# FINAL SCIENTIFIC REPORT
# Impacts and Adaptation Sub-component of the Climate Change Action Fund (CCAF)

**CCAF Project Number**: A117

**Project title**: **Using Winter Climatic Data to Estimate Spring Crown Dieback in Yellow Birch: A Case Study To Project Extent and Locations of Past and Future Birch Decline**

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## Summary

Yellow birch, a climatically sensitive tree species common to Ontario, Quebec and the Maritimes has been known to experience catastrophic dieback under certain meteorological conditions. Decline of birches (yellow and paper birch) occurred during the 1930-1980's in eastern North America and resulted in an estimated stem volume loss of 1,400 million $m^3$ over an area of 490, 000 $km^2$ (Pomerleau, 1991). Winter thaws and late spring frosts have been implicated in this decline (Braathe, 1957, 1995, Auclair, 1987).

Shoot or root freezing injury provided strong links with spring shoot dieback in yellow birch. A process-oriented model for assessment of risk of winter damage to seedlings and adult trees has been developed. The model uses winter climatic factors such as air/soil temperature, relative humidity, solar radiation and wind speed to predict the shoot water content, xylem cavitation, root/shoot freezing injury in relation to spring dieback. The assumptions governing the biophysical / physiological process model produced involves; winter twig water loss in relation to xylem water potential, xylem cavitation and embolism accumulation. Other assumptions relate freezing damage (plant hardiness) to minimum temperatures, while residual xylem embolism (that present after spring xylem refilling) is determined by root pressure mediated by root freezing injury. The residual air filled space left in the wood (embolism) and the resultant loss in water conductivity after flushing, together with potential root and shoot freezing injury was used to predict branch dieback. This model was used to predict risk of dieback at weather stations once the daily data was used in an adapted micro-meteorological / hydrological model (ForHyMIII) to generate daily soil temperatures.

Historical climate data, Geographic Information Systems (GIS) and geostatistics were used to evaluate the spatial extent and daily patterns of past winter/early spring thaws and late spring frost events of the 1930-1960's, a period with major birch decline events. After analysis of the 30-year period, anomalous years, (1936, 1944, 1945 and a later well documented winter-thaw and late spring frost in 1981) were spatially analyzed. Climate station data contained daily minimum, mean, maximum air temperatures, and precipitation for eastern Canada and northeastern United States.

An algorithm, *Weather Reader*, was developed which allowed us to join the Canadian and US data. The algorithm also calculates for the period of January 1 to May 31 and the accumulated degree days from start of a thaw event until its end. In addition, an annual summary was prepared for the number of thaw events that occurred, and for the maximum accumulation of degree days (heat accumulation) for the most severe thaw event per station, per year for the 30 year period was calculated. Definitions of thaws responses of vegetation (frost hardiness) and snow pack degradation (proneness to soil frost) were developed and were expressed as accumulated degree-days. Vegetative response to thaw (GDD = base 4 °C) was defined as

$$GDD = {}^{n}S_{i=1}([max + min]/2 - 4)$$

response of snow pack degradation to thaws (SDD = base 0 °C) was defined as

$$SDD = {}^{n}S_{i=1}([max + min]/2 - 0).$$

Each thaw event is defined to end when the minimum air temperature reaches -4 $^0$C

Anomalous thaws and late frost distributions and extents were spatially tracked on a daily basis with GIS and geostatistics (kriging). The climate scenario data at the terrestrial grid points provided by Environment Canada for x2 and x3 $CO_2$ were investigated. However, the data surprisingly lacked the anticipated temperature variations over the critical spring period (they were all buffered near the freezing point). Other data are being sought to carry out a meaningful analysis of projected climate change impact on birch health.

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## Using Winter Climatic Data to Determine Spatial and Temporal Patterns of Thaws and Late Spring Frost Events in Eastern Canada

### 1.1 Introduction

Evidence suggests that mean global surface temperatures have risen during the last century and a half, with a greater increase in winter than in summer (McElroy, 1994). It has been predicted that there will be future increases in temperature and that these will be greater at high latitudes (Hansen et al., 1988). Increased temperature variation could result in longer, more frequent, winter thaws than at present, which could have a greater effect on forest vegetation than slight changes in mean temperature (Cox et al., 1997). In addition, surface particulates from industrial sources may cause cooling, offsetting warming trends at times (Charleson et al., 1987; Wigley, 1989). The birch decline that occurred during the 1930-60's in eastern North America resulted in an estimated stem volume loss of 1,400 million $m^3$ of yellow and white birch over an area of 490, 000 $km^2$ (Pomerleau, 1991). Winter/early spring thaws and late spring frosts have been implicated in this decline (Braathe, 1957, 1995, Auclair, 1987). Thaws have also been proposed as the cause of the recent dieback in all but a few hardy commercial apple cultivars in New Brunswick, Canada (Coleman, 1992).

### 1.2. Background

1.2.1. Chronology and Locations of Past Yellow Birch Dieback

Dieback on yellow birch in the 1930's and 1940's was spectacular in rapidity and severity when compared to any other eastern hardwood species (Sinclair et al, 1987). Figure. 1.1 illustrates a summary of incidence and severity with an "active" phase from 1937 to 1949 and a "latent" phase from years 1950-1960 as adapted from Auclair 1987.

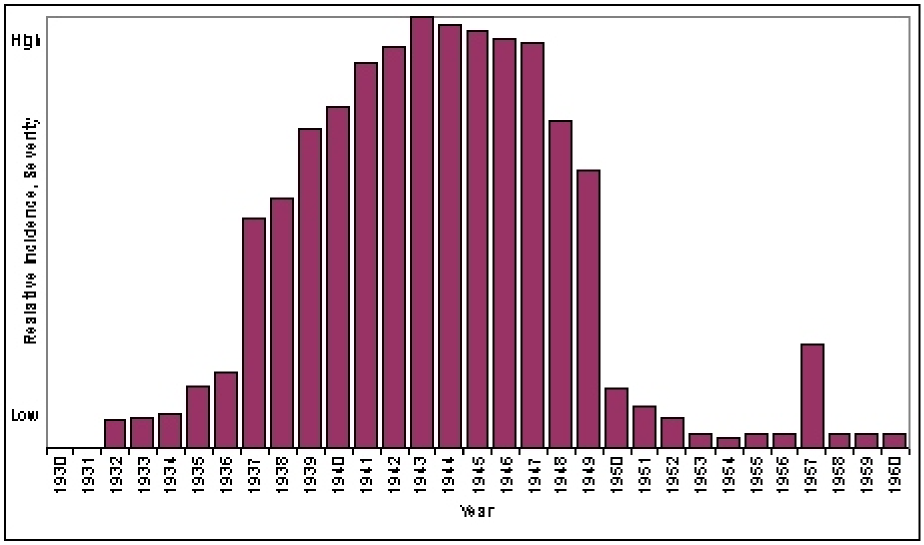



Figure 1.1. The relative indicence /severity of crown dieback of yellow and white birch in northern hardwoods of eastern Canada (after Auclair 1987)

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 the disease 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 (Canadian Forestry Service, 1944, Balch 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 and 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 in Cape Breton Island in 1947(Canadian Forestry Service 1947. This dieback on Cape Breton Island of yellow birch became progressively more severe in 1949 and 50 but had less evident by 1952(Canadian Forestry Service 1949, 1950, 1952). Lightly injured trees continued to show signs of improvement in New Brunswick but 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 since 1954(Canadian Forestry Service 1954).

Yellow birch dieback in Quebec was first observed in the Late 1930's. Pomerleau (1953b) reported on yellow birch dieback at St. Donat, North of Montreal in 1937 whereas Davidault (1953) first noted dieback in the Matapedia Valley in the Gaspe region in 1939. Between 1940 and 1942, dieback could be found in most inhabited areas of Quebec and had become particularly evident by 1941(Pomerleau, 1953b, Canadian Forestry Service 1951). 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, it was found as far west as the St. Maurice Valley (Canadian Forestry Service 1945). The disease had progressed by 1946 and was reported north of Montreal, in the Gatineau, and especially at St. Maurice. Improvement in the condition of trees was reported that year from the Gaspe region especially at Matapedia (Canadian Forestry Service 1946). By 1947, almost all merchantable birch in the area east of Rimouski were dead or dying; however, young trees, not too severely affected, were regaining their vigor (Canadian Forestry Service 1948, 49, 50). In the Lake St John Districts, 4 % of trees improved from 1948 to 1951, but on 85 % of the trees, dieback continued to progress (Martineau 1953). The %age of trees with injured crowns decreased from 40 % in 1950 to 30 % in 1952. Signs of improvement of birch were observed before 2 seasons of hot weather in 1951 and 1952, after which, renewed decline was noted in northern virgin forests which had previously shown symptoms of dieback (Canadian Forestry Service 1954). Similarly, an unhealthy condition developed after 2 months of dry, hot weather in 1955 (Canadian Forestry Service 1955). No appreciable change was noted the following year but some improvement was noted in 1957 except in Abitibi County were crown deterioration had increased since 1954(Canadian Forestry Service 1956, 1957). By 1958, the general health of yellow birch in Quebec was very good except for a new case of decline in Montmorency County suspected since 1956 (Canadian Forestry Service 1958). Dieback was last reported in Quebec in 1981 in an association with an unusual winter (Benoit et al 1981).

Dieback of yellow birch in Ontario has occurred since at least 1944. In that year, dieback was reported in eastern Ontario, and light to moderate 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; however, the rate of deterioration decreased in that the number of trees showing cessation of decline was increasing and the condition of some trees improved. Between 1948 and 1952, only 13 % of trees examined showed decline in crown condition of some trees and the bulk of this decline was either light or moderate, mortality not heavy (Sinclair 1952). The average rate of decline over the 1950-1951 and 1951-1952 periods and was not considered serious (Canadian Forestry Service 1953). Data from an Ontario survey, 1949-1954, did not disclose wide variations in severity of damage or of trends in deterioration within the survey area. 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 1951-1953 in the Sault St Marie, North Bay, Parry Sound, Lake Simcoe and Lake Erie Districts (Canadian Forestry Service, 1957). A map, as adapted from (Auclair, 1987, in Braathe 1995), showing the observed accumulated dieback for the 1930-1960 period is shown in Figure. 1.2.

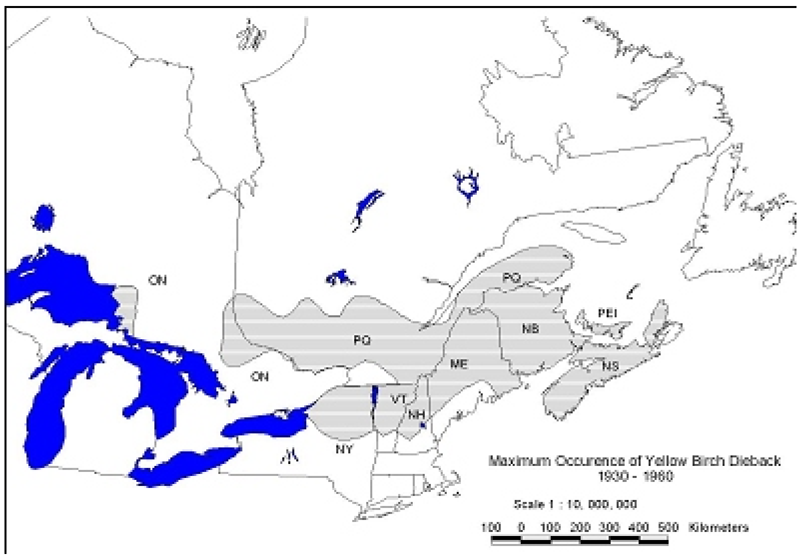



Figure 1.2. Map showing observed accumulated birch dieback. Shaded area identifies the maximum occurrence of yellow birch dieback reported in a symposium on birch dieback 1952 (Canada Department of Agriculture 1953) and in the forest decline workshop (LRATP, Workshop No. 6, 1986). Adapted from P. Braathe, 1995.

### 1.2.2. 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 contributing factor of the decline (Canadian Forestry Service 1943, 1944, 1946, 1947, Balch 1944; Pomerleau 1953b; Hawbolt 1947). Organisms such as fungi, bacteria, and insects were isolated and tested, are weak parasites and were not found to be in sufficient virulence to initiate dieback. Therefore, like the bronze birch borer, they require circumstances of weakness to invade yellow birch effectively and produce mortality in twigs and branches (Hawbolt 1947; Hill and Sinclair 1954; Hawbolt 1953; Hansborough 1953a; Redmond 1957a). A causal relationship between a virus and birch dieback symptoms was never established (Hansborough 1953b). Climatic analysis showed no evidence of spatial or chronological pattern in the occurrence of water deficiencies to account for the spread of observed diebacks (Clark and Hare 1953). Dieback symptoms were found in the crown when large proportions of the rootlets were killed. Braathe (1957) suggested a correlation between birch dieback and the March thaw of 1936. Similarly, Benoit et al (1981) suggested that an unusual thaw in February and periods of severe cold in March of 1981 provoked decline of yellow birch. Frost and drought have also been put forth as possible factors initiating dieback (Canadian Forestry Service 1953, 1955, 1966, 1967, 1984; Ontario Regional Reports 1983, 1984).

### 1.2.3. Experiments on Causal Mechanisms

Early studies focused on bronze birch borer as the 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 tree radial growth increment (Hawbolt 1947, 1952; Hawbolt and Skolko 1948; Barter 1953c; Clark and Barter), observations on the effect of soil moisture (Greenidge 1953; Fraser 1953; Fraser and Mawson 1953; Pomerleau 1959). And soil temperature (Redmond 1955) on crown dieback or radial growth. Specific events such as sudden spring flooding, intense cold winters without complete snow cover (Pomerleau 1944) and the effect of deep soil frost (Pomerleau 1990), were also observed to coincide with dieback of yellow birch. Cumulative results of injections studies, root excavations, and an extended survey of the trends in moisture distribution in the species over a prolonged period, suggested that the locus of action of the disease was in the roots (Greenidge 1953).

Braathe in (1995) conducted thaw-freeze experiments in 1988, 1989, and 1994 reproduced dieback symptoms; small chlorotic and curled leaves, failure of bud growth and progressive dying back of twigs from the ends. Such symptoms on yellow birch appeared after a frost of –5 °C at bud burst stage 3, where green tips of leaves were visible. In March and early April this stage seems to need at least 100 degree days (base temperature 4 °C), whereas about 50 degree days are adequate in late April and May.

Pomerleau (1991) reported evidence of a link between birch decline and root depth. He also linked birch decline with winter thaws, which degrade snow pack rendering the roots subject to deep soil frost. Sperry et al. (1988a) concluded that one mechanism of thaw-freeze induced damage in sugar maple was seasonal occurrence of xylem embolism, which reached a maximum of 84 % in February. They suggested that small bubbles of air, formed as frozen sap thawed, grew during further thaw cycles and later expanded under high water potentials to block stem xylem elements. Winter xylem cavitation in diffuse-porous trees such as birch is generally refilled by springtime root pressure (Sperry et al., 1987). Sperry et al. (1994) observed that when root pressure in birch was artificially suppressed by overlapping cuts across the stem, essentially simulating root damage by frost after a thaw, existing embolisms were not refilled and shoot dieback was extensive.

Extensive xylem cavitation was documented in birches showing crown dieback in New Brunswick (Greenidge, 1951); however, at the time, it was not attributed to winter thaw-freeze cycles. Sperry et al. (1992) determined that, in the two diffuse-porous species, more than 90 % of vessels cavitated 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 et al. (1997) subjected two year old paper birch to simulated winter thaws of various durations in climate-controlled chambers. The simulated thaws induced dieback in shoots of treated plants. Although the stem thaw treatment did not significantly increase dieback, there were significant correlations between growing degree days (GDD) above 4 °C and both shoot dieback and % reduction in conductive xylem. All trees that received > 60 GDD died back to some extent. Plants in the root and stem thaw treatment that received more the 60 showed a significant increase in dieback and a significant loss of conducting xylem after a period of growth recovery in the greenhouse. Furthermore, higher correlations between GDD during a thaw and both the extent of dieback and the loss in conductive xylem were found in trees subject to the root + stem thaw than in trees exposed only to the stem thaw treatments. The occurrence of dieback in response to winter/early spring thaw, and its close correlation with irreversible losses of xylem conductivity due to embolisms, coupled with an inability to refill the xylem because of root damage, support the view that these processes may be key initiating factors initiating birch decline.

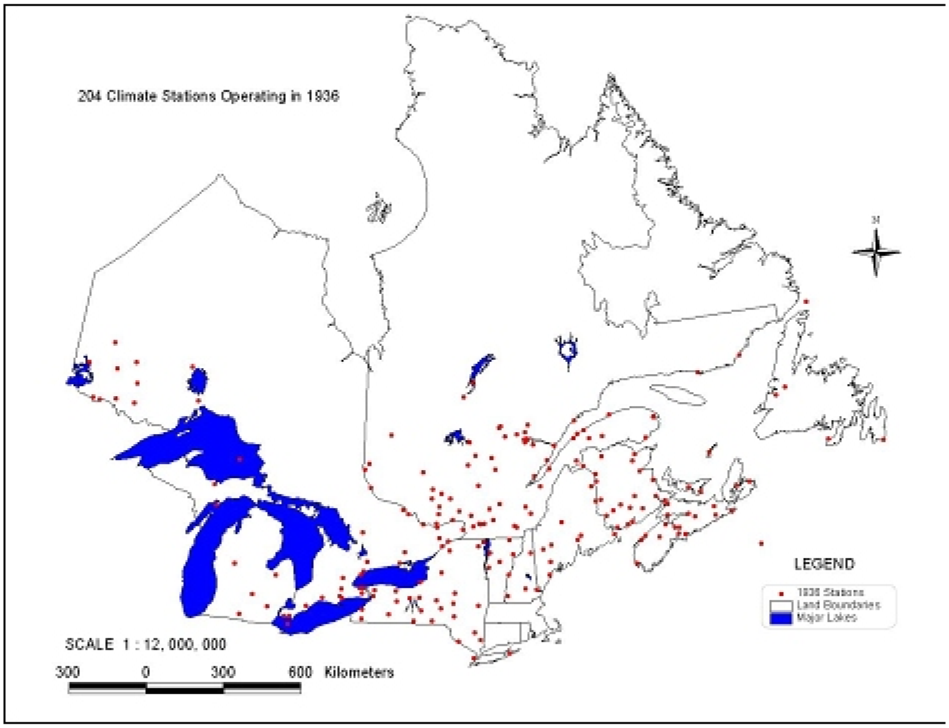
## 1.3. Objectives

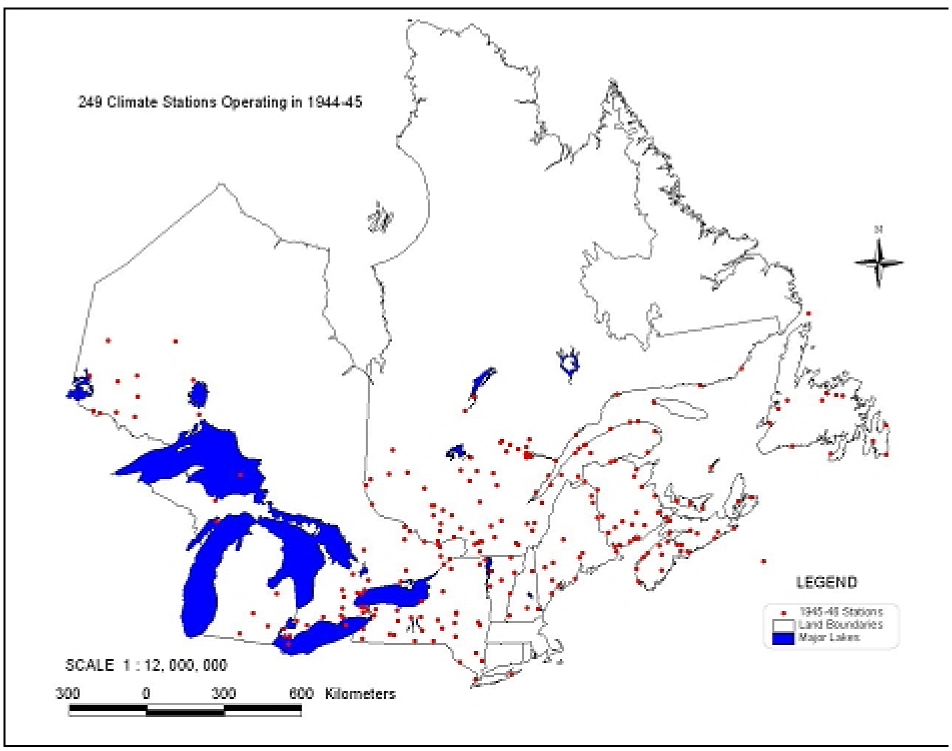
Use historical meteorological climate station data using a Geographic Information System (GIS) and geostatistics to evaluate the spatial extent and patterns of certain historical winter/early spring thaws and late spring frost events that occurred during the 1930-1960's birch decline events. Suspected years include 1936, 1944, and 1945, and a later well documented 1981 winter-thaw and late spring frost.

