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Publication de la Société canadienne de météorologie et d'océanographie, le Bulletin climatologique offre un moyen d'information sur la climatologie. Le comité de rédaction encourage en particulier la soumission de manuscrits sur la climatologie appliquée (comme l'agriculture, le commerce, l'énergie, l'environnement, la pêcherie, la sylviculture, la santé, les loisirs, les transports, et les ressources en eau), les changements et la variabilité du climat, la prospective climatologique, les applications des modèles du climat (inclus la climatologie physique), et les études régional (inclus les océans). Il est publié grâce à une subvention accordée par le gouvernement canadien par l'intermédiare du Conseil de recherches en sciences naturelles et en génie.

Les auteurs peuvent choisir de soumettre leurs manuscrits aux "Articles", "Notes de Recherches", ou "Nouvelles et Commentaires". Ils doivent l'indiquer sur la lettre d'accompagnement du manuscrit. Les articles de recherche et les "Notes" sont indépendamment soumis à l'examen d'au moins deux appréciateurs anonymes. Le rédacteur en chef examine les "Nouvelles et Commentaires" conjointement avec le comité de rédaction. On accepte les articles soit en français, soit en anglais. Il faut envoyer un résumé, de préférence en français et en anglais.

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Foreword / Avant-Propos

The review of topical and geographic coverage of contributions to the *Bulletin* in recent years will appear in the December issue.

Le *Bulletin* publiera le sommaire des sujets et des régions qui ont caractérisé son contenu ces dernières années dans le numéro de décembre.

Alec Paul
Editor / Rédacteur en chef

Towards Defining Appropriate Averaging Periods for Climate Normals

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and
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[Original manuscript received 21 April 1993;
in revised form 27 July 1993]

ABSTRACT

There is considerable debate concerning the development and use of climate normals for planning, in part because many activities have variable planning horizons. For example, the utility industry often needs heating degree-day (HDD) normals which are capable of predicting short- term (1-5 years) annual, winter (December-February) and extended winter (October-April) HDD conditions. In a response to this need, historical climate data from 41 stations in Illinois were used to determine the optimal lengths of averaging periods for normals for use in predicting HDD values for 1-5 years into the future and for the subsequent 5-year average value. We did this by examining all averaging periods up to 30 years in length, plus the World Meteorological Organization normal, which is a special kind of average. The optimal averaging period is arrived at through evaluation of each mean by four methods. Each of the evaluation methods produced very similar rankings of the averages, indicating that the results of the overall evaluation are based on the data and not on the method used in the evaluation. In general, the 11-year mean is best at predicting HDD values 1 year into the future, while means of about 20 years in length are best at predicting 2-5 years ahead and for the subsequent 5-year average. It is not appropriate to immediately extrapolate these results to other climate variables and other regions of the world. More work in this area is clearly warranted.

RÉSUMÉ

Plusieurs discussions ont présentement court sur le perfectionnement et l'utilisation des normales climatiques pour la planification d'activités, en partie parce que ces dernières s'étendent sur une période de temps variable. Par exemple, l'industrie des services a fréquemment besoin des normales de degrés-jours de chauffage (DJC), qui peuvent prévoir les DJC hivernaux (décembre à février) annuels à court terme (1 à 5 ans) et des hivers prolongés (octobre à avril). Pour répondre à ce besoin, on a étudié les données climatiques de 41 stations météorologiques de l'Illinois pour calculer les périodes moyennes optimales des normales et prévoir les DJC des cinq prochaines années et la

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valeur moyenne de cinq ans subséquente. Pour ce faire, nous avons examiné toutes les périodes moyennes, allant jusqu'à 30 années, en plus des normales de l'Organisation météorologique mondiale qui utilise une moyenne spéciale. Nous avons déterminé la période moyenne optimale à partir de chaque moyenne calculée, selon quatre méthodes différentes. Chaque méthode a produit un rang semblable des moyennes, ce qui indique que l'évaluation globale dépend des données et non de la méthode de calcul utilisée. En général, la moyenne de 11 ans prévoit le mieux les DJC de l'année suivante, alors que la moyenne de 20 ans prévoit le mieux les valeurs des 2 à 5 prochaines années et de la moyenne de cinq ans subséquente. Toutefois, il n'est pas conseillé d'extrapoler immédiatement ces résultats à d'autres variables climatiques et à d'autres régions du globe. Il est évident qu'on a besoin d'étudier ce domaine plus en profondeur.

