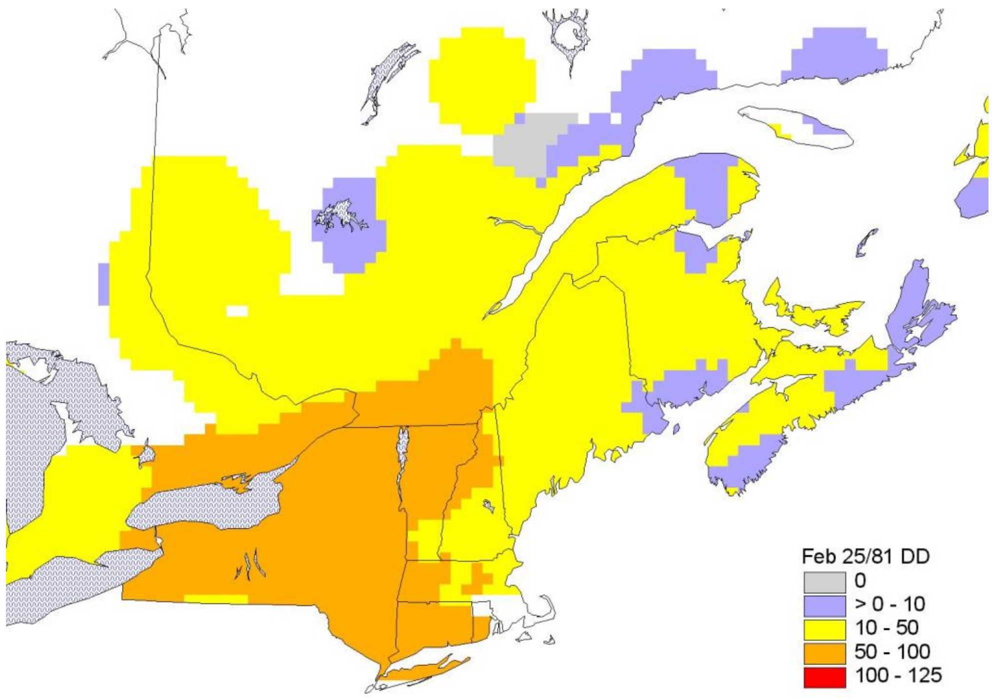


Figure 3.15. Map showing the accumulated degree-days (base 4 ^{0}C) during thaw at different time frames in 1981 for the winter thaw-freeze event, (a) one day after thaw commencement, (b) on a day in the middle during thaw, (c) at the height of accumulation, and (d) total area struck by the last frost.

c



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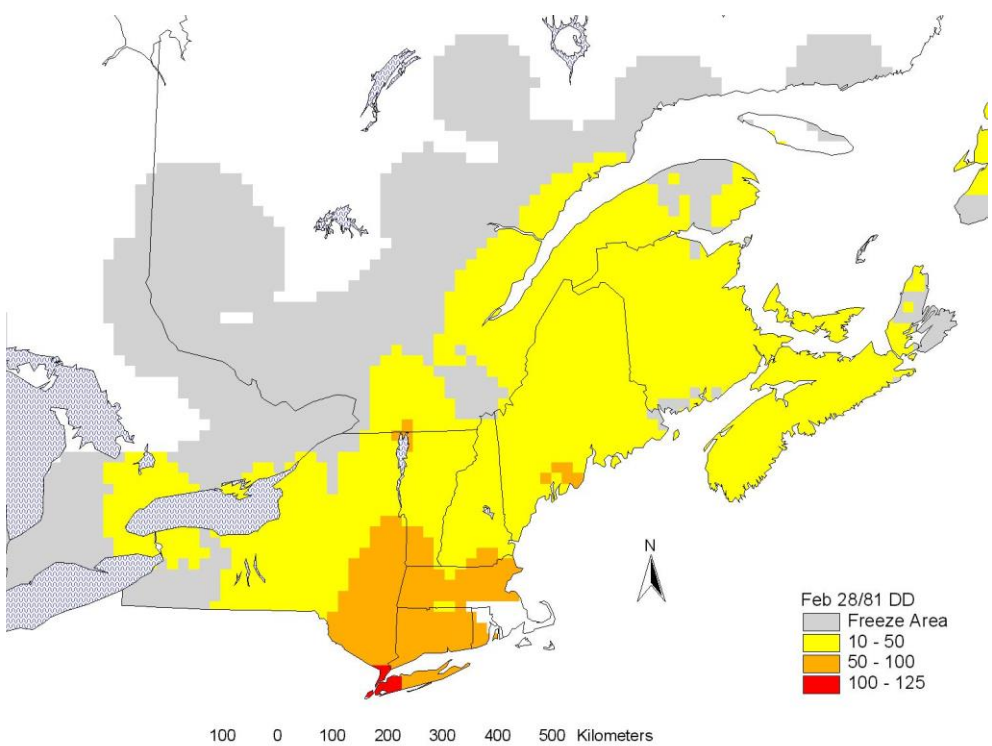


Figure 3.15. cont'd

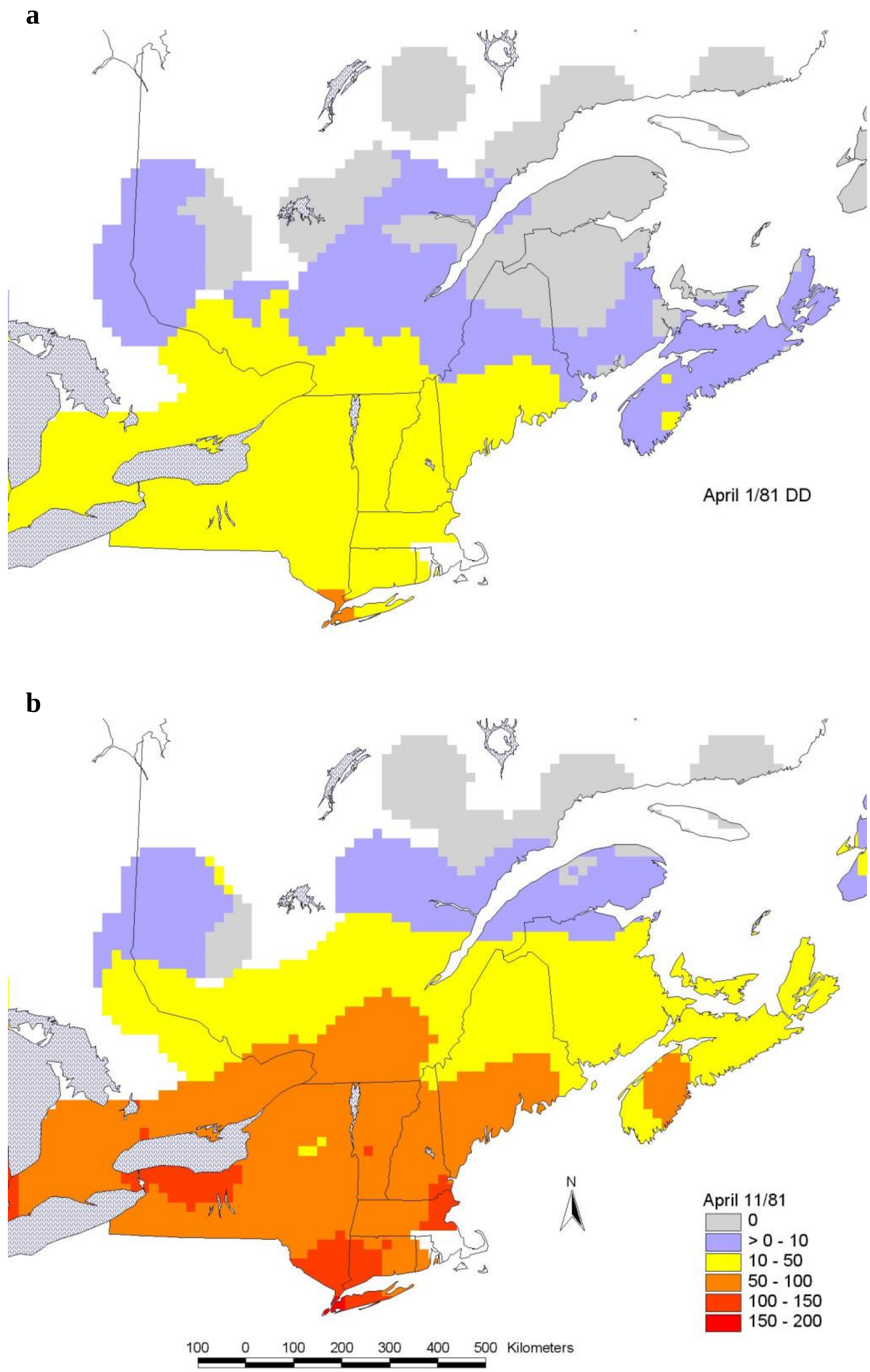
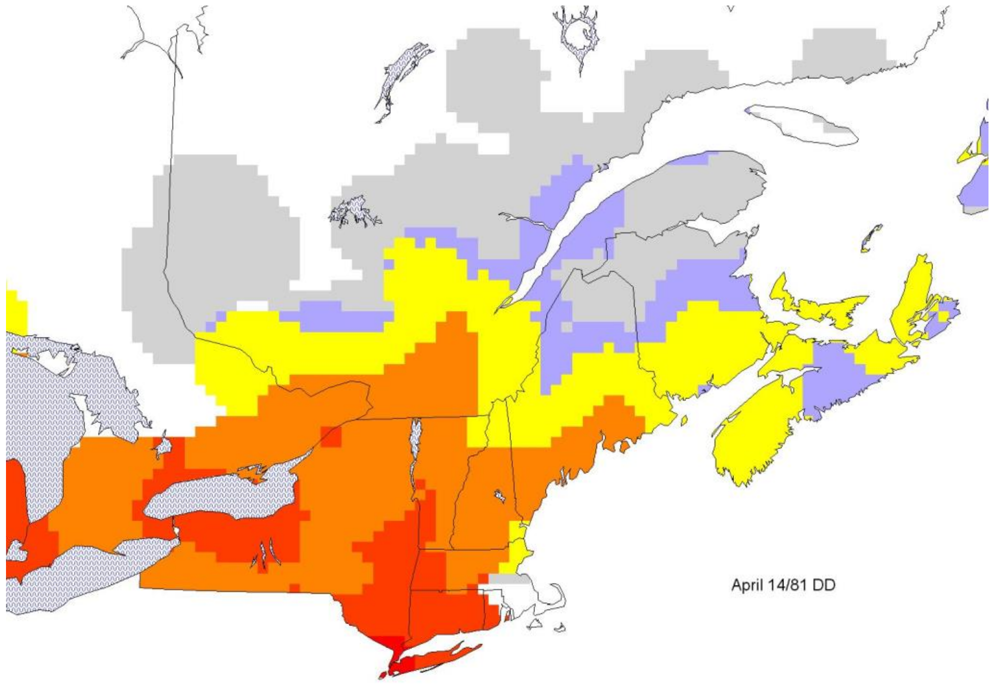


Figure 3.16. Map showing the accumulated degree-days (base 4 ^{0}C) during thaw at different time frames in 1981 for the early spring thaw-freeze event, (a) three days after thaw commencement, (b) on a day during the middle of thaw, (c) and (d) at the height of accumulation with frost starting in some locales, and (e) total area affected by the last frost.

c



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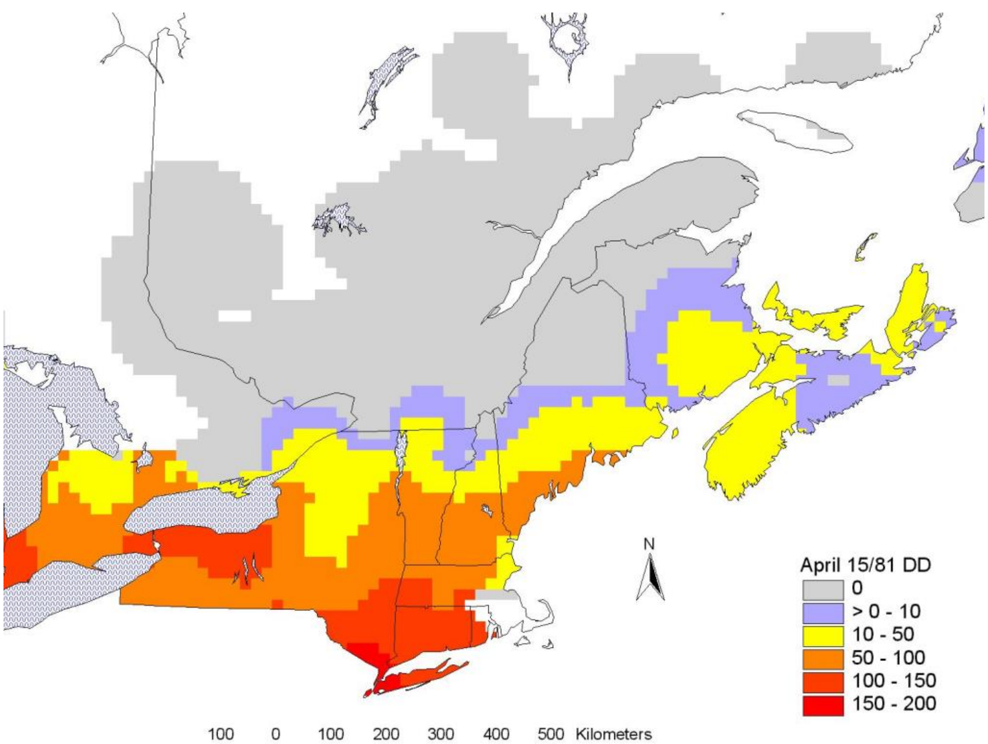


Figure 3.16. cont'd.

e

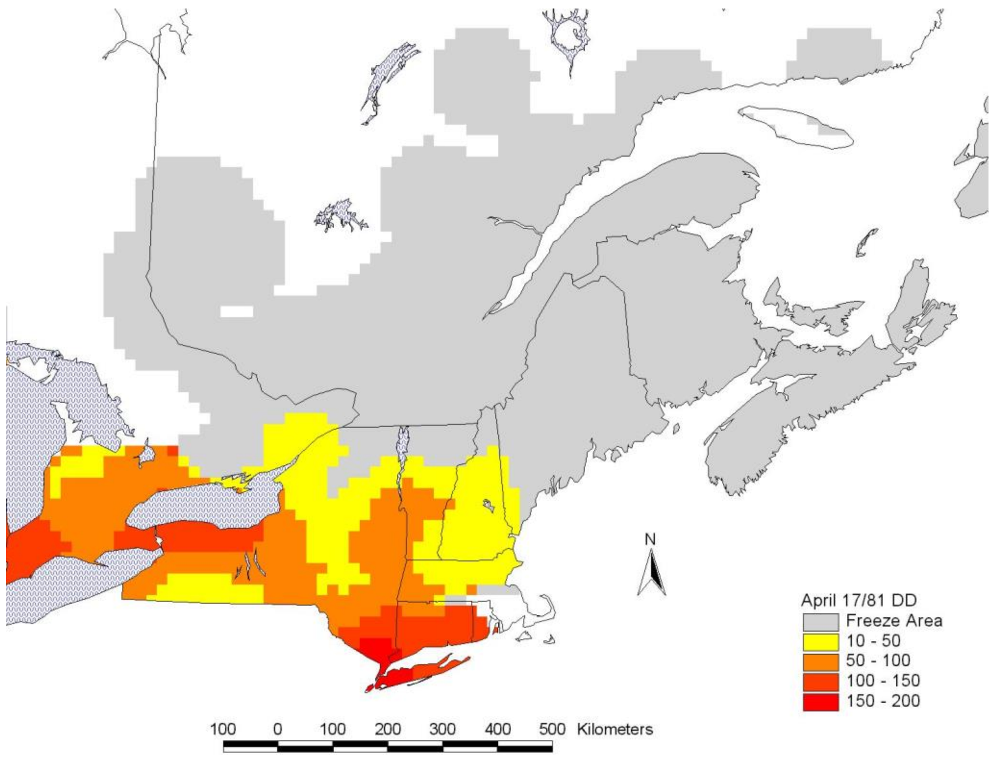


Figure 3.16. cont'd.

Summary

The techniques used in this chapter enable us to track, and spatially display temporally anomalous winter/early spring thaw-freeze events. The analysis of winter / early spring thaw-freeze events revealed that biologically significant events (GDD > 50) encompassing huge areas of eastern Canada and North-Eastern United States did occur in 1936, 1944, 1945, and also in 1957 (Appendix III, pg 142) and 1981. Other years, as illustrated in Appendix I, had more localized thaw-freeze events, which overlap with some of the larger events. Some of the years described had several thaw-freeze events. It can be concluded that:

1. The areas affected by several of these thaw-freeze events correspond well with the timing and locations of accumulated yellow birch dieback and decline.
2. Widespread anomalous weather patterns occurred at least 4 times during the 1930-1960 period. Fewer were additional minor events as well illustrated in Appendix I, each event covering different areas at different times.

CHAPTER 4

PREDICTING HISTORICAL FOREST SOIL TEMPERATURES AND SNOWPACK ACCUMULATIONS

Introduction

Knowledge of snowpack, frost and soil temperature is an important prerequisite for ecosystem process modeling and assessing the rates of many year-round processes of ecological significance (Yin and Arp, 1993). The presence of a thick snowpack is particularly important for the protection of tree roots and many soil organisms during times of severe cold, as is the case in most of northeastern North America from early to late winter, with occasional recurring frost episodes in early to late spring.

This chapter presents modeled snowpack depth and soil temperatures that were obtained with a process-oriented forest hydrology model that predicts snowpack depths based on the historical weather records for some of the weather stations that were part of the analysis in Chapter 3. The specific model used was ForHyM2, which is a non-spatial forest hydrology model, formatted in *Stella v 5.1.1 for Windows* ^{TM} (Arp and Yin, 1992; Yin and Arp, 1993; Meng et al., 1995 and Bhatti et al., 2000). This model uses daily weather records and general soil and forest canopy descriptions to predict soil moisture content, snowpack water equivalents and dynamics, and soil temperature as they vary with forest cover and soil substrate. Specifically, this model was used to simulate snowpack dynamics, and soil temperatures in the rooting zone of yellow birch forest types. This model has been validated for many soil moisture and temperature conditions for various forest conditions (Arp and Yin, 1992; Yin and Arp, 1993; Meng et al., 1995 and Bhatti et al., 2000).

The Model

ForHyM2 is an amalgamated version of the forest hydrology model ForHyM (Arp and Yin, 1992) and the forest soil temperature model ForSTeM (Yin and Arp, 1993), as introduced at the monthly scale by Meng et al. (1995), and at the daily scale by Bhatti et al. (2000). The hydrological processes addressed involve canopy interception, evapo-transpiration, snowpack accumulation, snowmelt, surface run-off, interflow, throughfall, and infiltration and percolation through the forest floor, the rooted portion of the mineral soil, and the subsoil beneath. Other processes added by Bhatti et al. (2000) are heat (energy) flow and balances, thermal properties (thermal conductivity and heat capacity), freezing and thawing, and temperature in the snowpack, the forest floor, and successive soil and subsoil layers. A flowchart illustrating water and heat fluxes is shown in Figure 4.1.

The model simulates latent heat transfer due to freezing and thawing as follows; each layer freezes when its temperature is 0 ^{o}C or below, and when its heat flux is negative. Freezing continues until all water within the layer is turned to ice. Layers will thaw when soil temperatures return to 0^{o}C, and when there is a positive heat influx. Then, incoming heat is used to melt the ice until all ice is melted. The model treats temperature change and related heat transfer by one-dimensional heat conduction process involving the atmosphere, the forest canopy, the snowpack, the forest floor, the soil and the subsoil.

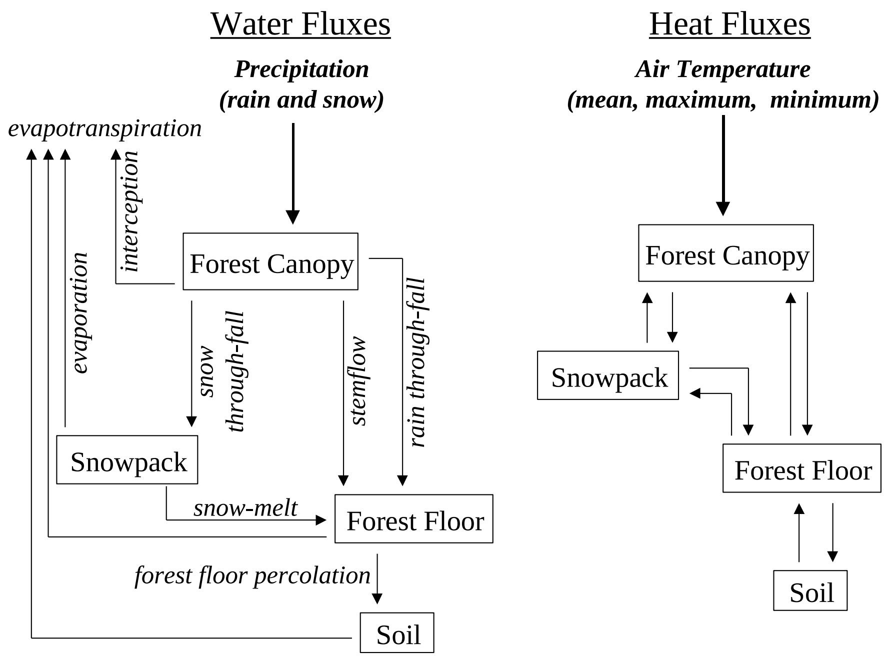


Figure 4.1. Flowchart of water (left) and heat (right) fluxes as considered in the ForHyM2 model (adapted from Meng et al., 1995).

Model Assumptions Specific to Winter Conditions

The following are assumptions specific to the winter simulations of soil temperature and snowpack dynamics: (1) snowmelt is proportional to the net energy gain of the snowpack when snowpack temperature is 0 ^{o}C; (2) heat flow through the snowpack and underlying soil layers is determined by the magnitude of the thermal gradients within the snowpack and soil, and by the thermal diffusivity coefficients of snow and soil; and (3) surface temperatures are calculated from daily energy balances (Bhatti et al 2000).

Model Inputs

Basic input requirements for ForHyM2 include daily weather records (recorded in open conditions). These include: daily minimum, mean and maximum air temperatures (^oC), and daily rainfall and snowfall (mm). Site-specific information includes conditions for mixed hardwood forests as described in Chapter 2 (yellow birch, sugar maple, beech). The generalized conditions for yellow birch as used in this model are 90 % deciduous, and 10% conifer. The minimum and maximum deciduous leaf area indicies are 2 and 4 m^2/m^2, respectively. The coniferous leaf area index is 6 m^2/m^2. The forest floor depth is 5 cm, and the rooting depth is 25 cm. The soil has a silt loam texture. With ForHyM2, daily solar radiation input is obtained from a daily solar radiation module.

Model Calculations

ForHyM2 calculates daily air and soil temperatures in the rooting zones (duff/mineral soil interface, 10 cm and 20 cm depth) and snowpack conditions for typical yellow birch site conditions for the years 1935-36, 1943-44, 1944-45 and 1980-81. The model also calculates within stand temperature conditions. Within stand temperatures are mostly affected by the leaf area index (= stem density index in winter for hardwoods). For this study, which mostly relates to leafless conditions, there is little variation from the open condition. Here, there are only minor variations within the vertical temperature profile. Calculations are based on a hydrological year that starts at the beginning of August, and ends on the following 31st of July.

Model Calibration Specific to Tolerant Hardwood Conditions

Most of the model parameters were retained as reported in and Arp and Yin, (1992); Yin and Arp, (1993); Meng et al., (1995) and Bhatti et al., (2000). An investigation of the effective Stem Area Index (SAI) for tolerant hardwoods in winter were done for typical immature-mature yellow birch stands of age and size for which dieback is generally observed. SAI was obtained with the TRAC system (Tracing Radiation and Architecture of Canopies). TRAC is an optical device, which measures gap fraction and gap size. Gap fraction is defined as the percentage of gaps in the canopy at a given zenith angle. It is obtained from radiation transmittance. With this method, it was found that the mean SAI of 15 hardwood stands was 1.3 m^2/m^2**,** with a standard deviation 0.4 m^2/m^2. The default model value was 2.0 m^2/m^2. A sensitivity analysis was performed to test the difference between the two values. The difference was found to be insignificant in model outputs for soil temperature and snowpack dynamics.

Test Areas for Snowpack and Soil Temperature Predictions

Ten weather stations were selected as follows for detailed snowpack and soil temperature evaluations:

1. they needed to be within the range of observed birch dieback;
2. for the time period since 1930, these stations represent the greatest heat accumulations for single thaw-freeze events,
3. they fall along a general east-west gradient.

The stations that were selected are listed in Table 4.1. Also listed in this table are the years of the worst thaw-freeze occurrences.

Table 4.1. Climate stations used in the ForHyM2 and Birch Dieback model.

Year	Station Name	Station #	Elevation (mASL)	Latitude	Longitude
1936	Thetford Mines, QC	7028440	311	46.40 N	71.19 W
1936	Barrage Mercier, QC	7030457	236	46.43 N	75.59 W
1936, 44, 45	Fredericton, NB	8101600	40	45.55 N	66.37 W
1936, 44, 45	Stillwater, NS	8205600	17	45.11 N	62.00 W
1944	Lac Onatichiway, QC	7063683	305	48.54 N	71.20 W
1944, 45	Barrage Lac Morin, QC	7050455	198	47.39 N	69.31 W
1945, 81	Lennoxvillle, QC	7024280	181	45.22 N	71.49 W
1981	Kemptville, ON	6104025	99	45.00 N	75.38 W
1981	Lambton, QC	7024000	366	45.50 N	71.50 W
1981	Nepisiquit Falls, NB	8103500	34	47.24 N	65.47 W

Results

A total of 36 model runs were done to capture the worst thaw-freeze events since 1930. Of these runs, only a subset of these runs are presented in this Chapter, to illustrate the main trends. The same runs are also used in Chapter 5, to analyze the relationship between the temperature simulations and potential risk for frost-induced shoot and root injuries. In this Chapter, the results are displayed in Figures 4.2 to 4.5 by showing:

1. mean within stand air temperatures
2. modeled temperature at the duff(organic)/mineral soil interface, i.e., the location of highest fine root density
3. modeled snowpack dynamics (changes in snow depth).

In general, depth of snowpack greatly influences soil temperatures by providing insulation from fluctuating air temperatures. For example, in winters of reduced snow cover (< 10 cm), soil temperatures at a depth of 2.5 cm were observed to drop 10 ^{o}C below the 16-year normal of –2 ^{o}C at Fredericton, NB, Canada (Salonius et al., 1977).

In assessing snowpack and soil temperature regimes as they varied across eastern Canada since 1930, by year, and in evaluating the impact of these regimes on shoot and root injuries in yellow birch (and other tree species), it is important to observe the timing of the air temperature fluctuations in relation to the local snowpack accumulations. Across eastern Canada, various combinations can occur, as illustrated in Figures 4.2 to 4.6, as follows:

1. Late snowpack accumulations and early snowmelt events in 1935/36 likely allowed for considerable soil frost throughout the winter across eastern Canada (Figure 4.2).
2. Late and very limited snowpack accumulations in 1943/44 likely allowed for considerable soil frost throughout the winter in the southern parts of eastern Canada; the northern parts likely were protected by early and long-lasting snowpack accumulations (Figure 4.3).
3. Late and very limited snowpack accumulations in 1944/45 would have allowed for considerable soil frost throughout the winter in Atlantic Canada; forests in Quebec and further west were likely protected by early and long-lasting snowpack accumulations (Figure 4.4).
4. Very limited snowpack and very early snowmelt events in 1980/81 likely lead to very deep soil frost penetration through most of Eastern Canada (Figure 4.5 and 4.6).

Details

As can be seen in Figures 4.2a and 4.2b, snow in southern Quebec at Thetford Mines, QC (311 m ASL) in the year of 1935 started to occur in November, but – according to the simulations - was not calculated to accumulate to a sizeable snowpack until the beginning of January in 1936. By that time, the duff/mineral soil interface temperature should have dropped to –9.0^{o}C on two occasions. Figure 4.2b illustrates this situation at Barrage Mercier (236 m ASL) within the Lower Ottawa and Gatineau River Basin, where temperatures likely dropped to -5.7^{o}C for the same year. Snowmelt was likely complete in the forests of southern Quebec at the end of May 1936.

Figure 4.2c represents conditions at Fredericton, NB (40 m ASL), and shows that snowpack accumulation likely began in December 1935, and quickly reached an adequate depth to buffer the soil against low air temperatures for most of the winter. The minimum duff/mineral soil interface temperature reached –7.0^{o}C only once in that year. Mean air temperatures for Fredericton had similar trends to those in Quebec (December – March), but did not reach the low temperatures recorded in Quebec. Figure 4.2d illustrates the situation for Stillwater, NS (17 m ASL), where air temperatures significantly higher than those observed in Fredericton were recorded for the same period. The snowpack began to accumulate in late December 1935, but soil temperatures were likely sustained above -2.5^{o}C throughout the winter.

1935-1936

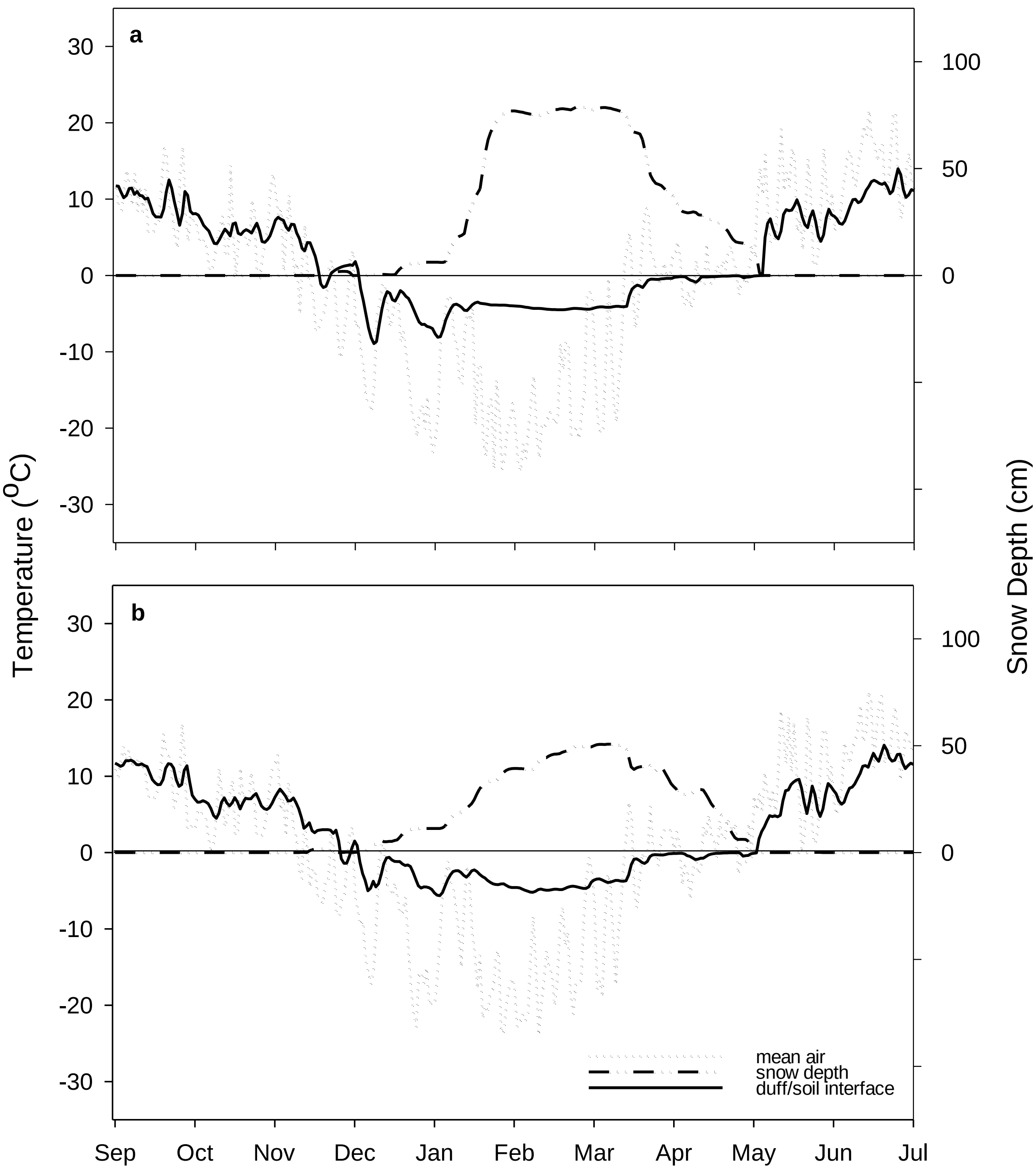


Figure 4.2. ForHyM2 model outputs showing modeled mean air temperature (°C), modeled snow depth (cm) and temperature at the duff/mineral soil interface (°C) for (a) Thetford Mines, QC (7028440) and (b) Barrage Mercier, QC (7030457) for the winter and spring periods of 1935-1936.