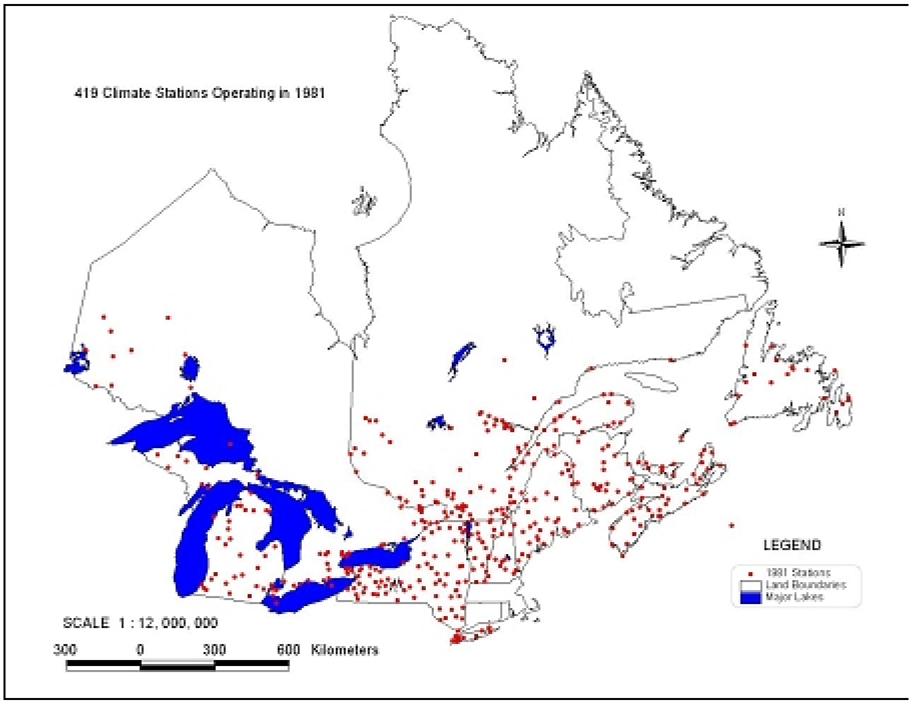
## 1.4. Methodology

### 1.4.1. Daily Weather Records

Daily meteorological data from 1930-1990's for which winter/spring climate is suspected (1936, 1944, 1945, 1981) to have caused birch decline was used. Climate station data contain daily minimum, mean, maximum air temperatures, and precipitation covering the historical range of dieback encompassing most of eastern Canada and northeastern United States (Figure 1.3). Figs. 1.3a-c show the locations of climate station locations operational for the particular years in question. The projection used for the purposes of this report, is Lambert Conformal Conic, WGS 84, decimal degrees converted to meters, Central Meridian –75. The regional focus of this report is eastern Canada.


204 Climate Stations Operating in 1936
LEGEND
1936 Stations
Land Boundaries
Major Lakes
SCALE 1 : 12, 000, 000
300
0
300
600
Kilometers


249 Climate Stations Operating in 1944-45
LEGEND
1945-46 Stations
Land Boundaries
Major Lakes
SCALE 1 : 12, 000, 000
300
0
300
600
Kilometers




Figures. 3a–c. Map showing eastern Canada and United States projected in meters using Lambert Conformal Conic and the spatial distribution of, (a) 204 climate stations operating in 1936, (b) 249 climate stations operating in 1944-45 and, (c) 419 climate stations operating in 1981.

Two definitions of winter thaws, vegetative and snow pack degradation response, were developed and are expressed as accumulated degree-days. Vegetative response thaw (GDD = base 4 $^{o}$C) is defined as follows: when the daily maximum temperature reaches +4 $^{0}$C, growing degree days are accumulated based on the mean daily temperature value above 4 $^{0}$C. The thaw event ends when the daily minimum temperature reaches a value of -4 $^{0}$C ($GDD = {}^{n}S_{i=1}([max + min]/2 - 4)$). Snow pack degradation response thaws (SDD base 0 $^{0}$C) were defined as follows: when the daily maximum temperature reaches 0 $^{0}$C, degree days are accumulated based on the mean daily temperature (above 0 $^{0}$C). The thaw event ends when the minimum air temperature reaches -4 $^{0}$C ($SDD = {}^{n}S_{i=1}([max + min]/2 - 0)$).

An algorithm, *Weather Reader*, was developed to convert American daily climate station data into metric, joins the two data sets together (Canadian and American), and joins coordinate files with station data files. The algorithm calculates, for the period of January 1 to May 31; (1) daily accumulated degree days from start of a thaw-frost event until the end; (2) annual summary for the number of thaw-frost events and; (3) maximum accumulation of degree days (heat accumulation) for the highest single thaw-frost event per station, per year. The results of the algorithm were then imported into *ArcView 3.1*, converted from text file format into an ArcView file, projected to meters in Lambert Conformal Conic. For daily accumulation of degree days, files were exported as DBF files into a beta version of *GS+ for Windows* to calculate geostatistics.

### 1.4.2.Geostatistics

Geostatistics is used to estimate a data value for locations that cannot be sampled directly by examining data taken at locations that can be sampled. The ability to predict the unknown locations is influenced by the spatial arrangement of the known sample locations. If a model of spatial correlation can be established, this model can be used to interpolate data values at the unknown locations (Babish, 2000).

The term geostatistics refers to a spatial interpolation technique known as kriging. Kriging is a weighted moving average method for estimation based on known observations. The results of kriging are dependent upon the distance between the sampling locations and the point of estimation. The effectiveness of kriging depends upon how well the daily climate station data represent the daily degree day accumulation for the specific thaw-freeze definitions.

Kriging provides the best local estimate of the mean value for the climate station daily values (regionalised variables). Measurements that change at every location they are measured at are called regionalised variables. Regionalised variables are variables that fall between random variables and completely deterministic variables. Regionalised variables recognize the fact that properties measured in space follow an irregular pattern that cannot be described by a mathematical function. Regionalised variables describe the daily climate data with

geographical distribution (Babish, 2000).
The main difference between kriging and a simple distance-weighted average, as used in simple Inverse Distance Weighted interpolation is that kriging allows flexibility in defining the interpolation model and takes into account the model of the spatial process (the variogram). Kriging provides a measure of the error or uncertainty of the contoured surface. Since the estimation variances can be mapped, the confidence placed in the estimates can be calculated.

Kriging was carried out in two steps:

1. The sample semivariance was used to estimate the shape of the variogram (a curve that represents the semivariance of degrees days as a function of distance). The variogram describes the spatial relationship between the daily weather records.

2. The estimated semivariance function is used to determine the weights needed to define the contribution of each climate station to the interpolation. Climate stations close to the point for which an estimated value is to be generated contribute the most to the interpolation. The output ASCII formatted grids were generated and then exported from *GS+* and imported into *ArcView 3.1* for display.

A variance plot provides information on how well the interpolated values fit the overall model that was defined by the user. The plot of the variance can be used as a diagnostic tool to refine the model. The goal is to develop a model with an even distribution of variance that is a close to zero as possible.

Kriging was chosen as the preferred method as it reduces the extreme weighting of values caused by irregular distribution of sample points (as shown in Figs. 1, 2 and 3), 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.

Kriging works best with data sets, which have regions of densely scattered data and regions of lightly scattered data. Kriging can take into account redundant data (clustering) and possible anistropies (Babish, 2000).

Daily accumulated degree day files for specific days and years were then be exported as ASCII grid files from *GS+ for Windows* and subsequent import into *ArcView 3.1.* for spatial and temporal mapping of individual thaw-freeze events.

## 1.5. Results and discussion

Years 1936, 1944, 1945, and 1981 were analyzed with use of GIS and geostatistical software to assess the spatial and temporal patterns of the thaw events in question.

1.5.1. 1936 thaw event

The 1936 thaw events for a station in Nova Scotia are shown in Figure 1.4.

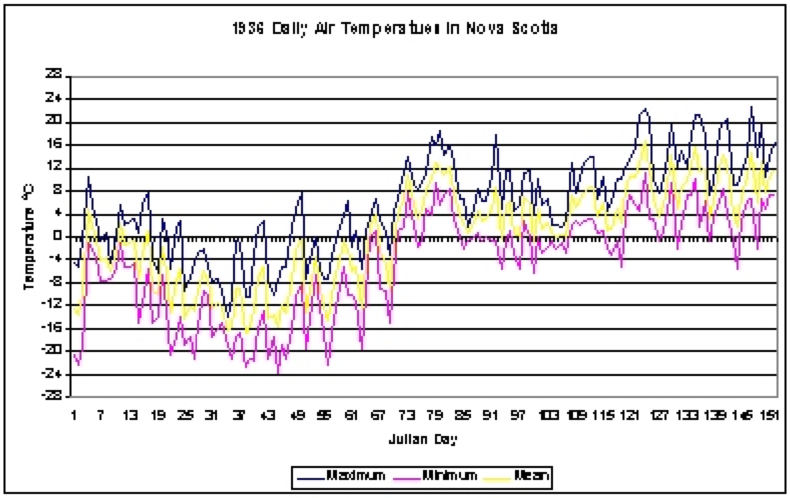
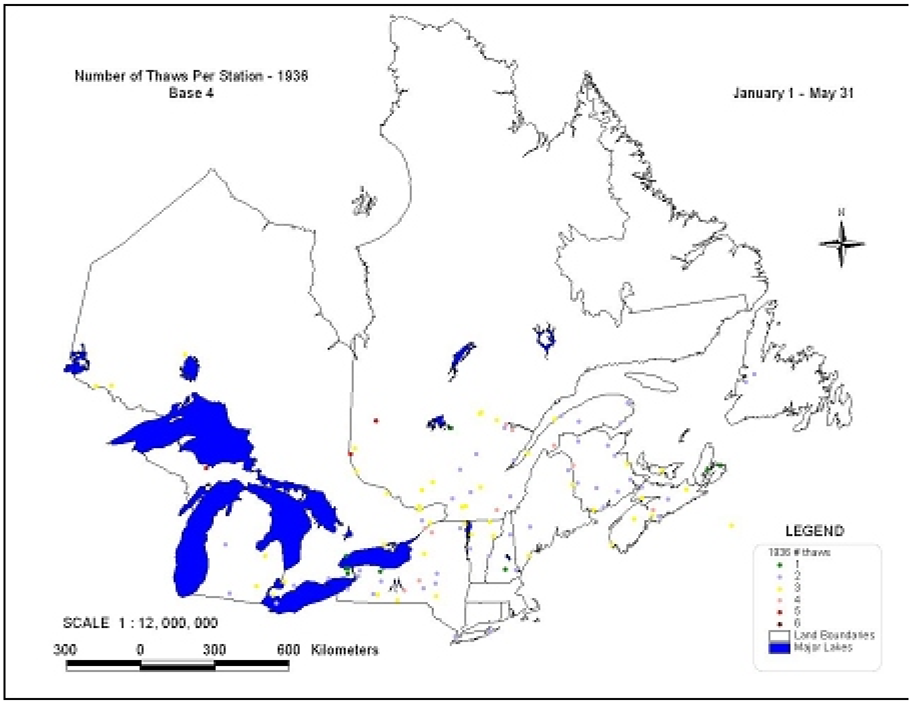



Figure. 1.4. Temperature time series for a station in Nova Scotia from January 1 to May 31 1936. A thaw from March 14(day 74) to April 10(day101) with another 2 thaw events and subsequent late frost.

Figures 1.5a and b illustrate the distribution for the number of thaw events per station and the maximum heat accumulation for a single event during the period of January 1 to May31 in 1936.


Number of Thaws Per Station - 1936
Base 4
January 1 - May 31
N
LEGEND
1936 # thaws
1
2
3
4
5
6
Land Boundaries
Major Lakes
SCALE 1 : 12, 000, 000
300 0 300 600 Kilometers

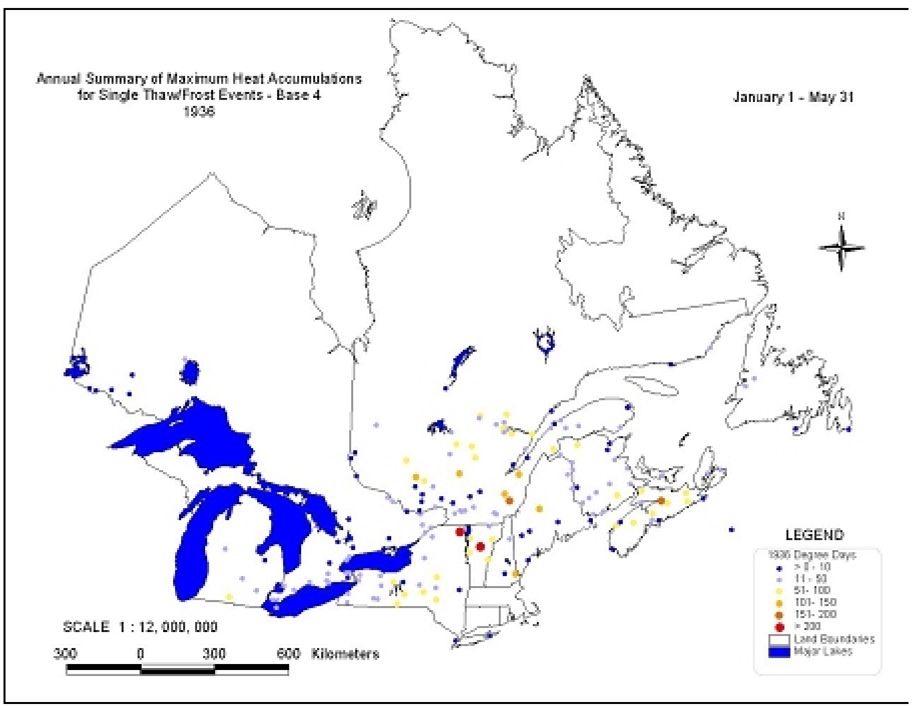

Annual Summary of Maximum Heat Accumulations
for Single Thaw/Frost Events - Base 4
1936
January 1 - May 31
N
LEGEND
1936 Degree Days
> 0 - 10
11 - 50
51- 100
101- 150
151- 200
> 200
Land Boundaries
Major Lakes
SCALE 1 : 12, 000, 000
300 0 300 600 Kilometers

Figure. 1.5a and b. Map showing, (a) the distribution and number of thaws events, (b) and maximum heat accumulations for single events in 1936.

The variogram describes the expected difference in value of degree days between pair of samples within a given orientation for 1936. As seen in Figure 1.6, the semivariance increases with distance until approximately 500km's (sill) when the samples are no longer related to each other. The semivariogram was calculated using an active lag distance of 750 km's, a lag class distance interval of 50 km's using a spherical model with an $r^2$ value of .980.

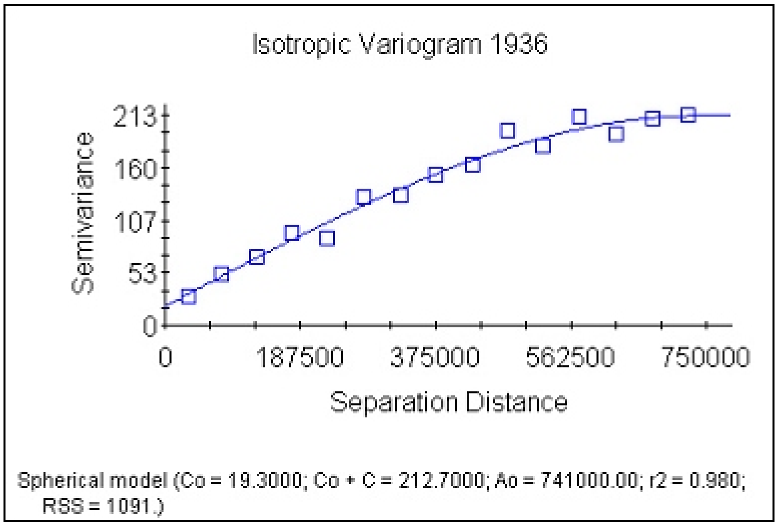
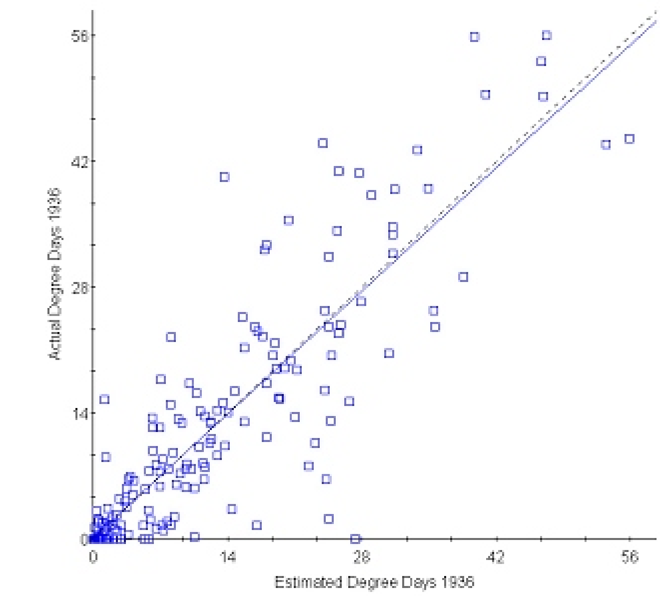



Figure. 1.6. Variogram demonstrating the shape of variogram as a function of distance for a typical day during thaw in 1936.