1. INTRODUCTION

Determination of the optimal averaging period for climate normals is an open question in climate research, as is indicated by the work of several researchers in recent years (e.g., Lamb and Changnon, 1981; Dixon and Shulman, 1984; and Karl, 1988). Should averaging periods be selected in order to best capture the long-term character of weather for a period of, for example, 30 years, as is the current World Meteorological Organization (WMO) practice (WMO, 1983)? Or should a short-term averaging period be used in order to best capture the more immediate nature of, for example, the next year's weather, as was suggested by Court (1968) and Lamb and Changnon (1981)? The answers to these questions are partially dependent on the intended use of the results. Climate dependent economic activities have specific requirements for incorporating climate normals into decision making. These requirements vary widely between types of activities. Certain agricultural decisions are based on the expected conditions of the next growing season, which may be best predicted by short-term averages. At the other extreme, decisions concerning large fixed capital investments with long operating lifetimes, such as the sizing of water reservoirs, are based on the climate over several decades (White, 1980).

The purpose of this paper is to explore the question of the appropriate length of a climate average and the dependency of the length of the period on its intended use. As a vehicle in the exploration of these questions we use the problem of determining the optimal normal for use by power companies in "weather normalization" of revenues and costs, an exercise many utilities undertake before seeking a rate change. The climate variable used most often by power companies in the weather normalization process is the heating degree-day total (HDD), which is the variable we explore here. In the discussion that follows, we review relevant research, briefly describe the information needs of the power industry, describe the data and methods used to assess the climate averages, and present the results of our analysis.

2. RELEVANT RESEARCH

Several authors have conducted research concerning climate "normals" and how well these can predict future conditions (e.g., Court, 1968; Lamb and Changnon, 1981; Dixon and Shulman, 1984; and Sabin and Shulman, 1985). Climate, until recently, has been considered stable, with only random variation around a mean value (Sabin and Shulman, 1985). This average or mean value has come to be called the "normal." This follows the traditional statistical concepts of central tendency and implies that confidence in the mean increases with more observations (more years of data in this case). Therefore, stations with the longest records were thought to provide the best means. Court (1968) pointed out that this assumption has two faults: 1) climate is now understood to vary across many time scales, which can cause the standard deviation of a climate measurement to increase through time rather than decrease; and 2) longer records are prone to data inhomogeneities caused by changes in instrumentation, exposure, and time of observation (Mitchell, 1976; National Academy of Sciences, 1975; Karl and Riebsame, 1984; and Karl, 1988). To minimize these effects, the World Meteorological Organization (WMO) adopted a 30-year mean that is updated every decade (WMO, 1967). Karl (1988) suggests that significant decadal fluctuations are often imbedded within the 30-year means which may limit their usefulness.

Court (1968) argues that the best empirical test of reliability for climate means is their ability to predict future conditions. While Guttman (1989) states that climate normals are not appropriate for prediction, they will continue to be used until better forecasting methods become available. Using the Court (1968) premise several groups of researchers have tried to define the most appropriate averaging period for a normal. Lamb and Changnon (1981) examined four stations in Illinois and concluded that a 5-year running mean was best able to predict seasonal temperatures for the next year. Dixon and Shulman (1984), however, building on the Lamb and Changnon analysis, examined heating degree-days for six U.S. stations and found that running means 10-30 years in length were better able to predict the next year's HDD total.

Dixon and Shulman (1984) were critical of the method used by Lamb and Changnon (1981) for two reasons. First, only selected means were used (5, 10, 15, 20, 25 and 30 years). They noted that in this approach, the individual best predictors are constrained to those means tested and therefore the selection and number of means influence the results. Second, although the 5-year mean was most frequently the best predictor, it also produced the largest prediction errors when it was not the best predictor. It is clear that these studies have called into question the appropriateness of using one average, usually the WMO 30-year normal, for all situations.

To date, no study has considered the problem of a normal's effectiveness as a predictor for conditions more than one year into the future, a capability required for certain applications, such as utility weather normalizations. Additionally, little attention has been given to the spatial variability of optimal normals for various uses. These two problems are partially addressed here in the context of HDD normals for the mid-continent USA.