1935-1936 cont'd

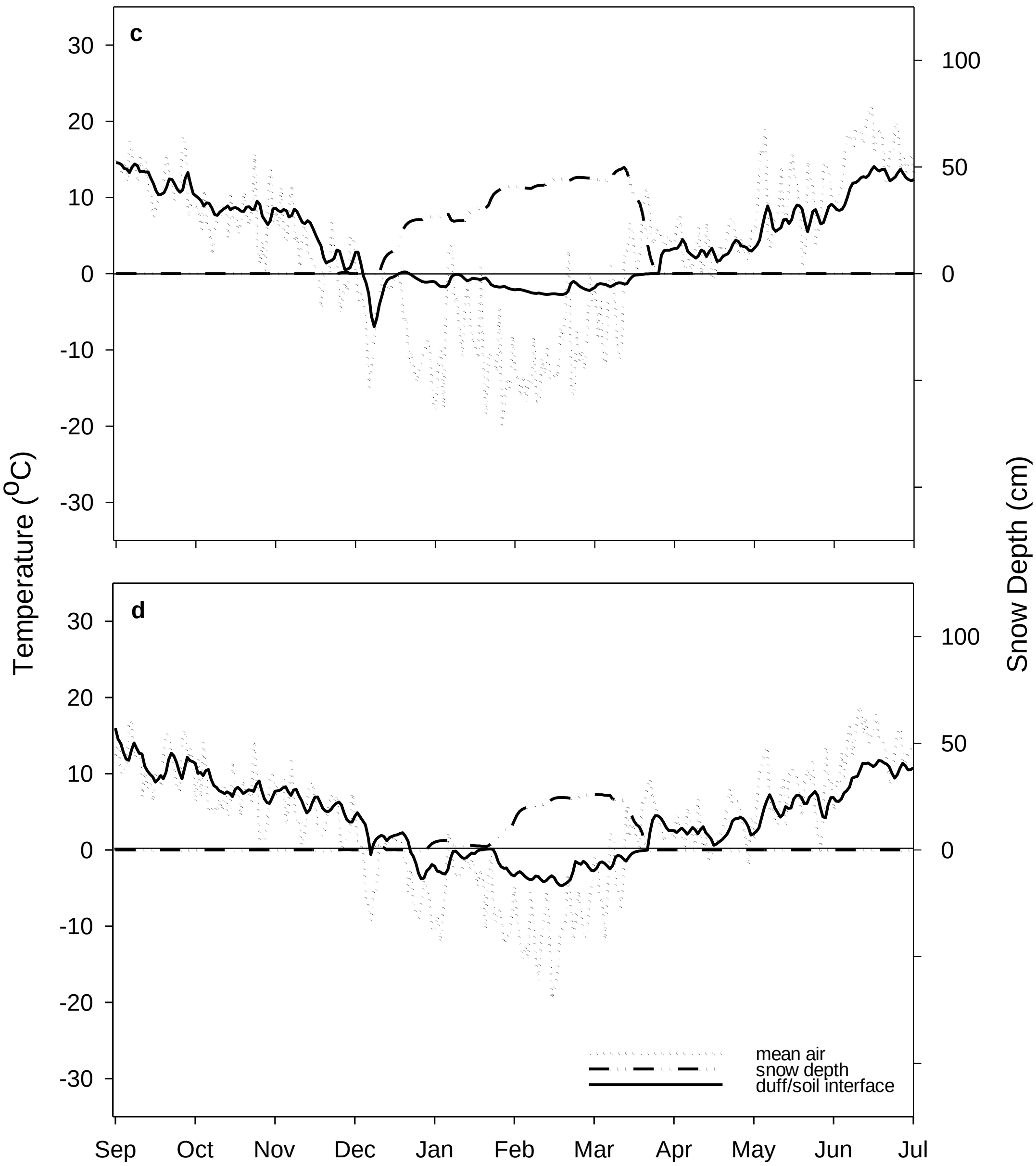


Figure 4.2 cont'd. ForHyM2 model outputs showing modeled mean air temperature (^{o}C), modeled snow depth (cm) and temperature at the duff/mineral soil interface (^{o}C) for (c) Fredericton, NB (8101600) and (d) Stillwater, NS (8205600) for the winter and spring periods of 1935-1936.

ForHyM2 outputs for snowpack and air and soil temperature conditions during 1943 - 1944 are illustrated in Figures 4.3a-d. Figure 4.3a presents the condition for Lac Onatichiway in the Lac St. Jean Basin, at the northern limit of yellow birch. This area, as calculated, accumulated snow to a depth of 1.25 m, starting from mid November and lasting until the end of May. The minimum duff/mineral soil interface temperature was calculated to be –3.3^{o}C. In contrast, snowpack at Barrage Lac Morin was calculated to accumulate at the end of December, and that snowpack likely disappeared by the beginning of May 1944. The calculated minimum duff/mineral soil interface temperature was –6.6^{o}C, which occurred in February (Figure 4.3b).

The 1943-44 case for Fredericton and Stillwater is illustrated in Figure 4.3c and d, showing a similar pattern of air temperatures and calculated snowpack accumulation beginning at the start of December 1943, followed by a complete loss of snowpack by the end of April 1944. Stillwater received more snow than Fredericton in that year. Calculated minimum soil temperatures were –8.4^{o}C for Fredericton and –5.9^{o}C for Stillwater.

1943-1944

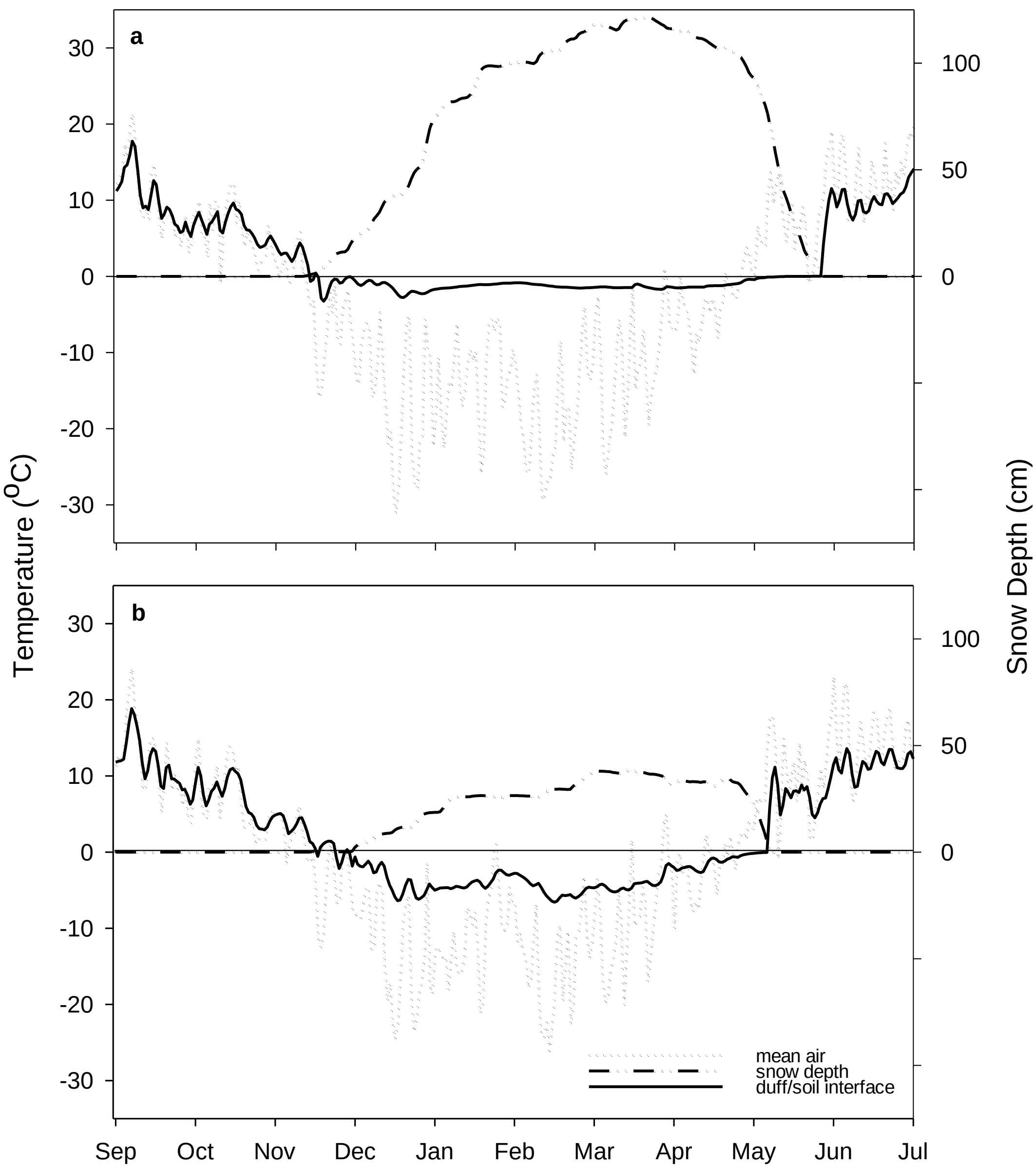


Figure 4.3. ForHyM2 model outputs showing modeled mean air temperature (^oC), modeled snow depth (cm) and temperature at the duff/mineral soil interface (^oC) for (a) Lac Onatichiway, QC (7063683) and (b) Barrage Lac Morin, QC (7050455) for the winter and spring periods of 1943-1944.

1943-1944 cont'd

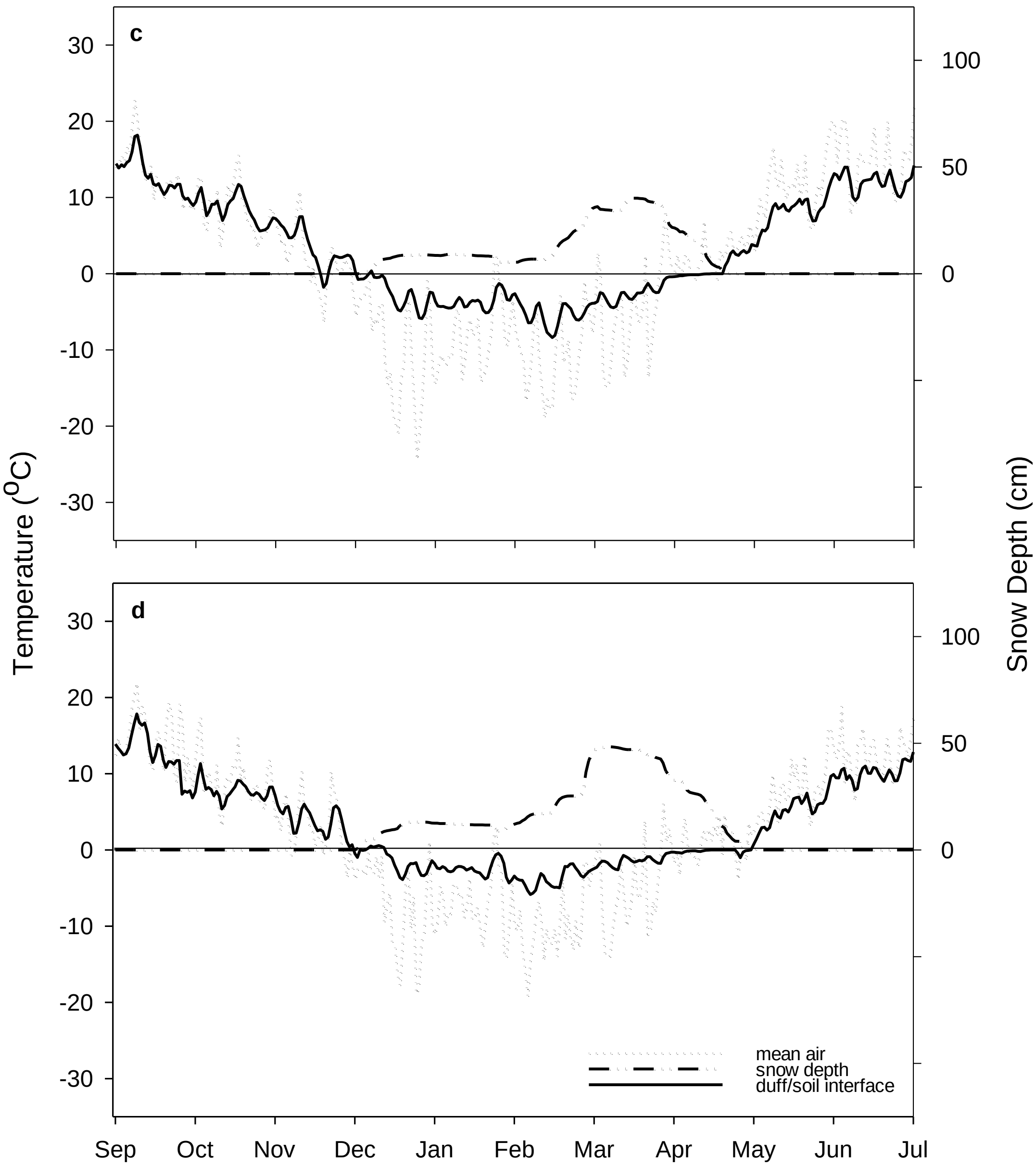


Figure 4.3 cont'd. ForHyM2 model outputs showing modeled mean air temperature (^oC), modeled snow depth (cm) and temperature at the duff/mineral soil interface (^oC) for (c) Fredericton, NB (8101600) and (d) Stillwater, NS (8205600) for the winter and spring periods of 1943-1944.

Figure 4.4 illustrates ForHyM2 model outputs for the winter of 1944 - 1945. Figure 4.4a and b show similar patterns of snowpack accumulation for stations in Lennoxville and Barrage Lac Morin. In both cases, snowpack accumulations amounting to 1 m were calculated to occur at the beginning of December and these should have completed melting by the start of April at Lennoxville and by mid- April at Barrage Lac Morin. The calculated minimum soil interface temperatures were –1.3^{o}C and -1.0^{o}C, respectively. At the same time, calculated soil temperatures in Fredericton dropped to –5.0^{o}C before snowpack would have accumulated at the end of December 1944. Total snow depth at Fredericton was calculated to be 75 cm, while snowpack depth at Stillwater was limited to about 25 cm, and calculated minimum soil temperature dropped to –4.0^{o}C. In 19944/45, therefore, frost formations were calculated to be more extensive in Atlantic Canada than in Quebec.

1944-1945

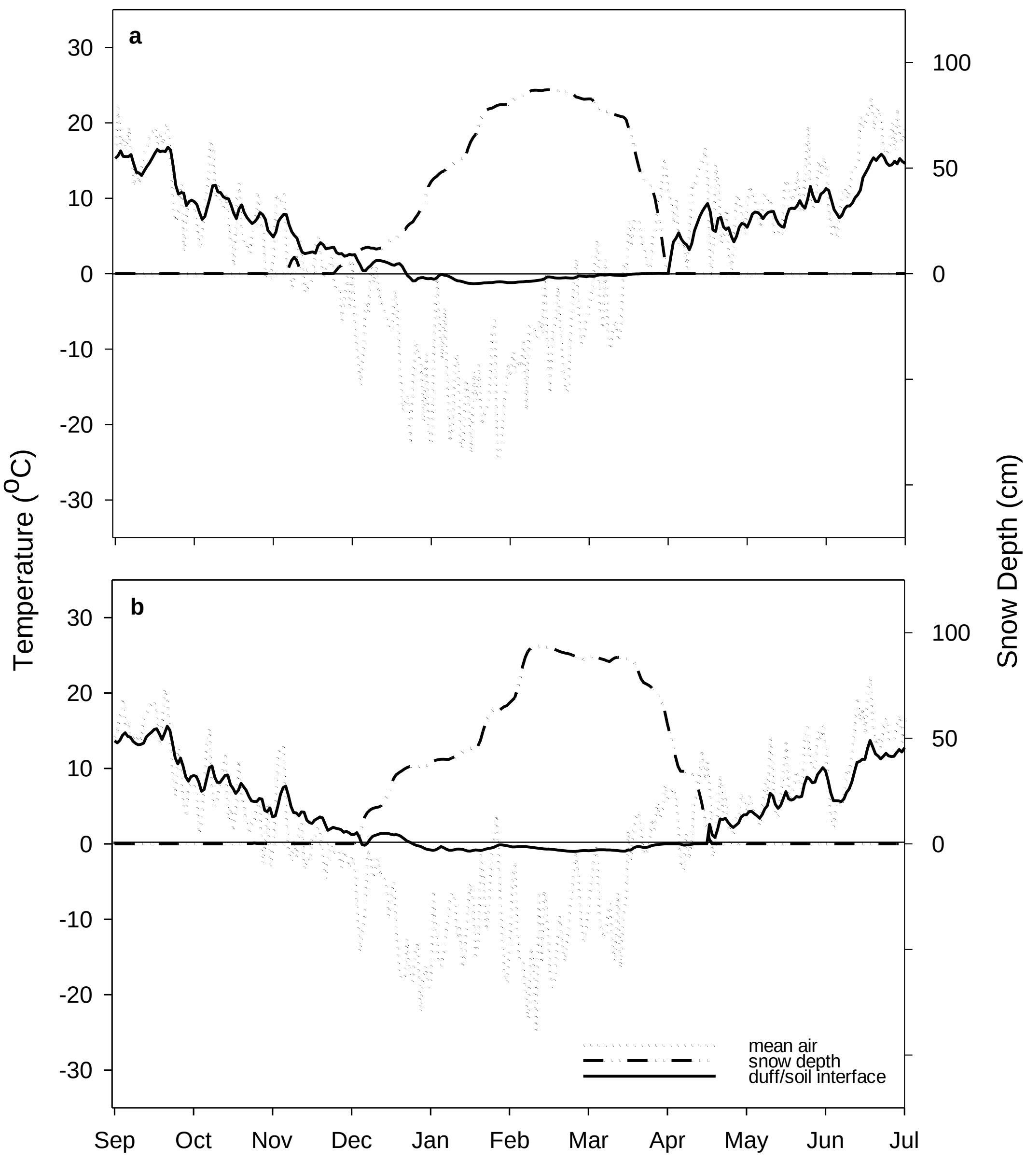


Figure 4.4. ForHyM2 model outputs showing modeled mean air temperature (^oC), modeled snow depth (cm) and temperature at the duff/mineral soil interface (^oC) for (a) Lennoxville, QC (7024280) and (b) Barrage Lac Morin, QC (7050455) for the winter and spring periods of 1944-1945.

1944-1945 cont'd

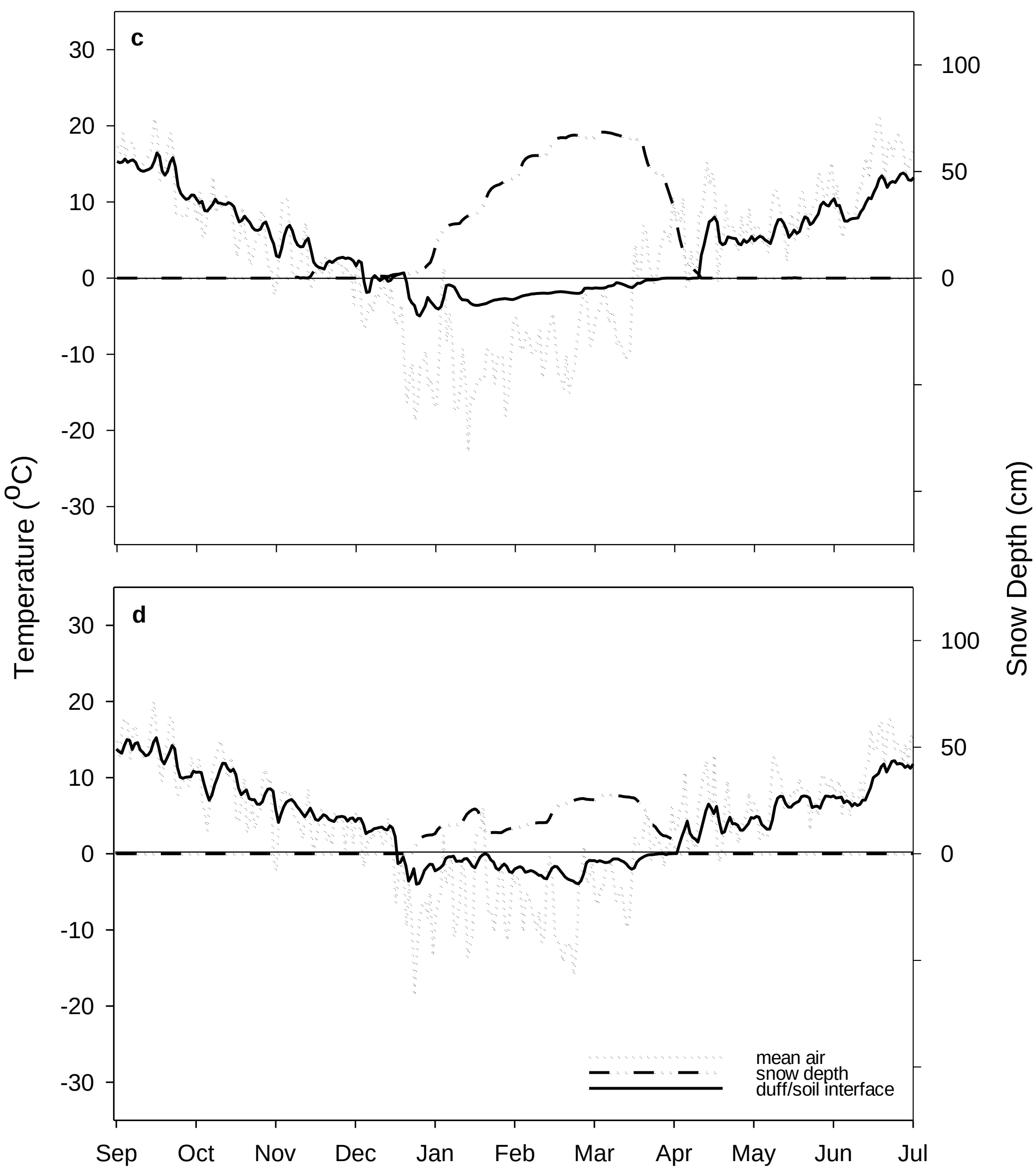


Figure 4.4 cont'd. ForHyM2 model outputs showing modeled mean air temperature (°C), modeled snow depth (cm) and temperature at the duff/mineral soil interface (°C) for (c) Fredericton, NB (8101600) and (d) Stillwater, NS (8205600) for the winter and spring periods of 1944-1945.

Snowpack and mean air temperatures for the winter of 1980-1981 are shown in Figure 4.5. The focus for 1980-1981 is eastern Ontario, southern Quebec and northern New Brunswick, which all underwent a major thaw-freeze event from February 14 – February 28, and experienced an unusually cold March. Figure 4.5a illustrates conditions at Kemptville, ON (99 m ASL) in the eastern Ontario Counties, where snow was calculated to accumulate at the start of December of 1980, and this snow was then calculated to have completely disappeared by the end of February 1981. At that point, soil temperature likely dropped from above 0^{o}C to – 3.0^{o}C on two occasions. The minimum soil temperature was calculated to be -6.2^{o}C, was likely limited to 25 cm (extremely cold January). At Lambton, snow was calculated to accumulate in the middle November, but not in substantial amounts until the start of December 1980. Calculated soil temperatures for Lambton dropped to -5.4^{o}C at the beginning of March. The pattern was similar for Lennoxville, were the minimum soil temperature was calculated to be -4.3^{o}C.

At Nepisiguit Falls (34 m ASL) in northern New Brunswick, the calculated timing for the accumulating and disappearing of snow was similar, but snowmelt was likely delayed until the end of February, and some snow should have remained until mid April of 1981. A lowest soil temperature of -6.0^{o}C would have occurred after the calculated snowmelt event in April 1980-1981.

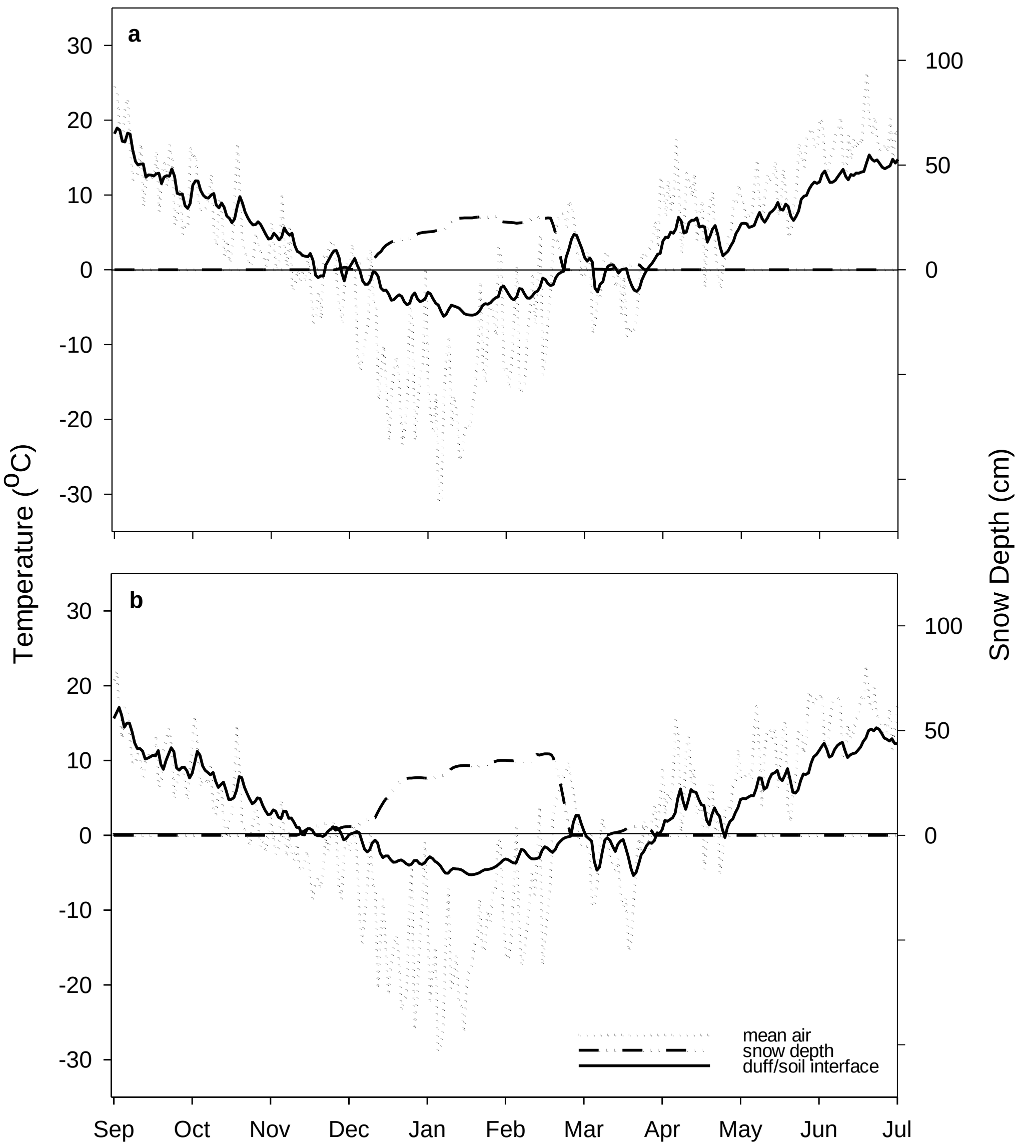


Figure 4.5. ForHyM2 model outputs showing modeled mean air temperature (^oC), modeled snow depth (cm) and temperature at the duff/mineral soil interface (^oC) for; (a) Kemptville, ON (6104025) and (b) Lambton, QC (7024000) for the winter and spring periods of 1980-1981.

1980-1981 cont'd

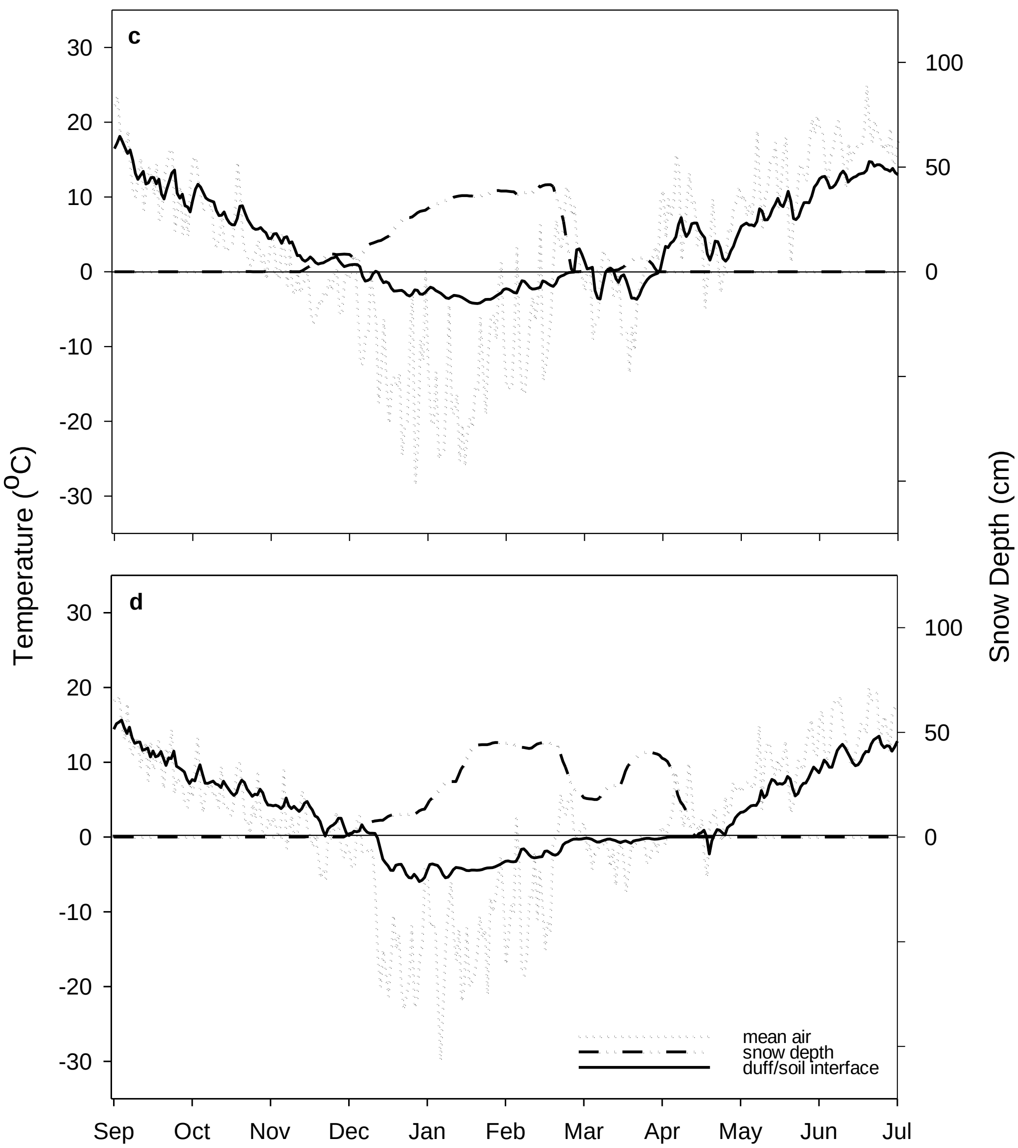


Figure 4.5 cont'd. ForHyM2 model outputs showing modeled mean air temperature (°C), modeled snow depth (cm) and temperature at the duff/mineral soil interface (°C) for; (c) Lennoxville, QC (7024280) and (d) Nepisiguit Falls, NB (8103500) for the winter and spring periods of 1980-1981.