The correlogram for 1936, as shown in Figure 1.7 represents the spatial autocorrelation and starts cycling at around 500 km's. The greater the value of Moran's I the stronger the autocorrelation, ie. I>0 exhibits a strong positive autocorrelation, I=0 exhibits a random distribution of values and I<0 exhibits and strong negative autocorrelation.




Regression coefficient = 0.978 (SE = 0.039 , r2 =0.765,
y intercept = 0.224, SE

Figure 1.7 represents the spatial autocorrelation and starts cycling at around 500 km's.

A cross validation of actual versus expected values in Figure 1.8 shows the model is representing the data well with a cross validation result of $r^2$ = 0.765.

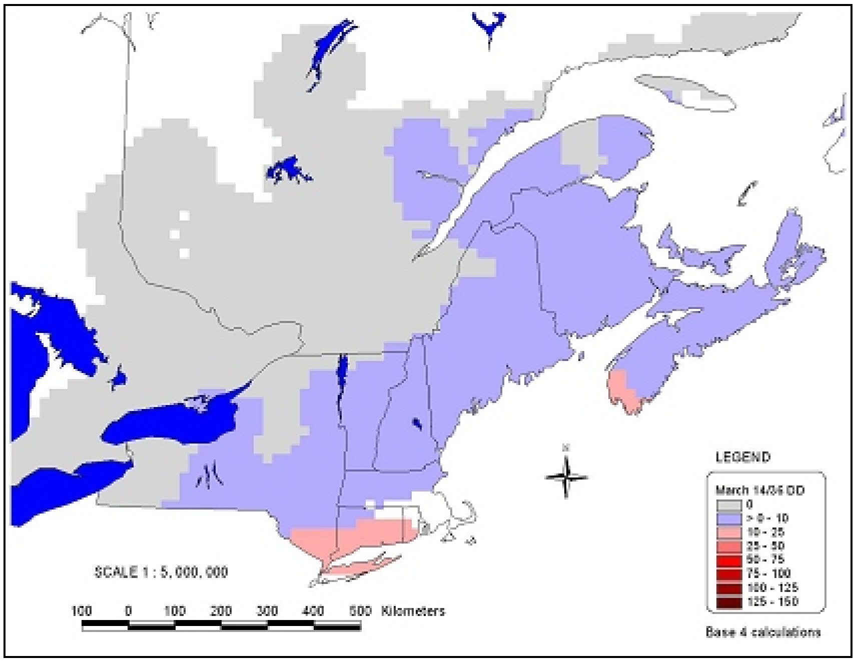
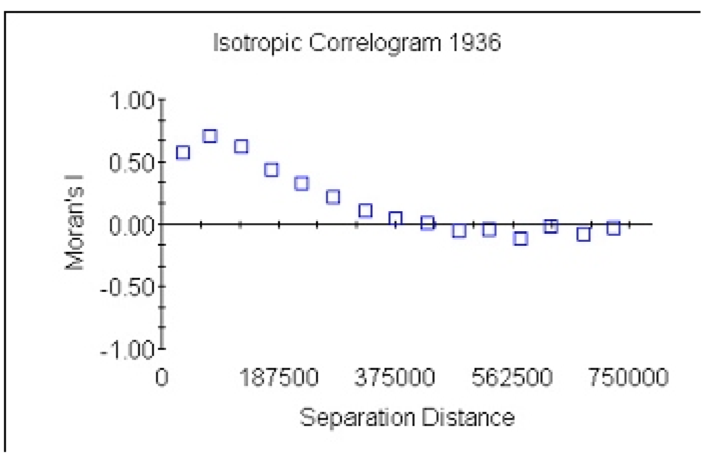



Figure 1.8. Cross validation of actual versus expected values for a typical day in 1936.




The kriged surface is represented as a 20km grid cell size, 16 nearest neighbors of 100km's resulting in a grid of 156 columns and 72 rows and begins on March 14, ends on April 10. Figs. 9 show the spatial and temporal progression of thaw which shows the magnitude and spatial extent of the first thaw event.

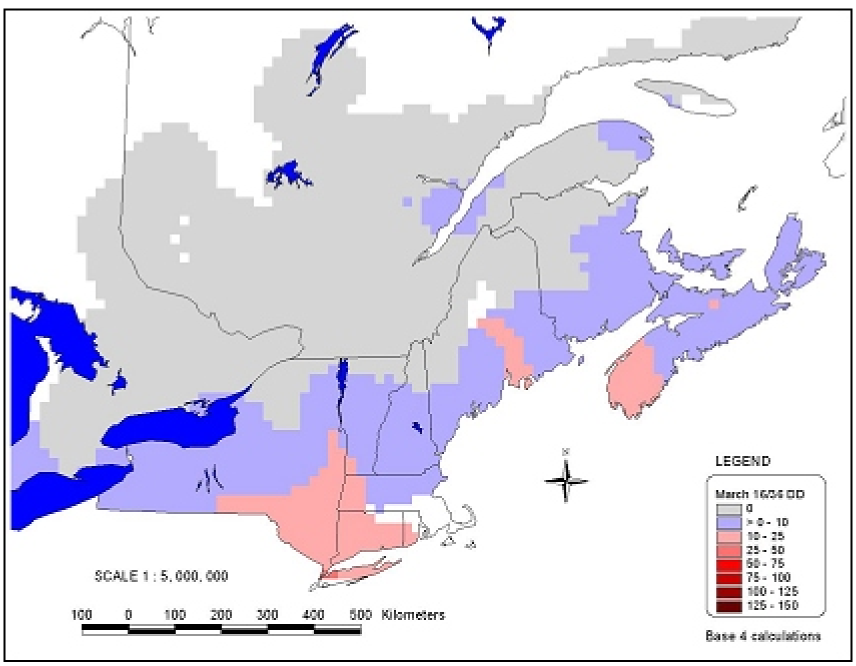
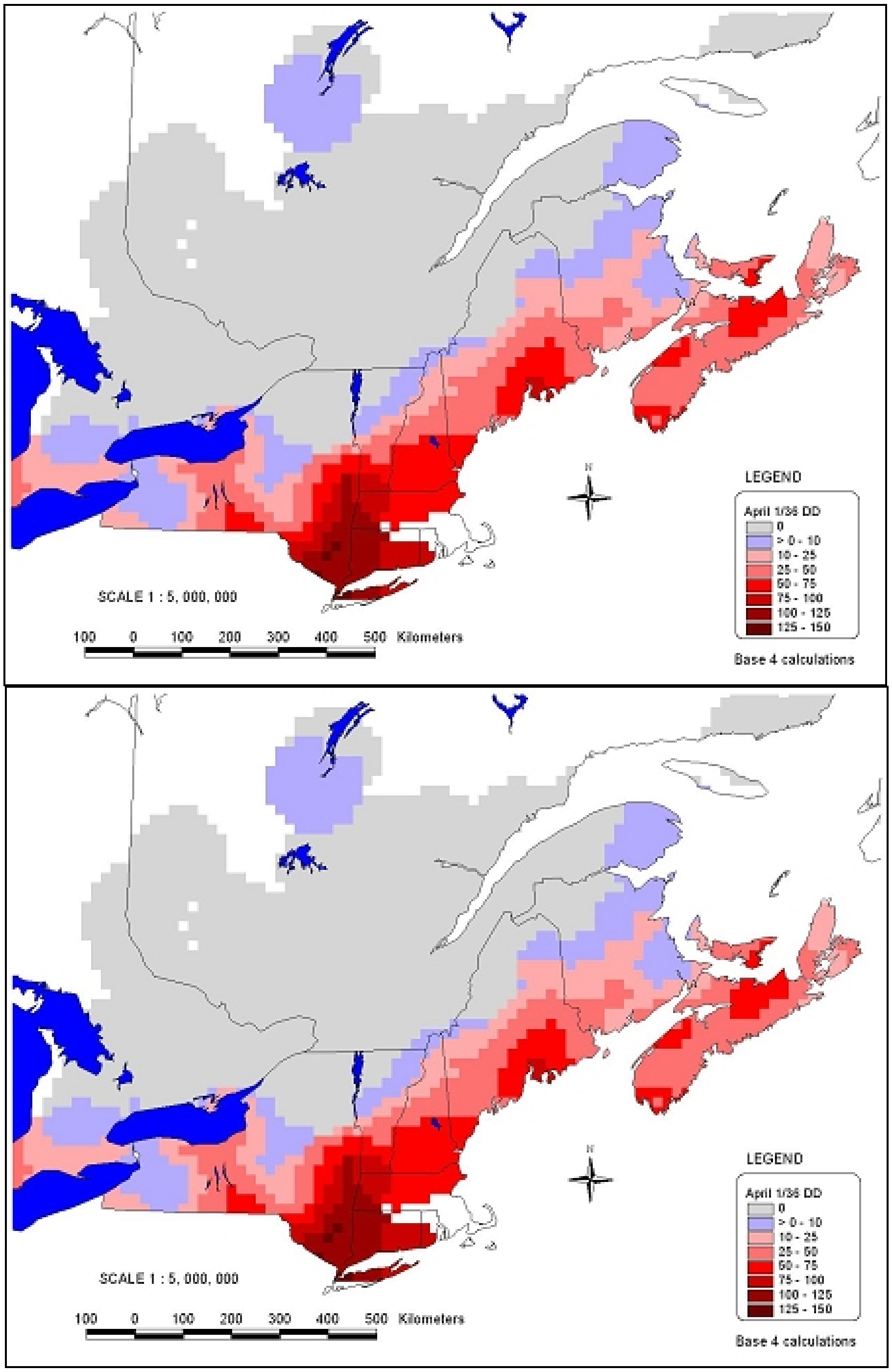
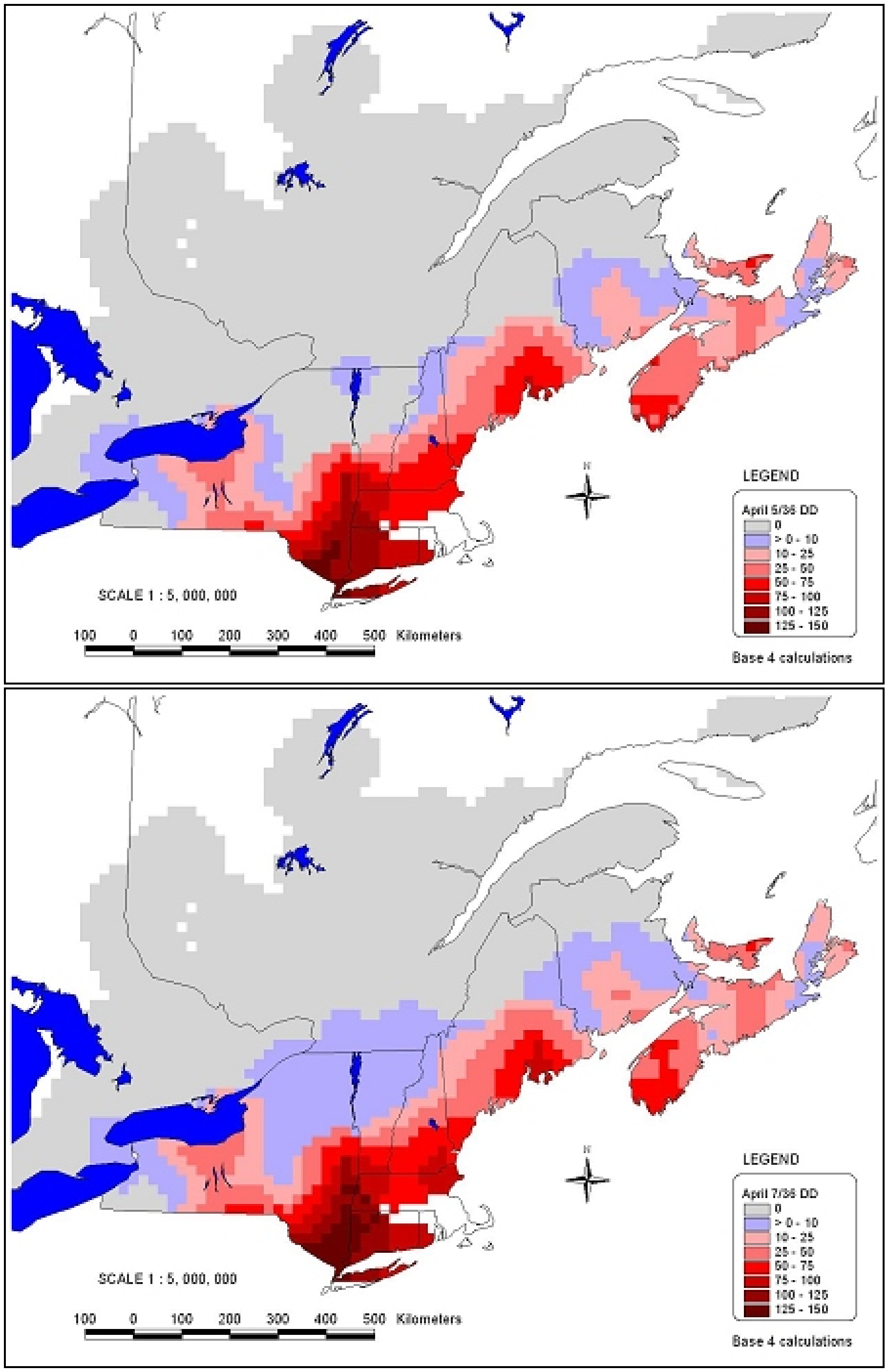


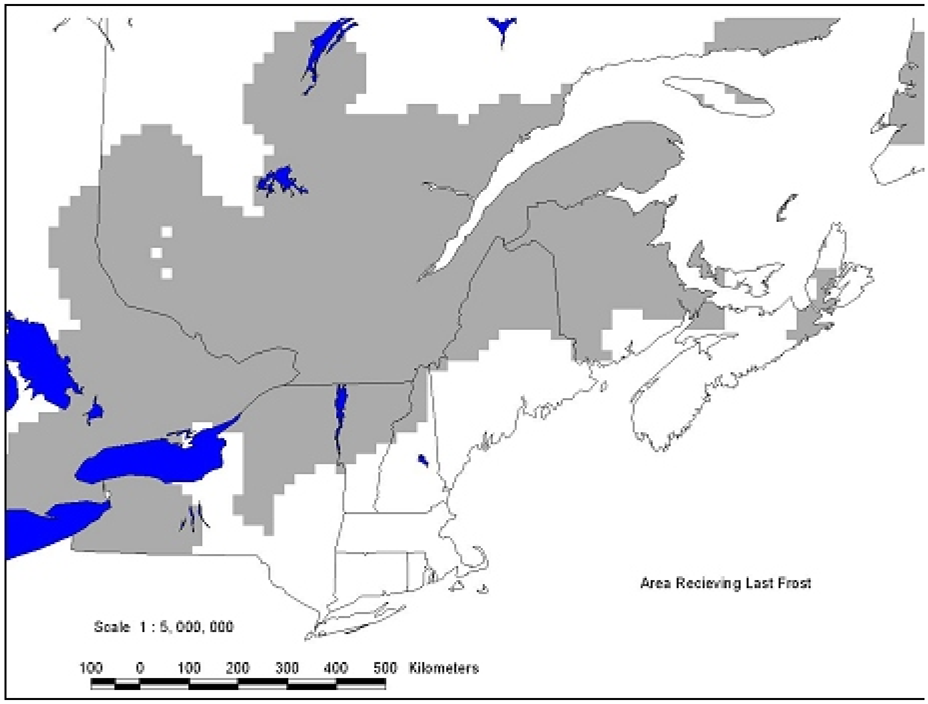

Figure 1.9. Maps showing daily accumulated degree days in 1936 from the start of the thaw event until the end.




Figures. 1.9 cont'd. Maps showing daily accumulated degree days in 1936 from the start of the thaw event until the end.




Figures. 1.9 cont'd. Maps showing daily accumulated degree days in 1936 from the start of the thaw event until the end.




Figures 1.9 cont'd. Maps showing daily accumulated degree days in 1936 from the start of the thaw event until the end.

<u>1.5.2. 1944 thaw event</u>

As shown in Fig. 10, the 1944 thaw shows a normal progression for spring and undergoes a late frost on April 17 (day 138). The area that received the late frost was mostly in Quebec's Gaspe Peninsula and some areas of northern New Brunswick. This late frost is thought to have done considerable damage to buds and twigs due to phenological activities having been well advanced.