3. SPECIFICATION OF CLIMATE INFORMATION NEEDS OF UTILITIES

Utilities often use climate normals to adjust ("weather normalize") sales revenues and costs to the level that would occur in a year of normal weather (called a test-year), all else being equal. These adjustments are viewed as necessary because space heating fuel needs, which make up a large part of most utilities' sales, are highly dependent on the severity of winter conditions as measured by a weather variable such as HDD's or average temperatures (Quayle and Diaz, 1980; Findlay and Spicer, 1988). The purpose of this process is to assure, in the words of the Pennsylvania Public Utility Commission (1980), that "extraordinary occurrences such as abnormal weather conditions . . . not be reflected in test-year levels." Abnormal weather conditions which affect sales, costs or profits are not a valid basis for seeking rate increases. For example, it is not valid for a company to base a rate increase request on data for a year which had an unusually warm winter, which decreased consumption and sales revenues. From the standpoint of the utility, decreases in revenues after normalization has been performed are likely to build a stronger supporting case for a rate change (Gillan, 1984).

It has been pointed out that the most critical problem in weather normalizing sales revenues is determination of what constitutes "normal" weather in order to measure the degree of abnormality of actual weather conditions (New York Public Utility Commission, 1960; Gillan, 1984). Utilities require a climate normal which accurately depicts the expected heating degree day total within their market area for periods ranging between one and five years into the future. Five years is the general maximum lifetime of a given set of rates in Illinois and is therefore the upper predictive limit used in this study (Illinois Commerce Commission, personal communication).

The traditional approach in weather normalization has been to use the 30-year mean, which is updated once each decade, of HDD's (hereafter called the WMO normal). Two potential problems can occur in using the WMO normal to perform a weather normalization, both relating to the now commonly accepted idea that climate varies on timescales that are shorter and longer than 30 years. The first problem is that the WMO normals are calculated only once every 10 years, at the beginning of a new decade. Thus it is quite possible that a hypothetical weather normalization performed in 1989 might have used the WMO normal constructed from 1951-80 data. Because the utility and the rate commission are both interested in projecting consumption and sales revenues based on "normal" weather, is it reasonable to use an average which is up to 9 years out of date and includes data from only the first year of the 1980's?

The second, perhaps more important, problem is the question of whether a 30-year mean, which is updated once a decade, is the most appropriate normal to use in establishing what is the normal climate at any point in time. For example, the WMO normal for 1941-70, which would have been used in a 1970's normalization in Illinois, included the century's warmest temperatures and lowest HDD totals up to that date and thus described a climatic regime different from the 1970's (Changnon, 1984). We hope to contribute to the answers to these two problems.

4. DATA AND METHODOLOGY

In seeking the optimal averaging period for predicting 1-5 years into the future, we examine all possible averaging periods or normals (1 to 30 year running means plus the WMO normal) by using a variety of evaluation techniques that are sensitive to different aspects of prediction error. HDD's are accumulated for different periods within a year in order to explore differences in the results which may be related to the definition of the heating season. Specifically, we examined HDD accumulations for the whole year, winter (defined as December to February) and extended winter (defined as October to April).

The temperature data used in this study (which were converted to HDD's and summed over the periods discussed above) were obtained from the National Climatic Data Center (NCDC). Forty-one stations across Illinois were chosen to provide representative spatial coverage (Fig. 1). Data were obtained for the period 1901-1984 (with the exception of Kankakee, where recording began in 1917). Data for 1985-86 were obtained late in the study and were only used in constructing Figures 1 and 3. These 41 stations are a subset of 61 high quality stations discussed in Changnon (1979).

Four methods were used to evaluate the predictive ability of the different averages: root-mean-square-error (RMSE), mean-square-error (MSE), mean-absolute-error (MAE) and the "WINS" method (explained below). The results for each method were ranked according to the predictive accuracy of the average (best to worst), and an assessment was made of the differences in the rankings from the four methods. An examination of the top-ranked means across Illinois for each method and for each prediction period (1-5 years into the future, plus the 5 year average) provides a basis for choosing the best overall average.