Discussion

The ForHyM2 model has already been tested extensively in terms of calculations for snowpack, soil temperature, soil frost, and also other hydrological variables such as soil moisture, stream discharge and soil water table (Arp and Yin, 1992; Yin and Arp, 1993; Meng et al., 1995 and Bhatti et al., 2000). For this reason, further model testing was not conducted. It is assumed that each of the 36 model runs, including those displayed in Figures 4.2 to 4.5, adequately represent conditions as they would have occurred at each location. A comparison of actual measured snow depth versus ForHyM2 modeled snowpack dynamics, however, is provided in Figure 4.6 for Lennoxville, QC in 1981.

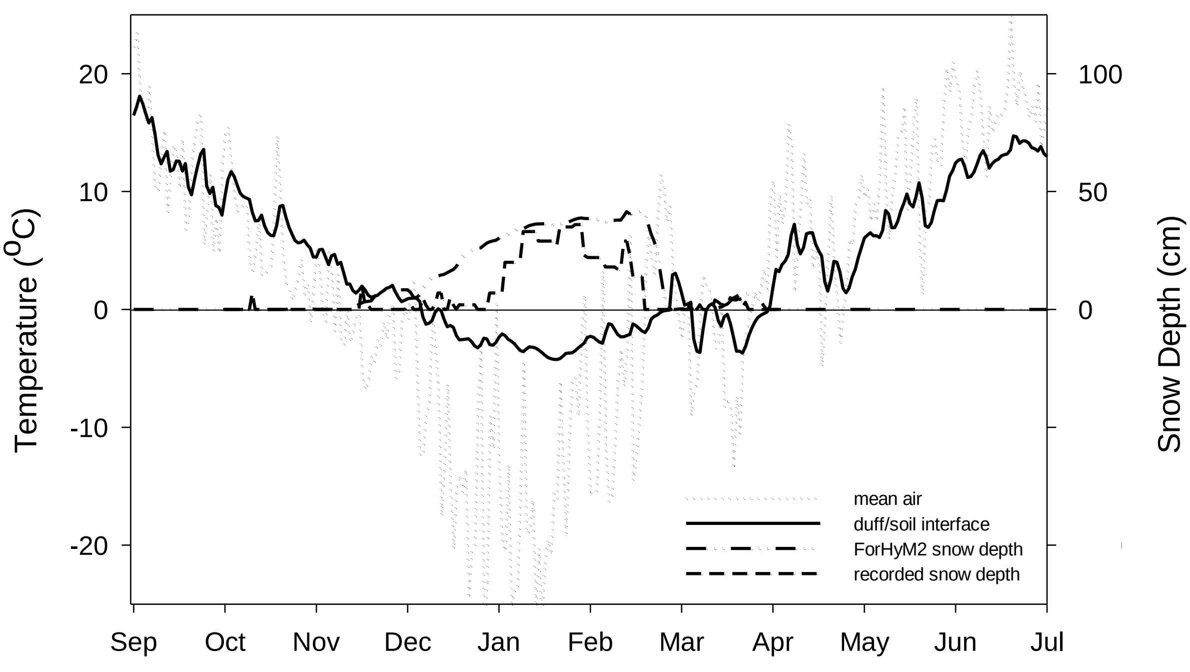


Figure 4.6. Time series showing ForHyMII modeled mean air temperature (^{o}C), modeled forest condition snow depth (cm), climate station (open conditions) measured snow depth (cm), and ForHyM2 calculated temperature at the duff/mineral soil interface (^{o}C) for Lennoxville, QC (7024280) for the winter and spring periods of 1980-1981.

For this comparison, one should note that the recorded snowpack accumulations are for open-ground conditions, which are standard for forest clearings in which most of the more remote weather stations are located. Open-ground snowpack accumulations, however, differ from below-canopy snow accumulations for several reasons:

- Snow melt events are usually more extensive and occur earlier on open-ground than below canopy because of exposure to higher energy inputs in the open,
- Snow accumulations may be less on open areas because of wind drift, and subsequent catch in the neighboring forest,
- There may be less snow on the ground in forests due to canopy interception of the snow.

The model-calculated snowpack accumulations above those recorded for the open ground condition at Lennoxville appeared to be realistic, and are in keeping with general expectations.

CHAPTER 5

PREDICTING HISTORICAL YELLOW BIRCH FREEZING INJURIES

Introduction

Observing and tracking change in phenological behaviour of plants has become an important focus in ecological research (Schwartz, 1999). For example, the seasonal timing of spring events such as budding (bud swell, bud break, etc…), leafing or flowering of plants highly depends on the accumulation of growing degree-days. Generally, early accumulation of growing degrees in late winters and early spring promotes an early decrease of frost hardiness, an early conversion of plant starch into soluble carbohydrates, an early development of plant sap in many woody species, and an early promotion of flowering and leafing (Chmielewski and Rotzer, 2001). Even during winter thaws of significant duration, considerable loss of soluble carbohydrates may occur as a result of plant respiration (Van den Drissche, 1979, Ogren, 1996). This, in turn, lowers the sugar-induced protection of cells and plasma membranes against frost damage (Santarius, 1982, Steponkus, 1984).

The primary purpose of this chapter is to present and utilize a recently developed process-based Birch Dieback Model (Zhu et al. 2002). The objective is to asses and quantify the risk of frost damage in shoot and root tissues of yellow birch by location and by year for notable thaw-freeze events. This is to determine

1. extent of shoot and root freezing injury,
2. subsequent reduction in the early-season root pressure,

3. extent of incomplete reversal of winter-induced xylem cavitation, and subsequent shoot dieback.

Risk of frost damage in yellow birch has already been documented and reported for simulated and natural winter conditions (Cox and Malcolm, 1997; Zhu et al. 2000, 2001). In particular, soil freezing at -10.0^{o}C was found to cause a 10-20 % increase of relative electrolyte leakage (REL) in roots, a reduction of root pressure, an increase in un-restored winter cavitation, and considerable shoot dieback in potted yellow birch seedlings. In this, the measurement of shoot and root freezing injuries by REL proved to be a reliable indicator of frost hardiness (see also DeHayes and Williams, 1989). Xylem cavitation was determined as % loss of hydraulic conductivity. For yellow birch, over-wintering shoots may loose 75 to 100 % of their hydraulic conductivity. Springtime root pressure, however, eliminates winter cavitation normally in injured plants. Lack of cavitation reversal, in contrast, can be directly related to thaw duration, and to subsequent soil, root and shoot freezing, including progressive shoot desiccation (Zhu et al. 2000, 2001).

The Dieback Model

With the Birch Dieback Model (Figure 5.1), it is possible to estimate/model shoot water content, extent of xylem cavitation, and extent of shoot and root freezing injuries from daily weather records for air temperature and precipitation, and a mean monthly summary of local solar radiation. Daily weather and solar radiation inputs are converted into realistic soil temperature projections, day-by-day, and year-round, as already shown in Chapter 4. Air and soil temperatures, in turn, are converted into cumulative air and soil degree-days, by way of air and soil heat summations. Air temperatures are, furthermore, used to calculate rates of evapotranspiration from vegetative surfaces such as leaves and twigs. Water loss through evapotranspiration leads to xylem cavitation when the tree or seedlings stems are frozen. Based on air and soil temperatures, cumulative degree-days above 4^{o}C are used to evaluate percent level of potential shoot and root injury. All of this is based on empirical research that was done to evaluate shoot and root hardiness in relation to cumulative degree-days above 4^{o}C. Also based on cumulative degree-days are the calculations that determine the onset and the extent of root pressure, and related reversal of the winter-induced of xylem cavitation.

The model was also developed to simulate the biological switches that control the onset of dormancy and other ontogenetic processes, by tracking;

1. the entire phenology of root and shoot hardening,
2. xylem cavitation,
3. the reversal of the same by way of root pressure build-up in the spring, with and without the occurrence of frost-induced shoot and root injuries.

Formulating the control mechanism for onset of dormancy and other ontogenetic processes required special attention. This was done by introducing a chilling-trigger, and the empirical assessment of the chilling requirement for dormancy development. The chilling requirement prevents premature development during warm spells in autumn and early winter, and is the only mechanism that maintains dormancy. Dormancy develops when air temperature is between –3.5^{o}C and 10^{o}C, and dormancy development attains its highest rate at 3.5^{o}C (Sarvas 1972, 1974; Linkosalo 2000).

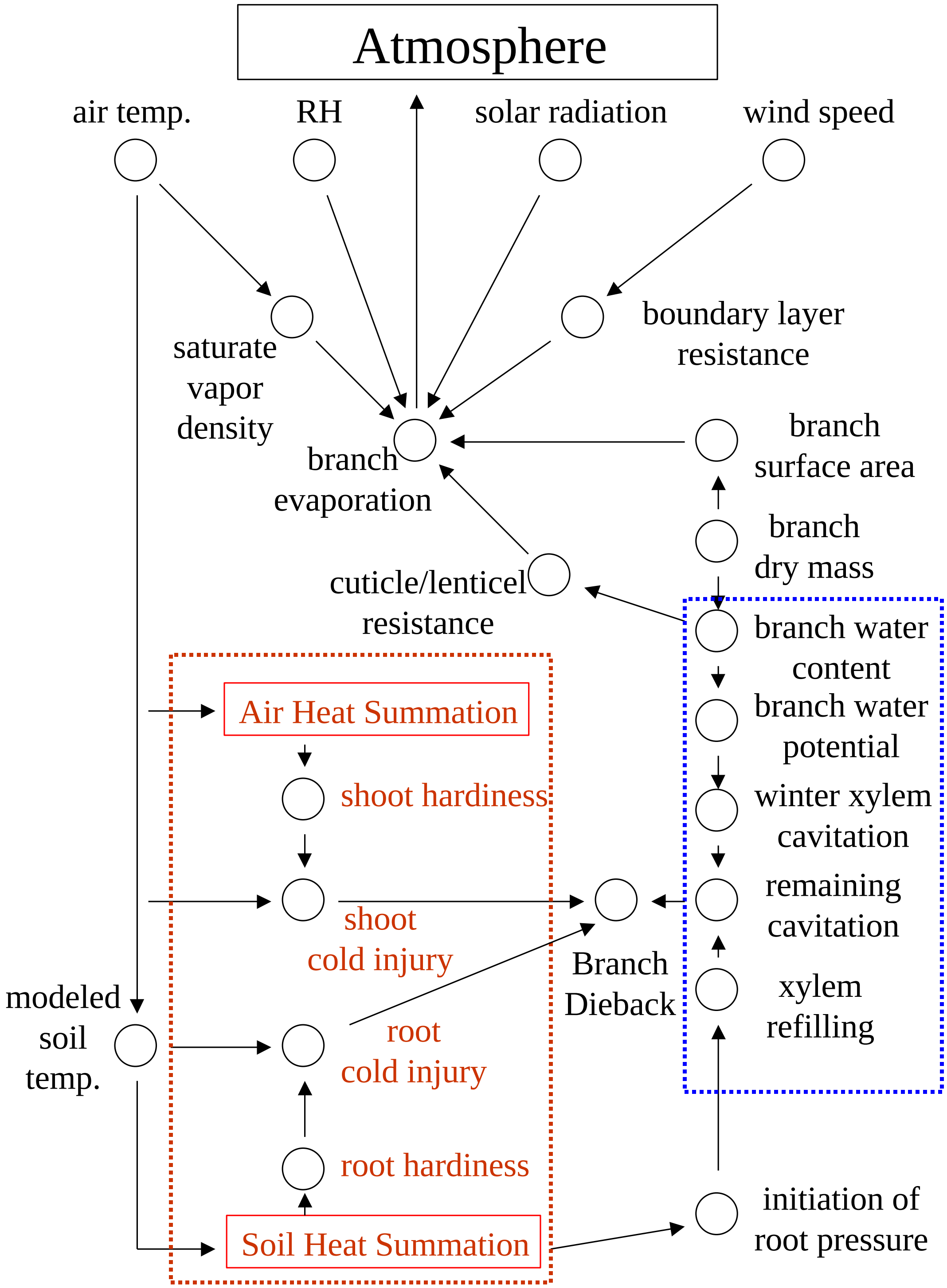


Figure 5.1. Showing schematic diagram of the Birch Dieback model. Branch water relations are outlined in blue while the heat summation/phenology sub-model is outlined in red. In this sub-model, shoot dieback is empirically linked to extent of shoot and root freezing injuries (adapted from Zhu, 2002)

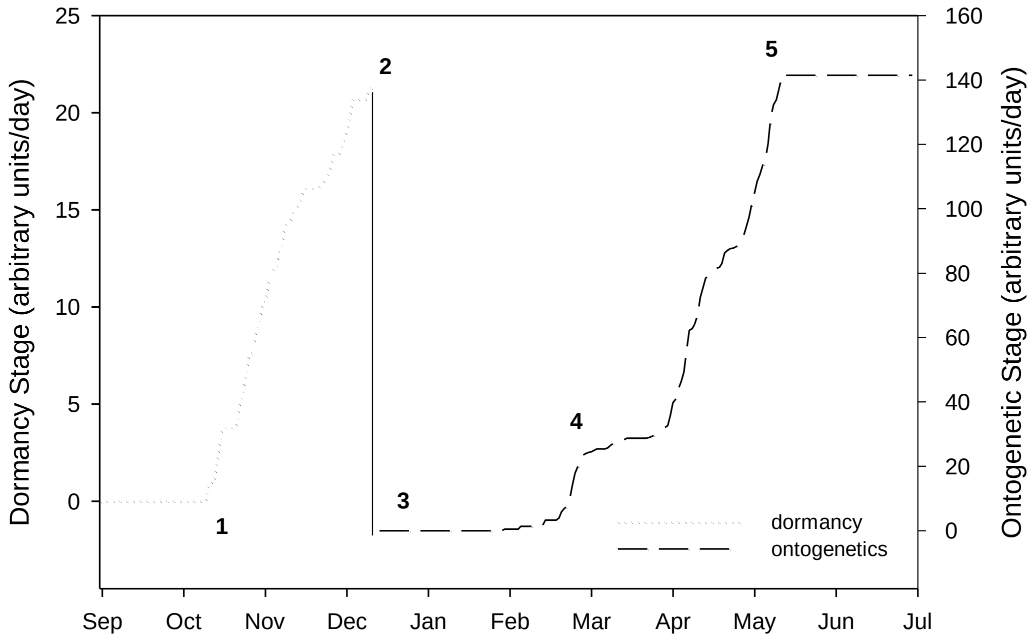


Figure 5.2. An example of modeled dormancy and ontogenetic development in yellow birch of Lennoxville, QC in 1980-1981 which is considered to be an anomalous year. 1 = leaf fall; 2 = complete dormancy; 3 = starting point of heat summation; 4 = starting point of root function (development of root pressure); 5 = bud burst (modeled after Sarvas 1972, 1974; Linkosalo 2000 *in* Zhu 2002b).

Once dormancy stage reaches a threshold value, dormancy is complete and ontogenetic development of buds can proceed if temperatures remain favorable for this development. The starting date for dormancy varies from year to year. Bud initiation (bud swell and subsequent bud burst) occurs when the ontogenetic stage of development exceeds a threshold value.

To obtain a critical value for completion of dormancy, mean leaf fall dates were obtained for three consecutive years in parts of the study area. Similarly, mean dates for root pressure initiation and bud burst were obtained to determine the timing of the end of dormancy.

Model Assumptions

Key assumptions governing the biophysical and physiological processes of the Birch Dieback model are that: **(1)** water loss through evaporation and sublimation in winter twigs can be estimated from daily changes in micro-meteorology; **(2)** decrease in branch water content during thaw-freeze cycles induces xylem cavitation; **(3)** frost injury to shoot and root system negatively affects the stem and branch xylem refilling capability; **(4)** residual xylem cavitation after spring refilling leads to branch dieback.

Model Calibration

Laboratory experiments conducted by Cox and Malcolm (1997) and Zhu et al. (2000, 2001) have already established all of the required model parameters. These parameters were directly obtained from experimentally determined relationships among xylem moisture content, xylem water potential, and xylem cavitation, and between soil/air temperatures to root/shoot injuries. Field observations of mature yellow birch trees were also used to parameterize extent of shoot dieback in reference to extent of xylem cavitation and root and shoot freezing injuries. Following parameter extraction, and additional fine-tuning of model calculations, it was possible to have all model predicted values for xylem cavitation, REL, root pressure, and % shoot dieback fall within the 95% confidence interval of the corresponding mean observed field values (Zhu et al. 2000, 2001).

To re-construct the observed historical birch dieback events in 1936, 1944, 1945 and 1981, climate records from the beginning of September to the end of June were used to run the Birch Dieback Model. This included the winter and spring periods of 1935-1936, 1943-1944, 1944-1945, and 1980-1981. A total of 36 model runs were conducted, as previously described in Chapter 4. Cell damage in shoots or roots was estimated when daily air and soil temperatures (as calculated) crosses the model-estimated root or shoot hardiness curves (cross-over). All of these results are shown in Figures 5.3 to 5.6. In each of these Figures, the following items are displayed:

1. calculated soil temperature at the duff / mineral soil interface;
2. three root hardiness curves corresponding to the specific soil temperature that would induce 10, 15 and 20% levels of potential root injuries;
3. three shoot hardiness curves corresponding to the specific air temperature that would induce 20, 25 and 30% levels of potential shoot injuries;
4. the timing of when the calculated soil temperature curves cross the hardiness curves.

Results

Inspection of Figures 5.3 through 5.6 reveals the following:

1. Cross-overs between air and calculated soil temperatures and specific temperature-dependent shoot and root frost hardiness curves may occur at any time during winter. Cross-overs, however, are most prevalent in early to late spring. Next, cross-overs may occur in early winter when snowfall is delayed. Cross-overs do not occur in years when deep snowpacks accumulate early, or when snow melt occurs late.
2. In some years and certain locations, cross-overs only occur for roots, and in other years and locations, only for shoots. Yet in other years and locations, cross-overs occur for both shoots and roots. In all of these, potential for shoot injuries appear to be – as calculated - more prevalent than root injuries.

Details

1935-1936

Figure 5.3 illustrates daily changes in root and shoot cold-hardiness of yellow birch for the winter and spring periods of 1935-1936. Snow depths were considerable, thus the onset of activity in roots was somewhat delayed (beginning of May). Shoots, according to the air heat summation of that year, likely began ontogenetic development at the beginning of April. The first de-hardening activities in the shoots were likely triggered by a minor thaw in March in parts of the study area where higher heat sums (GDDs) accumulated quickly. At Thetford Mines, root cell injuries may have occurred at a level of 10 % in December and January; shoot cell injuries of 25 – 30 % were estimated to occur in May and June. At Barrage Mercier, yellow birch likely experienced a slightly earlier onset of ontogenetics than at Thetford Mines, but estimated root and shoot levels were similar.

In Fredericton, root activities likely started at the beginning of April, and roots were calculated to be fully de-hardened by the end of that month. Ontogenetic development in shoots likely began at the end of March, and was likely completed by the start of June. Root cell injuries were estimated at 10 % in December while no shoot cell injuries were calculated to occur. Stillwater would have had the earliest onset of ontogenetics for both roots and shoots. No root cell injuries were estimated but shoot cell injuries of 25 - 30% likely occurred in April and May.

Thetford Mines, QC

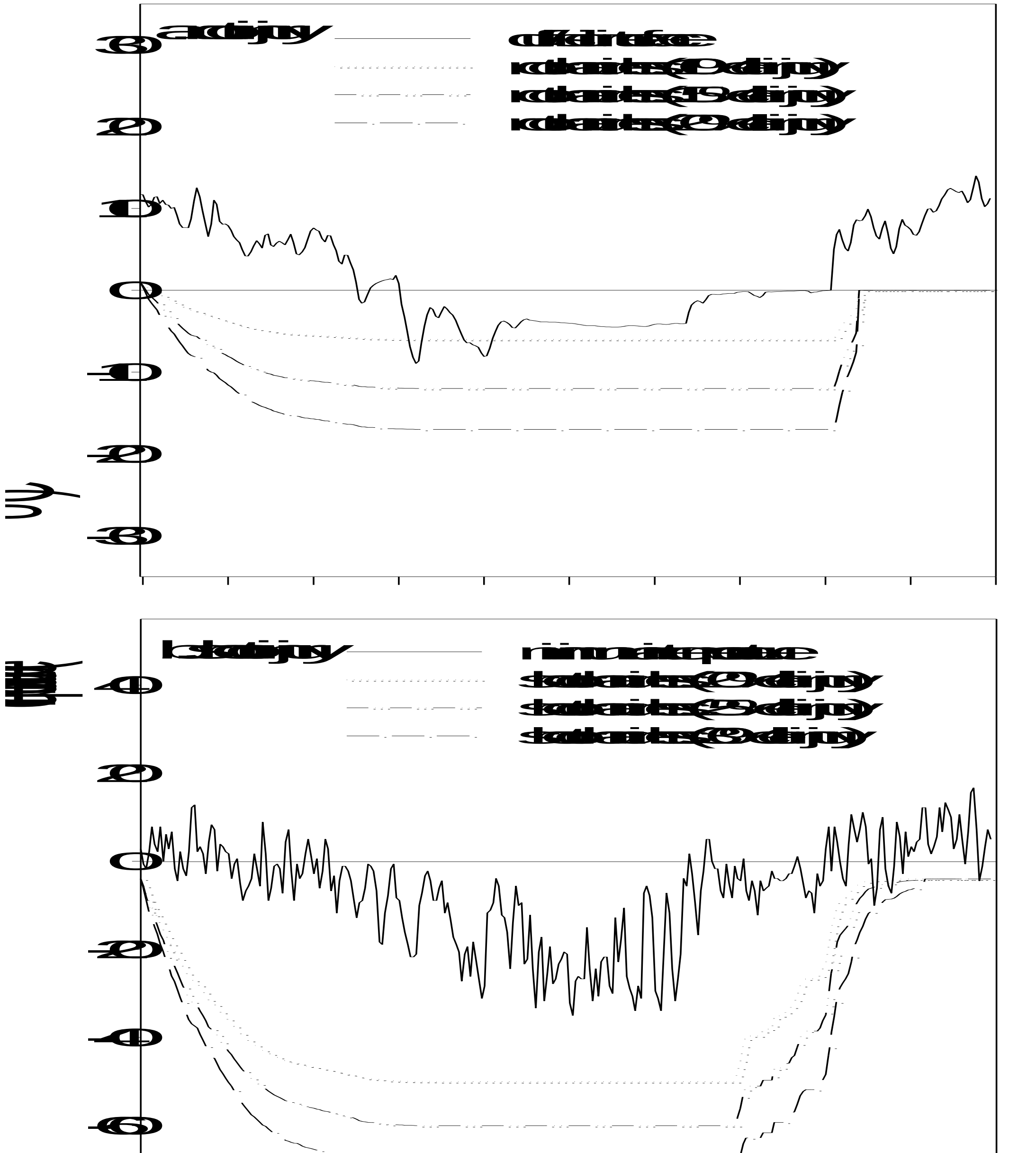


Figure 5.3. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Thetford Mines, QC (7028440) during the winter and spring periods of 1935-1936. Cross-overs (estimated cell damage) are calculated to occur in December and January for roots and on three separate occasions during May and June for shoots. Air temperature is actual climate station data, while soil temperature is calculated output from ForHyM2 model.

Barrage Mercier, QC

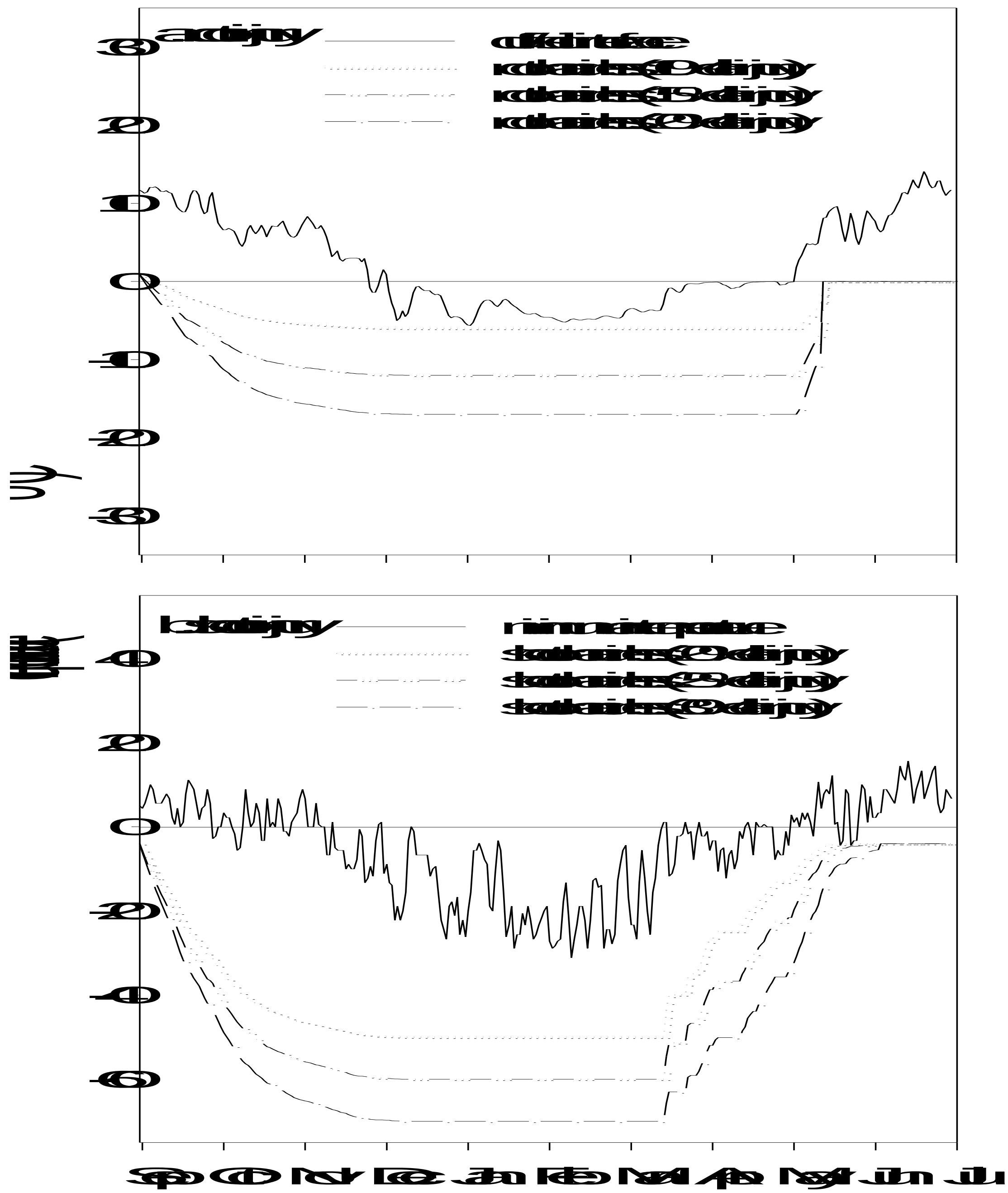


Figure 5.3 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Barrage Mercier, QC (7030457) during the winter and spring periods of 1935-1936. Cross-overs (estimated cell damage) were barely avoided in December and January for roots and calculated to occur on two separate occasions during May for shoots.

Fredericton, NB

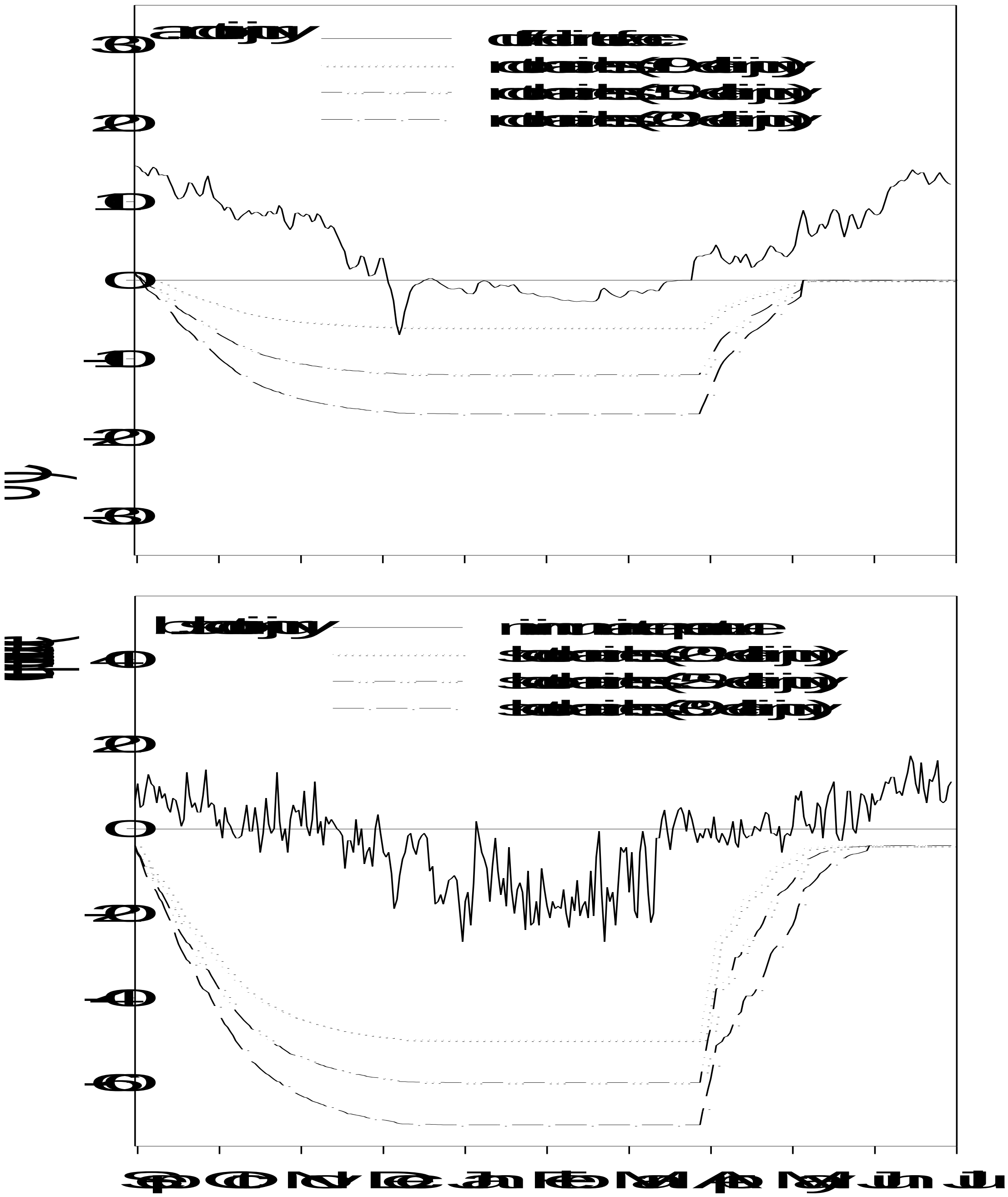


Figure 5.3 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Fredericton, NB (8101600) during the winter and spring periods of 1935-1936. A cross-over (estimated cell damage) is calculated to occur in December for roots while cross-overs are barely avoided for shoots during April and May.