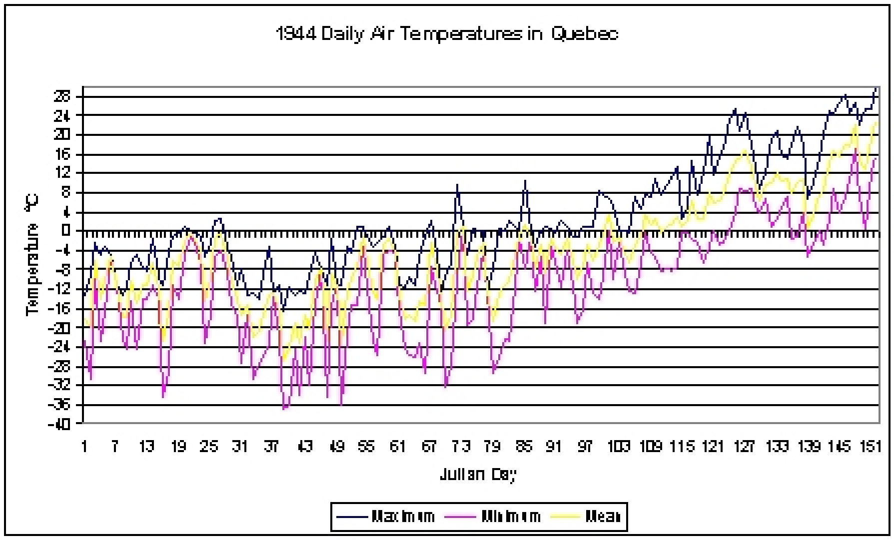
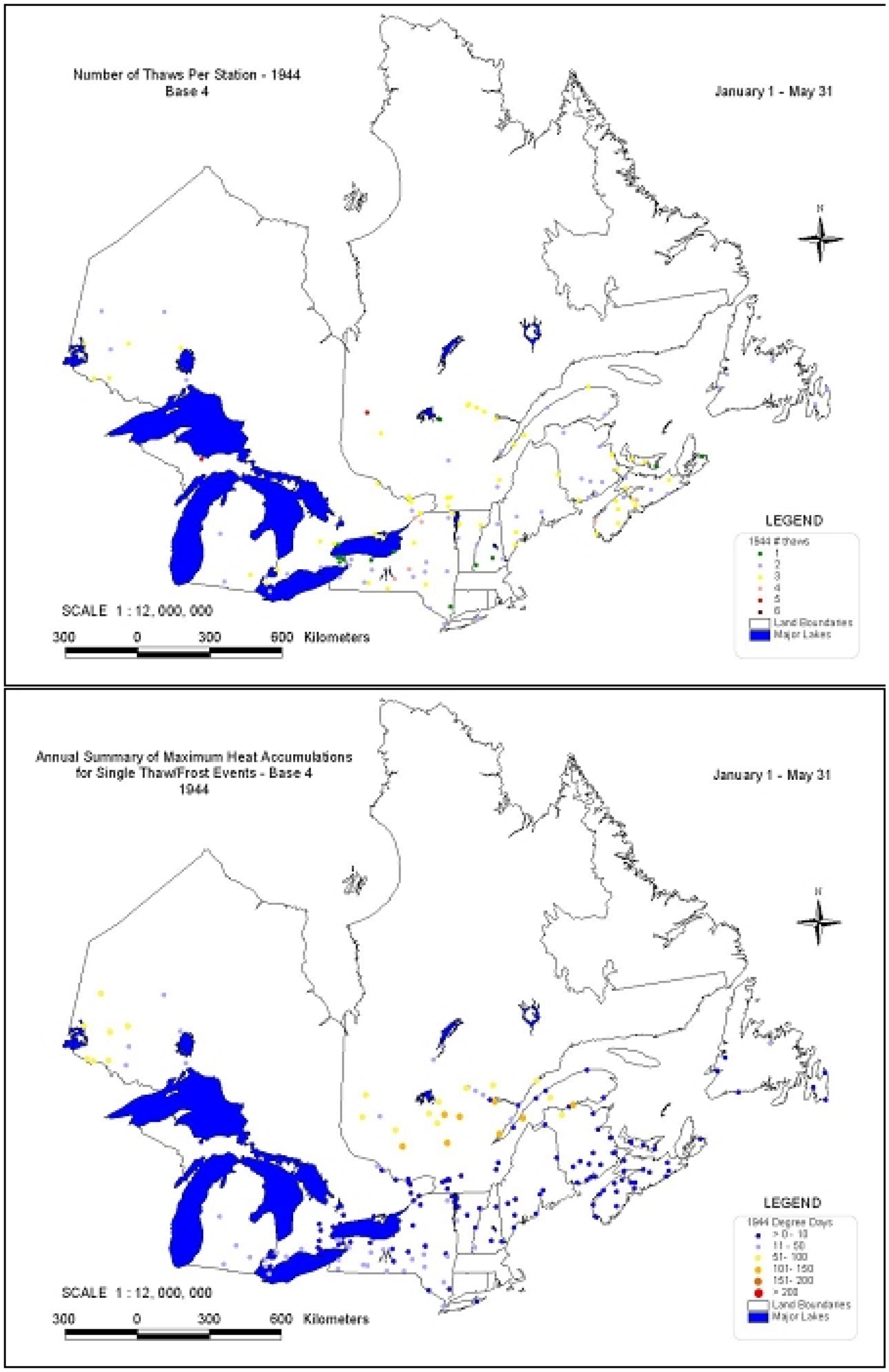
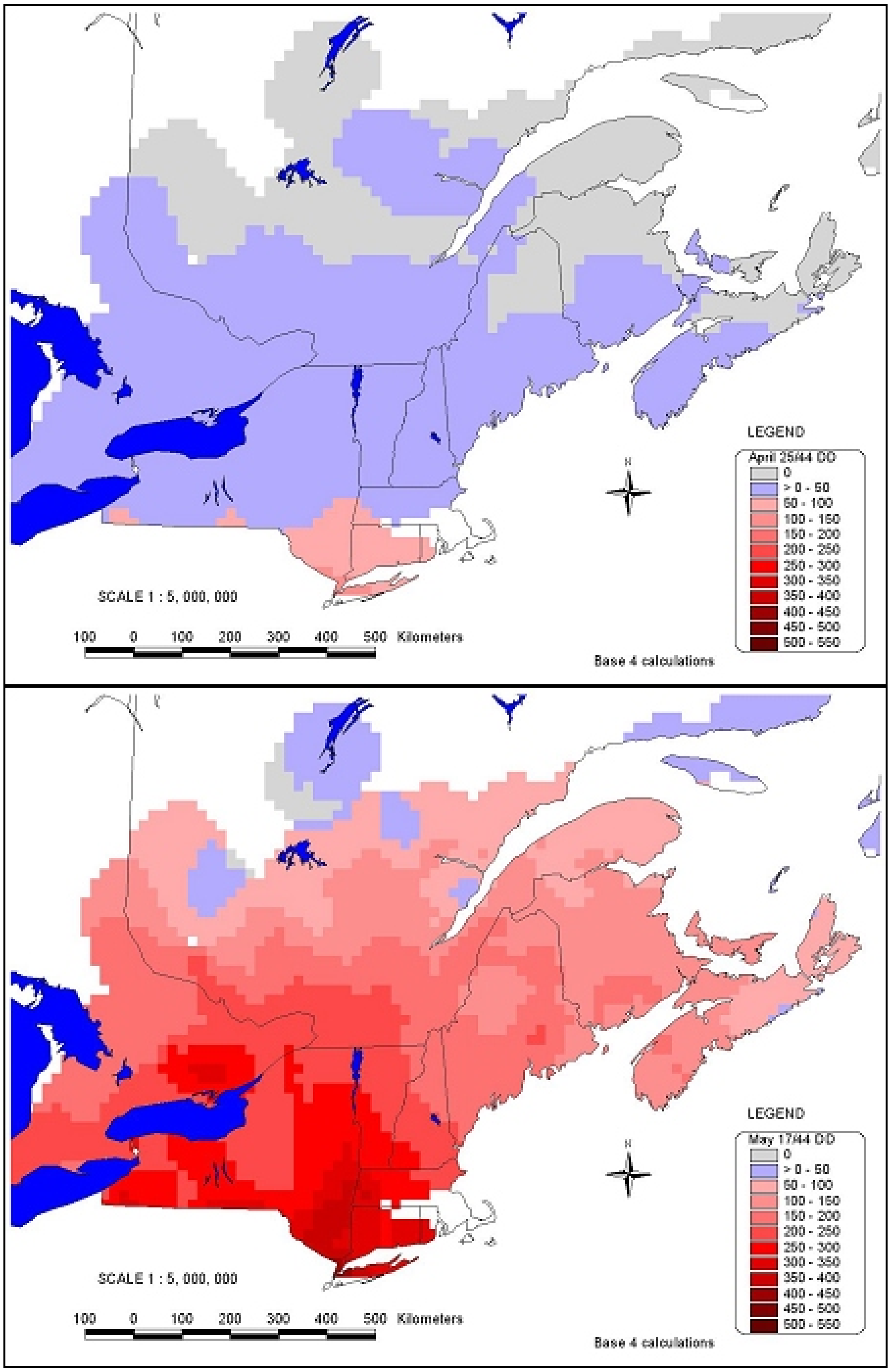


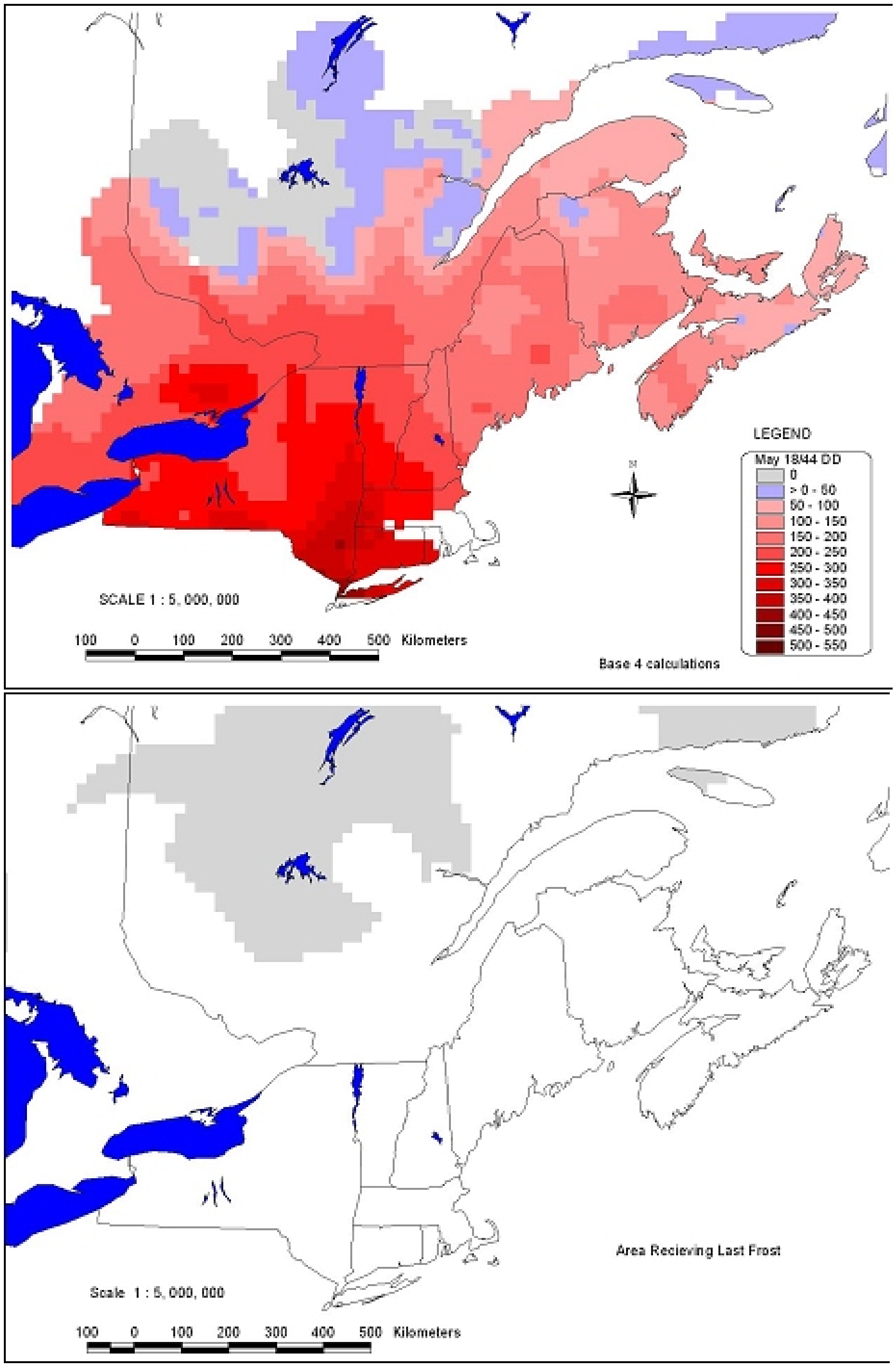

Figure 1.10.Temperature time series for a station in Quebec from January 1 to May 31 1944 showing a late frost.




Figures. 1.11a-b. Map showing, (a) the distribution and number of thaws events, (b) and maximum heat accumulations for single events in 1944.




Figures. 1.12. Maps showing daily accumulated degree days in 1944 from the start of the thaw event until the end.




Figures. 1.12 cont'd. Maps showing daily accumulated degree days in 1944 from the start of the thaw event until the end.

1.5.3. 1945 thaw event

The year 1945 had an extraordinary warm spring (record spring temperatures in most areas) with a subsequent frost in the middle of April.

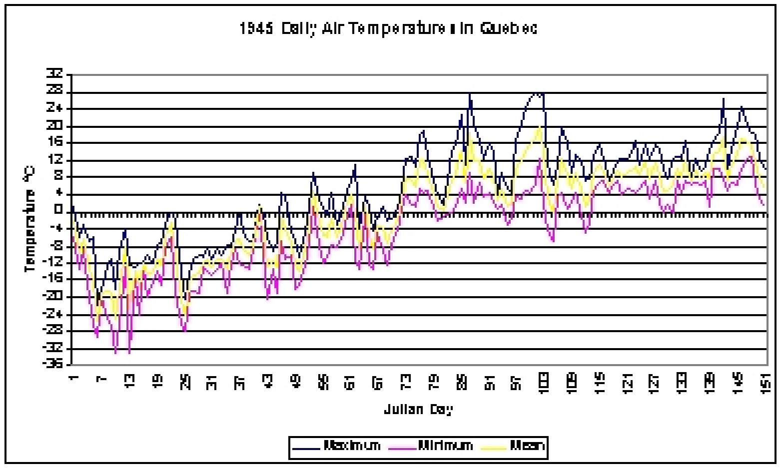
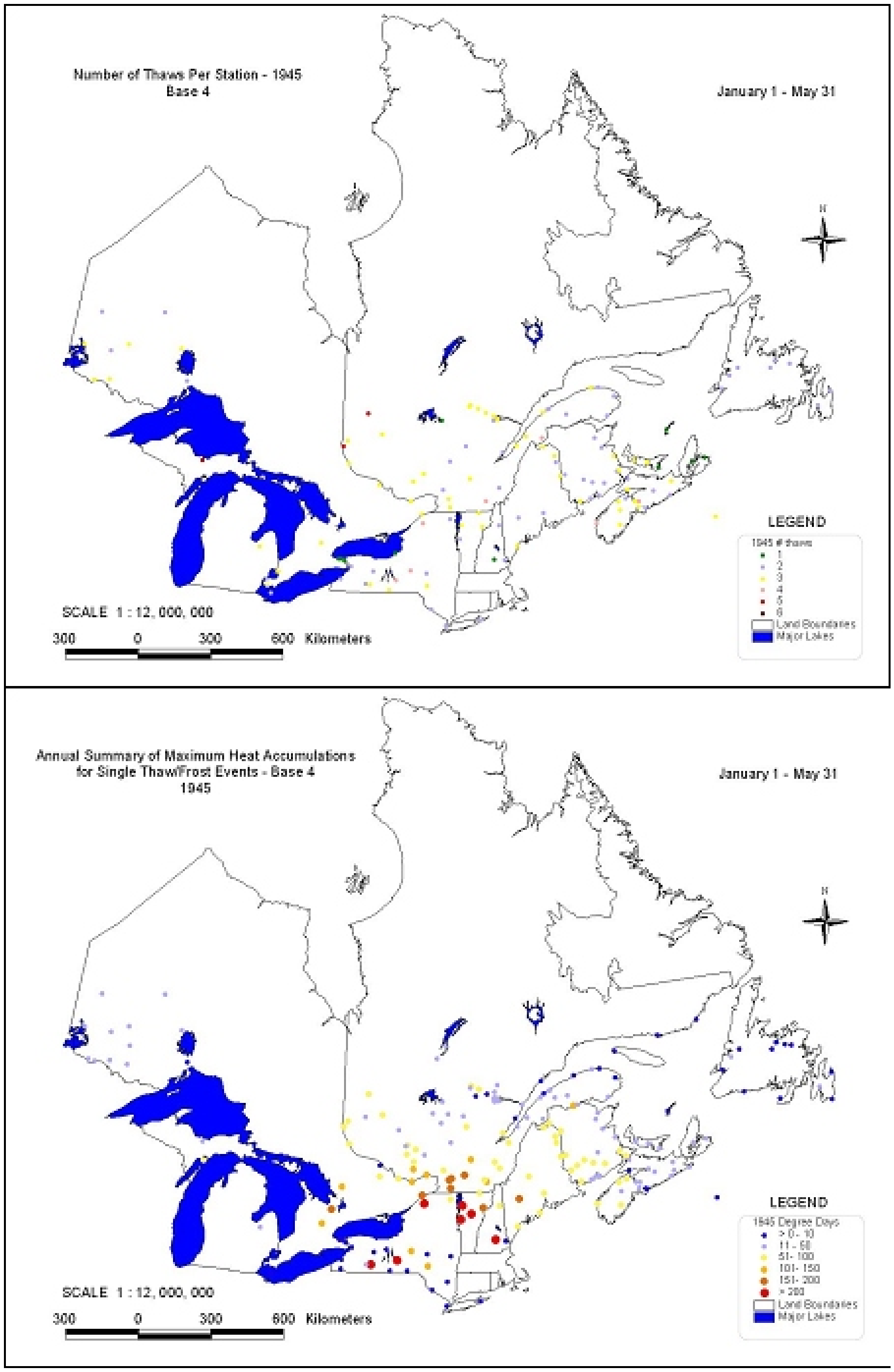
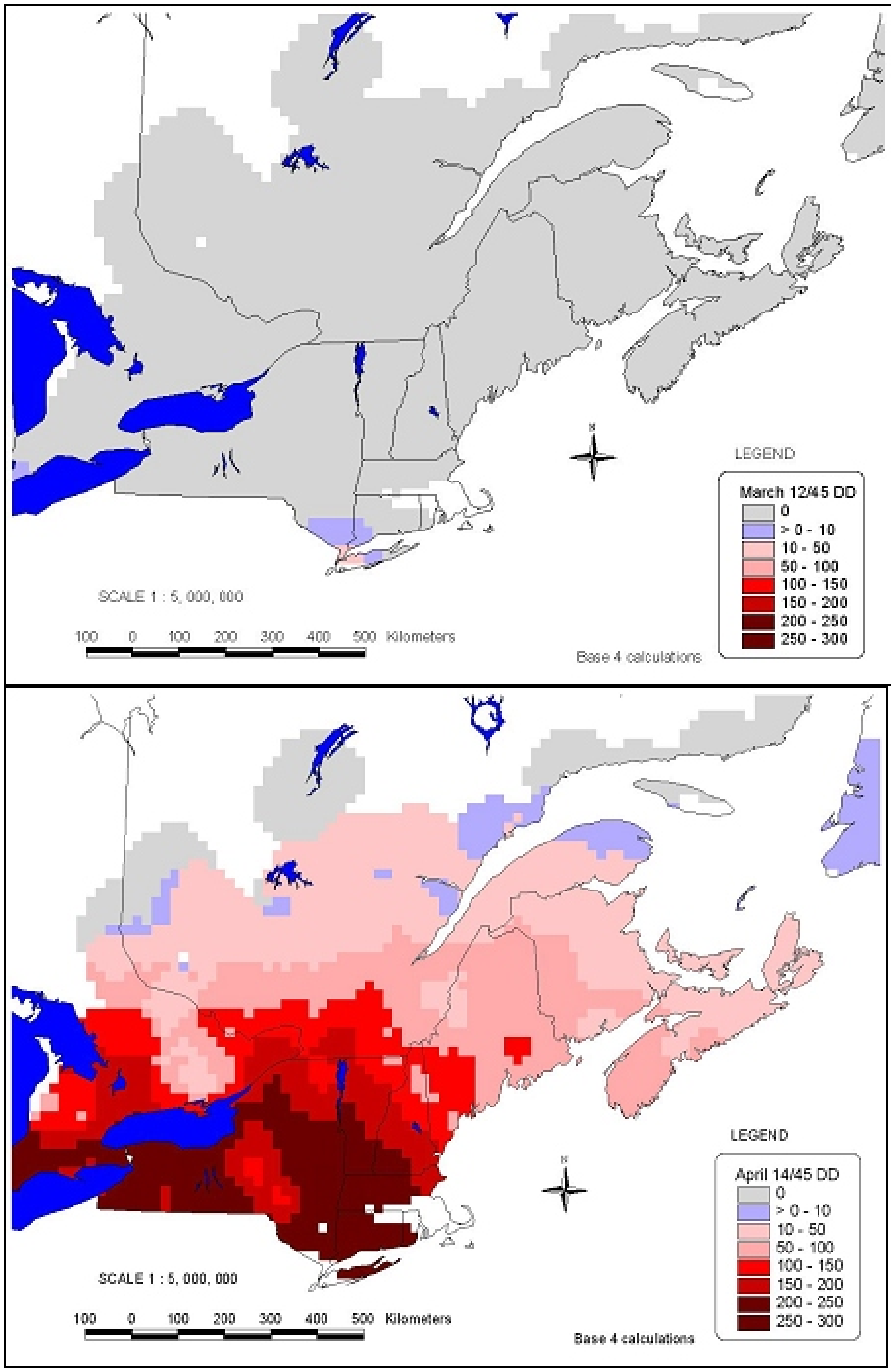



Figure 1.13 Temperature time series for a station in Quebec  from January 1 to May 31 1945.