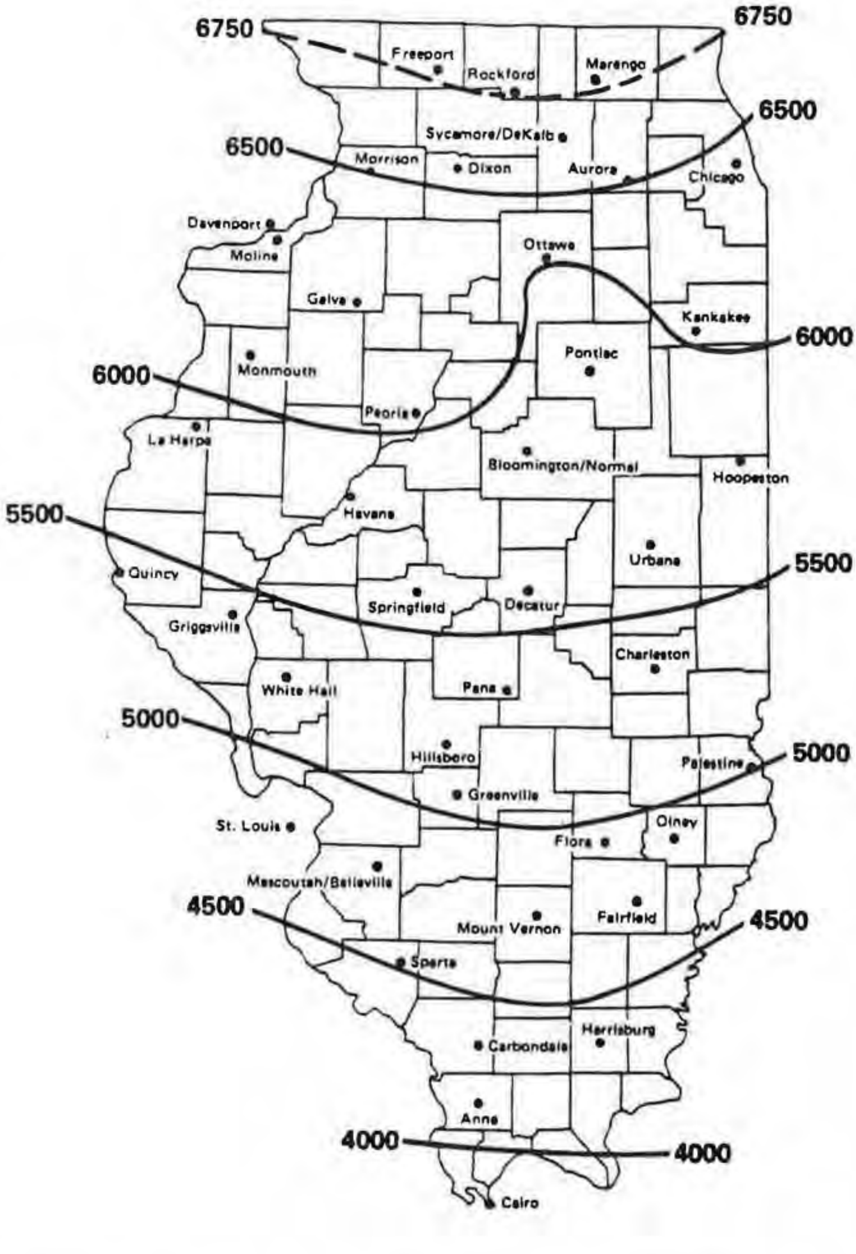

FIGURE 1 Climate stations used in this study and isolines of mean annual HDD values (1901-1986).

The form of these methods is as follows:

$$RMSE = [1/n \Sigma (\Delta X)^2]^{1/2} \quad (1)$$

$$MSE = 1/n \Sigma (\Delta X)^2 \quad (2)$$

$$MAE = 1/n \Sigma | \Delta X | \quad (3)$$

In each method, ΔX represents the difference between the mean HDD total and the HDD total for the year or period to which it was being compared, n represents the number of years over which comparisons were made. Because our longest mean is 30 years, our first comparison is for 1931. The last comparison is for 1984, therefore n has a value of 54.