Stillwater, NS

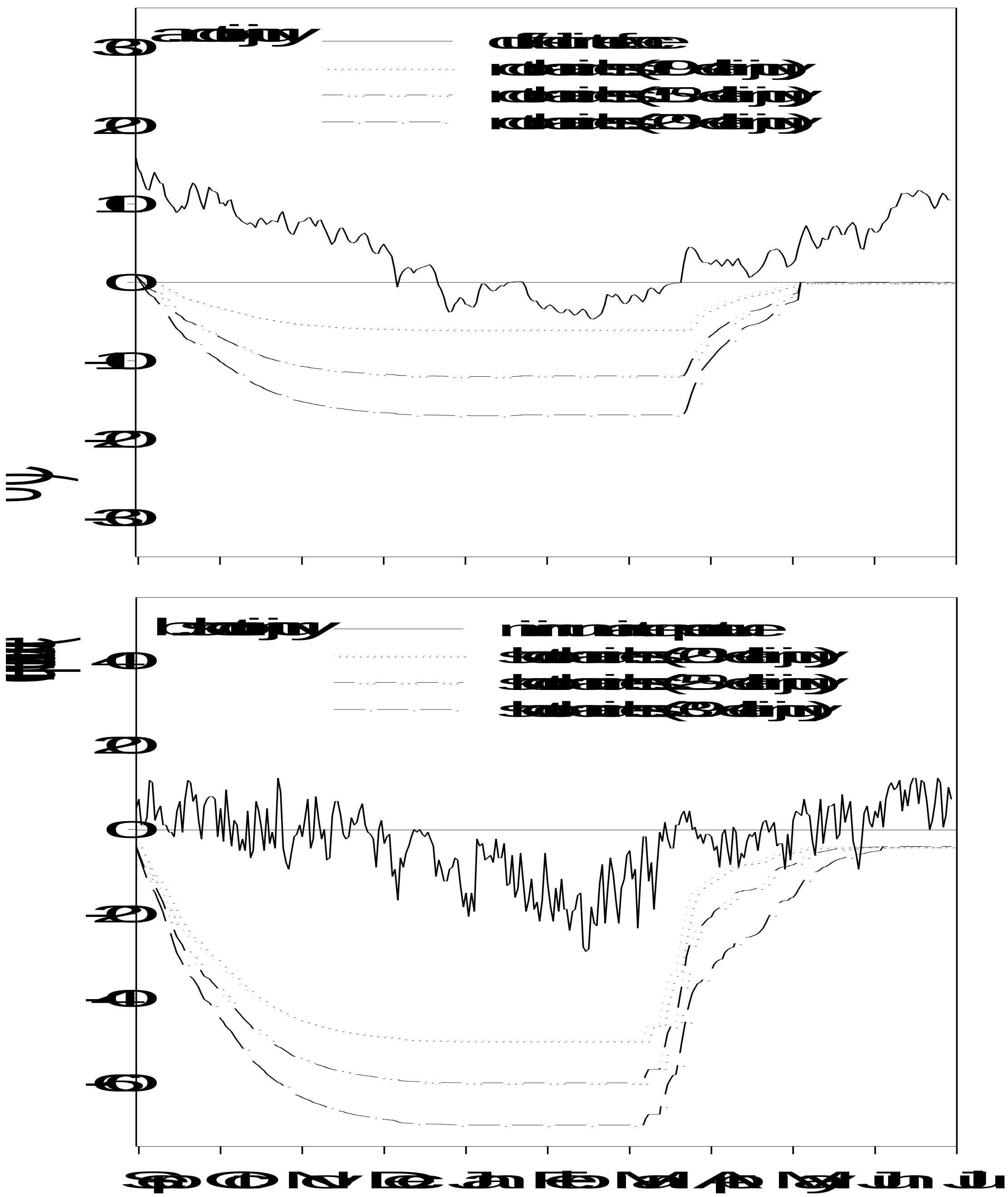


Figure 5.3 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Stillwater, NS (8205600) during the winter and spring periods of 1935-1936. Cross-overs (estimated cell damage) are calculated for four separate periods during April and May for shoots.

1943-1944

Figure 5.4. illustrates daily changes in root and shoot cold-hardiness of yellow birch for the winter and spring periods of 1943-1944. No early thaw period was calculated to occur during the spring, but a late frost in May and in June was very likely for some of the areas. At Lac Onatichiway, there were no indications of potential root cell injuries, but shoot cell injuries of 20 - 25% may have occurred during May. At Barrage Lac Morin, root cell injuries would have been less than 10 % in December and February, but shoot cell injuries of 20 - 30% were estimated for May and June. At both stations in Quebec, ontogenetic development likely started and proceeded rapidly at the end of April.

Ontogenetic development in Atlantic Canada likely began at the start of April and was likely complete by the end of May. At Fredericton, root cell injuries in December and February were estimated to be at the 10 % level, while shoot cell injuries were not likely. At Stillwater, soil temperatures were calculated to drop below –4.0 ^{0}C on four occasions. Root cell injuries were estimated to be at 10 % in February, but shoot cell injuries were estimated at 25 - 30% during May and June.

Barrage Lac Morin, QC

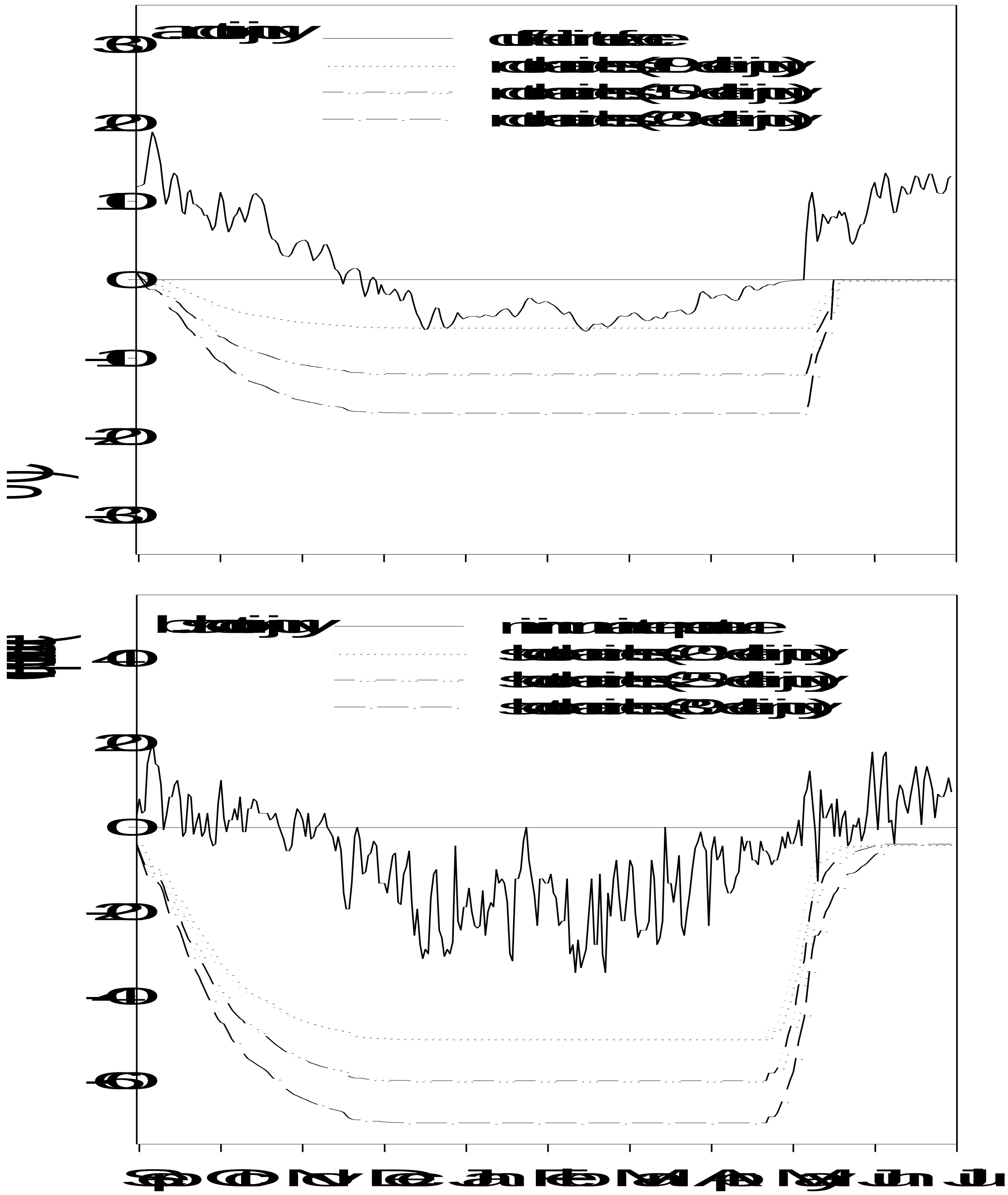


Figure 5.4. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Barrage Lac Morin, QC (7050455) during the winter and spring periods of 1943-1944. Cross-overs (estimated cell damage) are calculated to occur on two occasions in December and one in February for roots and on four separate occasions during May and June for shoots.

Fredericton, NB

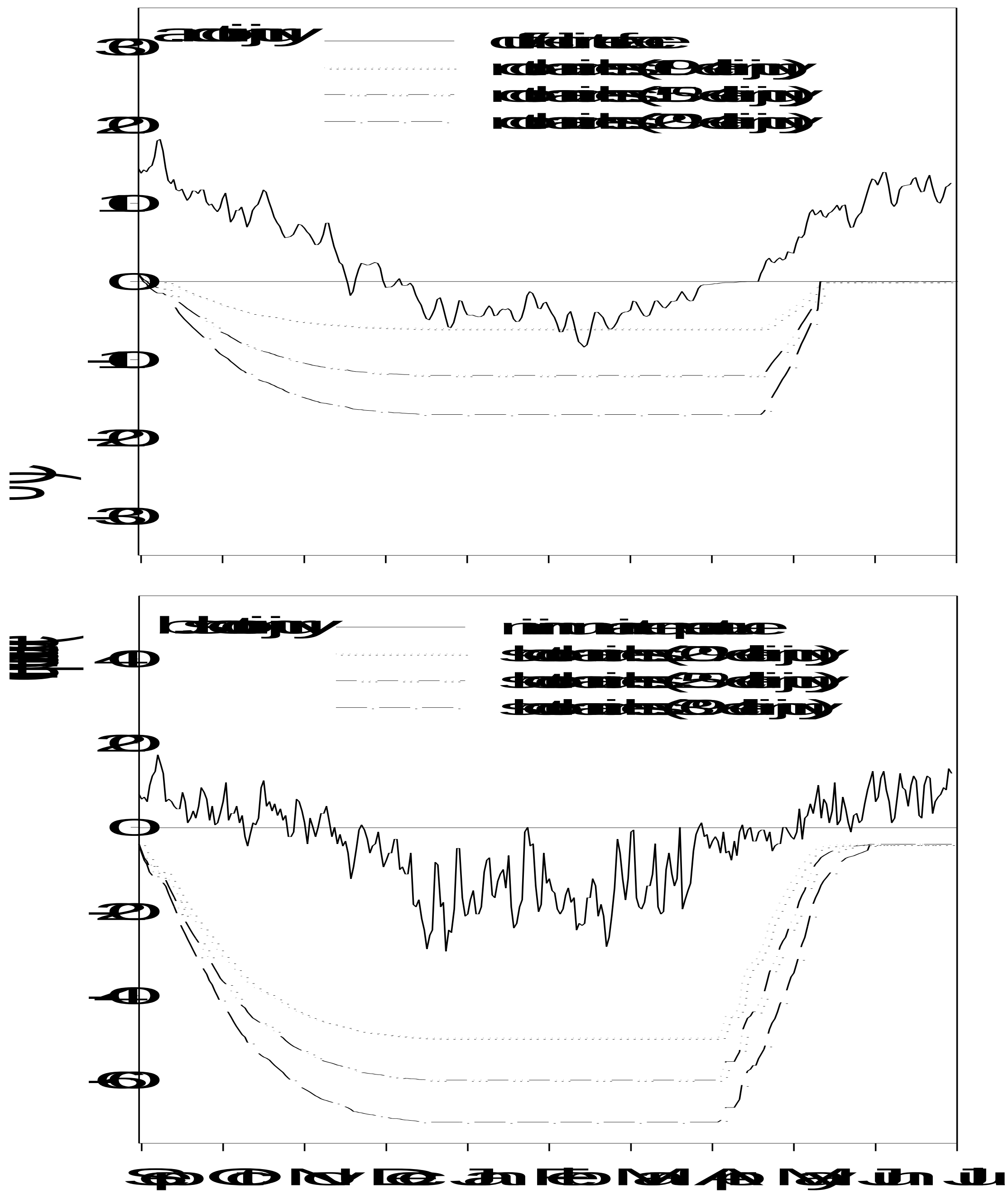


Figure 5.4 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Fredericton, NB (8101600) during the winter and spring periods of 1943-1944. Cross-overs (estimated cell damage) are calculated to occur in December and January for roots and on three separate occasions during May and June for shoots.

Stillwater, NS

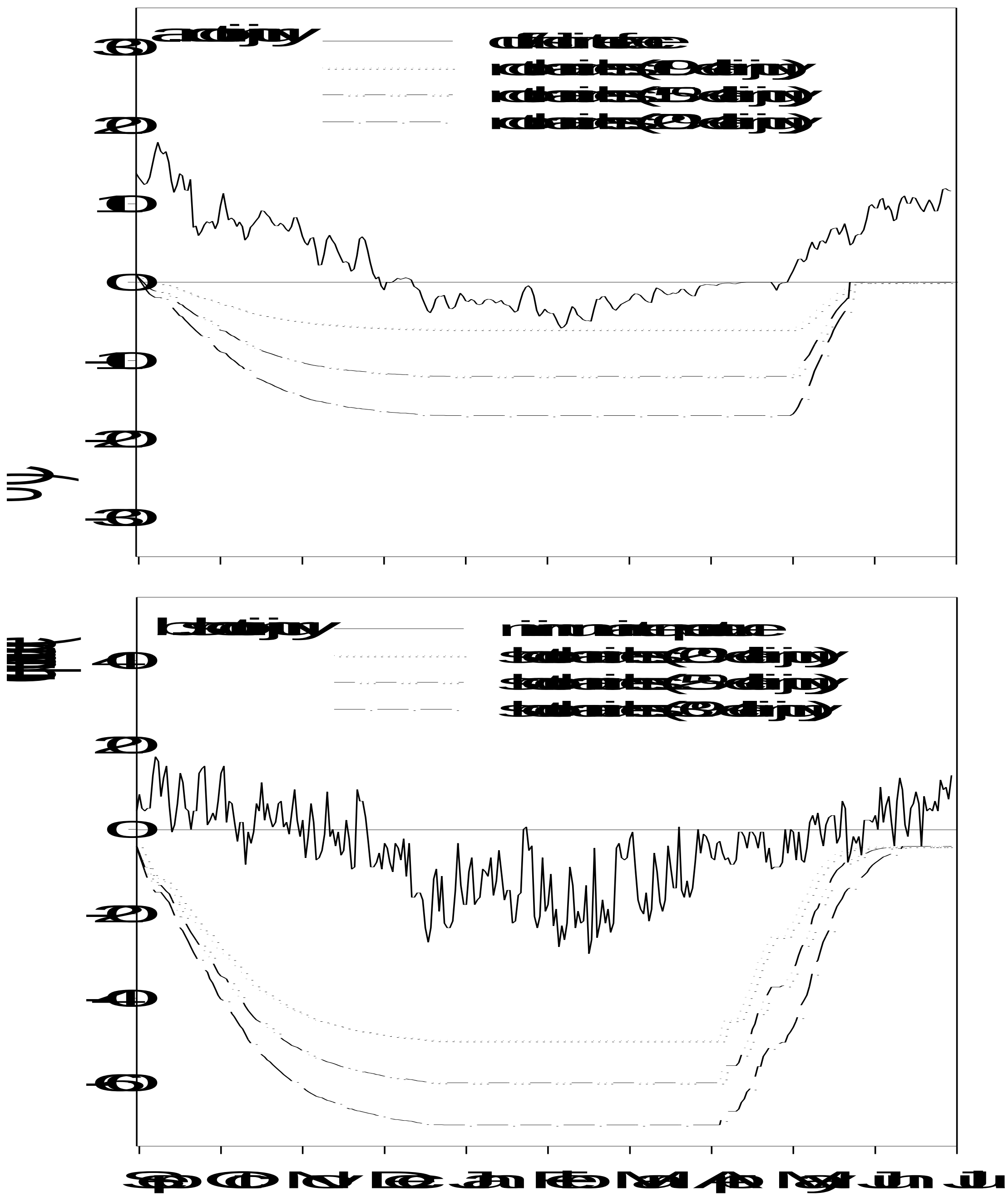


Figure 5.4 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Stillwater, NS (8205600) during the winter and spring periods of 1943-1944. Cross-overs (estimated cell damage) are calculated to occur once at the beginning of February for roots and on four separate occasions during May and June for shoots.

1944-1945

March of 1945 had a record of high mean air temperatures, with the first three weeks of April exhibiting the same mild weather over most of the study area. This resulted in high sums of GDD before the re-occurrence of frost (Figure 3.14, Chapter 3). Shown in Figure 5.5 is the soil temperature and shoot/root situation at Lennoxville, Barrage Lac Morin, Fredericton and Stillwater: here, there were no estimates of root cell injuries, but shoot cell injuries of 25 % were estimated to occur during April. Ontogenetic development was calculated to advance rapidly during March and April. None of the four stations representing the 1944-1945 period received risk of rootlet freezing damage, as a result of adequate snowpack insulation. Stations in Atlantic Canada received a January thaw which had effects on shoot hardiness, with greatest accumulations degree-days in Nova Scotia.

1980-1981

Figure 5.6.illustrates daily changes of root and shoot cold-hardiness of yellow birch during the winter and spring of 1980-1981. At Kemptville, Ontario, root cell injuries were estimated to occur at 10 % in January, and likely escaped freezing injuries in March. Shoot cell injuries of 20 - 30% were estimated to occur during March and April. At Lambton, root cell injuries estimated to be at 10 % in March and April while shoot cell injuries of 20 – 30 % were estimated to occur during April and May. At Lennoxville, root cell injuries were likely absent, but shoot cell injuries of 20 – 30 % were estimated to occur during March, April and May. At Nepisguit Falls root cell injuries might have been at the 10 % level in December and January, while shoot cell injuries of 20 % were likely during mid April.

Lennoxville, QC

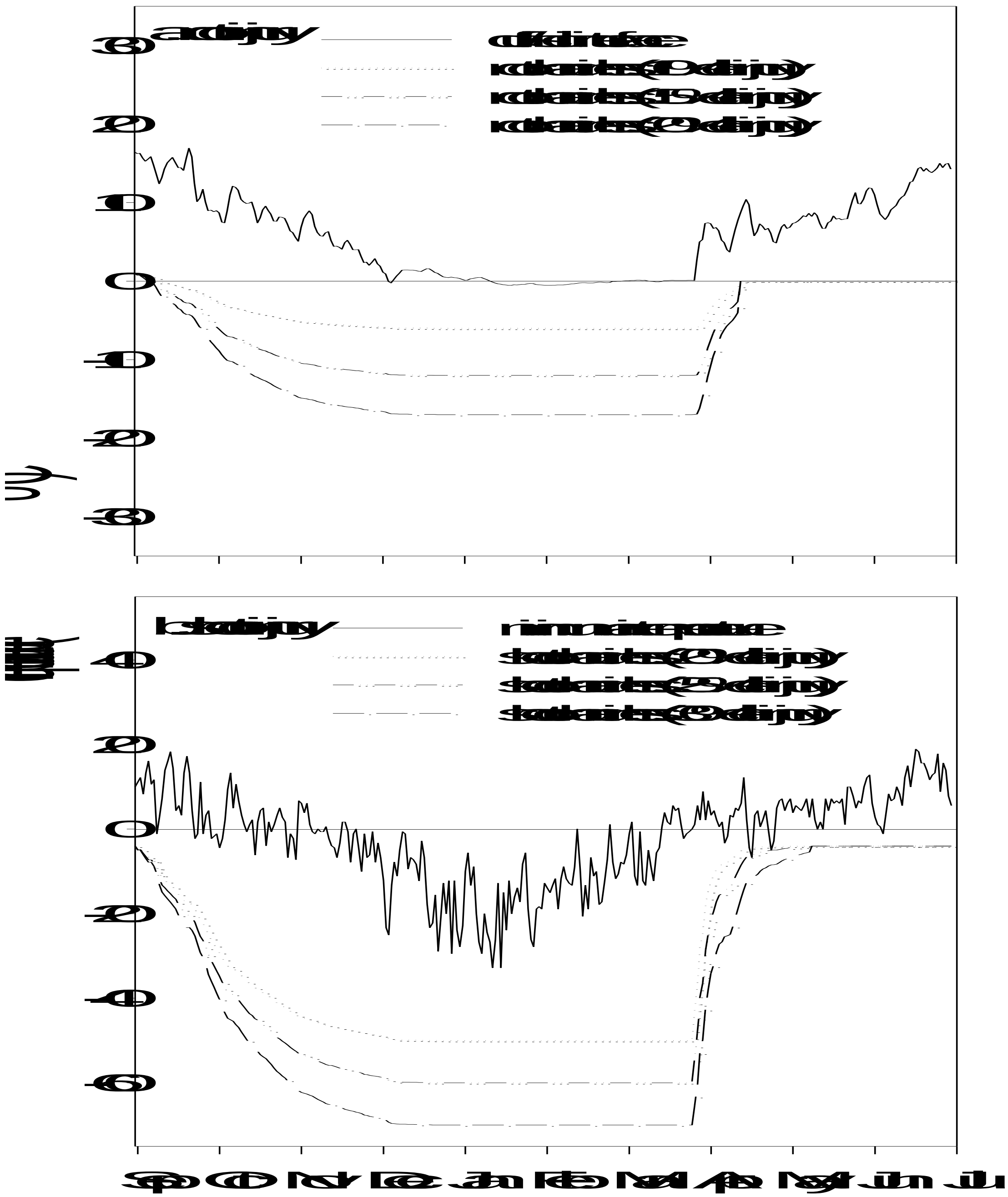


Figure 5.5. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for, Lennoxville, QC (7024280) during the winter and spring periods of 1944-1945. Cross-overs (estimated cell damage) are calculated to occur on two separate occasions during April for shoots.

Barrage Lac Morin, QC

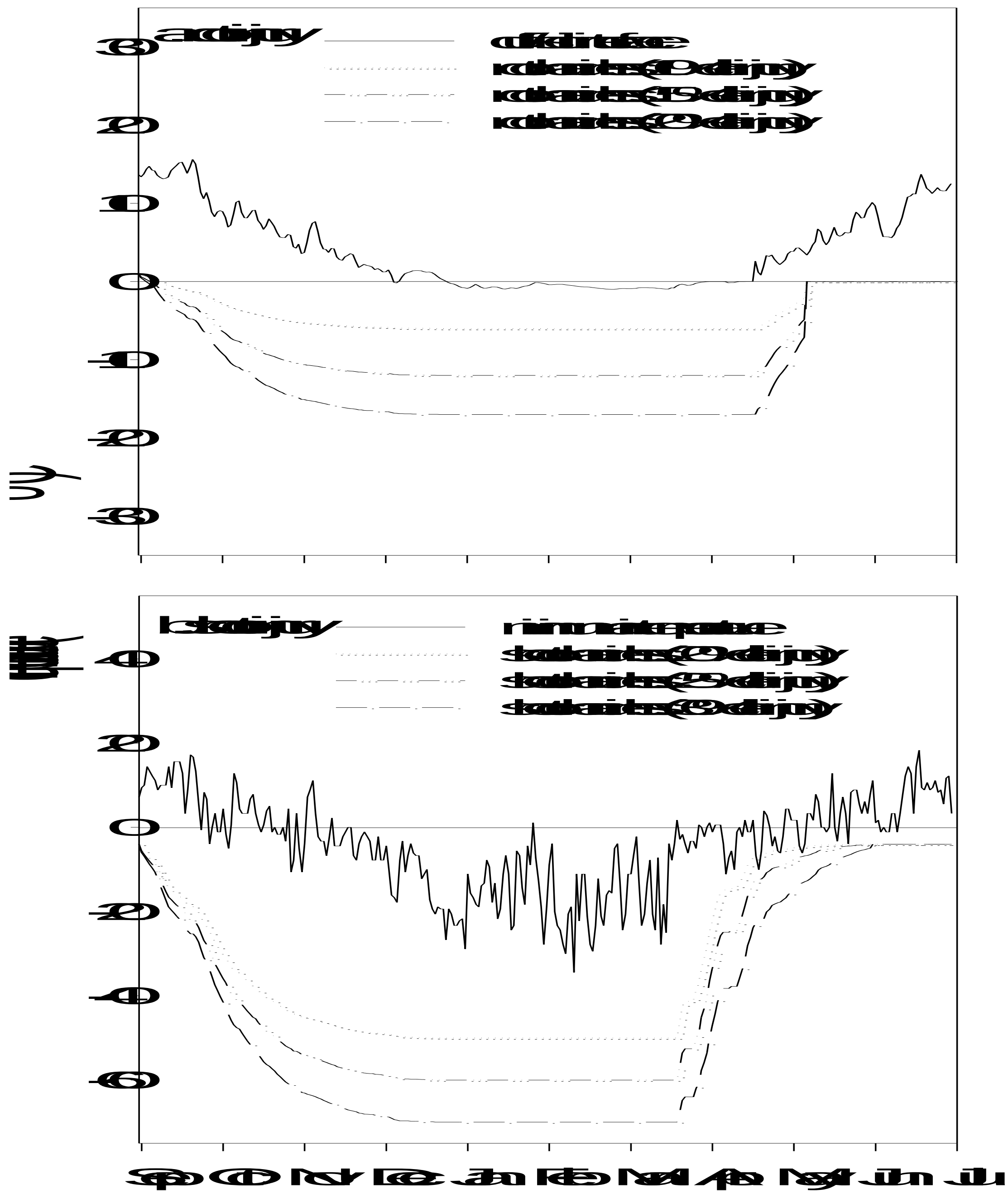


Figure 5.5 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Barrage Lac Morin, QC (7050455) during the winter and spring periods of 1944-1945. Cross-overs (estimated cell damage) are calculated to occur on four separate occasions during April and May for shoots.

Fredericton, NB

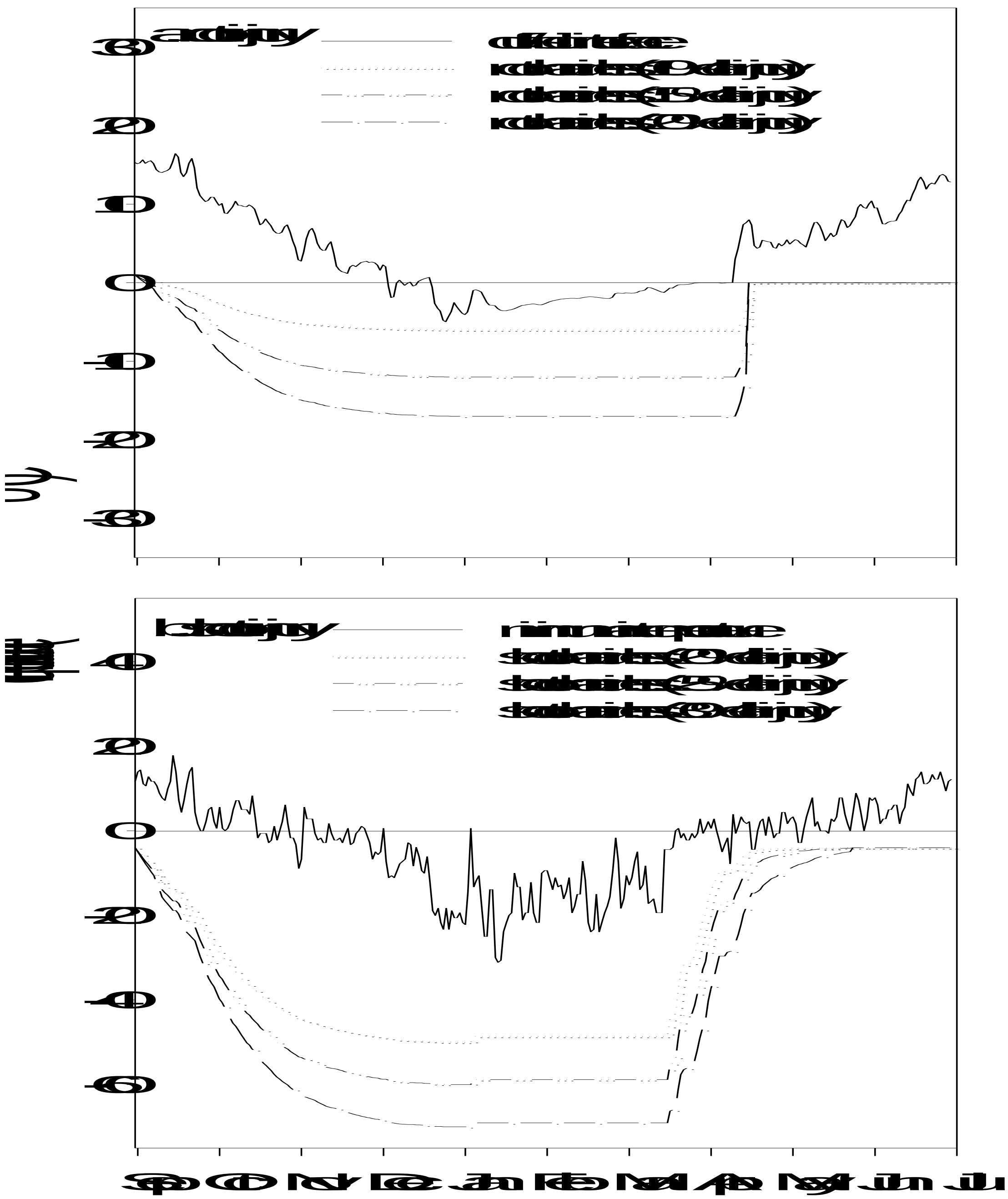


Figure 5.5 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Fredericton, NB (8101600) during the winter and spring periods of 1944-1945. A cross-over (estimated cell damage) is calculated to occur once during April for shoots.