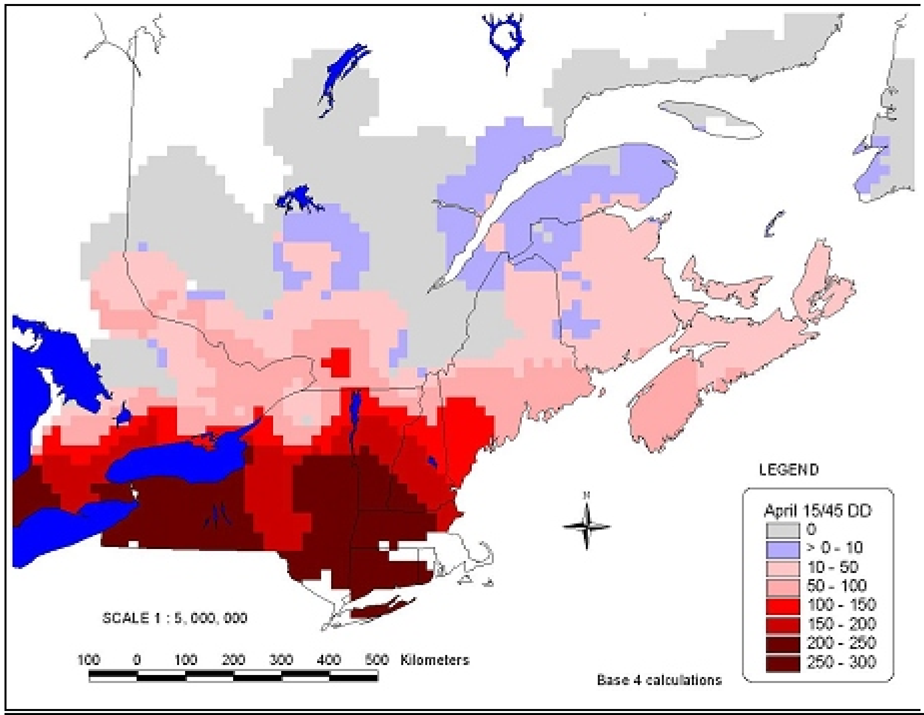
Figures 1.14a and b illustrate the distribution for the number of thaw events per station and the maximum heat accumulation for a single event during the period of January 1 to May31 in 1945.

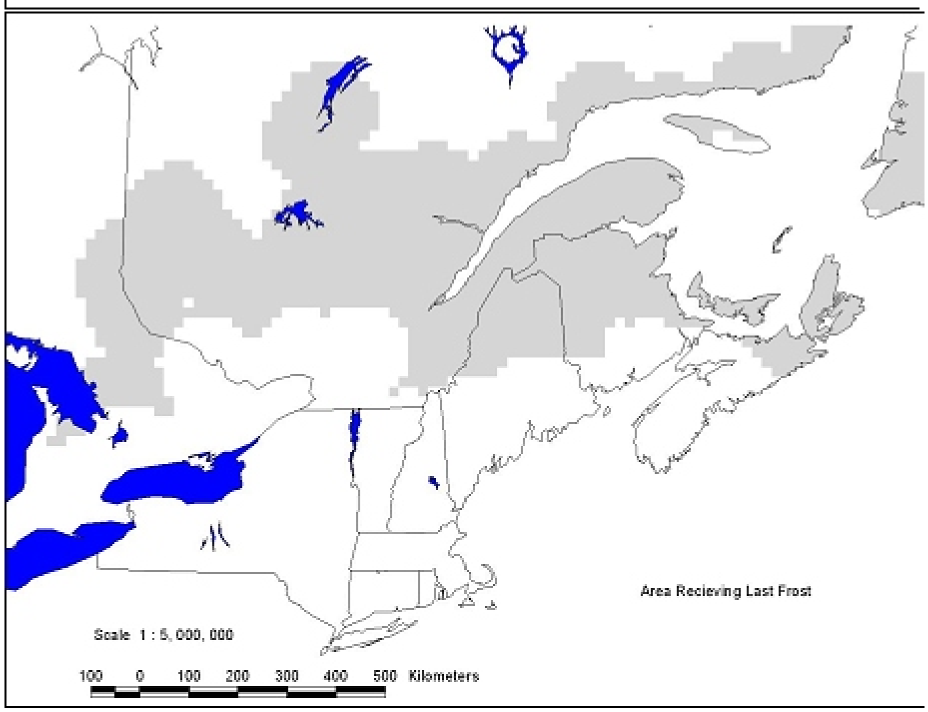



Figs. 1.14a–b. Map showing, (a) the distribution and number of thaws events, (b) maximum heat accumulations for single events, base 4 calculation, in 1945.




Figs. 1.15. Maps showing daily accumulated degree days in 1945 from the start of the thaw event until the end.




Figures. 15 cont'd. Maps showing daily accumulated degree days in 1945 from the start of the thaw event until the end.

1.5.4. 1981 thaw event

A well documented winter thaw for the winter of 1980/81 is illustrated in Figure 15 . Snow cover for the winters 1980 and 1981 was noticeably low, while temperatures of December 1980 and January 1981 were the coldest ever recorded in southern Quebec. In addition, this region sustained, from February 14 to February 28, 1981 the warmest and longest winter thaw recorded since the start of the century, during which time all snow covering the ground melted. The thaw was followed by a cold spell in mid March, which probably killed large quantities of twigs and small branches, particularly on maples, and severely damaged the root systems because of deep soils freezing. There was also a late spring frost, figure which occurred throughout most of southern Quebec, the Gaspe Peninsula and northern New Brunswick (Lachance, 1988).

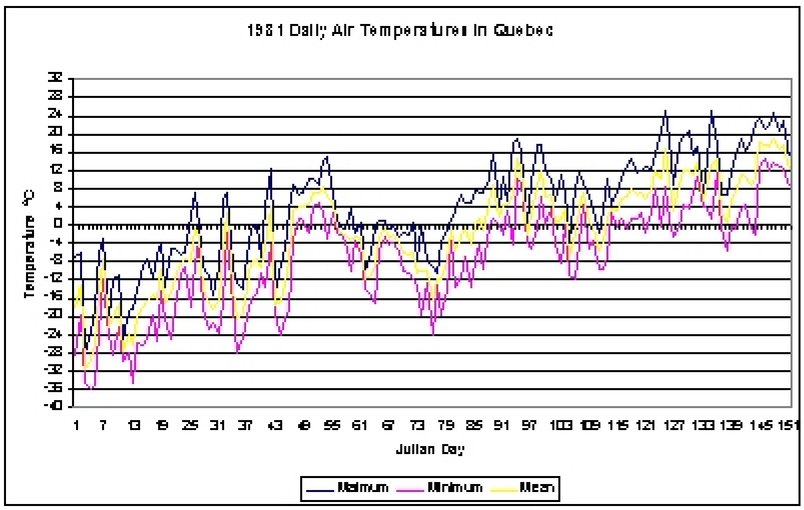
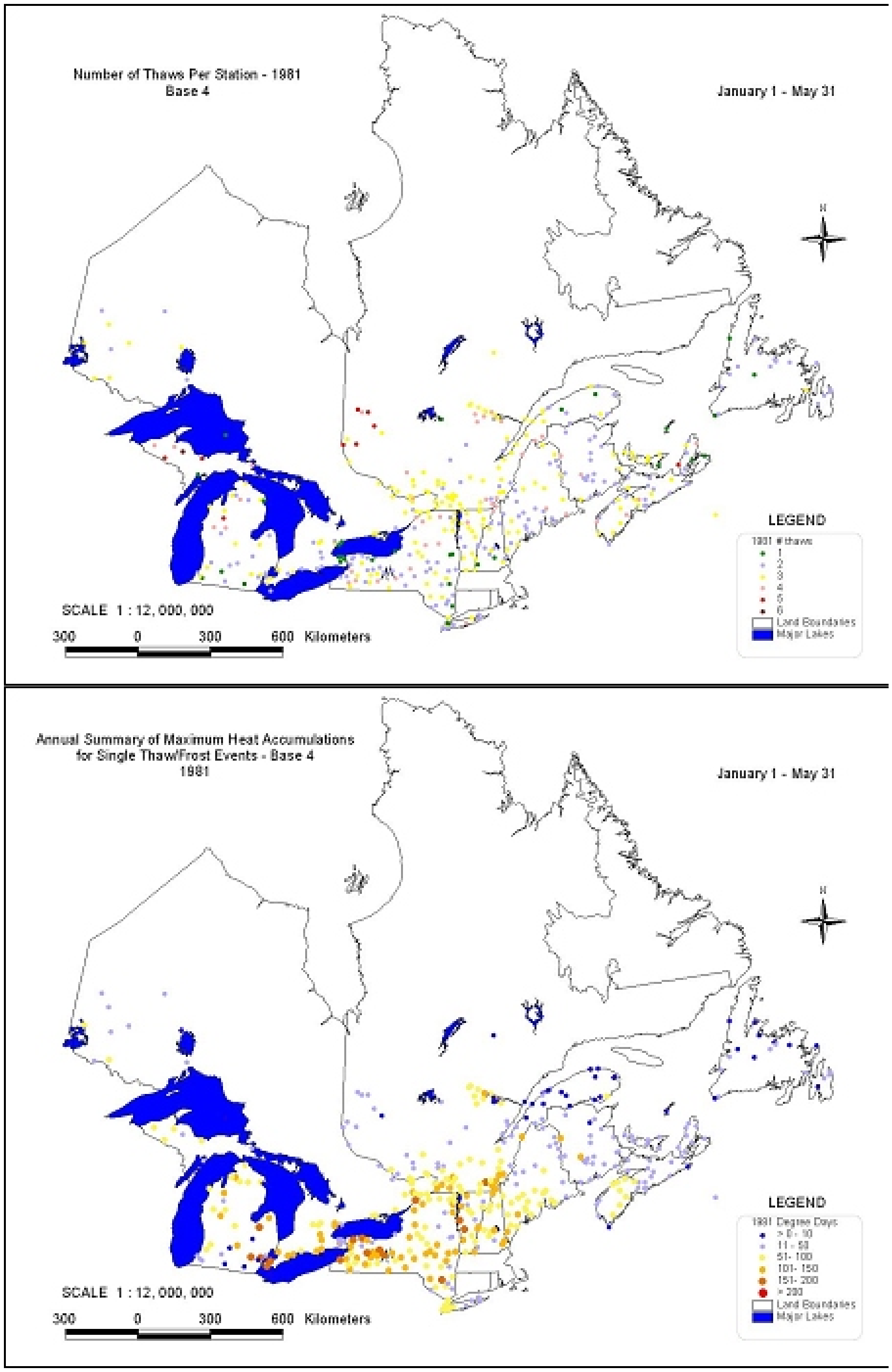



Figure. 1.16. Temperature time series for a station in Quebec from January 1 to May 31 1981 showing the winter thaw and late spring frost.




Figures. 1.17a and b. Map showing, (a) the distribution and number of thaws events, (b) and maximum heat accumulations for single events in 1981.

The variogram describes the expected difference in value of degree days between pair of samples within a given orientation for 1981. As seen in Figure 17, the semivariance increases with distance until approximately 550km's (sill) when the samples are no longer related to each other. The semivariogram was calculated using an active lag distance of 750 km's, a lag class distance interval of 50 km's using a spherical model with an $R^2$ value of .973

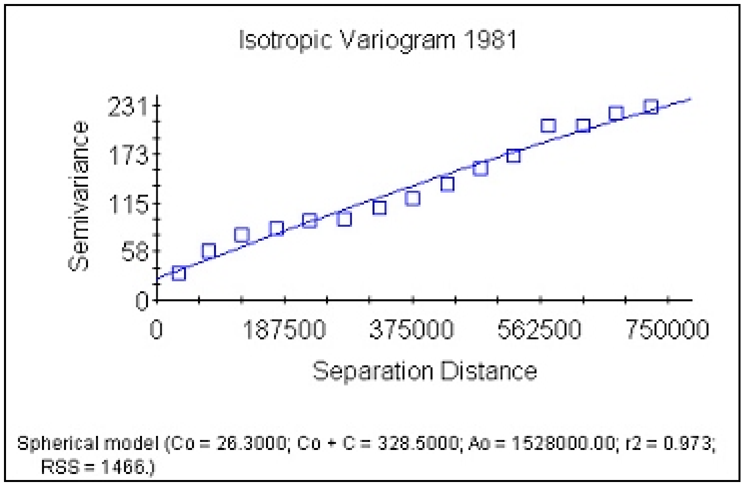



Figure. 1.18. Variogram demonstrating the shape of variogram as a function of distance for a typical day during thaw in 1981.

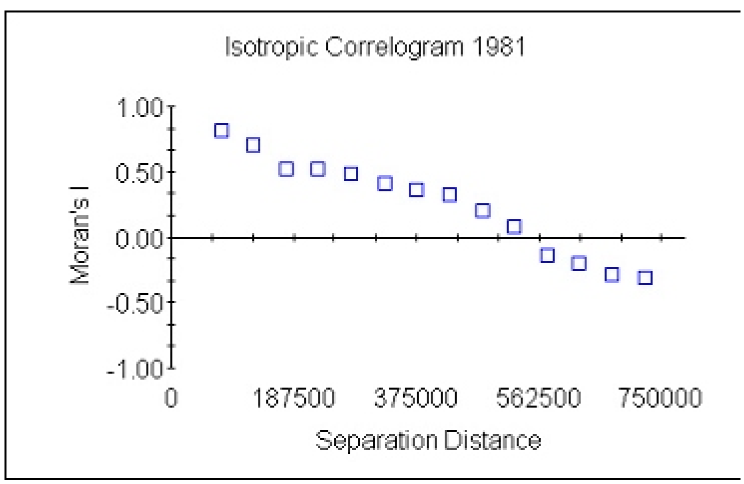



Figure 1.19. Correlogram showing spatial autocorrelation for a typical day during thaw in 1981.

The correlogram for 1981, as shown in Fig. 18 represents the spatial autocorrelation which starts cycling at around 550 km's. The 1981 correlogram had significantly higher values for Moran's I than 1936 mostly due to the spatial distribution of climate station values.

More stations values (204) in 1936 compared to 418 stations in 1981 provides better spatial coverage as well as enables the calculation of a "truer" variogram (increases significantly with the number of stations).

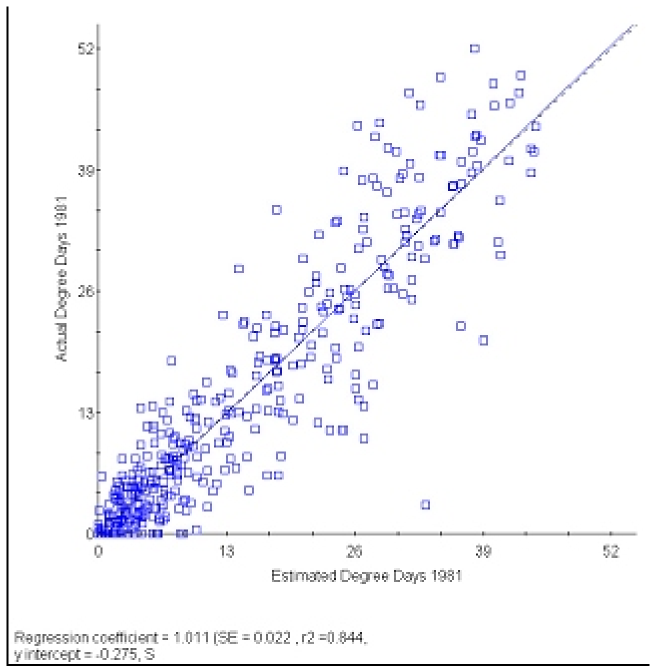



Fig. 1.20. Cross validation of actual versus expected values for a typical day in 1981.

A cross validation of actual versus expected values shows the model is representing the data with a cross validation result of $r^2 = 0.844$.

The kriged surface represented as a 20km grid cell size, 16 nearest neighbors of 100km's resulting in a grid of 156 columns and 72 rows with (A) a winter thaw beginning on February 14 and ending on February 28 and (B) the second late frost event beginning on April 24 and ending on May 17. Figs. 21 and Figs. 22 show the spatial progression of thaw and show the magnitude and spatial extent of the first thaw event.