The final method — the WINS method — is a modification of the method used by Lamb and Changnon (1981). It requires tabulating the number of times each mean has the lowest prediction error for a given year compared to all other means in a pair-wise fashion. This is done until all possible unique pair-wise combinations of means have been examined for that year. It is referred to as the WINS method because it is the sum of the wins by each mean over all of the other means through time. This is similar to summing a baseball team's World Series championships (winning over all other teams each year) through time.

The 1-30 year running means or normals, are first calculated for a base period (for example, 18 years based on 1913-1930 data). This mean is then used in each of the four evaluation methods as the predictor of the HDD total for 1-5 years into the future (1931-1935), as well as the average for those five years. Then the base period is shifted forward 1 year, the 18-year mean is recalculated (now based on 1914-31 data), and the mean is then used in each of the evaluation methods as the predictor of the next 5 years' (1932-36) HDD values, plus the subsequent 5 year average value. This is done until we have moved through the entire period of 1931 to 1984. The WMO normal, unlike the other averages, is only updated at the beginning of each decade and is then used over the next 10 years. Although the WMO did not adopt the 30-year mean until 1956, we have retroactively calculated them back to 1930 (i.e., the 1901-1930 mean)(WMO, 1967).

5. RESULTS AND DISCUSSION

Background Climatology

A background climatology of Illinois HDD's is helpful in framing our analysis. Figure 1 shows the average annual totals of HDD's for the period of 1901 to 1986. The time series plot (Fig. 2) for all sites averaged together reveals a downward trend in annual HDD's from 1901 to the mid-1930's. From the mid-