Stillwater, NS

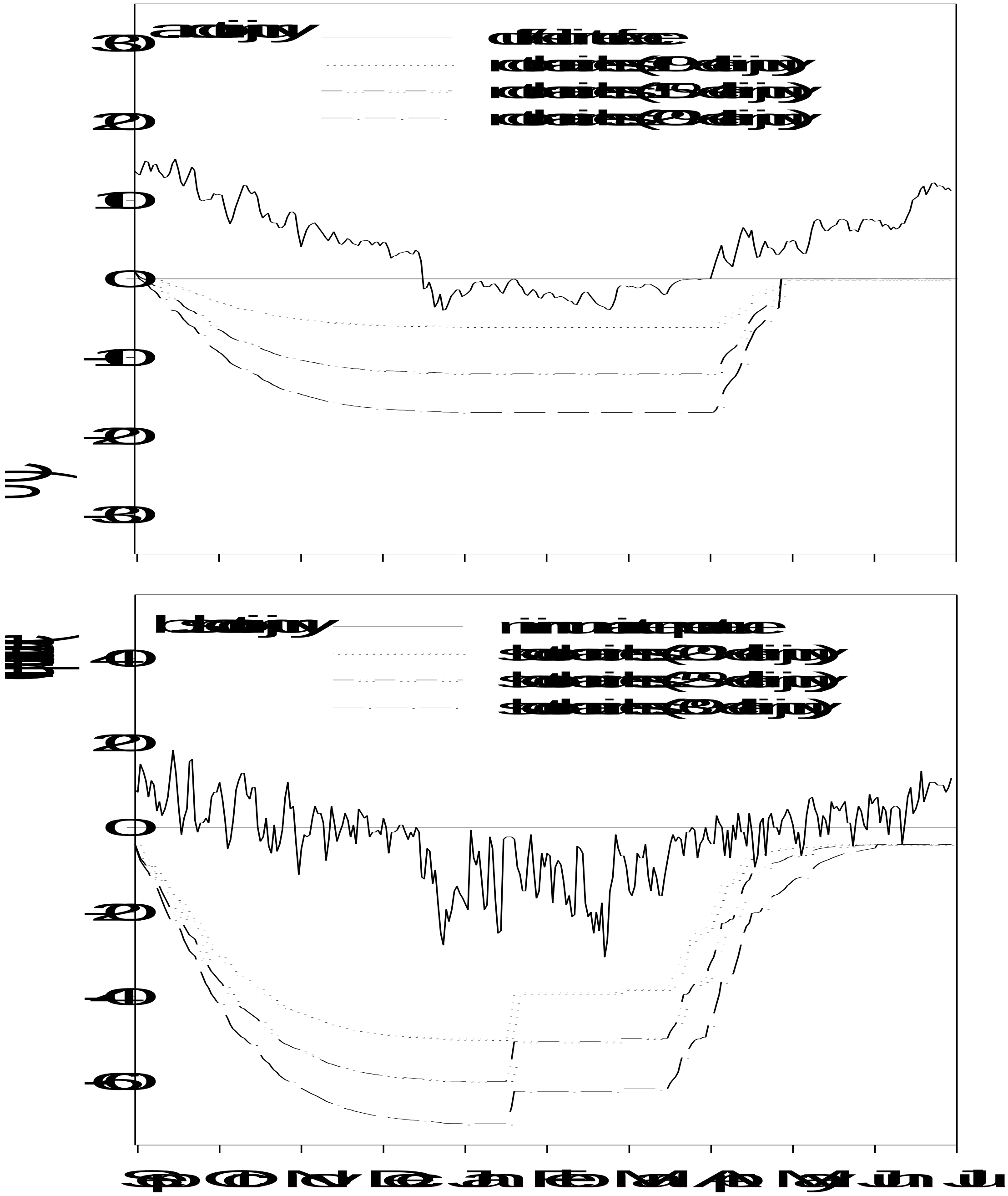


Figure 5.5 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Stillwater, NS (8205600) during the winter and spring periods of 1944-1945. Cross-overs (estimated cell damage) are calculated to occur on five separate occasions during April, May and June for shoots. The effects of the January thaw on shoot de-hardening are also illustrated.

Kemptville, ON

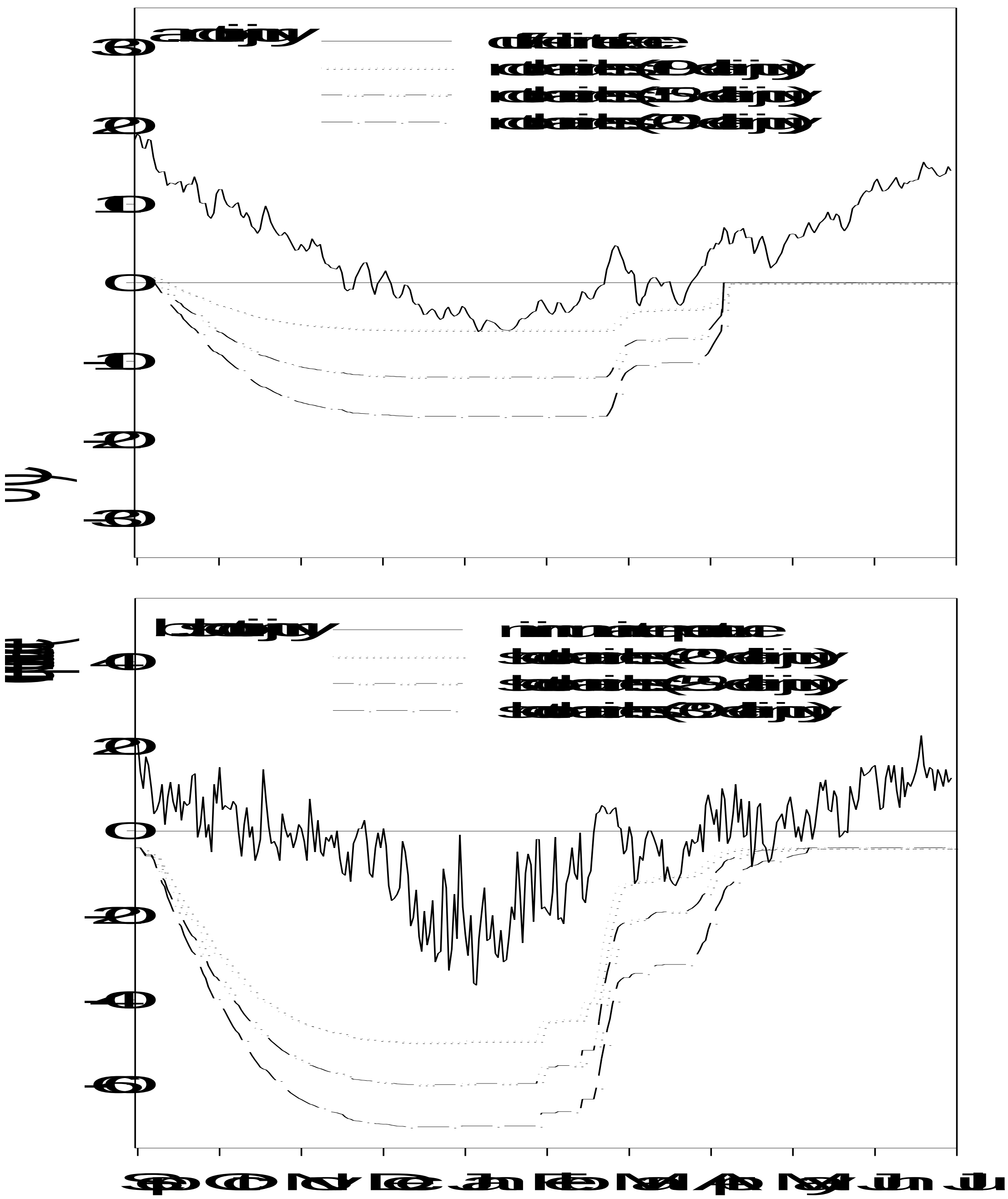


Figure 5.6. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Kemptville, ON (6104025) during the winter and spring periods of 1980-1981. Cross-overs (estimated cell damage) are calculated to occur twice in January and to barely escape cross-over in March for roots and four separate occasions during March and April for shoots. Effects of a thaw in February for root, and in February and March for shoot de-hardening are illustrated.

Lambton, QC

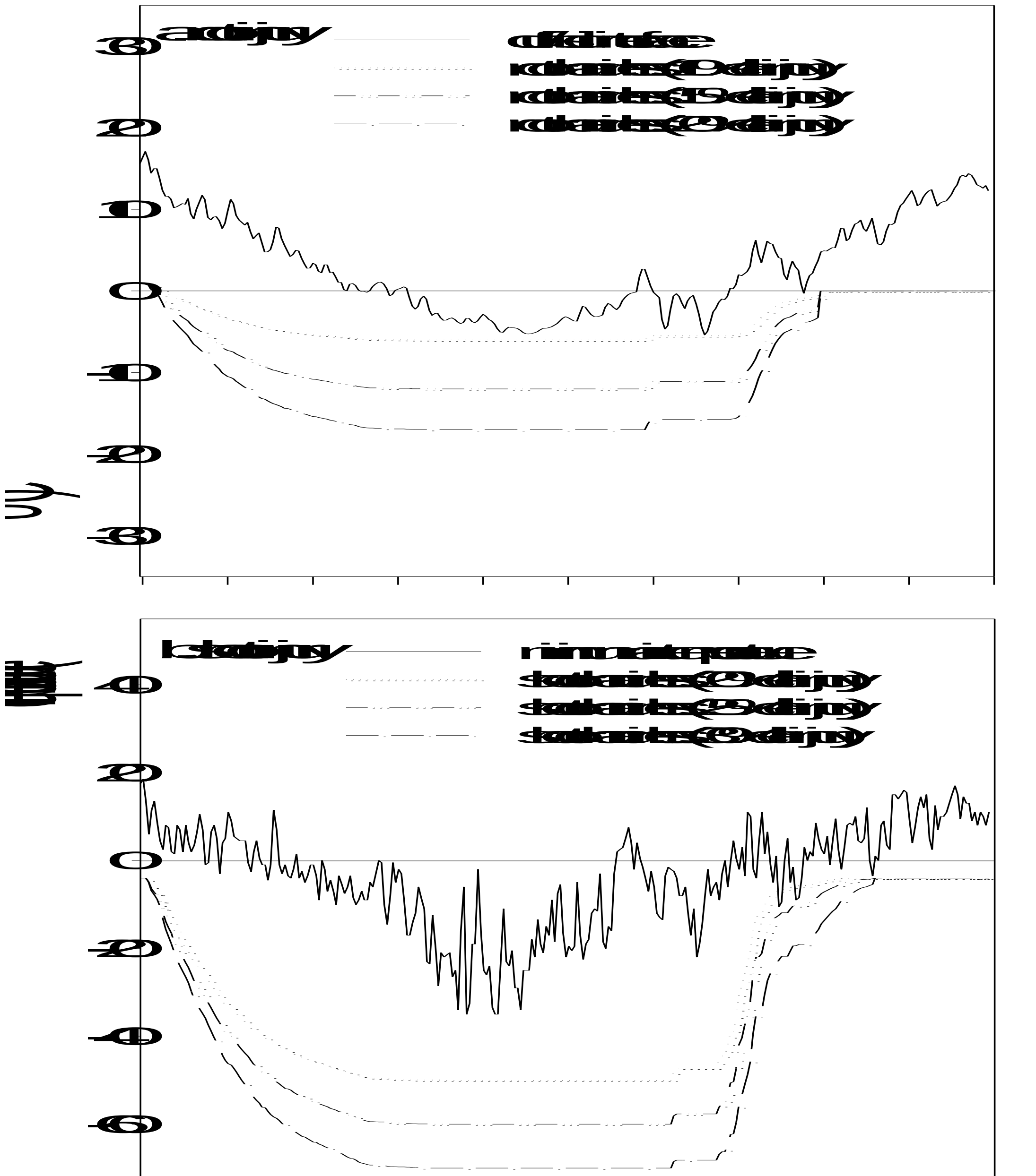


Figure 5.6 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Lambton, QC (7024000) during the winter and spring periods of 1980-1981. A cross-over (estimated cell damage) was calculated to occur in March for roots while three separate occasions were calculated during April and May for shoots. Slight February and March thaw effects on root and shoot de-hardening are also illustrated.

Lennoxville, QC

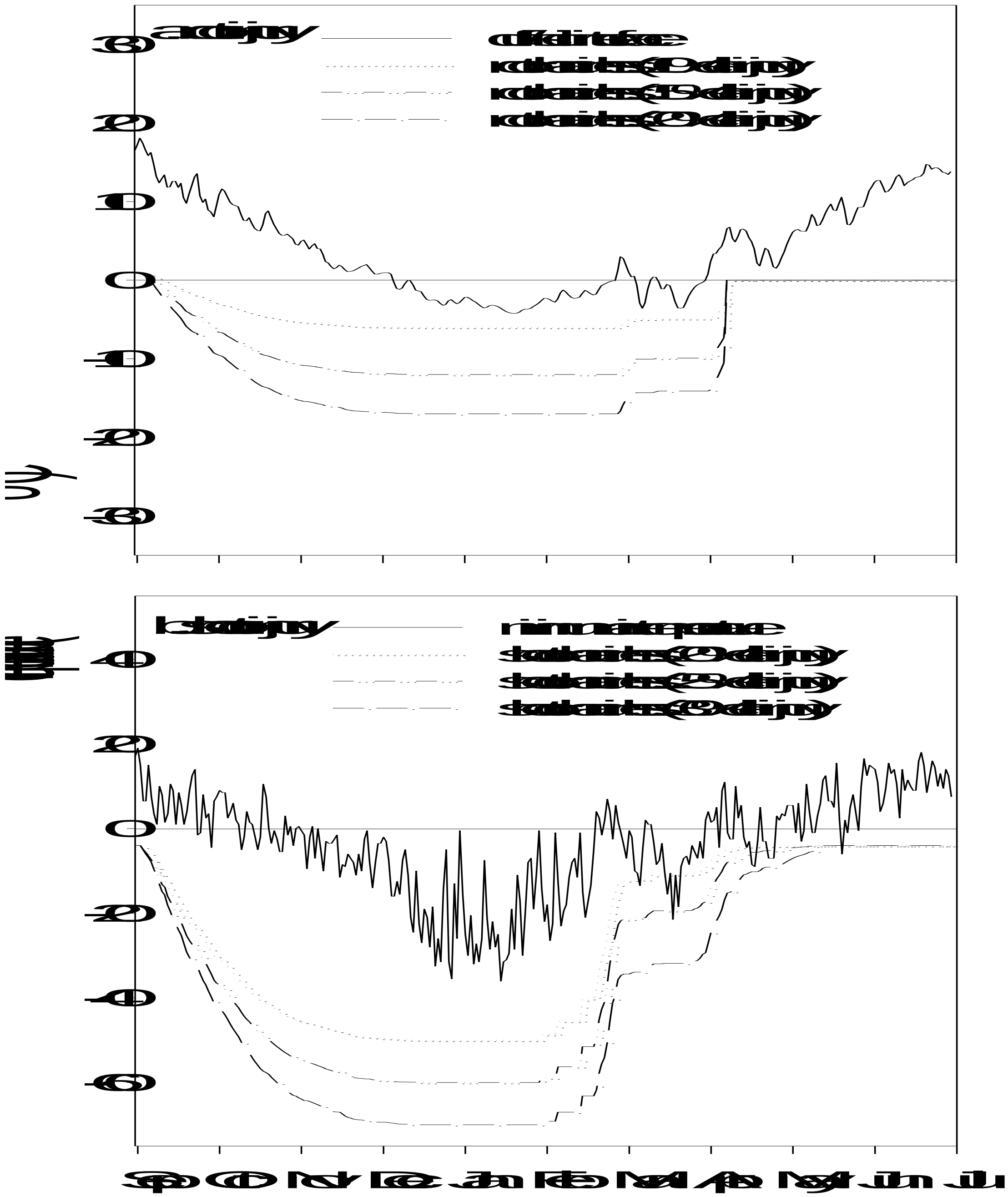


Figure 5.6 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Lennoxville, QC (7024280) during the winter and spring periods of 1980-1981. Cross-overs (estimated cell damage) were calculated to occur on five separate occasions during March, April and May for shoots. Effetcs of the February and subsequent March-April thaw on root and shoot de-hardening are also illustrated.

Nepisguit Falls, NB

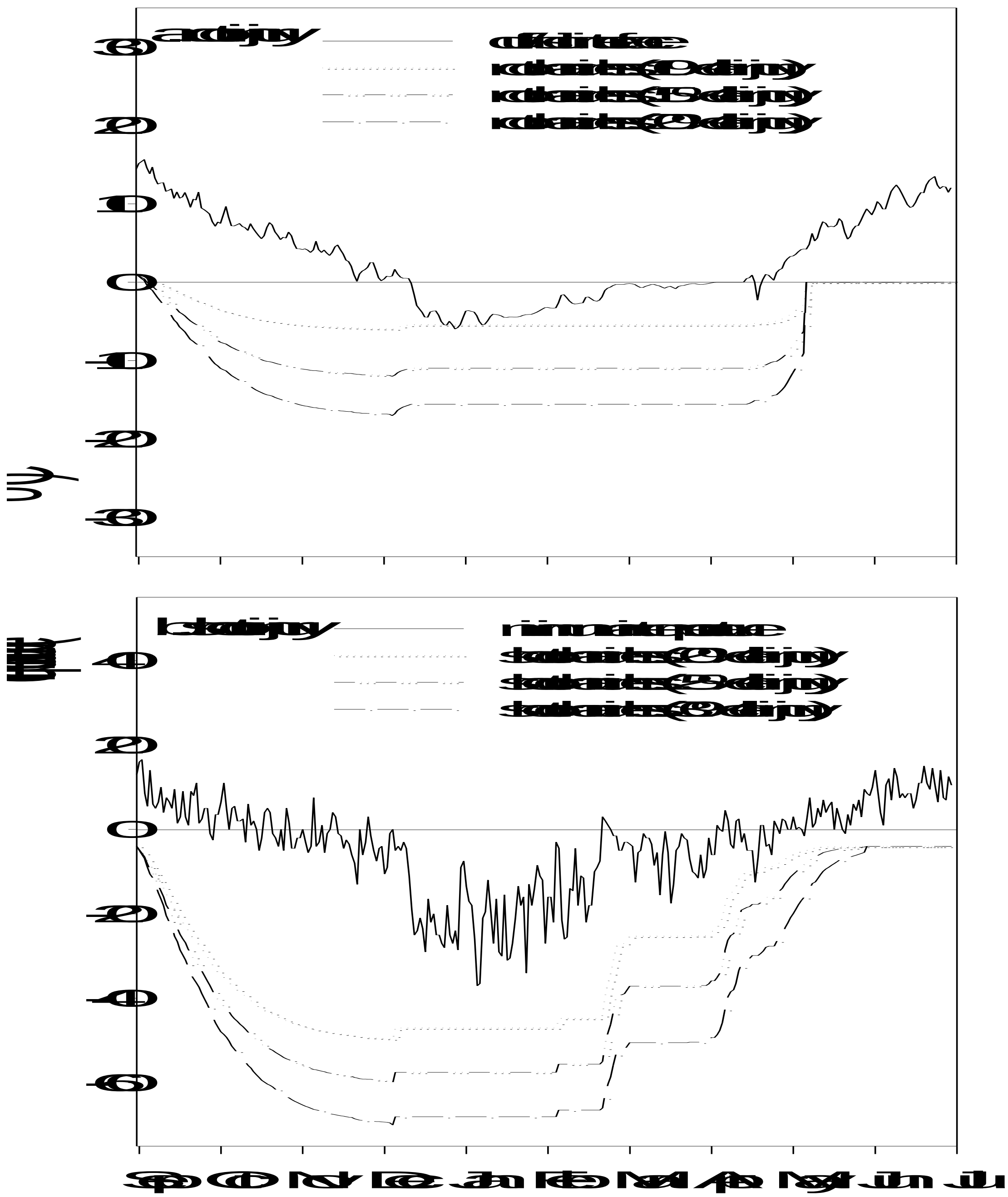


Figure 5.6 cont'd. Changes of (a) root and (b) shoot cold-hardiness of yellow birch for Nepisguit Falls, NB (8103500) during the winter and spring periods of 1980-1981. Cross-overs (estimated cell damage) were calculated to occur in December and January for roots only once during April for shoots. Effects of the December, February and March thaws on root and shoot de-hardening are also illustrated.

Concluding Remarks

The birch dieback model was run on a daily basis from September 1 to June 30, to simulate root and shoot injuries, xylem cavitation, spring root pressure, and resulting shoot/twig dieback. The inputs required for running the model refer to daily minimum temperatures for air (for shoots) and calculated daily temperature for soil (for rootlets and roots), daily relative humidity, daily solar radiation, and wind speed. Outputs from the model suggest the occurrence of root and shoot cell freezing damage, consistent with historical observations and timing of birch dieback events. These model runs are thought to be consistent for all stations that had accumulated similar degree-days before frosts, for similar regions, as illustrated in Chapter 3. While existing experimental data on potted seedlings may be problematic when scaling up to mature forest trees, it is thought that responses of frost hardiness would be similar in same aged tissues. Furthermore, the effects on cavitation may be exacerbated in taller trees due to greater distance of water transport, and great amounts of root pressure required to refill the winter-caviated xylem. With further calibration and verification (of in-field dieback), the birch-dieback model should become an important tool to assess weather related birch dieback symptoms, and risk of hardwood decline in general.

CHAPTER 6

LINKAGE TO CLIMATE CHANGE

It is anticipated that increased global temperatures due to recent climate change expectations may lead, among other things, to increased fluctuations in air temperature. If so, this would also mean longer, deeper, and perhaps more frequent winter/early spring thaw-freeze events than has been witnessed in the recent past. This chapter explores the potential use of the yellow birch dieback model for the interpretation of global climate change calculations in terms of likely recurrences of thaw-freeze events, and likely impacts of these events on future birch decline, based on current results of the Canadian Coupled Global Model.

It already appears that the average number and severity of thaw-freeze events have increased since 1930: Figure 6.1 illustrates yearly averages for the outputs from *Weather Reader* for the historical climate data for eastern Canada and North-Eastern United States. Perhaps this increase is artificial, because the number of reporting weather stations has doubled from 1930 to now. Still, as shown in Figure 6.1a, the number of thaws lasting longer than four days exhibits an increasing upward trend. Average maximum heat accumulations with GDD > 4^{o}C of the worst thaw events have increased as well. GDD (> 4^{o}C) accumulations greater than 50 during thaw before freezing were recorded for 1945, 1981, 1986, and 1987. These thaw-freeze events would have been widespread, given the nature of the calculations, illustrated for 1945 and 1981.

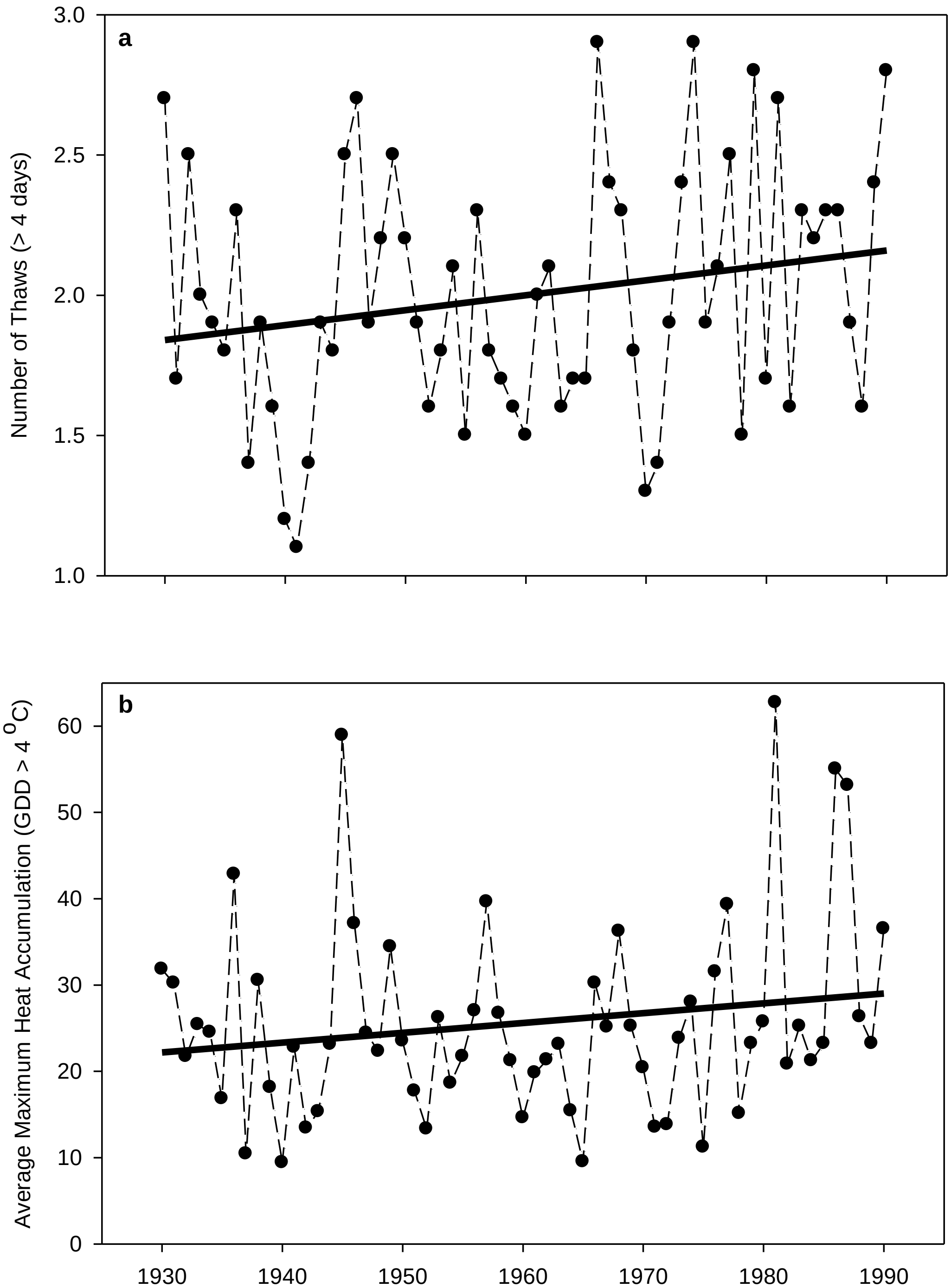


Figure 6.1. Time series of (a) the average number of thaws greater than 4 days in duration and (b) average maximum heat accumulation (GDD >4°C) for single greatest thaw event, per station for all stations recording in a given year. The number of stations (n) contributing to the average varies per year i.e., for 1936, n = 219 and 1981, n = 424.

Canadian Global Coupled Model Output (CGCM1)

The data set was produced by the first generation Canadian Global Coupled Model or CGCM1. The model output data consist detailed weather projections to the year 2100. Daily data are available in three 21-year time slices; 1975-1995, 2020-2040 and 2080-2100. This particular CGCM1 model output starts with greenhouse gas concentrations at a level that may have existed in 1900. Subsequently, the gas concentrations are increased by +1% every year until 2100. These increases lead to a doubling of the CO_2 concentrations in 1980, or a tripling of the pre-industrial concentrations of 1900. By 2100, the model's GHG concentration may have tripled the 1980 value, and four times the pre-industrial value. The direct cooling effects of sulfate aerosols (GHG+A) is also incorporated into the CGCM1model. Doing so reduces the overall impact of the greenhouse gas emissions on the air temperature calculations.

The climate change data are organized in grid format at a horizontal resolution of roughly 3.75°x 3.75° (400 km^2), with 10 vertical layers. There are 26 grid points covering the "historical birch dieback area" as shown in Figure 6.2. The points are located at the center of gravity of each grid cell.

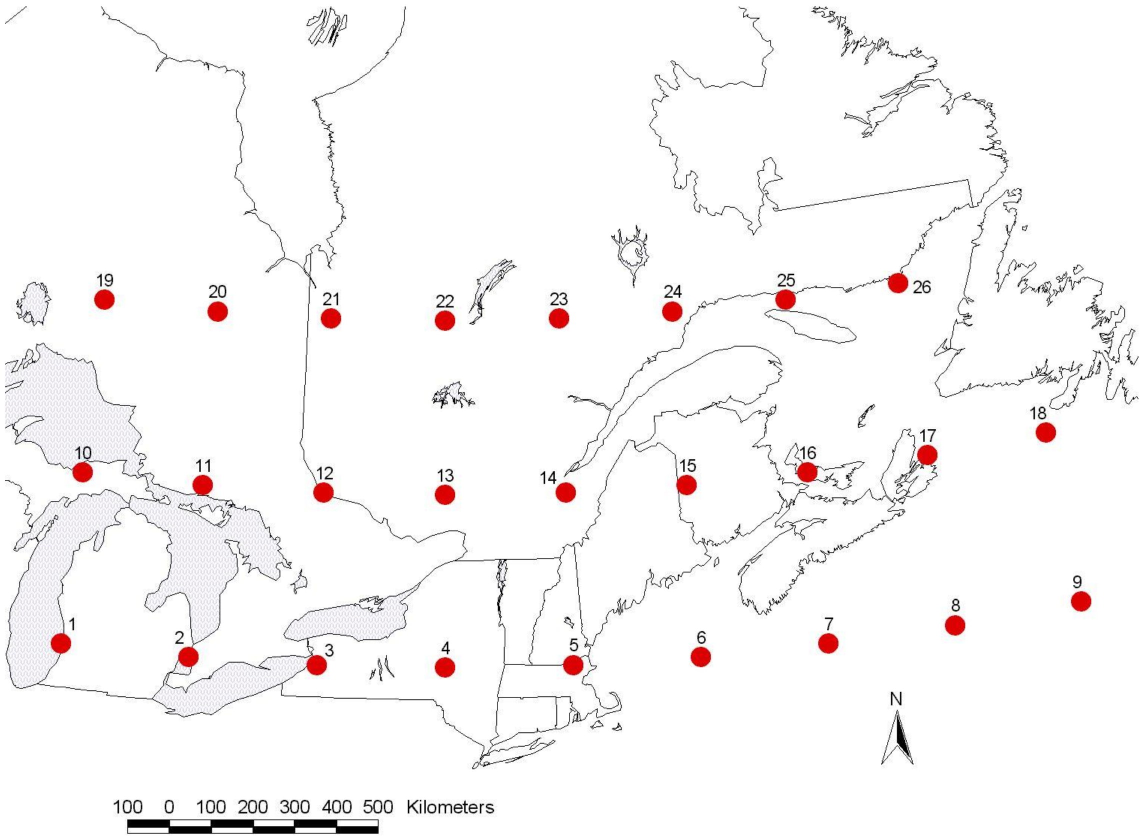


Figure 6.2. Map depicting location of grid centers for the 26 CGCM1 outputs.

Limitations of CGCM1 Scenario Data

A New Brunswick weather station (Aroostook, # 8100300) was used to compare 1990 mean daily temperatures (°C) with station 15 of the scenario output. As shown in Figure 6.3, the CGCM1 mean daily temperature is “dampened” significantly from January 1st until approximately the middle of March, when temperatures remain around 0°C until the end of May. Generally, the CGCM1 simulated air temperatures are significantly higher than those of the actual data, and lack the natural variability. This also means that the CGCM1 simulated air temperatures imply that CGCM1 is unable to simulate likely thaw-freeze events. In fact, very few thaw- freeze events are projected. All scenario grid points used in this study provide similar patterns to those illustrated in Figure 6.3.