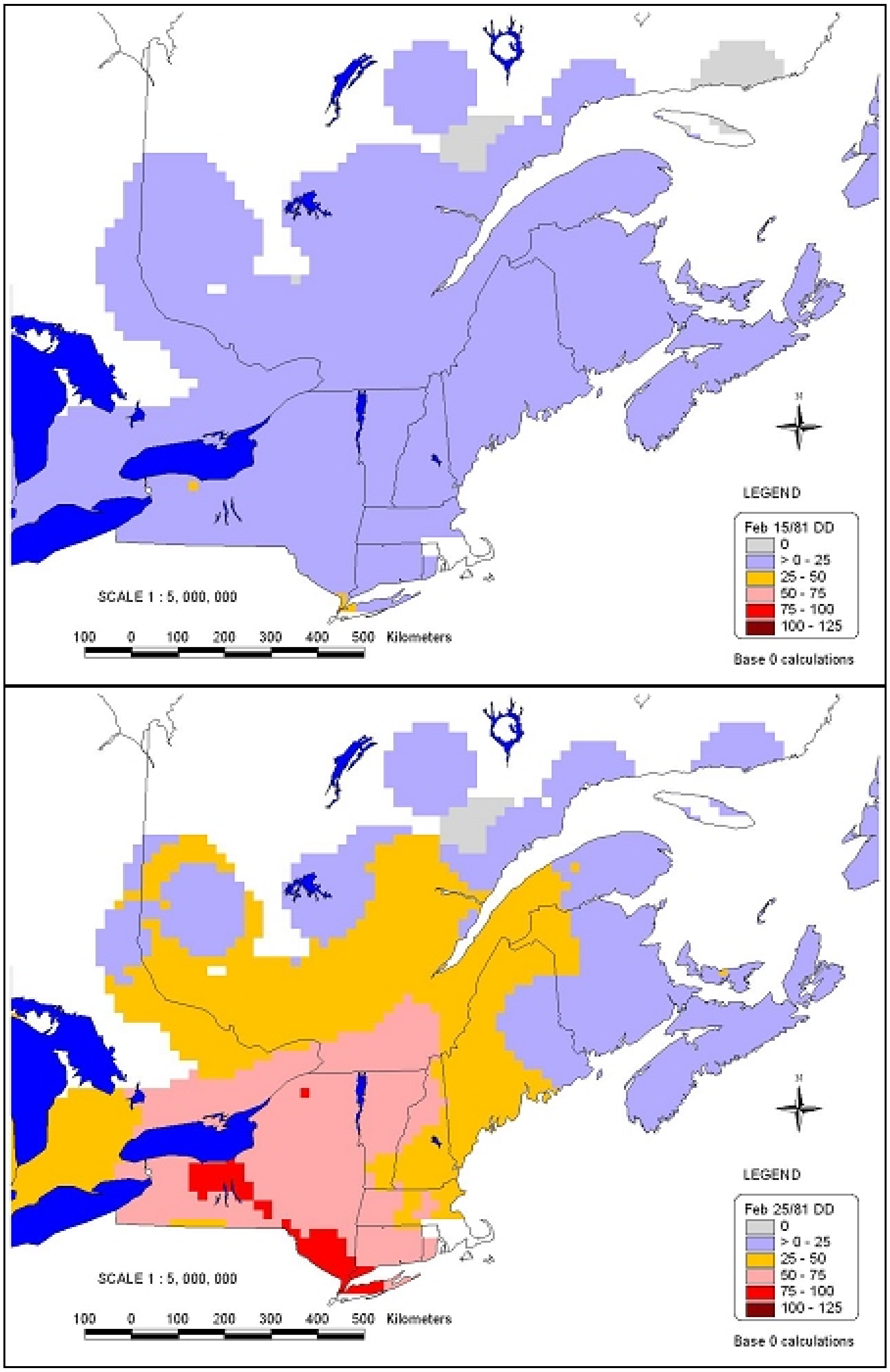
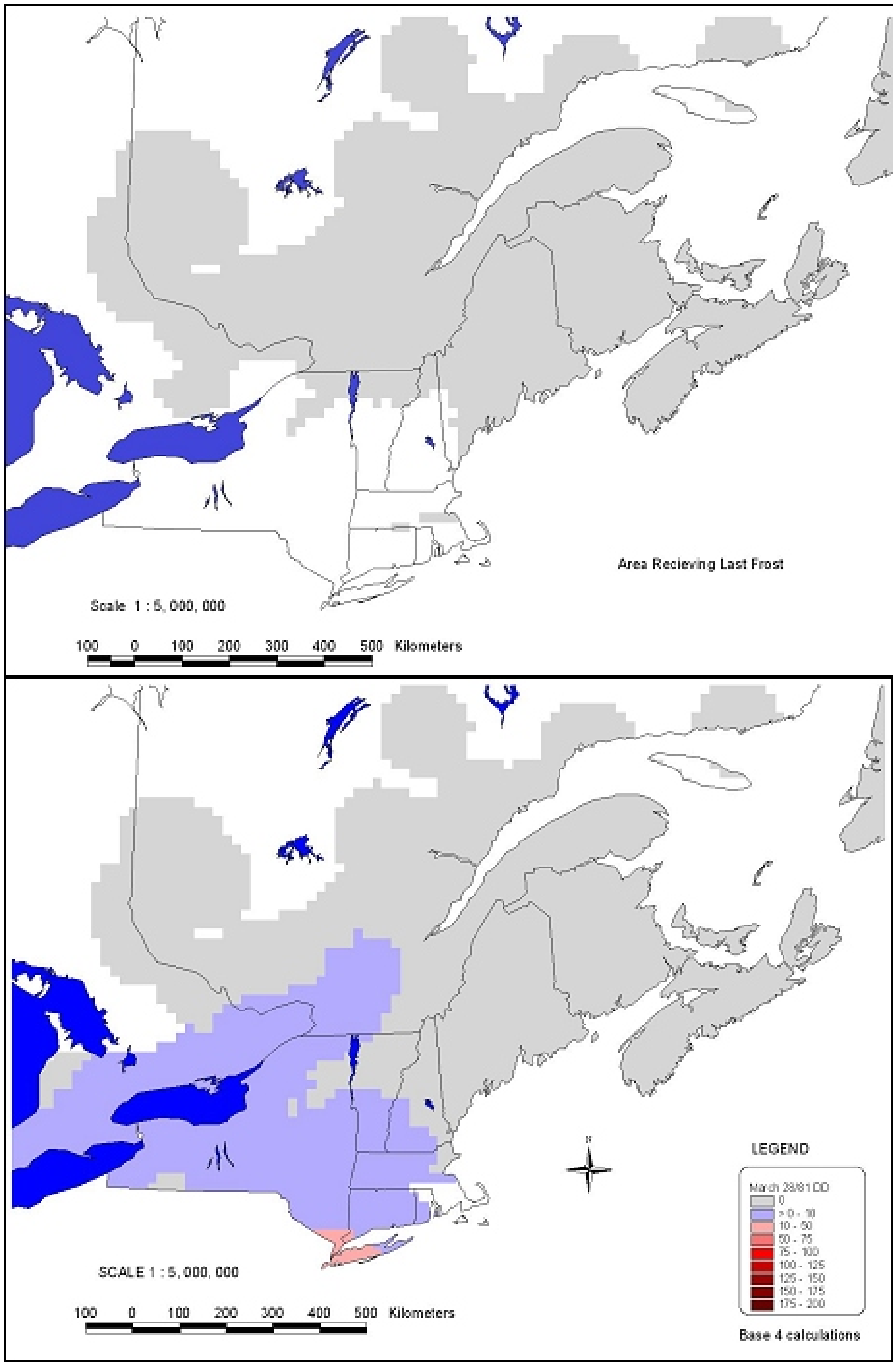
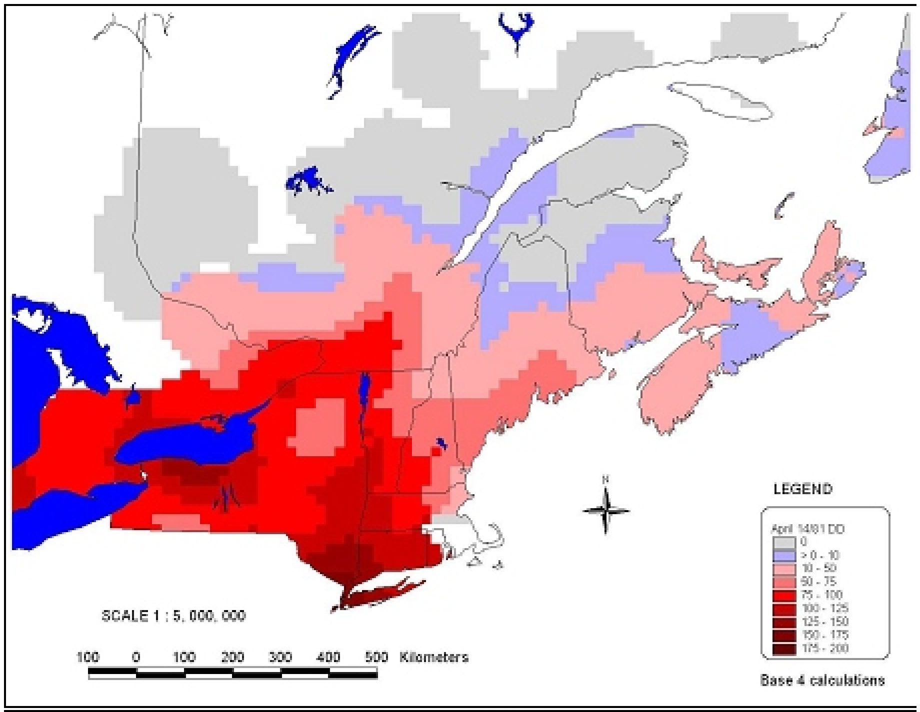
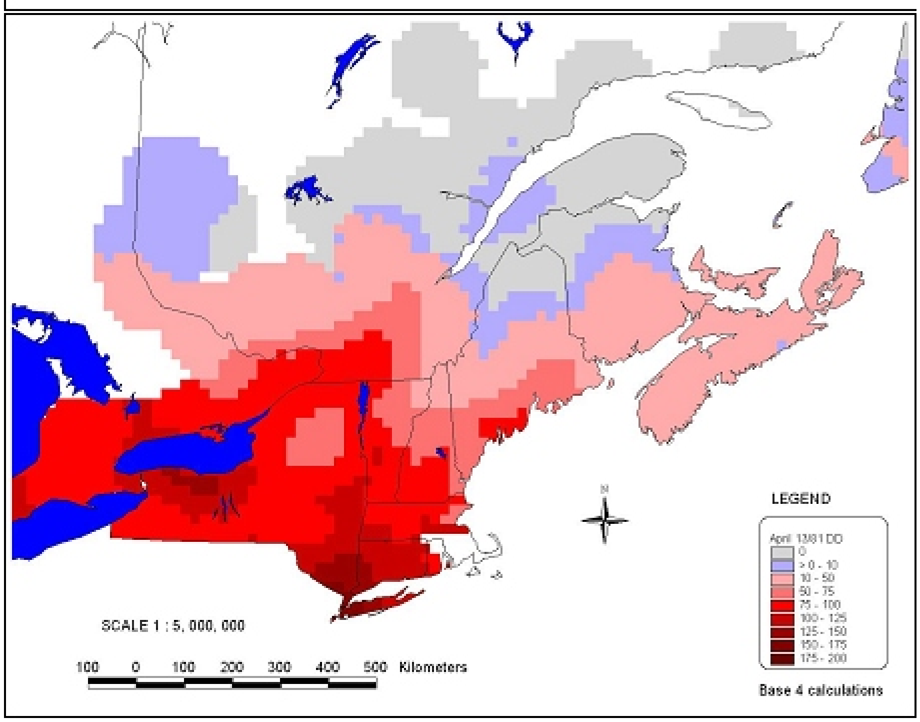



Figure 1.21. Maps showing daily accumulated degree days in 1981 from the start of the winter thaw event until the end.

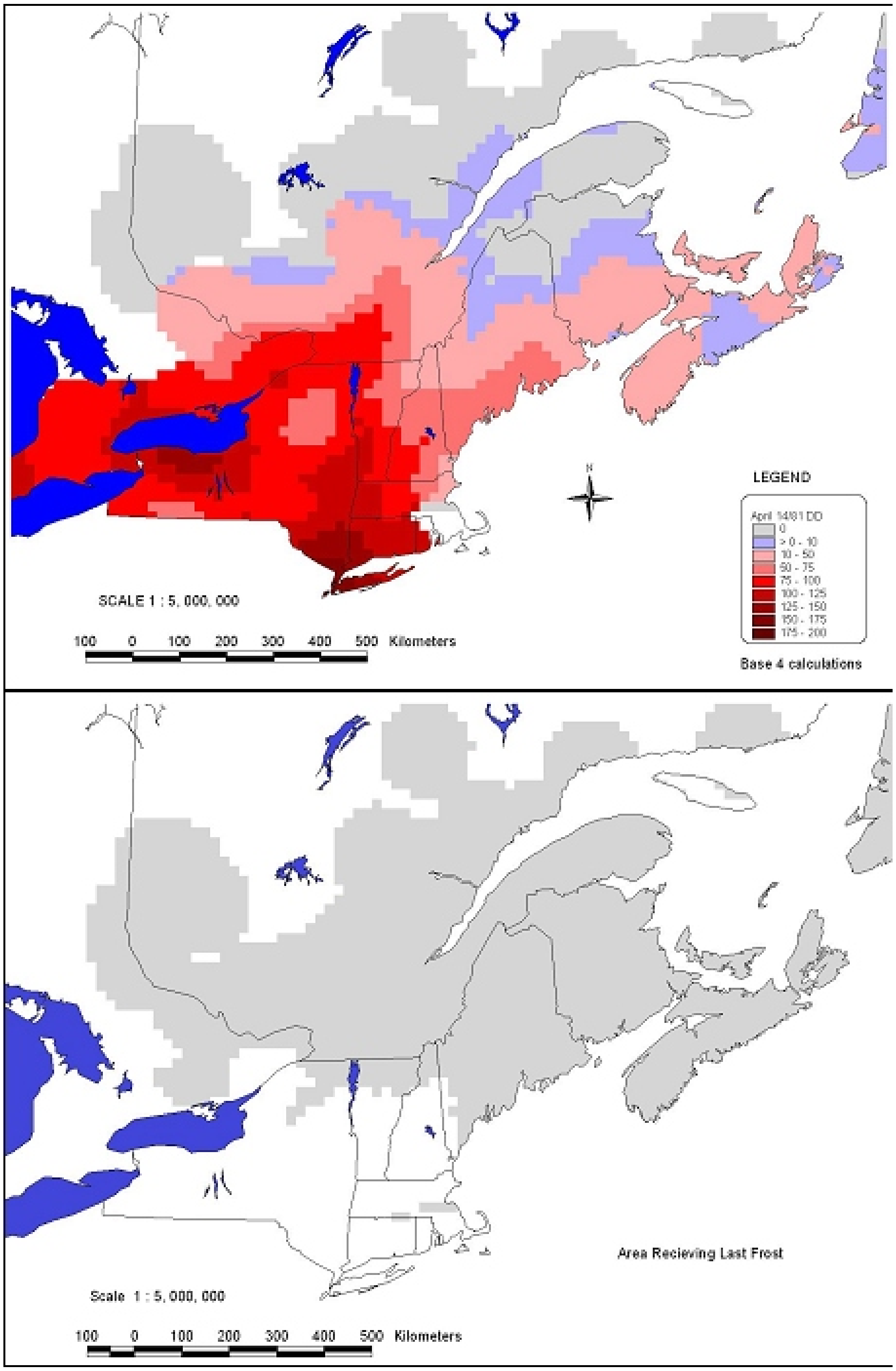



Figures 1.21. cont'd. Maps showing daily accumulated degree days in 1981 from the start of the winter thaw event until the end.\

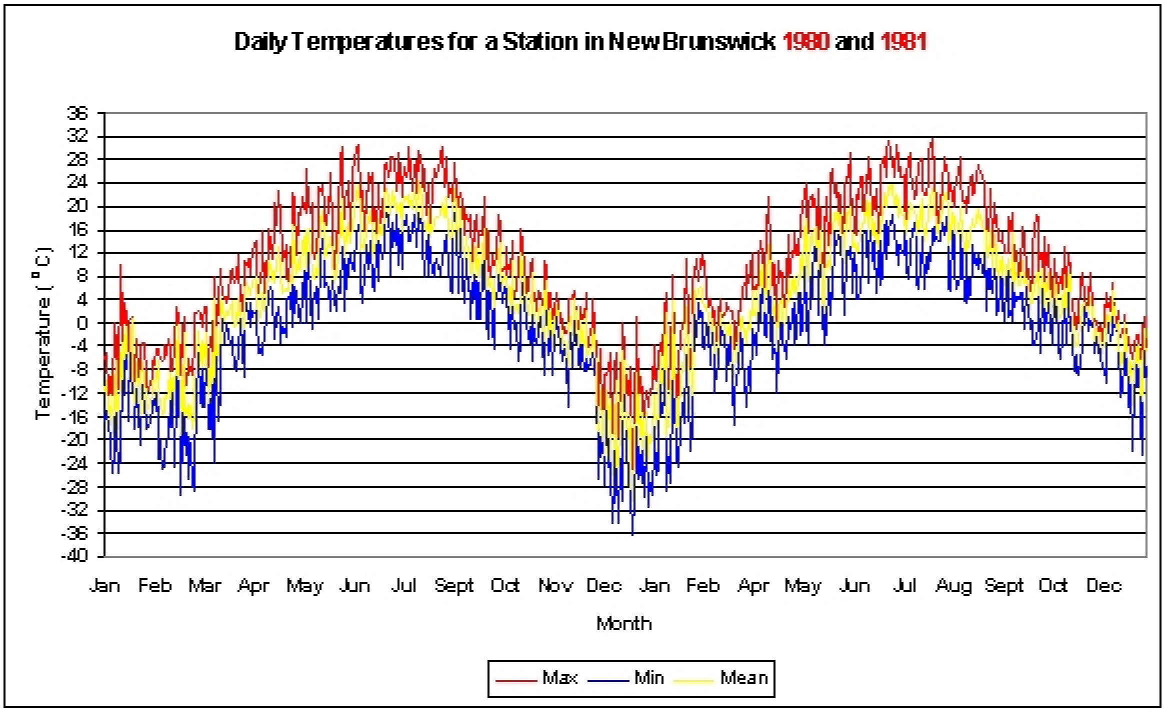



Figures 1.21. cont. Maps showing daily accumulated degree days in 1981 from the start of the spring thaw event until the end.




Figures 1.21 cont'd. Maps showing daily accumulated degree days in 1981 from the start of the spring thaw event and subsequent late frost until the end.