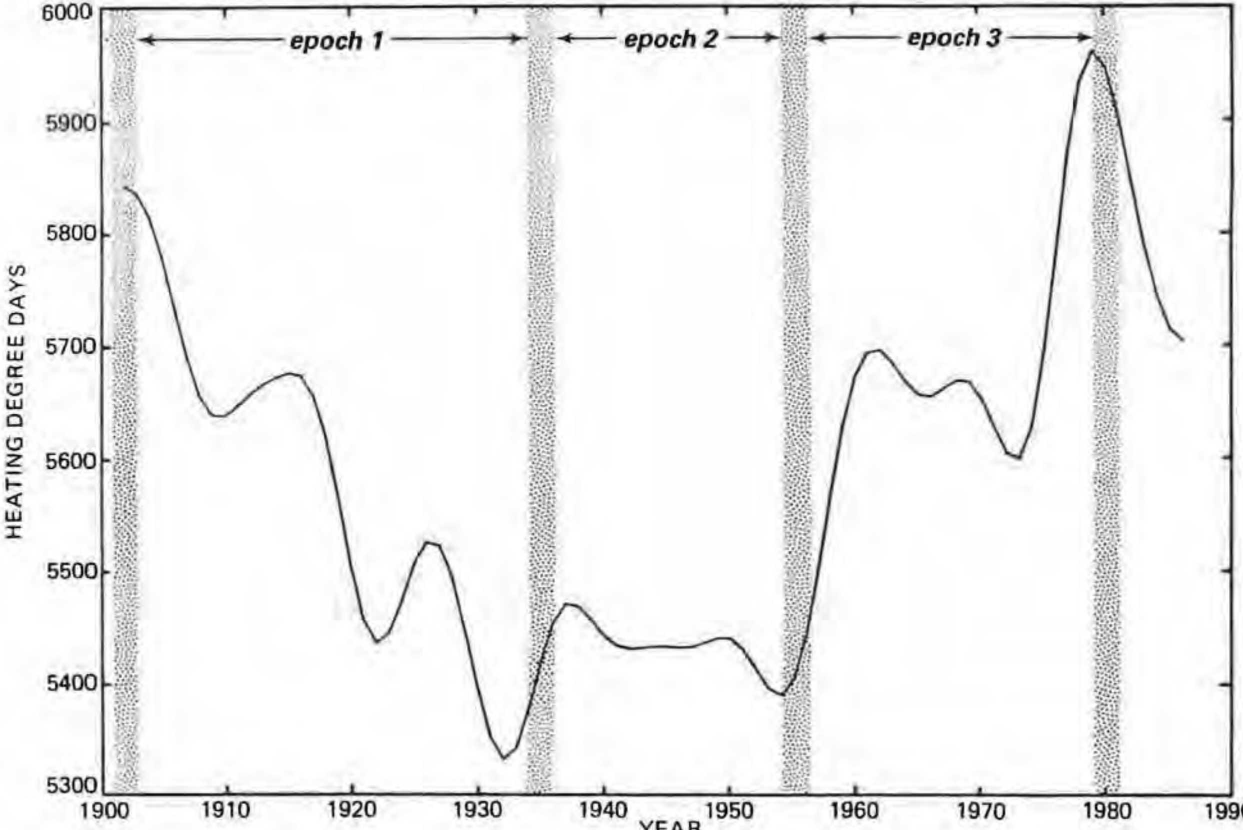

FIGURE 2 Smoothed, spatially averaged annual HDD totals through time for the 41 stations in the study.

1930's to the mid-1950's, HDD's level off before beginning an upward trend to 1980. These three distinct, visually discernable epochs have lengths of about 35, 20 and 25 years. The existence of these periods suggests that normals shorter than the epoch's length would make better predictors. For example, a long-term average applied during the relatively warm 1950's would have incorporated the higher HDD values from the earlier, colder epochs. Consequently, it would over-estimate the HDD values. A shorter averaging period would not incorporate as much of the earlier epoch and would better predict the 1950's HDD regime.

Evaluation Method Results

Spearman's rank order correlation analysis, a non-parametric test, was used to assess how well the rankings of the averages by the four different methods match each other. Based on the 31 possible positions, i.e., 31 observations, in the ranking (a rank of 1 being the "best" and 31 being the "worst"), the correlation matrix contains Spearman rank order correlation coefficients (r_s) which are all greater than or equal to 0.90 (all significant at $\alpha = 0.05$) (Griffith and Amrhein, 1991). This suggests that the four methods produce very similar rankings. Therefore the results of this study are attributable to the data and not to the methods used in quantifying the prediction error.

Due to the similarity between the rankings, only a representative sample of the rankings produced using all of the methods will be shown here (Table 1). Even though the rankings in Table 1 are quite similar, the results for the 5-year ahead average HDD value illustrate that the methods do not produce identical results. It is interesting to note that the very commonly used WMO normal does not perform well using any of the four evaluating methods.

Predicting Annual HDD Totals One to Five Years Ahead

Given that the four evaluation methods produce similar results, and to save space, we will discuss only the RMSE results from this point on. For predicting the next year ahead, the three top-ranked averaging periods are the 11-, 12-, and 10-year means, respectively (Table 2). The next 10 values in the ranking are generally clustered around the 20-year averaging period.

For predicting the second through fifth individual years the 19- to 16-year means do best (Table 2). For predicting the average annual total HDD's for the subsequent five years following the end of the mean, the means ranging between 16 and 20 years in length are ranked highest according to the RMSE method (Table 2). Long (e.g., 30-year) and short (e.g., less than about 6 years) means all do relatively poorly. It can be concluded that an average of 11 years is best, according to the criteria outlined herein, for predicting the annual HDD totals for the next year ahead in Illinois. For years 2-5 ahead, means between 19

TABLE 1 Best to worst rankings of the 1- to 30-year means and the WMO normal in predicting the 5-year ahead mean annual HDD total, according to the 4 evaluation methods.

rank	RMSE	MSE	MAE	WINS
1 (best)	18	18	19	19
2	19	19	18	18
3	17	17	10	17
4	20	20	8	20
5	16	16	9	16
6	21	21	17	21
7	10	10	20	15
8	15	15	11	22
9	11	11	16	8
10	9	9	21	9
11	22	22	15	11
12	14	14	22	10
13	12	13	12	14
14	13	12	14	23
15	23	23	13	12
16	8	8	23	13
17	24	24	7	24
18	25	25	24	25
19	26	26	25	7
20	7	7	26	26
21	27	27	27	WMO
22	28	28	28	27
23	29	29	29	6
24	30	30	30	28
25	6	6	6	30
26	5	5	5	29
27	4	4	4	5
28	3	3	3	4
29	WMO	2	WMO	3
30	2	WMO	2	2
31 (worst)	1	1	1	1

and 16 years are most appropriate, respectively. And for predicting mean annual totals for the entire upcoming 5-year period, an average of 18 or 19 years is best (supported by all of the methods, as shown in Table 1).