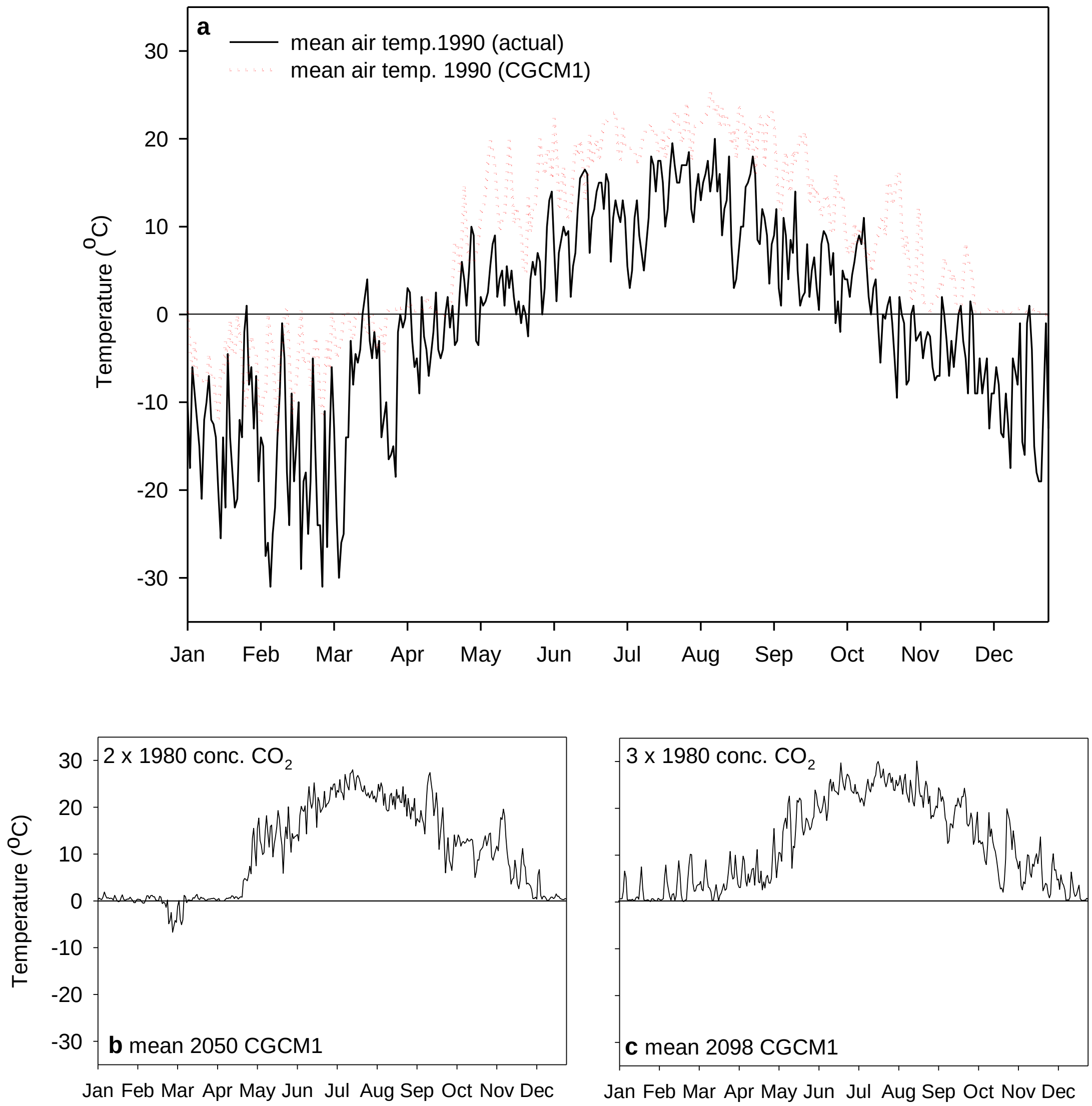


Figure 6.3. Temperature times series expressed as daily means in ^{0}C for (a) actual climate station data for a station in New Brunswick and CGCM1 model output for 1990, (b) mean daily CGCM1 for year 2050 and (c) mean daily CGCM1 for 2098. The year 2050 represents doubling the amount of 1980 CO_2 levels, and 2098 approximately tripling the 1980 levels.

As can be seen in Figure 6.3, the current climate scenario model suggests that air temperatures should become significantly higher, and sub-zero temperatures become shorter and are forecast to be non-existent towards the end of this century.

These unrealistic shortfalls may be attributed to the focus, the large spatial scale ($400\ km^2$), and resolution of the model output. Anomalous climatic events are generally those that are rare both in intensity and occurrence. At the present time, this model can only capture anomalous events on very large scales. Because of limited resolution, the current model is poorly suited to provide detailed information at regional levels, as illustrated in comparison with the historical weather records.

The *Weather Reader* algorithm (as described and used in Chapter 3) was used to read all of the CGCM1 time slices, to extract information on projected daily minimum, maximum and mean temperatures, all in ^oC. As already discerned, the outputs are of little significance in regards to thaw-freeze events. The greatest heat accumulation per single CGCM1 projected event for all grid points and for all years has a GDD of 46.2.

CHAPTER 7

THESIS CONCLUSIONS AND RECOMMENDATIONS

Overall Contributions

In the context of predicting risk of historical (and potential future) birch dieback timing and locations within eastern Canada, this thesis has provided the following research contributions:

1. A comprehensive review of birch dieback chronology, locations, proposed causal factors, and a description of experiments on causal mechanisms inciting dieback in eastern Canada during the 1930-1960 birch decline period.
2. A methodology for interpretation of biologically relevant thaw events using historical meteorological data, Geographic Information Systems (GIS) and geostatistics to reconstruct historical distributions of winter/early spring thaws and late spring frosts in eastern Canada as they existed during the 1930-1960 birch decline events.
3. Use of a process-based forest hydrology model (ForHyM2) that presents calculated forest micro-meteorological conditions based on daily weather data. This output provided essential input for a Birch Dieback Model to estimate spring birch dieback events for certain areas in eastern Canada.
4. Investigation of historical thaw event trends, and assessing possibilities of modeling future birch dieback in response to anticipated climate change.

Future Research Opportunities

1. To extend research to the examination of the first health observations of the Acid Rain Nation Early Warning System (ARNEWS) in reference to the 1981 winter thaw and late spring frost events in southern Quebec. The ARNEWS plots provide information such as tree ring data and branch dieback (among other information), and therefore may provide a signature of dieback caused by the winter thaw-freeze event as well as late spring frost event for this particular year. ARNEWS may contain the best available data to further validate the Birch Dieback Model.
2. To utilize a digital terrain model to determine the effects of land surface attributes on thaw-freeze events, at the landscape level. Important features refer to influence on; elevation, aspect, slope, slope position, air and soil, and on temperature impacts on thaw-freeze cycles.
3. To use regional climate change scenario model outputs in dieback modeling efforts once relative outputs become available.

LITERATURE CITED

Ameglio, T., F.W. Eweres, H. Cochard, H. Martinac, M. Vandame, C. Bodet and P. Cruiziat (2001). Winter stem xylem pressure in walnut trees: effects of carbohydrates, cooling and freezing. Tree Physiol. **21**: 387-394.

Arp, P.A., and X. Yin (1992). Predicting water fluxes through upland forests from monthly precipitation and mean monthly air temperature records. Can. J For. Res. **22**: 864-877.

Auclair, A.N.D. (1987). The distribution of forest declines in eastern Canada. *In* Forest Decline and Reproduction: Regional and Global Consequences. *Eds*. L. Kairiukstis, S. Nilsson and A. Straszak. Int. Institute for Applied Systems Analysis, Luxenburg, Austria, pp 307-320.

Auclair, A.N.D. (1993). Extreme climatic fluctuations as a cause of forest dieback in the Pacific Rim. Water Air Soil Pollut. **66**: 207-229.

Auclair, A.N.D., R.C. Worrest, D. Lachance, and H.C. Martin (1992). Climatic perturbation as a general mechanism of forest dieback. *In* Forest decline concepts. Edited by P.D. Manion and D. Lachance. American Phytopathological Society Press, St. Paul, Minn. pp. 38-58.

Auclair, A.N.D., John T. Lill and C. Revenga (1996). The role of climate variability and global warming in the dieback of northern hardwoods. Water, Air and Soil Pollut. **91**: 163-186.

Auclair, A.N.D., P.D. Eglinton and S.L. Minnemeyer (1997). Principal Forest Dieback Episodes in Northern Hardwoods: Development of Numeric Indices of Areal Extent and Severity. Water, Air and Soil Pollut. **93**: 175-198.

Babish, G. (2000). Geostatistics Without Tears. A practical guide to geostatistics, variograms and kriging. Ed. 4.81 Environment Canada, Ecological Research Division, Environmental Conservation Branch, Regina, SK pp 68.

Balch, R.E. (1944). The dieback of birch in the Maritime Region. Mimeo. Contrib. No. 3. Dominion of Canada, department of Agriculture, Division of Entomology, Fredericton, NB.

Balch, R.E. (1953). The birch dieback problem. *In*: Report on the Symposium on Birch Dieback. Summary of Proceedings Held in Ottawa, Canada, on March 21 and 22, 1952, at the Invitation of the Biological Sciences Division, Science Service, Department of Agriculture. Parts 1 and 2.

Balch, R.E. and J.S. Prebble (1940). The borne birch borer and its relation to the dying of New Brunswick forests. For. Chron. **16**: 179-201.

Benoit P.G., G.Bonneau, G. Laflamme, and R. Picher (1981). Insectes et maladies des arbres Quebec. Centre de Rescherches Forestiers des Laurentides du magazine FORET CONSERVATION **49** # 10.

Bhatti, J.S., R.L. Flemming, N.W. Foster, F.-R. Meng, C.P.A. Bourque, and P.A. Arp (2000). Simulations of Pre- and Post-Harvest Soil Temperature, Soil Moisture, and Snowpack for Jack Pine: Comparison with Field Observations. For. Ecol. and Mgt. **138**: 413-426.

Bier, J.E. (1953). Report on the Symposium on Birch Dieback. Summary of Proceedings Held in Ottawa, Canada, on March 21 and 22, 1952, at the Invitation of the Biological Sciences Division, Science Service, Department of Agriculture. Parts 1 and 2.

Braathe, P. (1957). Is there a connection between the birch dieback and the March thaw of 1936? For. Chron. **33**: 358-363.

Braathe, P. (1995). Birch dieback caused by prolonged early spring thaws and subsequent frost. Norw. J. Agric. Sci. Suppl. No. **20**, pp 50.

Braathe, P. (1996). Birch dieback-the effects of artificial spring frost on budburst and foliage. Norwegian Journal of Agricultural Sciences 10 no.1, 1-6.

Brown, S.C., K.S. Pregitzer, D.D. Reed, and A.J. Burton (2000). Predicting Daily Mean Soil Temperature from Daily Mean Air Temperature in Four Northern Hardwood Forest Stands. Forest Science. **46**: 297-301.

Burns, R.M. and B.H. Honkala (1990). Silvics of North America, Vols. 1 and 2. USDA Forest Service, Agricultural Handbook, pp 654.

Calme, S., H.A. Margolis, F.J. Bigras and C. Hebert (1994). Frost tolerance and bud dormancy of container grown yellow birch, red oak, and sugar maple seedlings. Tree Physiol. **14**: 1313-1325

Canadian Forestry Service (CFS) (1939-1985). Forest Insect Survey, Forest Insect and Disease Survey, Forest Insect and Disease Conditions in Canada. Ottawa, Canada.

Canavan, T. (1996). Climate of the Atlantic region *In* Climate variability and climate change in Atlantic Canada. *Edited by* R.W. Shaw. Occas. Rep. No.**9**. Environment Canada, Atlantic Region, pp 11-15.

Charlson, R.L., J.E. Lovelock, M.O. Andreae and S.G. Warren (1987). Oceanic phytoplankton, atmosheric sulphur cloud albedo and climate. Nature **326**: 655-661.

Chmielewski, F.M. and Thomas Rotzer, (2001). Response of tree phenology to climate change across Europe. Agric. and For. Met. **108**: 101-112.

Clark, J, 1961. Birch Dieback. Reprinted from Recent Advances in Botany. University of Toronto Press. 1551-1555.

Clark, J. and K. Hare (1953). Climate and the dieback of birch *In***:** Report on the Symposium on Birch Dieback. Summary of Proceedings Held in Ottawa, Canada, on March 21 and 22, 1952, at the Invitation of the Biological Sciences Division, Science Service, Department of Agriculture. Parts 1 and 2.

Coleman, W.K. (1992). A proposed winter-injury classification for apple trees on the northern fringe of commercial production. Can. J. Plant Sci. **72**:507-516.

Cox, R.M and J.W. Malcolm (1997). Effects of duration of a simulated winter thaw on dieback and xylem conductivity of *Betula papyrifera*. Tree Physiol. **17**: 397-404.

Cressie, N.A.C. (1990). Statistics for Spatial Data**.** John Wiley, New York.

Dansereau, P., and G. Pageau. (1966). Distribution geographique et ecologique du *Betula alleghaniensis*. Memoires du Jardin Botanique de Montreal. Montreal, Quebec. p 32.

Davidault, L. (1953). Evidence of spread or intensification as indicated by location and time of injury. *In*: Report on the Symposium on Birch Dieback. Summary of Proceedings Held in Ottawa, Canada, on March 21 and 22, 1952, at the Invitation of the Biological Sciences Division, Science Service, Department of Agriculture. Parts 1 and 2.

DeHayes, D.H. and W.M. Williams Jr. (1989). Critical temperature: a quantitative method of assessing cold tolerance. USDA General Technical Report NE-134.

Erdmann G.G., (1990). Yellow Birch. In Burns and Honkala. (Tech. Coords.) Silvics of North America, Vol 2. Hardwoods USDA Forest Service, Agricultural Handbook. pp 133-147.

Eyre, F. H., ed. (1980). Forest cover types of the United States and Canada. Society of American Foresters, Washington, DC. 148 p.

Fraser, D.A. (1953). Ecological studies in a hardwood stand at Chalk River with special reference to the condition of yellow birch. *In*: Report on the Symposium on Birch Dieback. Summary of Proceedings Held in Ottawa, Canada, on March 21 and 22, 1952, at the Invitation of the Biological Sciences Division, Science Service, Department of Agriculture. Parts 1 and 2.

Fraser, D.A. and C.A. Mawson (1953). Movement of radioactive isotopes of yellow birch and white pine as detected with portable scintillation counter. Can. J. Bot. **31**: 324-333.

George, M.F. and M.J. Burke (1986). Low temperature: physical aspects of freezing in woody plant xylem. *In* Forestry science: stress physiology and forest productivity. *Edited by* T.C. Hennessey. Martinus Nijhoff Publishers, Netherlands. pp 133-150.

Gilbert, Adrian M. (1965). Yellow birch (*Betula alleghaniensis* Britton). *In* Silvics of forest trees of the United States. H. A. Fowells, comp. U.S. Department of Agriculture, Agriculture Handbook 271. Washington, DC. p. 104-109.

Greenidge, K.N.H. (1951). Dieback: a disease of yellow birch (*Betula lutea* Michx.) in eastern Canada. PhD. Thesis, Dept. Biol., Harvard Univ., Boston, MA, 300 p.

Greenidge, K.N.H. (1953b). The moisture regime of healthy and diseased birch.: *In*: Report on the Symposium on Birch Dieback. Summary of Proceedings Held in Ottawa, Canada, on March 21 and 22, 1952, at the Invitation of the Biological Sciences Division, Science Service, Department of Agriculture. Parts 1 and 2.

Hache, U. and J.J. Sauter (1996). Xylem dysfunction during winter and recovery of hydraulic conductivity in diffuse-porous and ring-porous trees. Oceologia 105: 435-439.

Hammel H.T. (1967). Freezing of xylem sap without cavitation. Plant Physiology **42:** 55-66.

Hansen, J., I. Fung, A. Rind, S. Lebedeef, R. Ruedy and G. Russel (1988). Global climate changes as forecast by Goddard Institute for Space Studies three dimensional model. J. Geophys. Res. **93**: 9341-9363.

Hansborough, J.R.(1953). The significance of fungi and viruses associated with birch. *In***:** Report on the Symposium on Birch Dieback. Summary of Proceedings Held in Ottawa, Canada, on March 21 and 22, 1952, at the Invitation of the Biological Sciences Division, Science Service, Department of Agriculture. Parts 1 and 2.

Hawbolt, L.S. (1947). Aspects of yellow birch dieback in Nova Scotia. J. Forestry **45**: 414-422.

Hawbolt, L.S. (1952). Climate and birch “dieback”. Dept. Lands and Forests, Prov. of Nova Scotia. Bulletin No. 6.

Hawbolt, L.S. and A.J. Skolko (1948). Investigation of yellow birch dieback in Nova Scotia in 1947. J. Forestry **46**: 659-671.

Hengeveld, H.G. (2000). Projections for Canada's Climate Future. A discussion of recent simulations with the Canadian Global Climate Model. Meteorological Service of Canada, Environment Canada Cat. No. En57-2000-01E pp 27.

Hepting, G. H. (1971). Diseases of forest and shade trees of the United States. USDA Forest Service Agricultural Handbook 386, 658 pp.

Hill, A.W. and G.A. Sinclair (1954). Survey of the condition of yellow birch in Ontario, Canda. Department of Agriculture. Forest Pathology Laboratory, Maple ON.

IPCC (2001). Climate change 2001: The scientific basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). *Edited by* J.T. Houghton, Y. Ding, D.J. Griggs, N. Noguer, P.J. van der Linder, and D. Xiaosu. Cambridge, U.K.

Jarbeau, J.A., F.W. Ewers and S.D. Davis (1995). The mechanism of water stress induced embolism in two species of co-occurring chaparal shrubs. Plant Cell Environ. 18: 189-196.

Kujawski, R. F., and Paul C. Lemon. (1969). Ecological effectiveness of yellow birch in several Adirondack forest types. *In* Vegetation-environment relations at Whiteface Mountain in the Adirondacks. p. 162-191. J. Gary Holway and Jon T. Scott, co-investigators. Report 92. State University of New York, Atmospheric Sciences Research Center, Albany.

Lachance, D. (1988). Sugar maple decline, acid rain, pest interactions in the northeast. SAF 1988 National Convention, Rochester, NY. p 102-105.

Langan, S.J., F.W. Ewers and S.D. Davis (1997). Xylem dysfunction caused by water stress and freezing in two species of co-occurring chaparral shrubs. Plant Cell Environ. 20: 425-437.

Leblanc, S.G., J.M.Chen, and M. Kwong, 2002. TRAC MANUAL Tracing Radiation and Architecture of Canopies Version 2.1. Natural Resources Canada, Canada Centre for Remote Sensing. pp 24.

Lechowicz, M.J. (1984). Why Do Temperate Deciduous Trees Leaf Out At Different Times? Adaptation and Ecology of Forest Communities. The American Naturalist **124**: 821-842.

Linkosalo, T., T.R Carter, R. Hakkinen and P.Hari, (2000). Predicting spring phenology and frost damage risk of Betula spp. under climatic warming: a comparison of two models. Tree Physiol. **20**: 1175-1182.

LRTAP - Long Range Transported Air Pollution (1986). Workshop No. 6. Forest Decline Workshop. Wakefield, Quebec, October 20-22, 1986. Atmospheric Environment Service, Downsview, Ontario, pp. 233.

Martineau, R. 1953. Variation within injury classes on 223 white birch trees from 1948 to 1951. In: Report on the Symposium on Birch Dieback. Summary of Proceedings Held in Ottawa, Canada, on March 21 and 22, 1952, at the Invitation of the Biological Sciences Division, Science Service, Department of Agriculture. Parts 1 and 2.

McElroy, M.B. (1994). Climate on the earth: an overview. Environ. Pollut. **83**: 3-21.

Meng, F.-R., C.P.-A. Bourque, K. Jewett, D. Daugharty, and P.A. Arp (1995). The Nashwaak Experimental Watershed Project: Analysing Effects of Clearcutting on Soil Temperature, Soil Moisture, Snowpack, Snowmelt and Stream Flow. Water, Air and Soil Pollution **82**: 363-374.

Millers, I., D.S. Shriner and D. Risso (1989). History of hardwood decline in the eastern United States. USDA For. Serv., Den. Tech. Rep. NE For. Exp. Stn., Broomall, PA., 75 p.

Orgen, E., (1996). Premature dehardening in *Vaccinium Myrtillus* during a mild winter: a cause for winter dieback? Funct. Ecol. **10**: 723-732.

Pomerleau, R. (1944). Observations sur quelques maladies non parasitinaires des arbres dans le Quebec. Contribution du Service Forestiere; Ministere des Terres et Forets, Quebec

Pomerleau, R. (1953). History of hardwood species dying in Quebec. *In***:** Report on the Symposium on Birch Dieback. Summary of Proceedings Held in Ottawa, Canada, on March 21 and 22, 1952, at the Invitation of the Biological Sciences Division, Science Service, Department of Agriculture. Parts 1 and 2.

Pomerleau, R. (1959). Hardwood Dying Studies in Quebec: laboratory experiments on white birch seedlings. Unpublished manuscript. Canadian Forestry Service, Laurentian Forestry Centre, Ste. Foy, Quebec, Canada.

Pomerleau, R. (1991). Experiments on the causal mechanisms of dieback on deciduous forests in Quebec. Canadian Forestry Service, Quebec Region, Information Report LAU-X-96, 47 p.

Post, B. W., W. H. Carmean, and Robert 0. Curtis. (1969). Birch soil-site requirements. In Proceedings, Birch Symposium. p. 95-101. USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA

Quigley, K. L., and H. M. Babcock. (1969). Birch timber resources of North America. *In* Proceedings, Birch Symposium. p. 6-14. USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA.

Redmond, D.R. (1955). Studies in forest pathology XV. Rootlets, mycorrhiza, and soil temperatures in relation to birch dieback. Can. J. Bot. **33**: 595-627.

Redmond, D.R. (1957). The future of birch from the viewpoint of dieases and insects. For. Chron. **33**: 208-212.

Robson, D.J., W.J. McHardy and J.A. Petty (1988). Freezing in conifer xylem. II. Pit aspiration and bubble formation. J. Exp. Bot. **39**: 1091-1098.

Sajan, R.J. and D.C. Constable. (1984) Results of forest insect and disease surveys in Ontario. Ontario Regional Reports (1983).

Salonius, P.O., C.C. Smith, H. Piene, and M.K. Mahendrappa (1977). Relationships Between Air and Ground Temperatures in Spruce and Fir Forests. Maritimes Forest Research Centre, Fredericton New Brunswick, Information Report M-X-77. 14 p.

Sanitarius, K.A. (1982). The mechanism of cryoprotection of biomembrane systems by carbohydrates. *In* Plant cold hardiness and freezing stress. Vol. 2. Edited by P.H. Li and A. Sakai. Academic Press, New York. pp 475-486.

Sarvas, R., (1972). Investigations of the annual cycle of development of forest trees. Active periods. Commun. Inst. For. Fenn. **76**: 1-110.

Sarvas, R., (1974). Investigations of the annual cycle of development of forest trees. Autumn dormancy and winter dormancy. Commun. Inst. For. Fenn. **84**: 1-101.

Shaw, R.W. (1996). Climate Change and Climate Variability in Atlantic Canada. Workshop Proceedings, Halifax, Nova Scotia, Environment Canada - Atlantic Region Occasional Report No. 9.

Siccama, T. G. (1974). Vegetation, soil, and climate on the Green Mountains of Vermont. Ecological Monograph. **44:** 325-349.

Sinclair, G.A. (1952). Survey of the condition of yellow birch in Ontario. Dept. of Agr. Sci. Serv. Bi-monthly Prog. Rep. 8. pp. 2-3.

Sinclair, G.A. and A.W. Hill, (1953). Study of the condition of birch in Ontario. In: Canada Dept. of Agriculture, 1953. Report on the symposium on birch dieback. Summary of the meetings held in Ottawa, March 21 and 22, 1952. Forest biology division, Science Service, Dept of Agriculture, 182pp.

Sinclair, G.A. and H.H. Lyon, and W.T. Johnson (1987). Diseases of Trees and Shrubs. Ithaca and London: Comstock Publishing Associates, Cornell University Press. pp 440-451.

Sperry, J.S., N.M. Holbrook, M.H. Zimmermann and M.T. Tyree (1987). Spring filling of xylem vessels in wild grapevine. Plant Physiol. **83**: 414-417.

Sperry, J.S. and J.R. Donnelly and M.T. Tyree (1988). Seasonal occurence of xylem embolism in sugar maple *(Acer saccharum).* Am.J. Bot. **75**: 1212-1218.

Sperry, J.S. and J.E.M. Sullivan (1992). Xylem embolism in response to freeze -thaw cycles and water stress in ring-porous, diffuse porous , and conifer species. Plant Physiol.**100**: 505-613.

Sperry, J.S. (1993). Winter xylem embolism and spring recovery in Betula cordifolia, Fagus grandifolia, Abies balsamea and Picea rubens. *In* Water Transport in Plants under Climatic Stress. Cambridge University Press, Cambridge. pp. 86-98.

Sperry, J.S., K.L. Niclols, J.E.M. Sullivan and E. Eastach (1994). Xylem embolism in ring-porous, diffuse-porous and coniferous trees of Northern Utah and Interior Alaska. Ecology **75**: 1736-1752.

Steponkus, P.L. (1984). Role of the plasma membrane in freezing injury and cold acclimation. Ann. Rev. Plant Physiol. **35**: 543-584.

Schwartz, M.D. (1999). Advancing to full bloom: planning phenological research for the 21st century. Int. J. Biometeorology. **42** 113-118.

Tyree, M.T. and M.A. Dixon (1986). Water stress induced cavitation and embolism in some woody plants. Physiol. Plant. **66**: 397-405.

Walker, S.L., A.N. Auclair and H. Martin (1990). History of crown dieback and deterioration symptoms of hardwoods in eastern Canada. Part I and II. Federal LRTAP Liaison Office, Atmospheric Environment Service.

Ward, J.S. and G.R. Stephens (1997). Survival and growth of yellow birch (*Betula alleghaniensis*) in southern New England. Can. J. For. Res. **27**: 156-169.

Wigley, T.M.L. (1989). Possible climate change due to SO_2-derived cloud condensation nuclei. Nature **339**: 365-367.

Van den Driessche, R. (1979). Respiration rate of cold stored nursery stock. Can. J. For. Res**. 9**: 15-18.

Yin, X., and P.A. Arp (1993). Predicting forest soil temperatures from monthly air temperature and precipitation records. Can. J. For. Res. **23**: 2521-2536.

Zhu, X.B., R.M. Cox, and P.A Arp (2000). Effects of xylem cavitation and freezing injury on dieback of yellow birch (*Betula alleghaniensis*) in relation to a simulated winter thaw. Tree Physiol. **20**: 541-547.

Zhu, X.B., (2001). Role of xylem cavitation and freezing injury in yellow birch. Experiment and modeling. Ph.D. thesis, University of New Brunswick, Fredericton, NB.

Zhu, X.B., R.M. Cox, F.-R. Meng, and P.A. Arp (2001). Responses of xylem cavitation, freezing injury and shoot dieback to a simulated winter thaw in yellow birch seedlings growing in different nursery culture regimes. For. Ecol. and Mgt. **145**: 243-253.

Zhu, X.B., R.M. Cox, C.P.A. Bourque, and P.A. Arp (2002a). Thaw effects on cold-hardiness parameters in yellow birch. Can. J. Bot. **80**: 390-398.

Zhu, X.B., R.M. Cox, and C.P. Bourque (2002b). Unpublished. Yellow Birch Decline: Modeling. Xylem cavitation responses to winter weather.