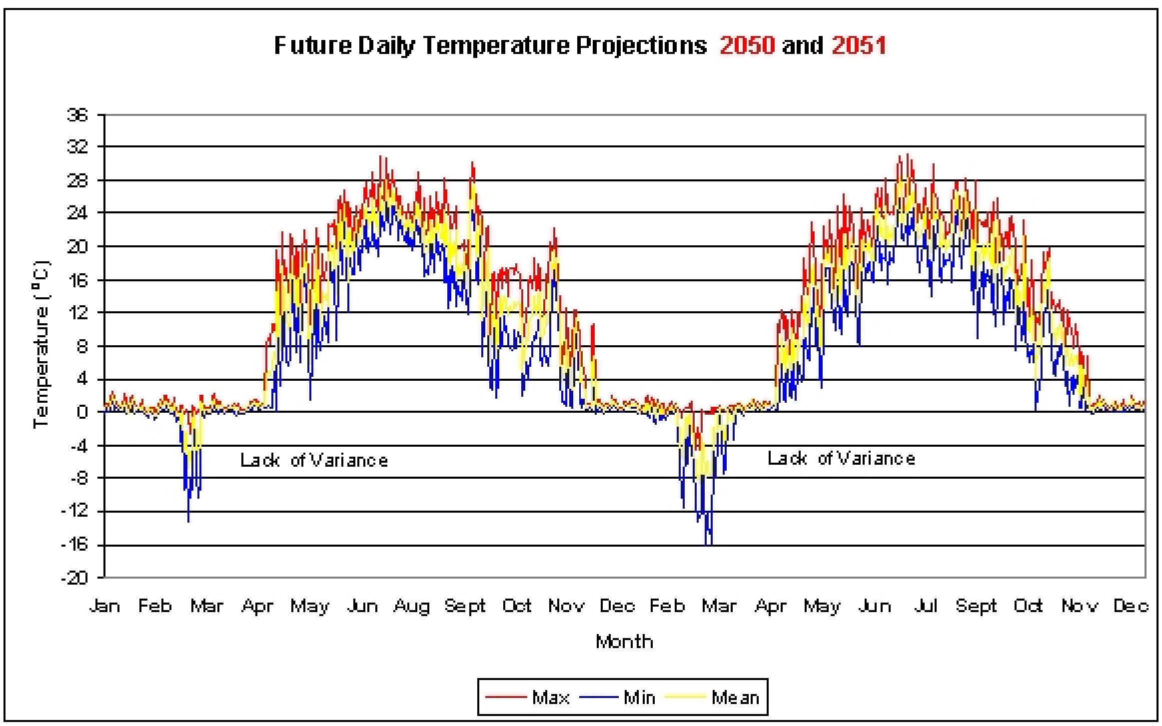




Figure 1.22 Comparison of actual daily air temperatures (max, mean and min) recorded at Aroostook - station # 8100300 (Top) with daily scenario output grid point 15 (Bottom).

Stations were chosen that fell within the thaw extents of the suspected years (previously shown in this report) were then run through ForHyMIII. a non spatial forest hydrology model that uses daily weather records and certain soil and forest canopy descriptions to predict soil moisture content, snow pack water equivalents/dynamics and soil temperature as they vary with forest cover. The forest hydrology model was used to estimate soil temperature and soil moisture in the rooting zones.

Basic input requirements include air temperature, total precipitation, snow fraction, forest cover type, leaf area index and soil texture and depth. The outputs (soil temperatures and snow pack water equivalents) of ForHyMIII were then used as essential inputs for the Birch Dieback Model.

### 1.6. Future daily temperature projections and their potential impacts.

Outputs of daily air temperature from the GCM scenario model were investigated with the aim of using them as input into the ForHyMIII hydrology model to produce the parameters that drive the Birch Decline Model (BDM) thus producing distributions of risk of future yellow birch declines. Although the capability is present the scenario data seemed to lack suitable variation over the critical spring period. An example of actual data showing the typical pattern of daily temperature variation compared to a typical pattern of the scenario data from grid cell 15 only 50 km distant from the weather station used for the comparison is shown in Figure 1.22. The investigators thought it prudent to shelve these potential outputs until there was suitable scenario data available.

### 1.7. Concluding Remarks

The methods demonstrated for determining winter/early spring thaws and late frost patterns, subsequent spatial and temporal tracking of these events has proven to be effective.

## Section II

## Birch Dieback Model

### 2.1. Introduction

The primary purpose of this study is to develop a process-based birch dieback model. For that reason, extent of shoot dieback, shoot xylem cavitation, shoot and root freezing injury and root pressure were measured in yellow birch (*Betula alleghaniensis* Britt.) under simulated- and natural winter conditions since 1997. Shoot xylem cavitation was determined as percent loss of hydraulic conductivity caused by embolism as the water column bread in the xylem vessels. Shoot and root freezing injuries were measured by way of relative electrolyte leakage (REL) and triphenyl tetrazolium chloride (TTC) reduction. It was found that winter shoot xylem cavitation was related to thaw duration, freezing temperature, and shoot dessication (Zhu et al. 2000, 2001). For seedlings and mature trees, shoots may lose 75 to 100 % of their hydraulic conductivity, and is an unavoidable winter phenomenon. Springtime root pressure in this species, however, was observed to almost eliminate the embolism caused by winter cavitation almost. A soil freezing temperature of -10 °C was found to cause a 10 % increase of root REL in potted yellow birch seedlings. This soil temperature also caused a considerable reduction of root pressure, hence leaving a large proportion of post-spring xylem embolism intact. This residual embolism was - in turn - associated with shoot dieback.

This process-based model was formulated to calculate shoot water content, extent of xylem cavitation and extent of shoot and root freezing injuries from weather records (Meteorological Service, Environment Canada) such as air and soil temperatures, relative humidity, solar radiation and wind speed (Figure 1). In this model, shoot dieback was empirically linked to extent of shoot and root freezing injuries and residual embolism. Laboratory experiments were used to generate the model-relevant process parameters. The parameters, that were needed to compute the cumulative, weather-affected moisture loss from the shoots, were based on an experimentally defined relationships among xylem moisture content, xylem water potential, and xylem cavitation, and between the extent of soil/air freezing to root/shoot injuries. Field observations for mature yellow birch trees correlated shoot dieback to extent of xylem cavitation and root and shoot freezing injuries. With model calibrations it was possible to have all model predicted values fall within the 95% confidence interval of the mean observed field values for most of the consecutive measurement dates.

### 2.2. Phenology

Plants in northern hemisphere generally experience cold-acclimation, hardinening and dehardening in fall, winter and spring. We also found that cold hardiness in yellow birch can be considerably reduced during winter due to thawing treatments. Therefore, a phenology sub-model was developed to serves as a biological switch in controlling the rate of dormancy and ontogenetics. Shoot dessication, xylem cavitation and cold acclamation were designed to be triggered by accumulated stages of dormancy and ontogenetic development (arbitrary units day$^{-1}$). The rate of dormancy was determined empirically by the chilling temperatures (Tc, -3.5 to 10.2 ºC, Linkosalo 2000 quoted from Savas 1974).

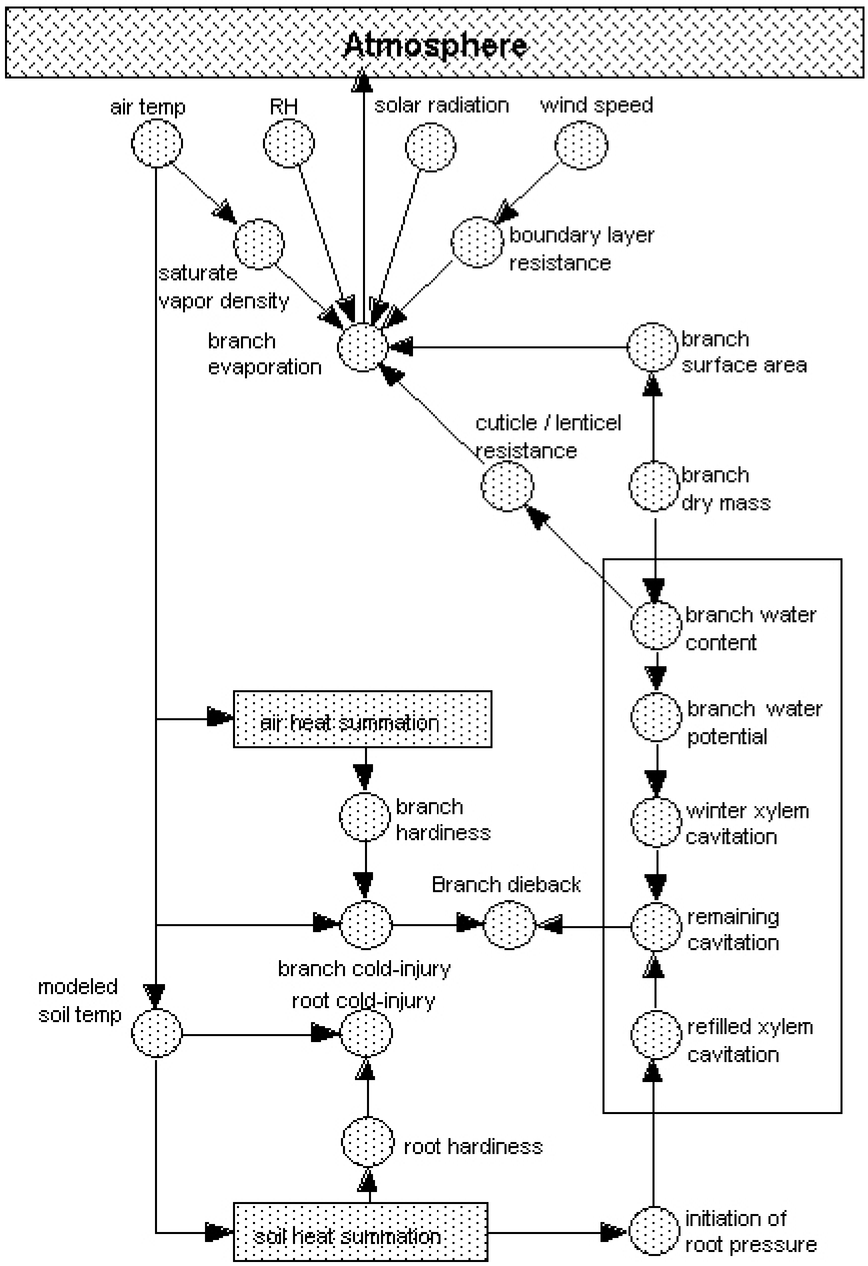


Figure 2.1. Schematic diagram of the "Birch Dieback Model".

This equation was reconstructed for yellow birch. The graph plotted from the equation showed the critical point at which dormancy completed and leaves fell (Figure 2.2).

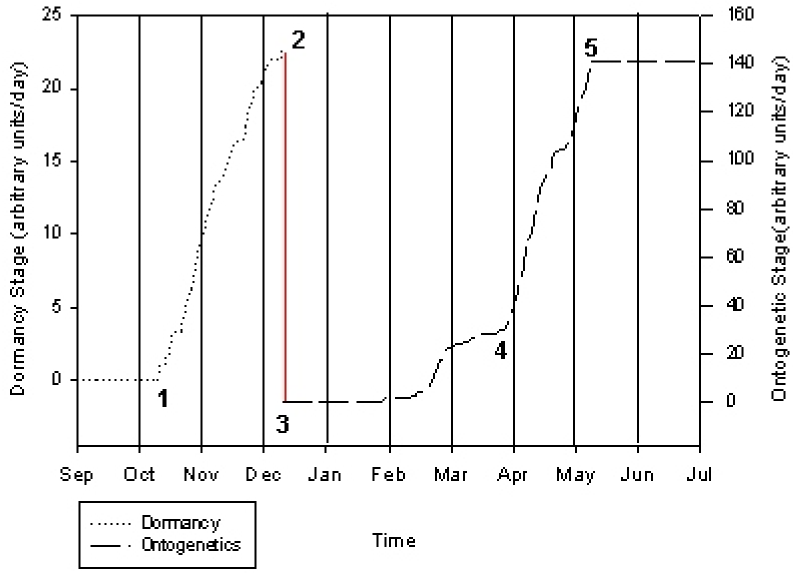



Figure 2.2. A typical example of modeled dormancy and ontogenetics in yellow birch of New Brunswick. 1 = leaf fall; 2 = complete dormancy; 3 = starting point of heat summation; 4 = starting point of root function; 5 = bud burst.

To obtain the critical value, the date of complete leaf fall was recorded for three consecutive years in this region. Mean value was chosen to represent the completion of dormancy development. The same method was also used to generate the critical points for root function and bud burst respectively. Initialization of root pressure and bud burst are the results of break down of dormancy. Both chilling requirements and day length are involved in the hormones-controlled process. For yellow birch, we chose chilling requirements in predicting its phenology.

### 2.3. Shoot water content and xylem cavitation

The calculations of the shoot water content in winter are strongly affected by the changes in the values of the branch surface resistance to water loss , and of the shoot interior temperature. Since surface resistance is determined by measurement and remains constant (i.e., assumed to be constant), shoot interior temperature is solely responsible for affecting the changes in shoot water content. shoot interior temperature, in turn, is controlled by solar radiation and wind speed. Until the initiation of spring refilling, the model estimated measured water content for individual trees well (Figure 3). Thereafter, spring-refilling of the shoot with water by way of activating the root pressure module was well demonstrated (Figure 2.3).

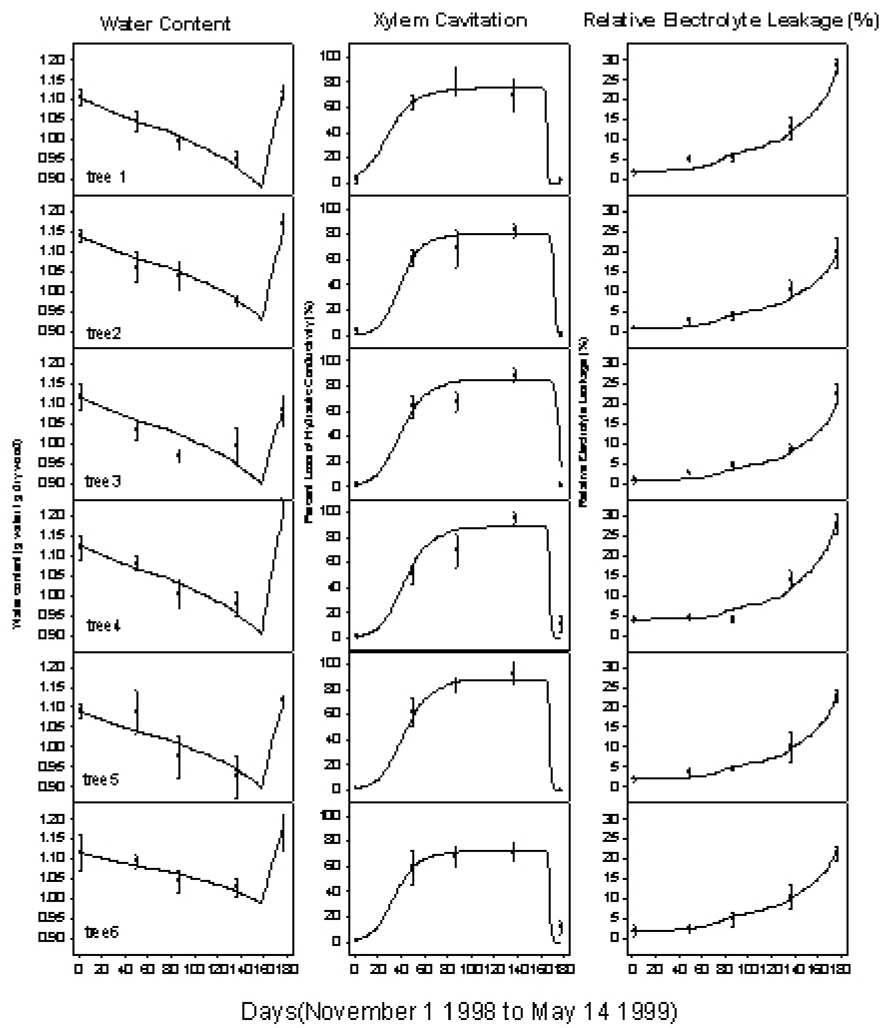



Figure 2.3. Actual and estimated shoot water content, xylem cavitation and relative electrolyte leakage in two-year-old twigs of mature yellow birch in 1998/1999. Six sample trees were used for the model calibration. Error bars represent 95 % confidence intervals around mean measurements on five branches (n = 5).

Winter xylem cavitation, in general, involves both shoot dessication and freeze-thaw effects. Thus, for practical reasons, coefficient values as obtained from laboratory experiments with summer twigs, needed to be adjusted to calibrate the winter xylem cavitation calculation.

### 2.4. Shoot dieback

The calculations for root and shoot freezing damage were determined by current soil and air temperature and the root and shoot hardiness that is sensitive to the heat summation and ontogenetic development. The calculation of shoot dieback predictions, in turn, were sensitive to the residual embolism, root freezing injury, and to shoot freezing injury in spring. Also , spring root pressure reductions followed the extent of root freezing injury, and the calculated root pressure was then used to determine the amount of residual xylem embolism. For the field observations, however, measured soil temperatures in 1998, 1999 and 2000 were not low enough to calculate root freezing injuries. As a result, accumulated embolism caused by winter xylem cavitation was calculated to be completely eliminated, leaving the estimated shoot dieback at its normal background level of 18.5 % (Table 2.1).

Table 2.1. Results of the measured and predicted percentage of shoot dieback in yellow birch. Dieback was determined as percent of dead tips in early June, (n = 150-250 per tree).

| Year | Site | Measured (%) ± 95 % confidence interval | Predicted (%) |
|---|---|---|---|
| 1998 | UNB woodlot | 20.2 ± 6.5 | 18.5 |
| 1999 | MacDonald Corner | 17.7 ± 7.9 | 18.5 |
| 2000 | UNB woodlot | 16.2 ± 6.5 | 18.5 |

### 2.5. Model sensitivity test

Model sensitivity test was conducted by using the winter soil temperatures with and without snow cover. As result, model outputs showed a significant effects of snow removal on springtime root pressure, xylem refilling and shoot dieback (Figure 2.4).

In the case of full snow cover, simulated soil temperature remained fairly constant at and/or above the freezing point for most of the days during winter (Figure 2.4a). The root system would be well protected under this condition, the healthy roots would possibly generate sufficient root pressure (about 90 kPa) during the spring (Figure 2.4b). This positive root pressure would then push water upward to re-hydrate xylem of the shoots (Figure 2.4c), thus reducing the calculated winter cavitation (Figure 2.4d). As a result, crown dieback was calculated to be minimum at 18.5 %.