Predicting Winter and Extended Winter HDD Totals

The best predictor of the next winter's HDD total (December-February) is the 20-year average (Table 3). The best predictor for years 2 through 5 and the 5-year average is also approximately the 20-year mean (Table 3). Aside from these differences, the winter season results are in general agreement with the annual results reported in the previous section.

The results for the extended winter season (October to April) are also very similar to the annual results. The 11-year mean is best for one year ahead predictions, while the 18- through 20-year means are best for years 2-5 and for the 5-year average.

TABLE 2 Averaging periods ranked from best to worst, by the RMSE method, for predicting annual HDD's and the 5-year ahead mean.

rank	1-year ahead	2-years ahead	3-years ahead	4-years ahead	5-years ahead	5-year mean
1 (best)	11	19	18	17	16	18
2	12	18	17	19	18	19
3	10	21	20	16	15	17
4	20	20	19	18	17	20
5	13	11	10	20	19	16
6	19	10	16	15	14	21
7	18	17	9	9	8	10
8	9	22	21	8	20	15
9	22	9	8	21	13	11
10	21	16	15	14	21	9
11	14	23	22	23	22	22
12	17	12	24	22	7	14
13	23	15	23	24	23	12
14	16	25	14	13	12	13
15	15	24	25	11	10	23
16	24	26	11	10	11	8
17	8	13	12	7	9	24
18	25	14	13	12	24	25
19	26	27	26	25	25	26
20	27	8	7	26	30	7
21	7	28	27	30	29	27
22	28	29	28	27	26	28
23	29	30	30	29	28	29
24	30	7	29	28	27	30
25	5	6	6	6	6	6
26	4	4	5	5	5	5
27	6	5	WMO	4	4	4
28	3	3	4	WMO	WMO	3
29	2	2	3	3	3	WMO
30	1	WMO	2	2	2	2
31 (worst)	WMO	1	1	1	1	1

TABLE 3 Summary of the top ranked means, using the RMSE method, for predicting 1-5 years ahead annual, winter, and extended winter HDD's and the 5-year ahead average HDD value for the same periods.

Year	Entire Year	December-February (winter)	October-April (extended winter)
1	11	20	11
2	19	22	19
3	18	21	20
4	17	20	19
5	16	19	18
5-year mean	18	19	19

Temporal and Spatial Variability of the HDD Pattern

A comparison of the 1968-86 spatial pattern of HDD's in Illinois with the pattern over the state in the entire period covered by our data shows evidence of a shift southward in the mean HDD pattern (Fig. 3). This illustrates that the spatial pattern of mean HDD's based on different averaging periods can vary. This figure also serves as further evidence that the mean for the entire period of record is not adequate for purposes which have short-term planning horizons (e.g., utility weather normalizations).

Minimal spatial variability in the pattern of the best predictive mean for a 1 year ahead prediction is found across Illinois (Fig. 4). The 11-year mean is the most frequently occurring optimal mean for most areas of the state. When this is not true for a station the optimal means tend to be either clustered around 11 years, or about 20 years. For 2 stations, Kankakee (optimal mean = WMO normal) and Carbondale (optimal mean = 3 years) this is not true; we have no explanation for these two anomalies.

6. SUMMARY AND CONCLUSIONS

In summary, daily temperature data from 41 long-term stations in Illinois were used to calculate yearly, traditional winter, and extended winter HDD values. Using these totals in conjunction with four evaluative methods allowed us to arrive at optimal predictive HDD means, as defined herein, for our period of record and for our area. Running means from 1 to 30 years in length, plus the WMO normal, were used to predict HDD totals for 1-5 years into the future, plus the future 5-year mean. The averaging period that had the minimum predictive error was considered to be the 'best' mean within the context of our investigation. Based on the results of the four evaluative methods, the means were ranked from best to worst in terms of predictive ability.

In general our results show that means of between about 10 and 22 years are the best predictors of 1-5 year ahead, and 5-year average, HDD conditions. The 11- through 13-year means seem to do best for the shorter term prediction (1 year ahead) and the 16- through 20-year means seem best at longer term predictions (2-5 years ahead and for the 5-year ahead average). The WMO normal generally did not perform well.