APPENDICIES

APPENDIX I

THE WEATHER READER ALGORITHM

WEATHER_READER
Author: Charles P.-A. Bourque
Date: March 15, 2000
Revised: January 28, 2001
Version: 1.1

```
program Weather_reader

        !MS$OPTIMIZE:'ON:xp'

        use portlib
        implicit none
        integer
year,month,weather_element,imn,i,j,k,i_day,total_number_of_days,set_minimum_num
ber_of_years
        integer
station_number,buffer,year_number,year_old,old_element,i_thaw_event,thaw_event_no
,iformat
        integer
old_year_total,beginning_year,icheck,icheck02,i_yr,No_years,i_time,i_station,output_y
ear
        character*7 station_names(0:2000),stationID
        character*1 switch

 ! *********************************************************
 ! * Settings for degree day and thaw duration calculations *
 ! *********************************************************
        real
base_temperature_one,base_temperature_two,frost_threshold,maximum_temperature,
&

degree_days_one,degree_days_two,old_DDG_01,current_degree_day_01,minimum_te
mperature, &

mean_temperature,current_degree_day_02,old_DDG_02,X,Y,max01,max02
        integer
thaw_duration,start_month,end_month,day_of_year,days_following_thaw,i_thaw, &
```

```
output_temperature,check_year,i_execute,frost_duration,i_station_count,number_of_tha
w_days, &

start_of_thaw_month,start_of_thaw_day,i_month,years_considered,first_year,last_year,
imnx, &

imn_open,istate,i_thaw_number,maximum_thaw_events,missing_data_switch

        integer, allocatable::variable(:,:,:,:),year_record(:,:),number_of_days(:)
        real, allocatable::array_X_coordinate(:),array_Y_coordinate(:)
        real, allocatable::output_array01(:,:,:),output_array02(:,:,:),annual_DD(:,:,:)
        real, allocatable::DD_end_of_thaw01(:,:,:),DD_end_of_thaw02(:,:,:)
        character*13, allocatable::output_char01(:,:,:),output_char02(:,:,:)
        character*10 value_check
        character*7 old_station,old_station02,station_id,station_test
        character*40 cofile
        character*24 cofile2
        character*3 cofile3
        character*40 input_files(15)
        character*19 cofile4,cofile5
        character (24) systime

        systime=ctime(Time())
        print *,' '
        print *, 'Current DATE & TIME: ',systime
        print *,' '
        print *,'.........................................................................'
    print
*,'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
>>>>>>>>>>>>>>'
    print *,'>                                                  >'

    print *,'>                 WEATHER_READER                   >'
    print *,'>                                                  >'
    print *,'>   Author: Charles P.-A. Bourque                  >'
    print *,'>   Date: March 15, 2000                           >'
    print *,'>   Revised: January 28, 2001                      >'
    print *,'>   Version: 1.1                                   >'
        print *,'>                                              >'

    print
*,'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
>>>>>>>>>>>>>>'
        print *,'.........................................................................'

        station_test="9999999"
        value_check="  -9999.00"
```

```
        first_year=1930
        last_year=1960
        number_of_thaw_days=4
        thaw_event_no=0
        frost_duration=0
        i_thaw_event=0
        i_execute=0
        maximum_thaw_events=20
        missing_data_switch=0
        i_station_count=0
        base_temperature_one=4.0  !base temperature for yellow birch
        base_temperature_two=0.0  !for calculating degree days above zero deg. C
        frost_threshold=-4.0      !minimum temperature that terminates a thaw
        start_month=1
        end_month=5
        output_temperature=3      !selects the appropriate weather element
        thaw_duration=0
        days_following_thaw=0
        i_thaw=0
        variable=-999
        icheck02=0
        old_year_total=0
        station_number=1
        year_number=0
        year_old=0
        check_year=year_old
        old_element=1
        old_DDG_01=0
        old_DDG_02=0
        beginning_year=0
        day_of_year=0
        station_names='blank'

!     input files and their locations are specified here
        input_files(1)='Raw data\CNDData\dly.txt'
        input_files(2)='Raw data\CNDData\ccaf.dat'
        input_files(3)='Raw data\USData\Maine.csv'
        input_files(4)='Raw data\USData\Michigan.csv'
        input_files(5)='Raw data\USData\NewHampshire.csv'
        input_files(6)='Raw data\USData\NewYork.csv'
        input_files(7)='Raw data\USData\Vermont.csv'
        input_files(8)='Raw data\CNDData\Canadian_xy.txt'
        input_files(9)='Raw data\USData\Maine_xy.txt'
        input_files(10)='Raw data\USData\Michigan_xy.txt'
        input_files(11)='Raw data\USData\NewHampshire_xy.txt'
        input_files(12)='Raw data\USData\NewYork_xy.txt'
        input_files(13)='Raw data\USData\Vermont_xy.txt'
        input_files(14)='Raw data\USData\us.csv'
```

```
        input_files(15)='Raw data\USData\us_xy.txt'

        icheck=0
        print *,' '
        print *,'...........................................................................'
        print *,'...........................................................................'
        print *,' '
        print *,' BEFORE YOU USE THIS SOFTWARE MAKE SURE THAT YOU
HAVE "Weather data",'
        print *,' "vegnDDG", AND "snowDDG" folders INSTALLED IN YOUR
WORKING DIRECTORY'
        print *,' '
        print *,'...........................................................................'
        pause
        print *,' '
        print *,'...........................................................................'
        print *,' '
        print *,' '
        print *,'...........................................................................'
        print *,' '
        print *,'Which DATA FORMAT do you want to use?'
        print *,'          option: 1 - CANADIAN, FREE-FORMAT (raw) data'
        print *,'                  2 - CANADIAN, ORACLE-extracted data'
        print *,'                  3 - AMERICAN, data'
        print *,'...........................................................................'
        print *,' '
        read(5,*)iformat
        print *,'...........................................................................'
        print *,' '
        if(iformat==1)then
          print *,'Make sure "dly.txt" is in CNDData in the "Raw data" folder
(working directory)'
        station_id="6012198"
        else if(iformat==2)then
          print *,'Make sure "CCAF.dat" is in CNDData in the "Raw data" folder
(working directory)'
                station_id="6011305"
        else if(iformat==3)then
          print *,'Make sure STATE DATA is in USData in the "Raw data" folder
(working directory)'
        end if
        print *,' '
        print *,'...........................................................................'
        pause
        print *,'Do you want to generate STATION DATA FILES? (y/n)'
        print *,'...........................................................................'
```

```
	print
*,'#####################################################################
######'
	print *,'##	If not, make sure that the STATION DATA FILES are
##'
	print *,'##	already in the "Weather data" folder of your working	##'
	print *,'##	directory				##'
	print
*,'#####################################################################
######'
	print *,'.....................................................................'
	allocate(number_of_days(1:12))

!    number of days per month
	number_of_days(1)=31
	number_of_days(2)=29
	number_of_days(3)=31
	number_of_days(4)=30
	number_of_days(5)=31
	number_of_days(6)=30
	number_of_days(7)=31
	number_of_days(8)=31
	number_of_days(9)=30
	number_of_days(10)=31
	number_of_days(11)=30
	number_of_days(12)=31

	read(5,*)switch
	print *,' '
	if(switch=='n'.or.switch=='N')then
		set_minimum_number_of_years=5
	  goto 30
	else if(switch=='y'.or.switch=='Y')then
	  print *,'Minimum NUMBER OF YEARS per station? (integer, >= 5)'
	  read(5,*)set_minimum_number_of_years
	  print *,' '
	  print *,'Provide START and END YEARS (in integer form, e.g., 1945): '
	  read(5,*)first_year,last_year
	  print *,' '
	  years_considered=last_year-first_year+1
	  allocate(variable(85,12,13,years_considered),year_record(85,13))
	end if

	if(iformat==1)then
	  open(1,file=input_files(1),status='old',form='formatted')
	else if(iformat==2)then
	  open(1,file=input_files(2),status='old',form='formatted')
	else if(iformat==3)then
```

```
                  print *,'Which American state would you like to process?'
                  print *,'    Option: 1 - Maine'
                  print *,'            2 - Michigan'
                  print *,'            3 - New Hampshire'
                  print *,'            4 - New York'
                  print *,'            5 - Vermont'
                  print *,'            6 - All states'
                  read(5,*)istate
                  if (istate==1)then
                        open(1,file=input_files(3),status='old',form='formatted')
                        station_id="170100"
                  else if (istate==2)then
                        open(1,file=input_files(4),status='old',form='formatted')
                        station_id="200032"
                  else if (istate==3)then
                        open(1,file=input_files(5),status='old',form='formatted')
                        station_id="270038"
                  else if (istate==4)then
                        open(1,file=input_files(6),status='old',form='formatted')
                        station_id="300015"
                  else if (istate==5)then
                        open(1,file=input_files(7),status='old',form='formatted')
                        station_id="430134"
                  else if (istate==6)then
                        open(1,file=input_files(14),status='old',form='formatted')
                        station_id="170100"
                  end if
            end if
            old_station=station_id
            old_station02=station_id
            j=1
            do while (j/=0)
200      continue
      if(iformat==1)then
                    read(1,10,end=25)station_id,year,month
10          format(a7,i4,i2)
      else if(iformat==2)then
                    read(1,*,end=25)station_id,year,month
                  else if(iformat==3)then
                    read(1,*,end=25)station_id,year,month
                  end if
                  if(year<first_year.or.year>last_year)goto 200
      !print *,station_id,', ',year,', ',month
      if(year/=year_old.and.year>=beginning_year)then
                   year_old=year
                   year_number=year_number+1
                   if(year>beginning_year.and.icheck02==0)then
                     do 106 i_yr=1,40
```

```
                                if(year==year_record(i_yr,1))then
                                 icheck02=1
                                 year_number=i_yr
                                 goto 107
                                end if
106                         continue
                        end if
                        icheck02=1
                       end if
107    backspace(1)
          if(month==2)then
           if(year==1932.or.year==1936.or.year==1940.or.year==1944.or. &

year==1948.or.year==1952.or.year==1956.or.year==1960.or.year==1964.or. &
              year==1968.or.year==1972.or.year==1976.or.year==1980)then
                  number_of_days(2)=29
                else
                  number_of_days(2)=29
                end if
          end if
          if(station_id==old_station)then
                if(year>=beginning_year)then
                 if (iformat==1)then

read(1,20,end=25)station_id,year,month,weather_element,(variable(year_number,month
,weather_element,imn_open),imn_open=1,number_of_days(month))
20         format(a7,i4,i2,i3,31(i6,1x))
                    else if (iformat==2)then

read(1,*,end=25)station_id,year,month,weather_element,(variable(year_number,month,
weather_element,imn_open),imn_open=1,number_of_days(month))
                    else if (iformat==3)then

read(1,*,end=25)station_id,year,month,weather_element,(variable(year_number,month,
weather_element,imn_open),imn_open=1,number_of_days(month))
                    end if
         if(weather_element==1.and.icheck==0)then
                  beginning_year=year
                     icheck=1
                 end if
                 year_record(year_number,weather_element)=year
                end if
               end if
      if(station_id/=old_station)then
                 beginning_year=0
                 old_year_total=No_years
                    year_number=0
                 old_station=station_id
```

```
                    station_number=station_number+1
                end if
        if(weather_element/=old_element)then
                    if(old_element==1)then
                          No_years=year_number-1
                        end if
                    old_element=weather_element
                        year_old=0
                    year_number=0
                        icheck02=0
                        backspace(1)
                        goto 200
                end if
                !if(station_number>490)print *,'access
violations',year_number,month,weather_element
                if(month==0)goto 200
        do 15 i=1,number_of_days(month)
              if(variable(year_number,month,weather_element,i)==-99999)then
                     variable(year_number,month,weather_element,i)=-999
                  end if
15      continue
        !print *,'here now01',',  ',station_id,',  ',old_station02
        if(station_id/=old_station02)then
          !print *,'here now02',',  ',station_id,',  ',old_station02
                  !pause
                  if(old_station02==station_test)then
                   !print *,'check',station_id,',
',old_station02,old_year_total,set_minimum_number_of_years
                   !pause
                  end if
                  if(old_year_total>=set_minimum_number_of_years)then
                    i_station_count=i_station_count+1
               cofile='Weather data\'//old_station02//'.csv'
                    station_names(i_station_count)=old_station02
                    buffer=i_station_count+6
                    print
*,station_names(i_station_count),',',old_year_total,',',i_station_count
               open(2,file=cofile,status='replace',form='formatted')
                    do 300 k=1,old_year_total,1
                      do 300 j=1,12,1
                        do 300 i=1,number_of_days(j),1
                          if(year_record(k,1)/=0)then

write(2,305)old_station02,year_record(k,1),j,variable(k,j,1,i)/10.,variable(k,j,2,i)/10., &

variable(k,j,3,i)/10.,variable(k,j,10,i)/10.,variable(k,j,11,i)/10., &

variable(k,j,12,i)/10.,int(variable(k,j,13,i))
```

```
305                  format(1x,a7,',',i4,',',i2,6(',',f10.1),',',i5)
              end if
300          continue
           close (2)
                        old_station02=station_id
                        variable=-999
                        year_record=0
                      end if
                      old_station02=station_id
                    end if
    end do
25   continue
    close (1)
           open(21,file='scratch.txt',status='replace',form='formatted')
           write(21,*)i_station_count,years_considered
           write(21,*)base_temperature_one,base_temperature_two,frost_threshold
           write(21,*)start_month,end_month,day_of_year
           do 4000 imn=1,i_station_count
             write(21,*)station_names(imn)
4000  continue
           close (21)
30   continue
    if(switch=='n'.or.switch=='N')then
             open(22,file='scratch.txt',status='old',form='formatted')
                   read(22,*)i_station_count,years_considered
             read(22,*)base_temperature_one,base_temperature_two,frost_threshold
             read(22,*)start_month,end_month,day_of_year
             do 4001 imn=1,i_station_count
               read(22,*)station_names(imn)
4001    continue
             close (22)
           end if
           if(switch=='y'.or.switch=='Y')deallocate(variable,year_record)
           allocate(output_array01(i_station_count,years_considered,160))      ! **
number of stations considered,
           allocate(output_array02(i_station_count,years_considered,160))      ! **
last_year-first_year+1 years, 160 days

allocate(DD_end_of_thaw01(i_station_count,years_considered,maximum_thaw_events)
)

allocate(DD_end_of_thaw02(i_station_count,years_considered,maximum_thaw_events)
)
           output_array01=-9999
           output_array02=-9999
           DD_end_of_thaw01=-9999
           DD_end_of_thaw02=-9999
           print *,' '
```

```
     print
*,'*****************************************************************'
     print *,'* Thaw & Degree-Day determination;  Temperature Thresholds:      *'
           print *,'*                  4, 0 and -4 deg.C                    *'
     print
*,'*****************************************************************'
           print *,' '
           year_old=0
           day_of_year=1
           do 3000 i_station=1,i_station_count
              cofile2='Weather data\'//station_names(i_station)//'.csv'
                    !print *,i_station,',',cofile2
              open(i_station,file=cofile2,status='old',form='formatted')
                    do while(i_execute==0)

read(i_station,*,end=3001)station_id,year,month,maximum_temperature,minimum_tem
perature,mean_temperature
                              do 710 imnx=0,years_considered-1
                                if(year==first_year+imnx)then
                                   output_year=imnx+1
                                          goto 711
                                end if
710        continue
711        continue
                              if(year/=check_year)i_time=0
                              check_year=year
                              if(month>=start_month.and.month<=end_month)then
                                 if(month==start_month.and.i_time==0)then
                                           day_of_year=1
                                           i_time=1
                                           thaw_event_no=0
                                           i_thaw_event=0
                                 end if
                                 if(minimum_temperature<=-99.0.or.maximum_temperature<=-
99.0.or.mean_temperature<=-99.0)then
                                          minimum_temperature=frost_threshold+0.1
                                          maximum_temperature=base_temperature_one
                                          mean_temperature=base_temperature_two
                                          missing_data_switch=1
                            !print *,'read
',station_id,year,month,maximum_temperature,minimum_temperature,mean_temperatur
e
                                          !pause
                                 end if
                                 if(minimum_temperature>frost_threshold)then
                                    if(maximum_temperature>=base_temperature_one)then
                                                 if(missing_data_switch==0)then
                                                   if(day_of_year==1)then
```

```
                                        old_DDG_01=0.0
                                        old_DDG_02=0.0
                                      end if
                                 days_following_thaw=0
                                      current_degree_day_01=(mean_temperature-
base_temperature_one)
                                      current_degree_day_02=(mean_temperature-
base_temperature_two)

if(current_degree_day_01>=0)degree_days_one=current_degree_day_01+old_DDG_01

if(current_degree_day_02>=0)degree_days_two=current_degree_day_02+old_DDG_02
                                      if(year==year_old)then
                                           thaw_duration=thaw_duration+1
                                         else
                                           thaw_duration=0
                                           i_thaw=0
                                         end if
                                      frost_duration=0
                                      i_thaw=1

if(i_thaw==1.and.thaw_duration>=number_of_thaw_days)i_thaw_event=1
                                      if(i_thaw==1.and.thaw_duration==1)then
                                        start_of_thaw_month=month
                                        start_of_thaw_day=day_of_year
                                      end if

output_array01(i_station,output_year,day_of_year)=degree_days_one

output_array02(i_station,output_year,day_of_year)=degree_days_two
                                      if(station_id==station_test)then
                                        print *,'station id01= ',station_id
                                        print *,'temps01=
',maximum_temperature,',',minimum_temperature,',',mean_temperature
                                        print *,'DDG01=
',degree_days_one,',',degree_days_two,',',day_of_year,',',month,',',year
                                        print
*,'duration01',thaw_duration,frost_duration,',',i_thaw_event,',',thaw_event_no
                                           print *,'start of
thaw=',start_of_thaw_month,',',start_of_thaw_day
                                        print *,'output
array01',output_array01(i_station,output_year,day_of_year),i_station,output_year,day_o
f_year
                                        pause
                                      end if
                                      old_DDG_01=degree_days_one
                                      old_DDG_02=degree_days_two
                                    end if
```

```
if(station_id==station_test.and.missing_data_switch==1)then
                                        if(year/=year_old)then
                                               thaw_duration=0
                                               frost_duration=1
                                               i_thaw=0
                                             end if
                                        print *,'station id01_switch=1:',station_id
                                        print *,'temps01=
',maximum_temperature,',',minimum_temperature,',',mean_temperature
                                        print *,'DDG01=
',degree_days_one,',',degree_days_two,',',day_of_year,',',month,',',year
                                        print
*,'duration01',thaw_duration,frost_duration,',',i_thaw_event,',',thaw_event_no
                                        print *,'start of
thaw=',start_of_thaw_month,',',start_of_thaw_day
                                        print *,'output
array01',output_array01(i_station,output_year,day_of_year),i_station,output_year,day_o
f_year
                                        pause
                                      end if
                                      missing_data_switch=0
                               else
                                 if(i_thaw==1)frost_duration=0
                                 if(i_thaw==0)then
                                       old_DDG_01=0
                                       old_DDG_02=0
                                       thaw_duration=0
                                      end if
                                      if(i_thaw==1)then
                                        if(year==year_old)then
                                               thaw_duration=thaw_duration+1
                                             else
                                               thaw_duration=0
                                               i_thaw=0
                                             end if
                                      end if
                                      if(i_thaw==0)then
                                        if(year==year_old)then
                                               frost_duration=frost_duration+1
                                             else
                                               frost_duration=1
                                             end if
                                      end if

if(minimum_temperature>=base_temperature_two)then
                                         current_degree_day_02=(mean_temperature-
base_temperature_two)
```

```
if(current_degree_day_02>=0)degree_days_two=current_degree_day_02+old_DDG_02
                                        end if

if(i_thaw==1.and.thaw_duration>=number_of_thaw_days)i_thaw_event=1

output_array01(i_station,output_year,day_of_year)=degree_days_one

output_array02(i_station,output_year,day_of_year)=degree_days_two
                                        if(station_id==station_test)then
                                          print *,' '
                                      print *,'temps02=
',maximum_temperature,',',minimum_temperature,',',mean_temperature
                                      print *,'DDG02=
',degree_days_one,',',degree_days_two,',',day_of_year,',',month,',',year
                                      print
*,'duration02',thaw_duration,frost_duration,',',i_thaw_event,',',thaw_event_no
                                            print *,'start of
thaw=',start_of_thaw_month,',',start_of_thaw_day
                                            pause
                                        end if
                                    end if
                               else
                                 if(mean_temperature>=base_temperature_two+2.0)then
                                     frost_duration=0
                                     if(i_thaw/=1)then
                                         old_DDG_01=0
                                         old_DDG_02=0
                                         thaw_duration=0
                                        end if
                                        if(i_thaw==1)then
                                          if(year==year_old)then
                                              thaw_duration=thaw_duration+1
                                            else
                                              thaw_duration=0
                                              i_thaw=0
                                            end if
                                        end if

if(i_thaw==1.and.thaw_duration>=number_of_thaw_days)i_thaw_event=1

output_array01(i_station,output_year,day_of_year)=degree_days_one

output_array02(i_station,output_year,day_of_year)=degree_days_two
                                        if(station_id==station_test)then
                                            print *,' '
                                      print *,'temps0x=
',maximum_temperature,',',minimum_temperature,',',mean_temperature
```

```
                                        print *,'DDG0x=
',degree_days_one,',',degree_days_two,',',day_of_year,',',month,',',year
                                        print
*,'duration0x',thaw_duration,frost_duration,',',i_thaw_event,',',thaw_event_no
                                               print *,'start of
thaw=',start_of_thaw_month,',',start_of_thaw_day
                                               pause
                                          end if
                                     else

if(i_thaw_event==1.and.thaw_duration/=0)thaw_event_no=thaw_event_no+1
                                          if(i_thaw_event==1)then
                                           !print *,'Number of Thaw Events
=',i_station,output_year,thaw_event_no,degree_days_one,degree_days_two

DD_end_of_thaw01(i_station,output_year,thaw_event_no)=degree_days_one

DD_end_of_thaw02(i_station,output_year,thaw_event_no)=degree_days_two
                                           !print *,'DD
=',DD_end_of_thaw01(i_station,output_year,thaw_event_no),DD_end_of_thaw02(i_sta
tion,output_year,thaw_event_no)
                                          end if
                                          i_thaw_event=0
                                   old_DDG_01=0.0
                                       old_DDG_02=0.0
                                       degree_days_one=0
                                       degree_days_two=0
                                       thaw_duration=0
                                       i_thaw=0
                                       if(year==year_old)then
                                           frost_duration=frost_duration+1
                                          else
                                               frost_duration=1
                                          end if
                                          start_of_thaw_month=0
                                          start_of_thaw_day=0

output_array01(i_station,output_year,day_of_year)=degree_days_one

output_array02(i_station,output_year,day_of_year)=degree_days_two
                                          if(station_id==station_test)then
                                           print *,' '
                                        print *,'temps03=
',maximum_temperature,',',minimum_temperature,',',mean_temperature
                                        print *,'DDG03=
',degree_days_one,',',degree_days_two,',',day_of_year,',',month,',',year
                                        print
*,'duration03',thaw_duration,',',frost_duration,',',i_thaw_event,',',thaw_event_no
```

```
                                        print *,'start of
thaw=',start_of_thaw_month,',',start_of_thaw_day
                                        pause
                                    end if
                                end if
                            end if
                            day_of_year=day_of_year+1
                          else
                            day_of_year=1
                            old_DDG_01=0
                            old_DDG_02=0
                            degree_days_one=0
                            degree_days_two=0
                            thaw_event_no=0
                          end if
                          if(year/=year_old)then
                            year_old=year
                          end if
       end do
3001     continue
                 close (i_station)
3000  continue
    !associate station id to x, y, and elevation values
         allocate(array_X_coordinate(0:2000),array_Y_coordinate(0:2000))
         if (iformat==1.or.iformat==2)then
           open(99,file=input_files(8),status='old',form='formatted')
         else if (iformat==3)then
                 if (istate==1)then
             open(99,file=input_files(9),status='old',form='formatted')
                 else if (istate==2)then
             open(99,file=input_files(10),status='old',form='formatted')
                 else if (istate==3)then
             open(99,file=input_files(11),status='old',form='formatted')
                 else if (istate==4)then
             open(99,file=input_files(12),status='old',form='formatted')
                 else if (istate==5)then
             open(99,file=input_files(13),status='old',form='formatted')
                 else if (istate==6)then
             open(99,file=input_files(15),status='old',form='formatted')
                 end if
         end if
         do 1000 i_station=1,i_station_count
           do while (i_execute==0)
                  read(99,*,end=1001)stationID,X,Y
                  !if(i_station>=169)then
                    !print *,stationID,X,Y,station_names(i_station),i_station
                    !pause
                  !end if
```

```
                if(station_names(i_station)==stationID)then
                  array_X_coordinate(i_station)=X
                       array_Y_coordinate(i_station)=Y
                       rewind(99)
                       goto 1001
                end if
              end do
1001    continue
1000  continue
        total_number_of_days=0
    do 7000 i_month=start_month,end_month,1
      total_number_of_days=total_number_of_days+number_of_days(i_month)
7000  continue
    print *,' '
    print *,'total_number_of_days=',total_number_of_days
        print *,' '

allocate(output_char01(i_station_count,years_considered,total_number_of_days),output
_char02(i_station_count,years_considered,total_number_of_days))
        do 8000 i_station=1,i_station_count
          do 8000 i_day=1,total_number_of_days
                do 8000 i_yr=1,years_considered

write(output_char01(i_station,i_yr,i_day),'(f10.2)')output_array01(i_station,i_yr,i_day)

write(output_char02(i_station,i_yr,i_day),'(f10.2)')output_array02(i_station,i_yr,i_day)
!                         print
*,output_char01(i_station,i_yr,i_day),output_char02(i_station,i_yr,i_day)

if(output_char01(i_station,i_yr,i_day)==value_check)output_char01(i_station,i_yr,i_da
y)=' '

if(output_char02(i_station,i_yr,i_day)==value_check)output_char02(i_station,i_yr,i_da
y)=' '
8000  continue
    do 6000 i_day=1,total_number_of_days
          write(cofile3,'(i3)')i_day
               cofile4='vegnDDG\day_'//cofile3//'.txt'
               cofile5='snowDDG\day_'//cofile3//'.txt'
               print *,cofile4,',',' ',cofile5
      open(1,file=cofile4,status='replace',form='formatted')
      open(2,file=cofile5,status='replace',form='formatted')

write(1,3002)'"stationID"','"X"','"Y"',((first_year+i_yr),i_yr=0,years_considered-1)

write(2,3002)'"stationID"','"X"','"Y"',((first_year+i_yr),i_yr=0,years_considered-1)
3002     format(1x,a11,',',a3,',',a3,',',<years_considered>('"',i4,'"',','),'"',i4,'"')
      do 5000 i_station=1,i_station_count
```

```
write(1,5001)station_names(i_station),array_X_coordinate(i_station),array_Y_coordina
te(i_station),(output_char01(i_station,i_yr,i_day),i_yr=1,years_considered)

write(2,5001)station_names(i_station),array_X_coordinate(i_station),array_Y_coordina
te(i_station),(output_char02(i_station,i_yr,i_day),i_yr=1,years_considered)
5001       format(1x,'"',a7,'"',',',f7.2,',',f7.2,',',<years_considered>(a10,','),a10)
5000    continue
        close (1)
                      close (2)
6000  continue
            deallocate(output_char01,output_char02)

            max01=0.0
            max02=0.0
            allocate(annual_DD(i_station_count,years_considered,1:3))

!     Station annual DD summary for snow & vegetation
      do 6200 i_station=1,i_station_count
               do 6200 i_yr=1,years_considered
                        do 6200 i_thaw_number=1,maximum_thaw_events
                                  if(DD_end_of_thaw01(i_station,i_yr,i_thaw_number)/=-
9999.0.or.i_thaw_number==maximum_thaw_events)then

max01=max(max01,DD_end_of_thaw01(i_station,i_yr,i_thaw_number))
                                    if(i_thaw_number==maximum_thaw_events)then
                                      annual_DD(i_station,i_yr,1)=max01
                                      max01=0.0
                                    end if
                                        end if
                                  if(DD_end_of_thaw02(i_station,i_yr,i_thaw_number)/=-
9999.0.or.i_thaw_number==maximum_thaw_events)then

max02=max(max02,DD_end_of_thaw02(i_station,i_yr,i_thaw_number))
                                    if(i_thaw_number==maximum_thaw_events)then
                                      annual_DD(i_station,i_yr,2)=max02
                                      max02=0.0
                                    end if
                                        end if
6200  continue

deallocate(output_array01,output_array02,DD_end_of_thaw01,DD_end_of_thaw02)

      open(8,file='Annual_VegN_DD.txt',status='replace',form='formatted')
      open(9,file='Annual_Snow_DD.txt',status='replace',form='formatted')

write(8,3012)'"stationID"','"X"','"Y"',((first_year+i_yr),i_yr=0,years_considered-1)
```

```
write(9,3012)'"stationID"','"X"','"Y"',((first_year+i_yr),i_yr=0,years_considered-1)
3012  format(1x,a11,',',a3,',',a3,',',<years_considered>('"',i4,'"',','),'"',i4,'"')
      do 7100 i_station=1,i_station_count

write(8,5011)station_names(i_station),array_X_coordinate(i_station),array_Y_coordina
te(i_station),(annual_DD(i_station,i_yr,1),i_yr=1,years_considered)
5011      format(1x,'"',a7,'"',',',f7.2,',',f7.2,',',<years_considered>(f10.2,','),f10.2)
7100  continue
      do 7200 i_station=1,i_station_count

write(9,5012)station_names(i_station),array_X_coordinate(i_station),array_Y_coordina
te(i_station),(annual_DD(i_station,i_yr,2),i_yr=1,years_considered)
5012      format(1x,'"',a7,'"',',',f7.2,',',f7.2,',',<years_considered>(f10.2,','),f10.2)
7200  continue
      deallocate(array_X_coordinate,array_Y_coordinate,annual_DD)
           close (8)
      close (9)
          end program
```

APPENDIX II

GEOSPATIAL INTERPOLATIONS

Geostatistics – quantifies the relationship between any two values separated by distance and uses this information to interpolate the values between the two locations.

Variogram –describes the expected difference in value between pairs of samples within a given orientation. The variogram controls the way that kriging weights are assigned to points during the interpolation, and consequently controls the quality of the results.

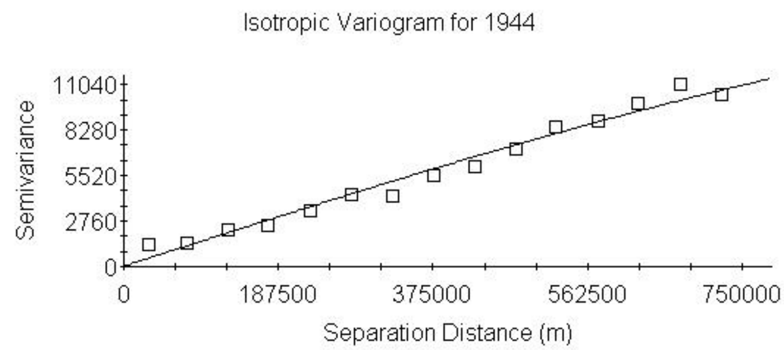
Semi-variance – is a measure of the degree of spatial correlation among sample data points as a function of the distance and direction between the sample data points.

Auto-correlation – measure of correlation between samples with increasing distance from one another. Moran’s I analysis is used to parametrize the degree of auto-correlation.

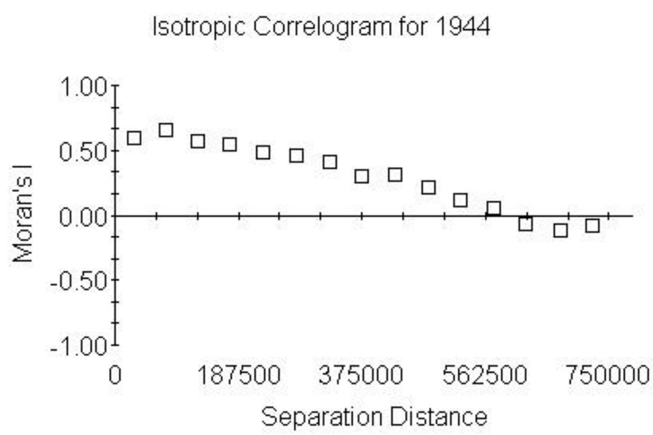
Cross Validation – is used to compare the impact of different models on interpolation results. In cross validation, a variogram model and search neighborhood are specified. Data values are then kriged at each sample location, assuming that particular sample is missing. The kriged values and true values are compared. The difference between these two values is the cross-validated residual. The cross-validation technique was used to evaluate the impact different kriging parameters on the interpolation results.

Kriging is the preferred method for the geospatial visualization of the thaw anamolies because kriging reduces the extreme weighting of values caused by irregular distribution of sample points, especially those that might result from clustering. Geostatistics detects spatial dependence among neighboring climate station values and defines the degree of dependence by giving quantifiable parameters. The spatial arrangement of climate stations for this study is clustered.

Geostatistical example for 1944



This isotropic variogram demonstrates the semivariance as a function of distance for a typical day during the thaw in 1944. The sill is reached at 600 km where the data is considered to be no longer spatially related; $r^2 = 0.980$.

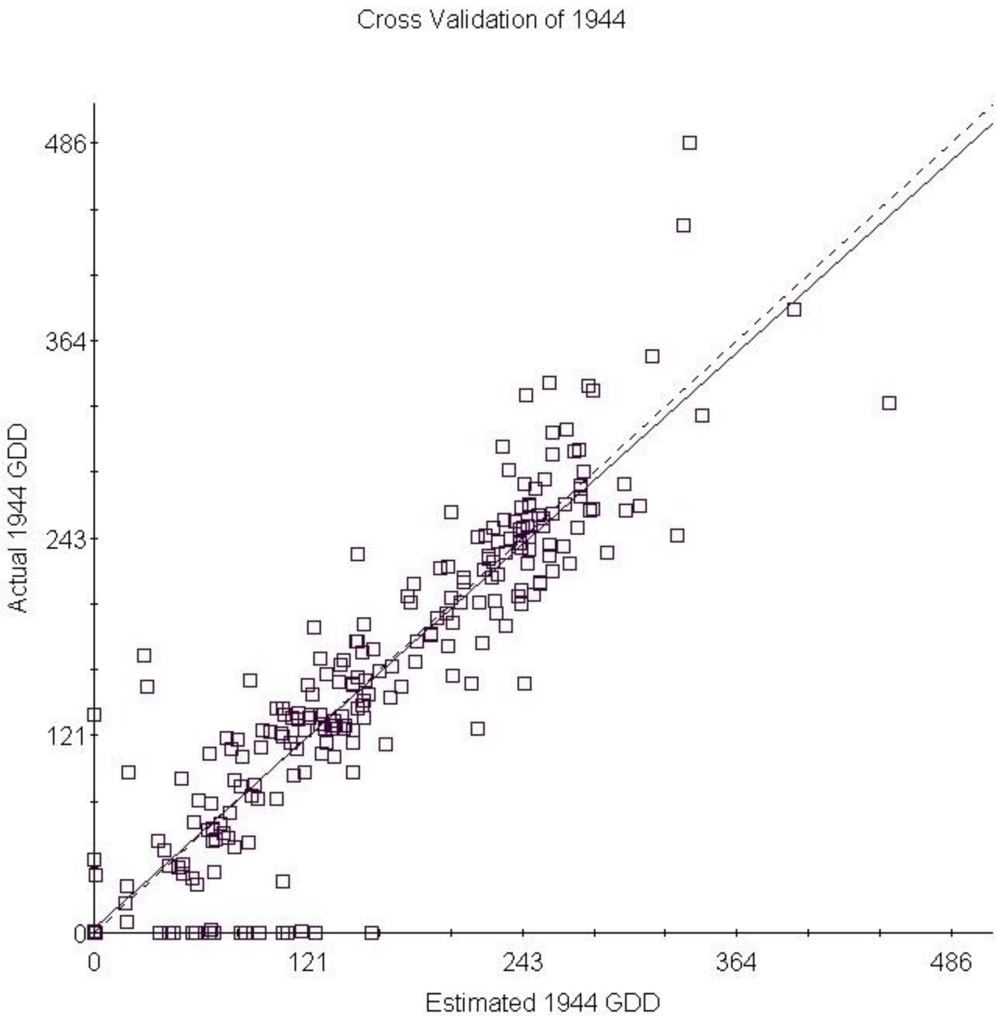


This isotropic correlogram demonstrates spatial autocorrelation as a function of distance for a typical day during the thaw in 1944. Values closer to +1 are strongly positively correlated; values closer to –1 are strongly negatively correlated.

The calculation of the above variogram enabled the calculation of expected difference in value of accumulated degree-days between pairs of samples within a given orientation for, e.g., 1944. For this year, the semivariance increased with distance until approximately 600 km. At that distance, point samples were no longer related to each other spatially. The variogram itself was calculated using an active lag distance of 750 km, with a lag class distance interval of 50 km, and using a spherical model. This variogram had an r^2 of 0.980.

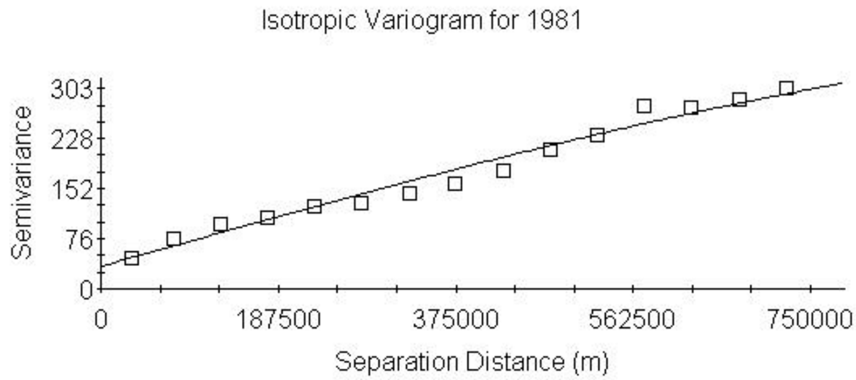
The correlogram for 1944 represents the spatial autocorrelation of the data. The degree of autocorrelation is represented by Moran's I: the stronger the autocorrelation, i.e., the larger I deviates from 0. In contrast, I = 0 exhibits a random distribution of values. Values of $I>0$ indicate a positive autocorrelation, and values of $I < 0$ exhibits indicate a negative autocorrelation. A cross validation of actual values of interpolated GDD values versus actual GDD values illustrates whether the geospatial model represents the actual data reasonably well. For the 1944 example, the cross validation had an r^2 value of 0.765.