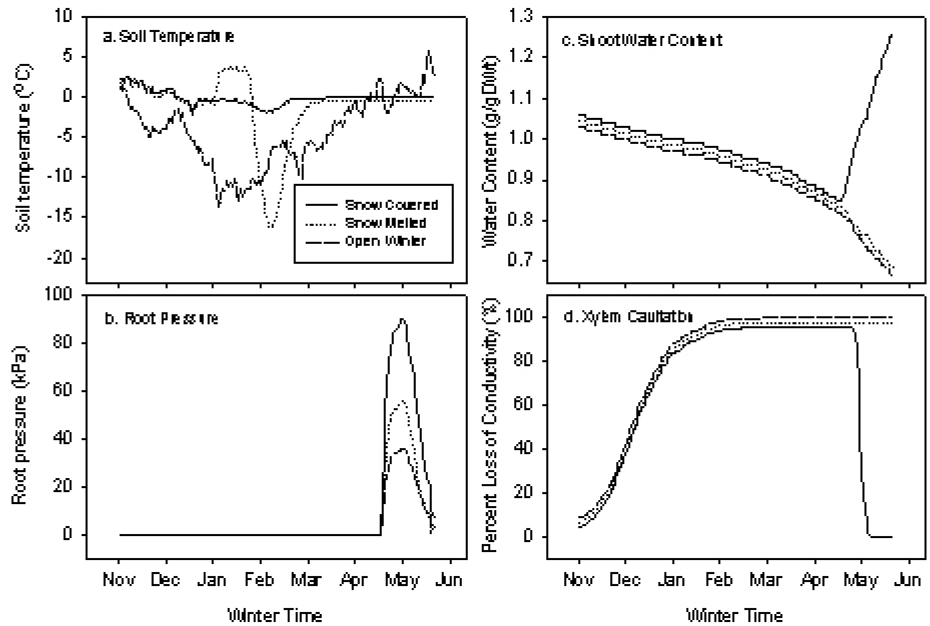



Figure 2.4. Comparison of modeled springtime root pressure, shoot water content and xylem cavitation in response to three soil temperature regimes in the root zone.

In the case of open winter, the site is assumed to snow free, as a consequence the soil temperature near the soil surface was simulated to fluctuate drastically throughout the winter in accordance with air temperatures (Figure 4a). The resulting soil frost was calculated to produce some injury, which would then decrease the springtime root pressure (Figure 4b). However, the extent of root pressure was simulated to be enough to push water from root to the certain level of canopy, leading to a partial recovery of canopy from winter dessication and xylem cavitation. The winter xylem cavitation in the branches at the top of canopy remained intact (Figure 4c,d), resulting in an estimation of 55% crown dieback(Figure 5).

In the case of a mid-winter thaw, ground snow is assumed to be thawed by a prolonged mid-winter thaw. During this time, soil temperatures were simulated as high as 5 °C for couple of weeks (Figure 4a), leading to a general reduction in cold-hardiness of the root. Subsequently, the roots should experience frost which was then estimated to lower the root pressure in spring (Figure 2.4b). Failure to transport sufficient water from the roots to canopy would lead to further xylem cavitation formed (Figure 2.4c,d). The residual xylem embolism is estimated to induce 75% crown dieback (Figure 2.5).

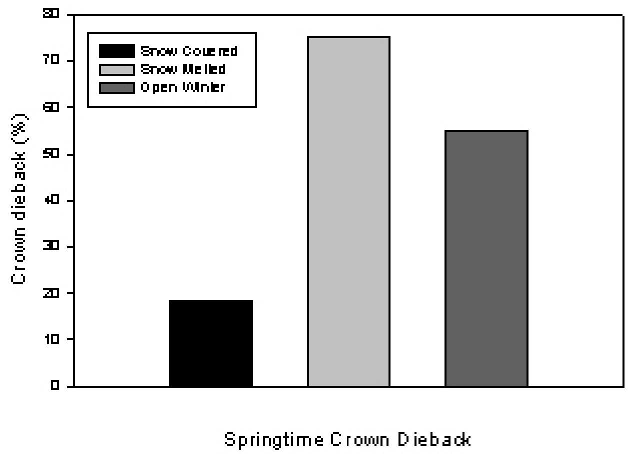



Figure 2.5. Comparison of modeled springtime crown dieback in response to three soil temperature regimes and the subsequent root pressure, shoot water content and xylem cavitation.

## 2.6. Model performance

To verify the model performance, data of shoot water content, xylem cavitation and relative electrolyte leakage were collected from five mature trees within the woodlot of the University of New Brunswick in the winter of 1999/00. Shoot dieback was also examined in these trees in early June, 2000. Model-calculated values were found to be within the 95% confidence intervals for water content, percent loss of hydraulic conductivity, and shoot relative electrolyte leakage (Figure 2.6). The calculated values for these parameters not only followed the trends of the measured values over winter, but also during spring. As observed for 1998/1999, no apparent branch dieback (<18 %) was observed and modeled for 1999/2000 (Table 2.1).

To re-construct the historical birch dieback events in 1936, 1945 and 1981, climate records from December to May in the winters of 1935 - 1936, 1944-1945, and 1980-1981 were used to run the birch dieback model. During these periods, the required soil temperature inputs were generated from a modified version of Hydrology model-ForHym . Soil frost (<-10°C) that caused 10 to 20 percent root cell death were predicted for the winters of 1930's in Quebec (Figure 2.7) and the winters of 1980's in Nova Scotia (Figure 2.8). However, shoot freezing injury was only predicted for the spring of 1981 in New Brunswick (Figure 2.9).

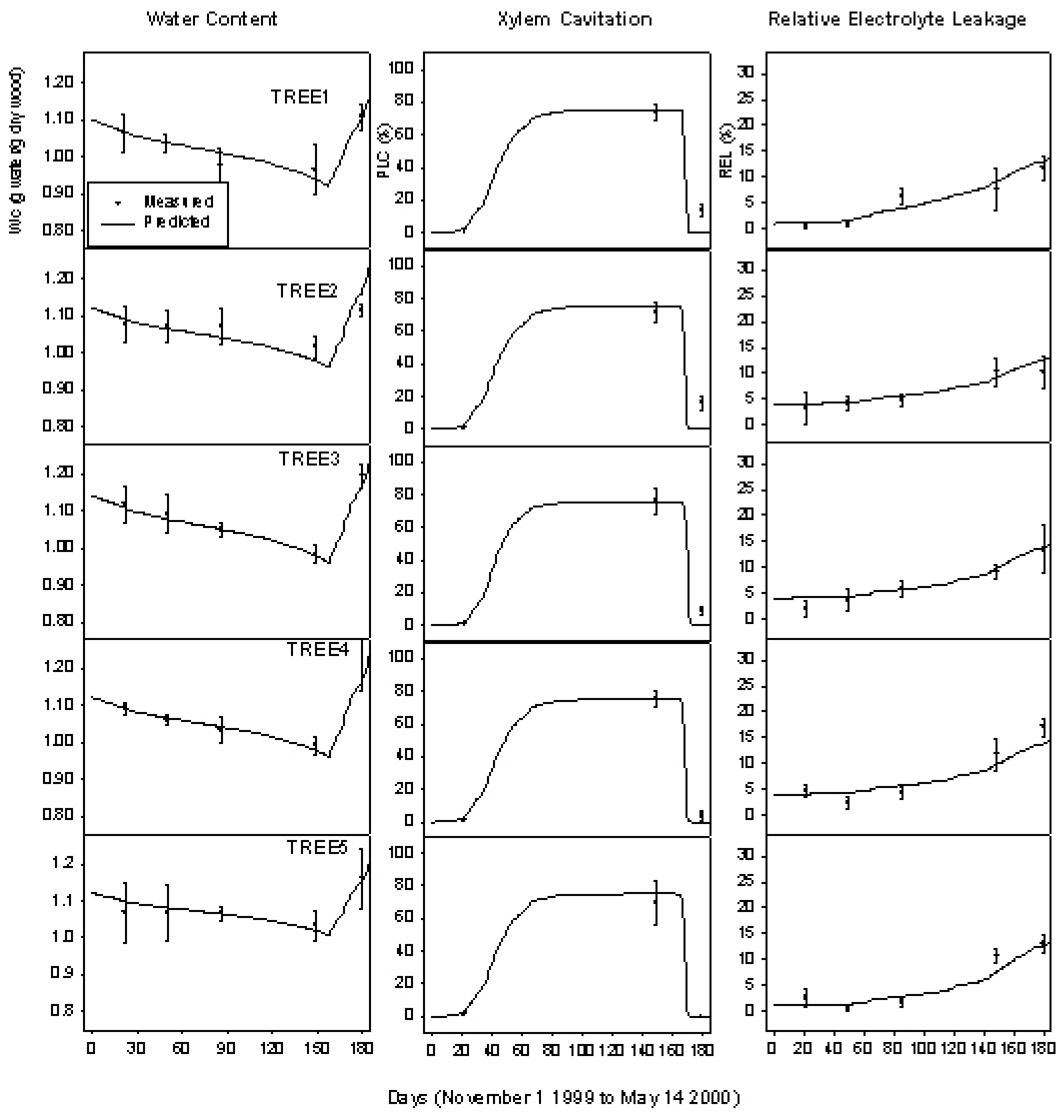



Figure 2.6. Modelled and measured water content, winter xylem cavitation and relative electrolyte leakage of mature yellow birch shoots (two-year old) in 1999/2000. The model was calibrated with data from other 6 trees measured in 1998/99. Error bars represent 95% confidence intervals around the mean for each date.

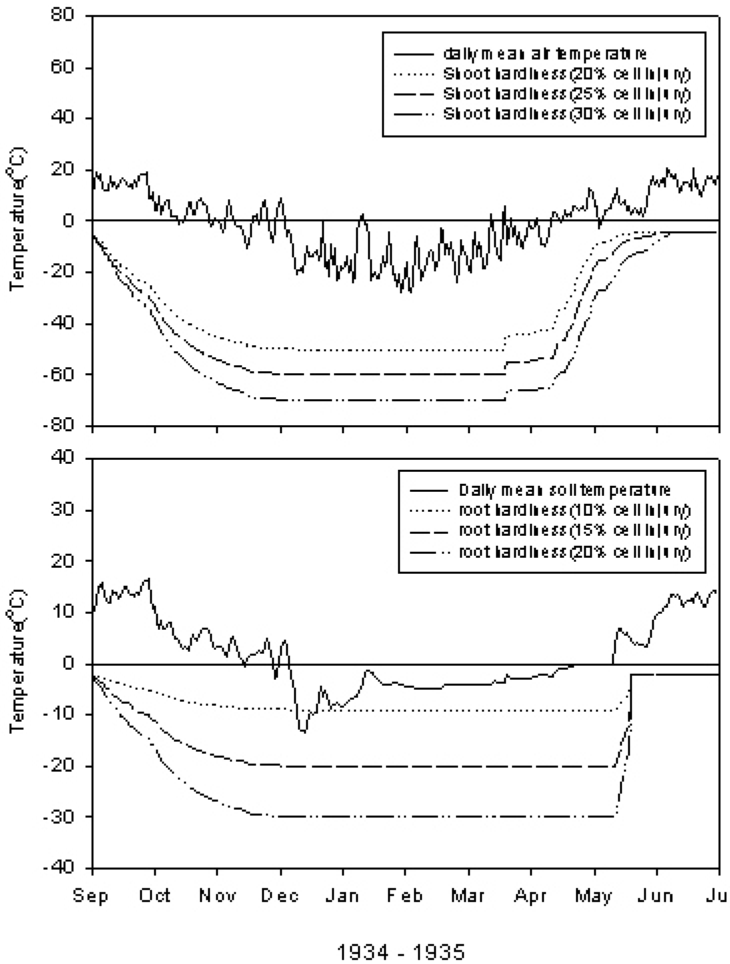



Figure 2.7. Changes of shoot and root cold-hardiness of yellow birch in Quebec. Root injury (10 % cell death ) was estimated in the early December. Air temperature was actually-measured while soil temperature was an output of ForHym (Yin and Arp 1993).

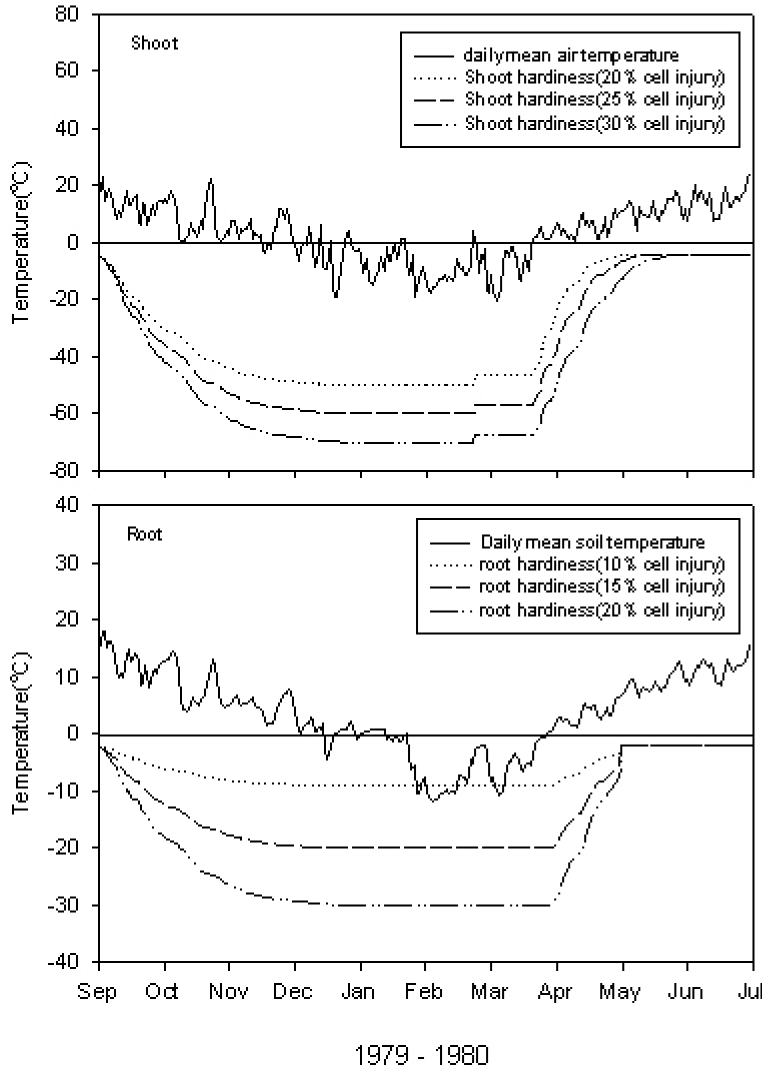



Figure 2.8. Changes of shoot and root cold-hardiness of yellow birch in Nova Scotia. Root injury (10 % cell death ) was estimated in the early February and March. Air temperature was actually-measured while soil temperature was an output of ForHym (Yin and Arp 1993).

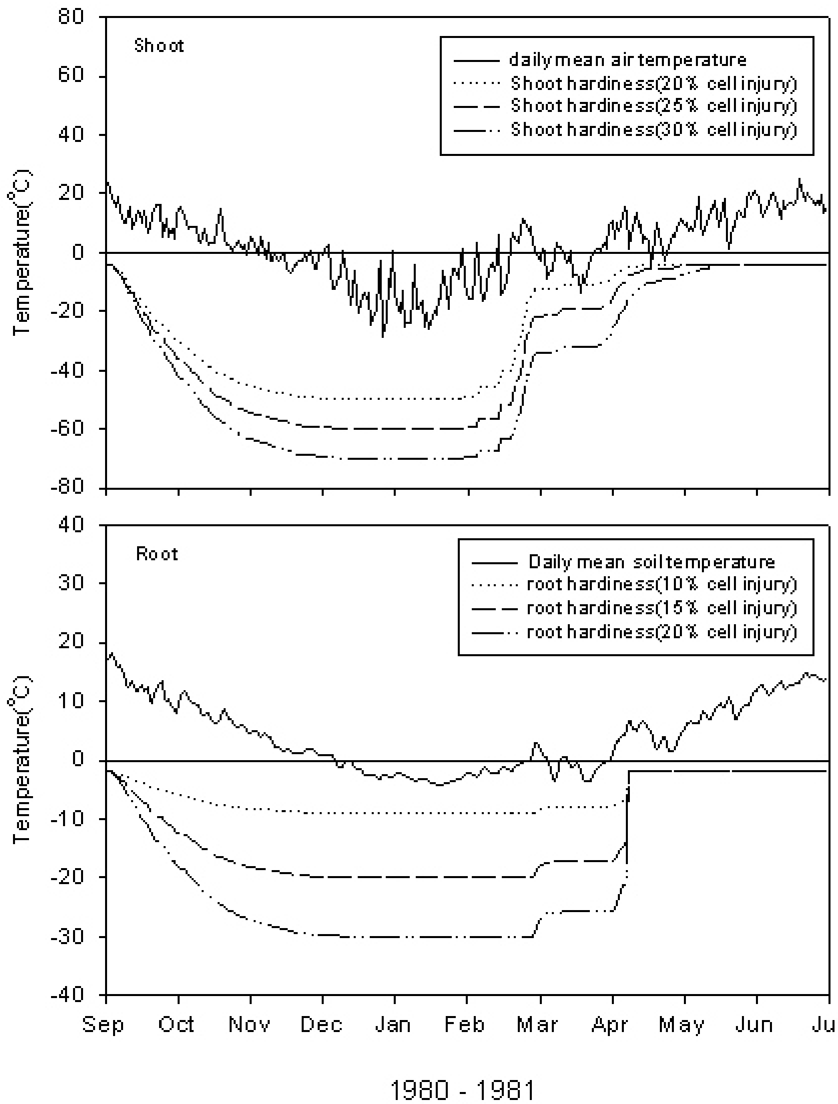



Figure 2.9. Changes of shoot and root cold-hardiness of yellow birch in Nova Scotia. Shoot injury (10-30 % cell death ) was estimated in the early May. Air temperature was actually-measured while soil temperature was an output of ForHym (Yin and Arp 1993).

The residual xylem embolism due to the lower root pressure was estimated to induce 55 % crown dieback in spring 1936. In contrast, more than 70 % crown dieback was calculated due to the root injury in the winter of 1979-80 together with the spring frost in 1981. In fact, severe dieback in hardwoods such as sugar maple was noted in 1981(Walker et al. 1990).

## 2.6. Concluding remarks

The birch dieback model was run on a daily scale 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 mean or minimum temperatures of air and soil, daily relative humidity, daily solar radiation, and wind speed. Some the empirical process parameters as determined by separate experiments, needed extra field-level adjustments, because some of the laboratory determinations do not correspond with the actual field conditions. The resulting model calculations regarding shoot water content, xylem cavitation and freezing injury indicate that the model, with a modicum of appropriate parameter adjustments, produces fairly reliable results. With further calibration and verification, this model will become an important tool for birch decline studies.

## References

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