For the 1981 thaw events, the semivariance increased with distance until approximately 550 km. The variogram for the 1981 events was calculated using an active lag distance of 750 km, a lag class distance interval of 50 km using a spherical model having an $r^2 = 0.972$. The correlogram for the 1981 data started cycling at around 550 km. This correlogram had significantly higher values (closer to 1) for Moran's I than the year 1944. This can be attributed to the higher density of reporting weather stations in 1981: 424 in 1981 versus 213 in 1944. The cross validation of actual versus interpolated values of GDD for 1981 had an r^2 value of 0.845.

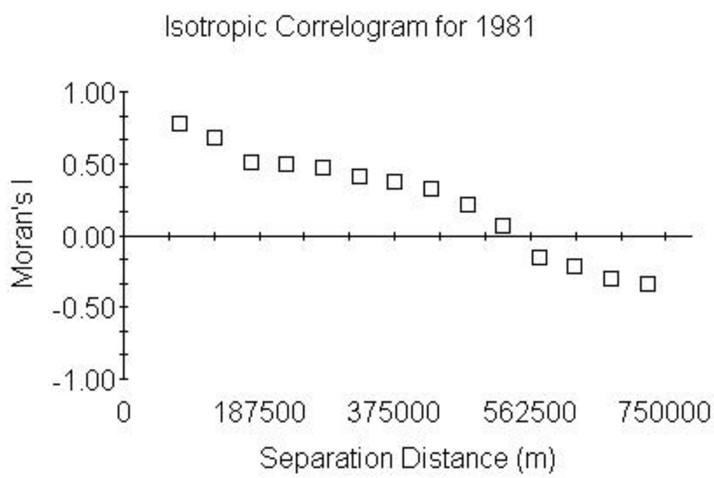


Cross validation of actual (calculated) versus expected (modeled) daily accumulated GDD values for a typical day representative of the 1944 data; r^2=0.765.

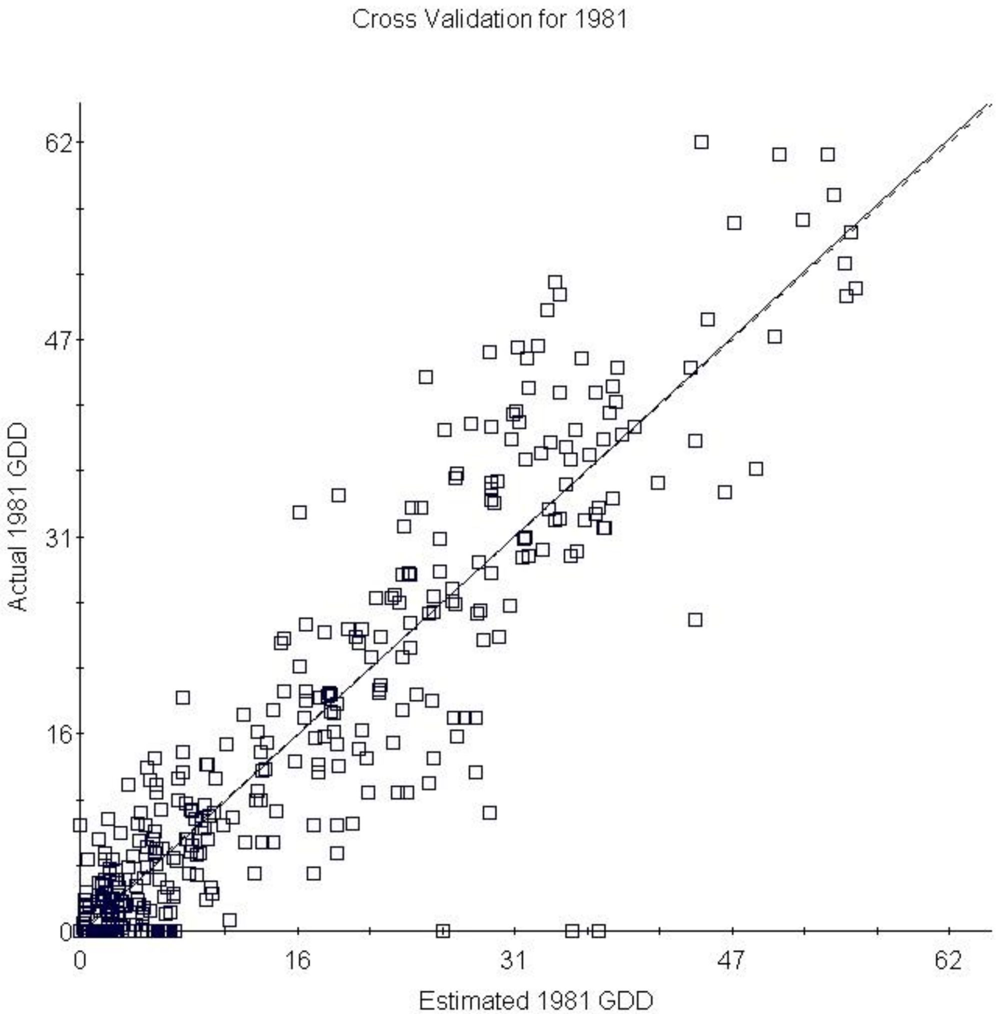
Geostatistical example for 1981



This isotropic variogram demonstrates the shape of the variogram, as a function of distance, for a typical day during the thaw in 1981. The sill is reached at 550 km where the data is considered to be no longer spatially related; $r^2 = 0.972$.



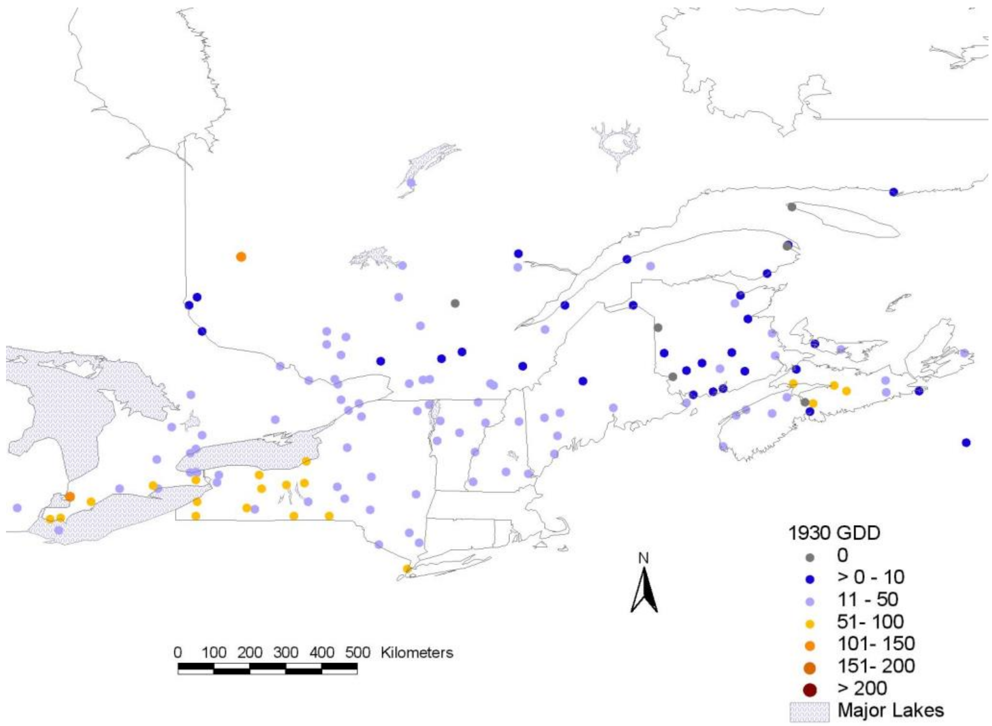
This isotropic correlogram demonstrates spatial autocorrelation as a function of distance, for a typical day during the thaw in 1981. Values closer to +1 are strongly positively correlated; values closer to –1 are strongly negatively correlated.

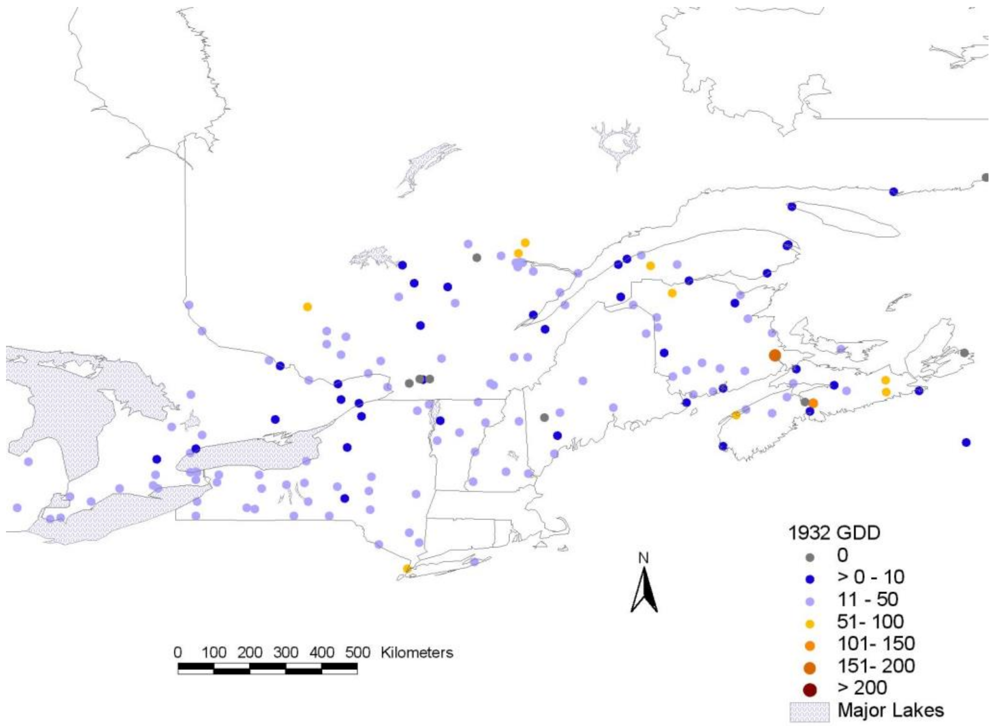


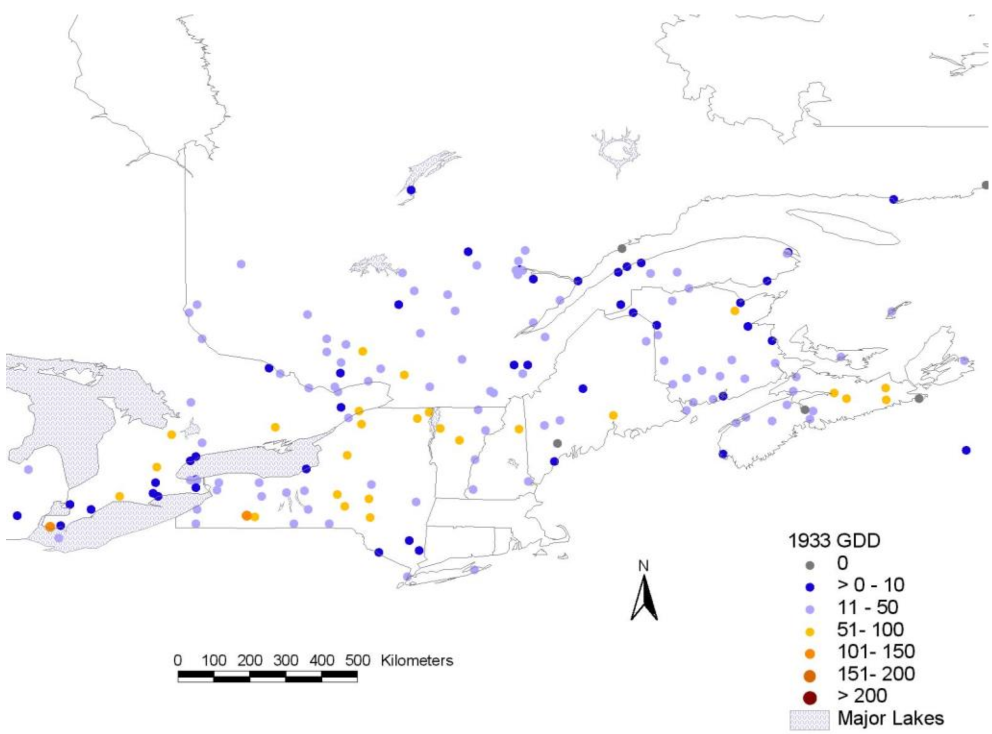
Cross validation of actual versus expected (modeled) GDD values for a typical day in 1981; r^2=0.845.

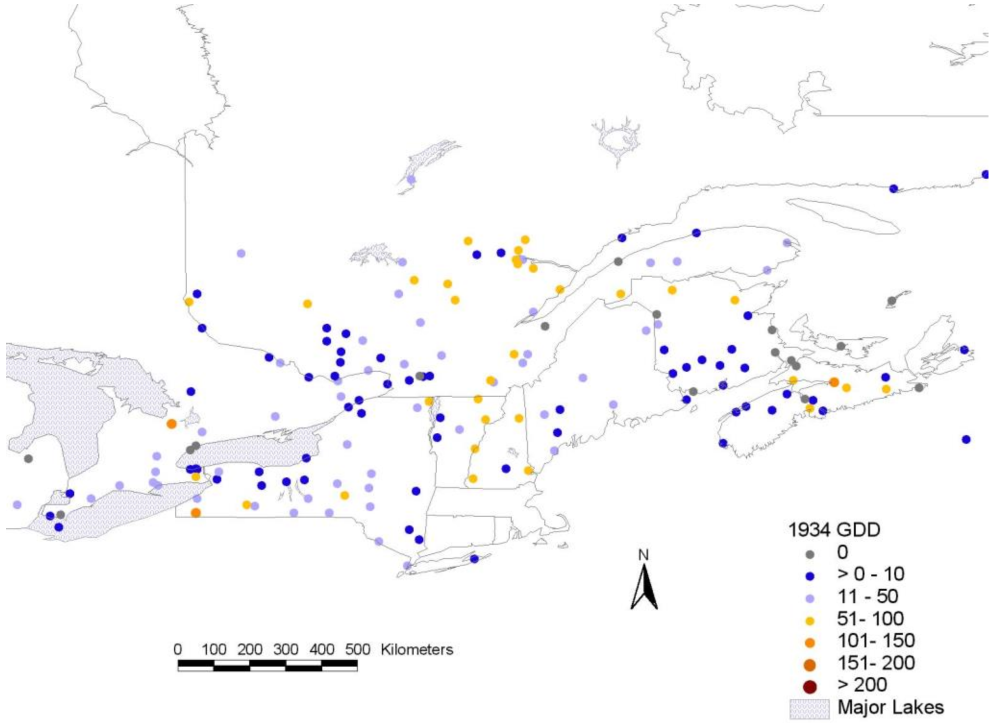
APPENDIX III

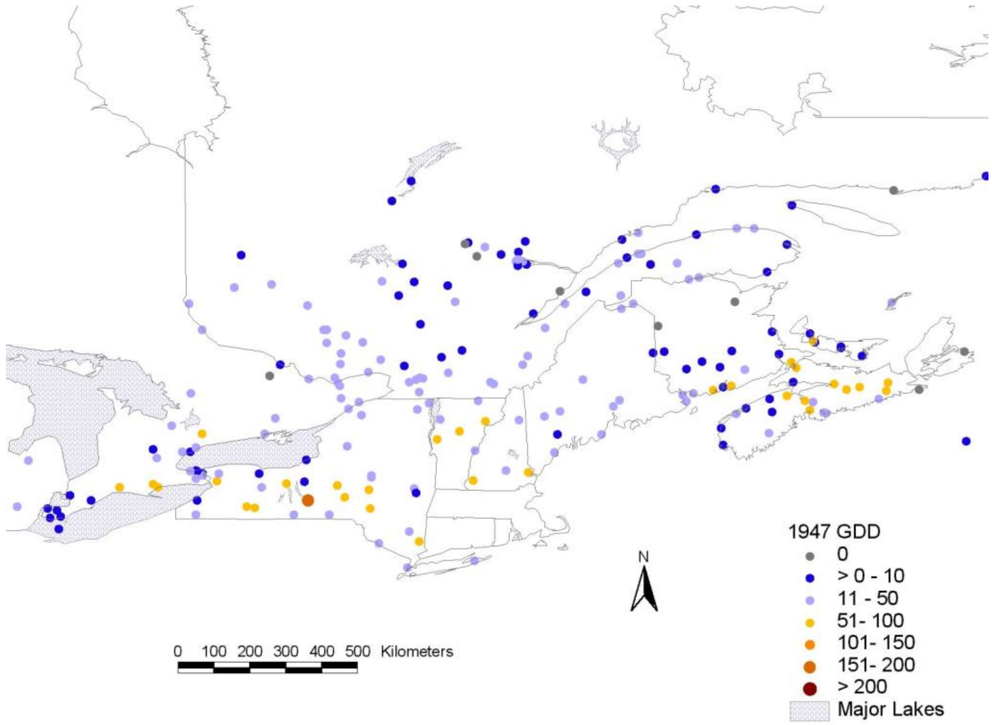
LARGEST THAW EVENTS IN EASTERN CANADA: 1930-1960 AND OTHER YEARS

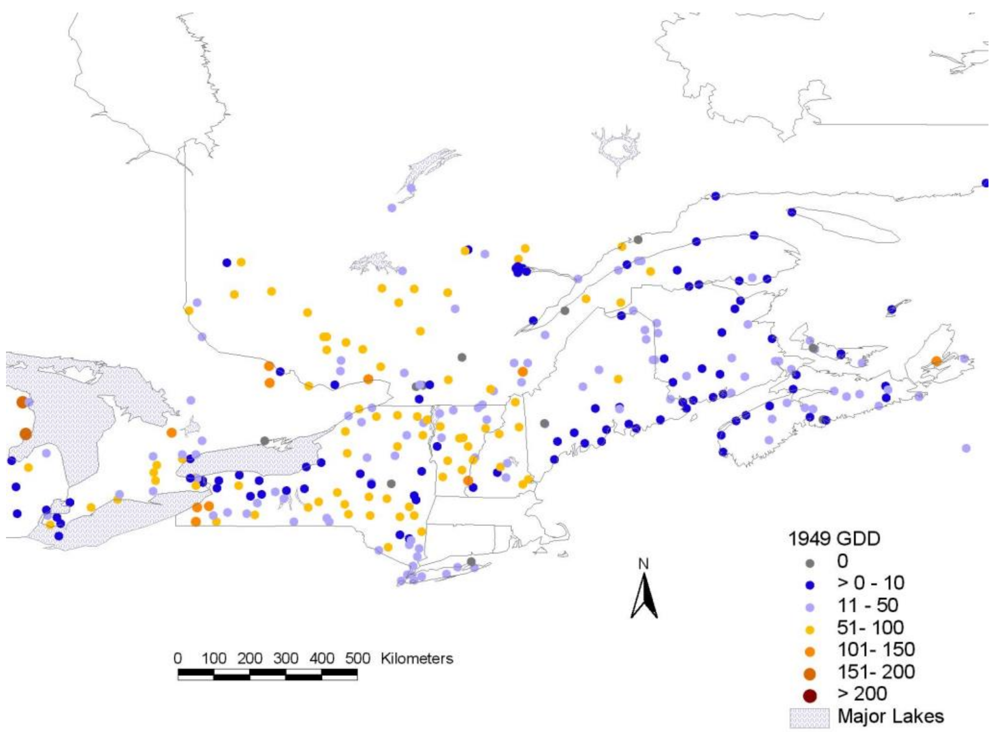


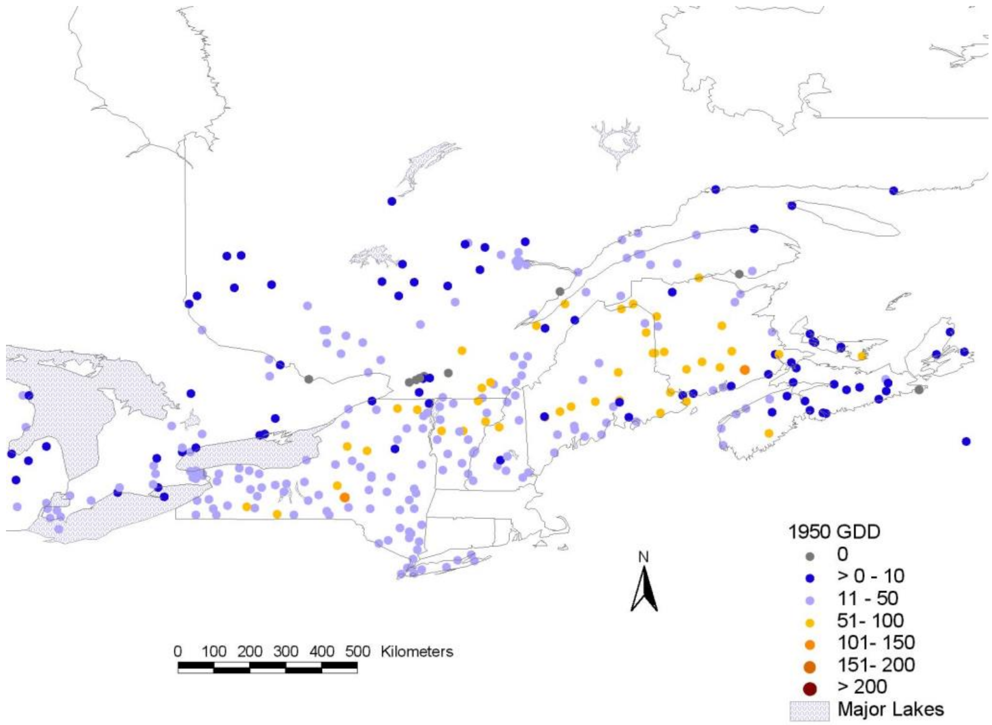

1932 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
N
0 100 200 300 400 500 Kilometers

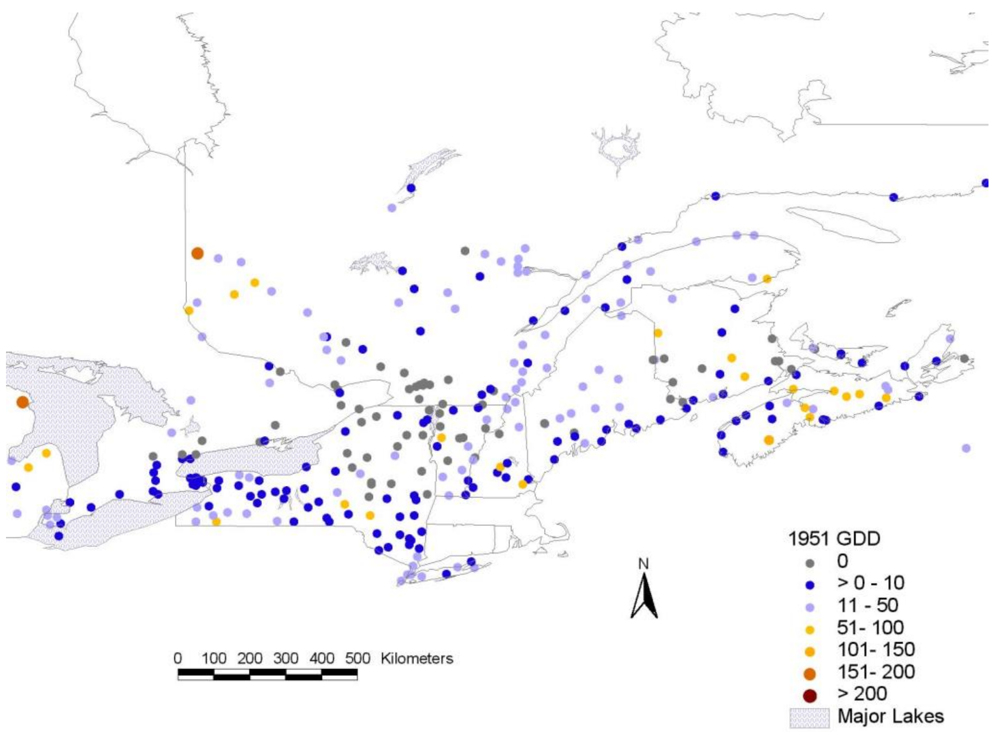

1933 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
N
0 100 200 300 400 500 Kilometers

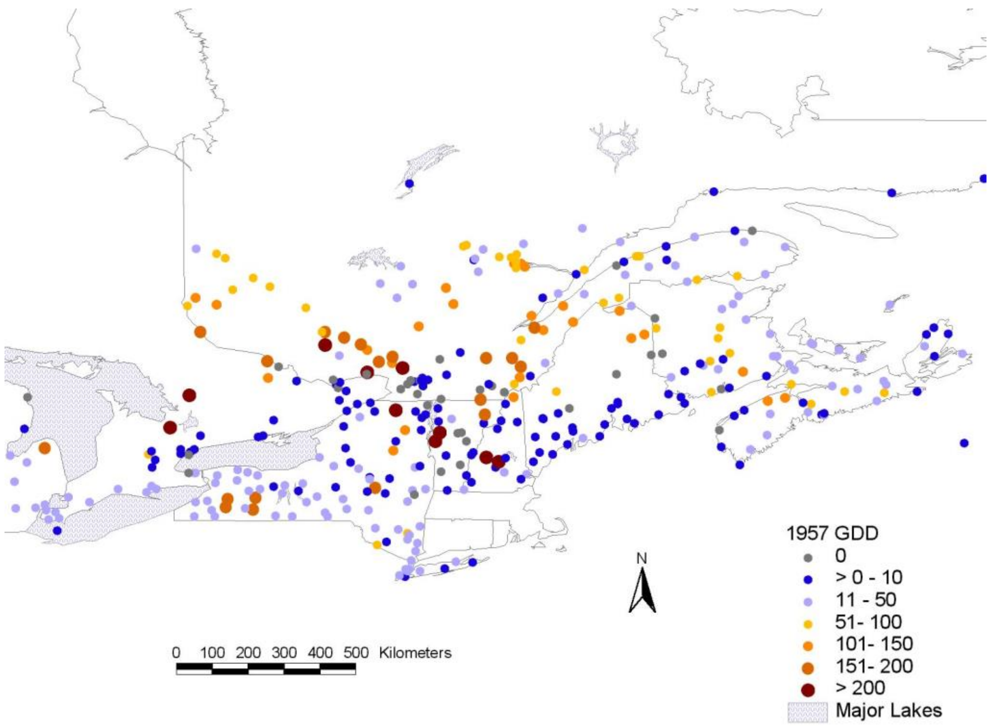

1934 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
N
0 100 200 300 400 500 Kilometers


1947 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
N
0 100 200 300 400 500 Kilometers

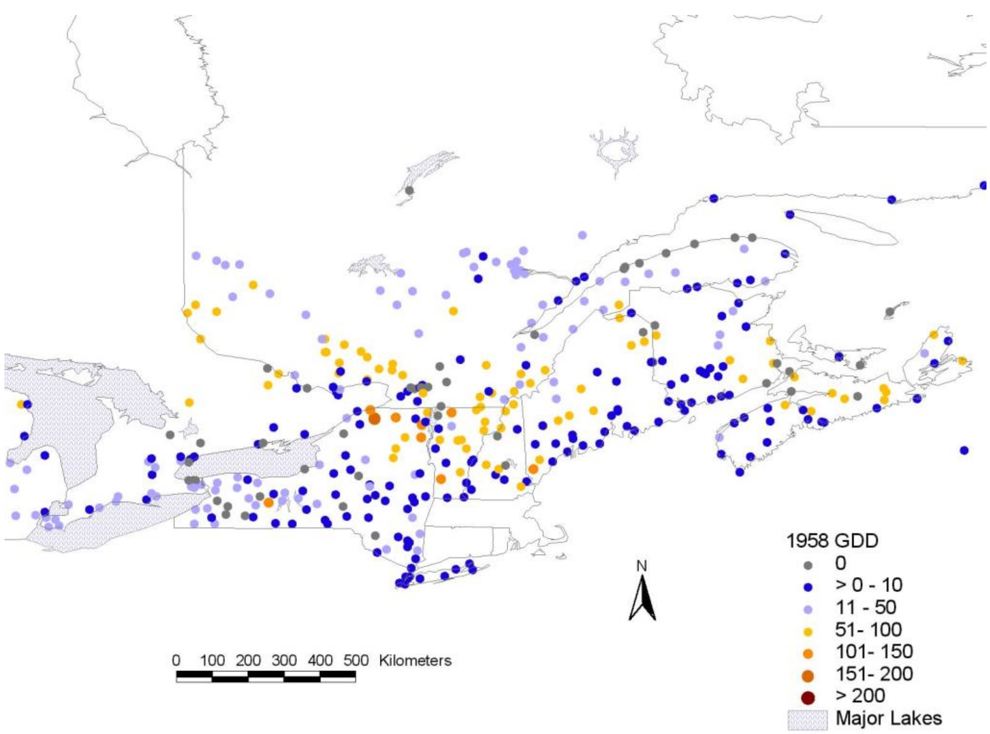

1949 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
N
0 100 200 300 400 500 Kilometers


1950 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
N
0 100 200 300 400 500 Kilometers

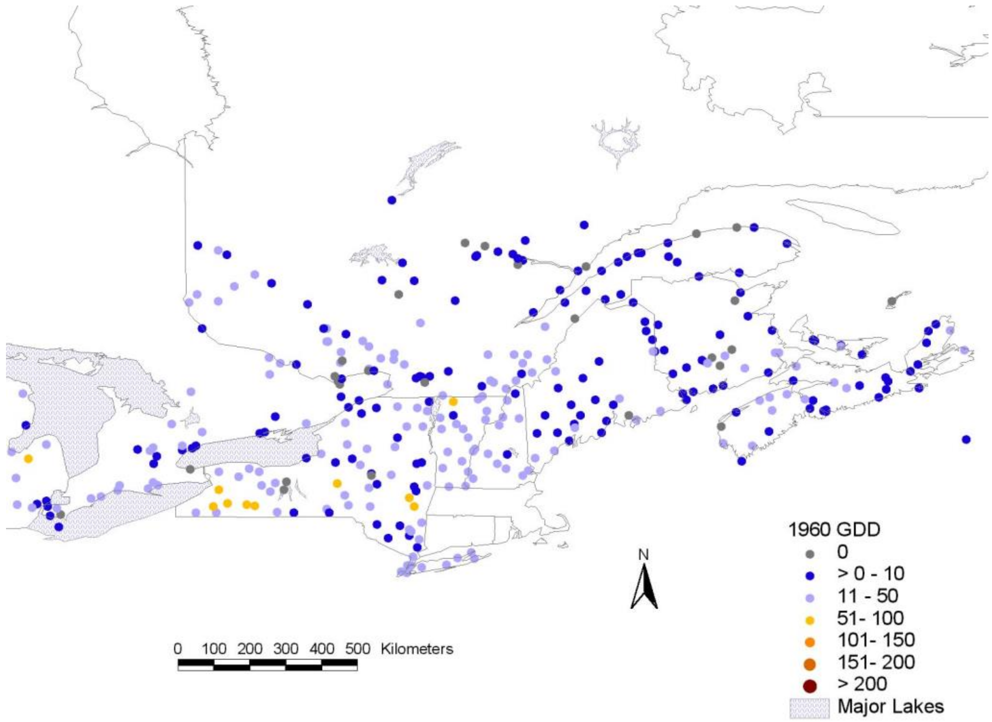

1951 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
N
0 100 200 300 400 500 Kilometers



1957 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
N
0 100 200 300 400 500 Kilometers



1958 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
N
0 100 200 300 400 500 Kilometers


N
1960 GDD
0
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Major Lakes
0 100 200 300 400 500 Kilometers

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