The differences between our work and that of Lamb and Changnon (1981) are due to several factors. We examined all averaging periods up to 30 years in length, plus the WMO normal, while they examined only selected means (5, 10, 15, 20, 25 and 30 years). Also, our evaluation methods allowed us to keep track of the performance of all of the means through time, not just the top-ranked mean. Additionally, we examined HDD values while they investigated mean seasonal temperature. Our results are in general agreement with those of Dixon and Shulman (1984).

In a limited fashion, we examined the spatial stability of the optimal averages across Illinois. Nineteen of the forty-one stations across Illinois conform to our general conclusion regarding the superiority of the 11-year mean for predicting 1 year ahead. Most of the rest of the stations, which do not agree,

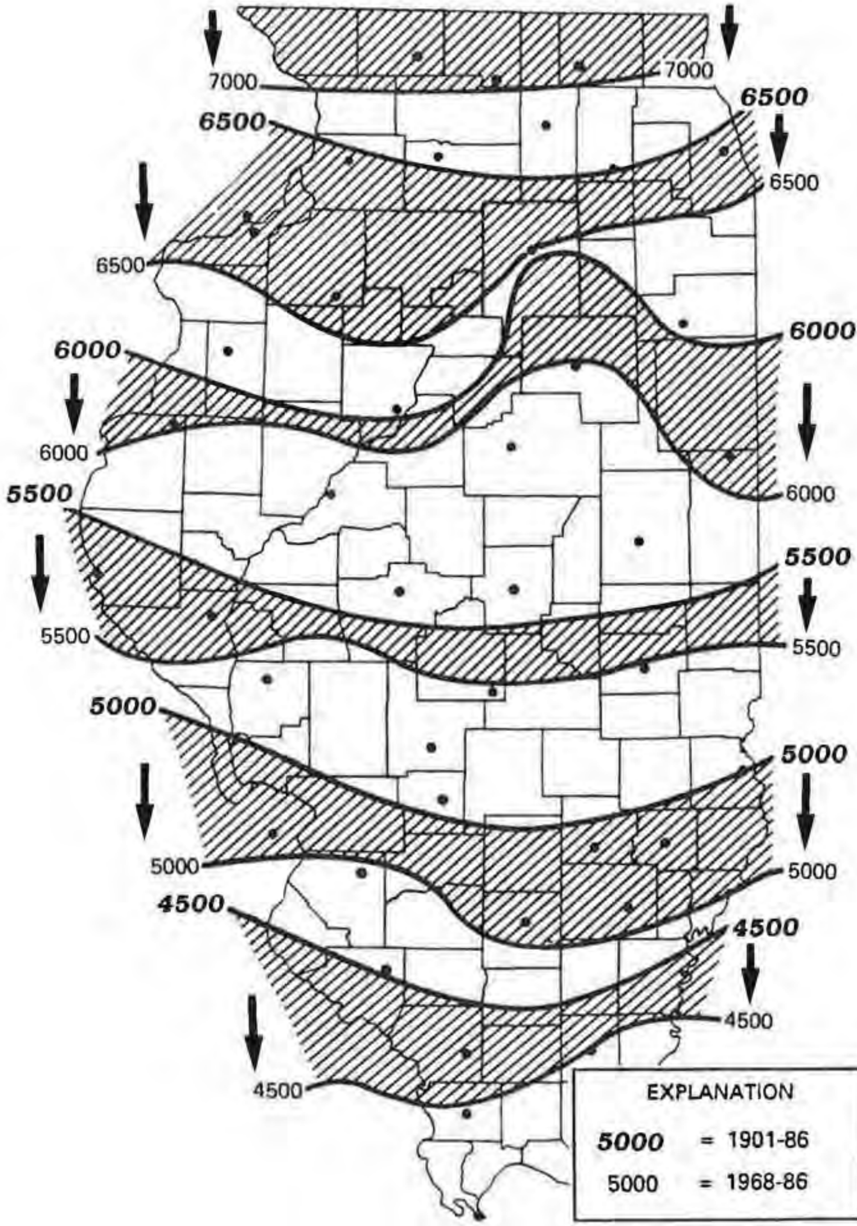

FIGURE 3 Map of the 1968-1986, 19-year average annual HDD pattern and the 1901-1986, 87-year average pattern showing the shift southward in HDD totals when averaged over the recent, shorter period.

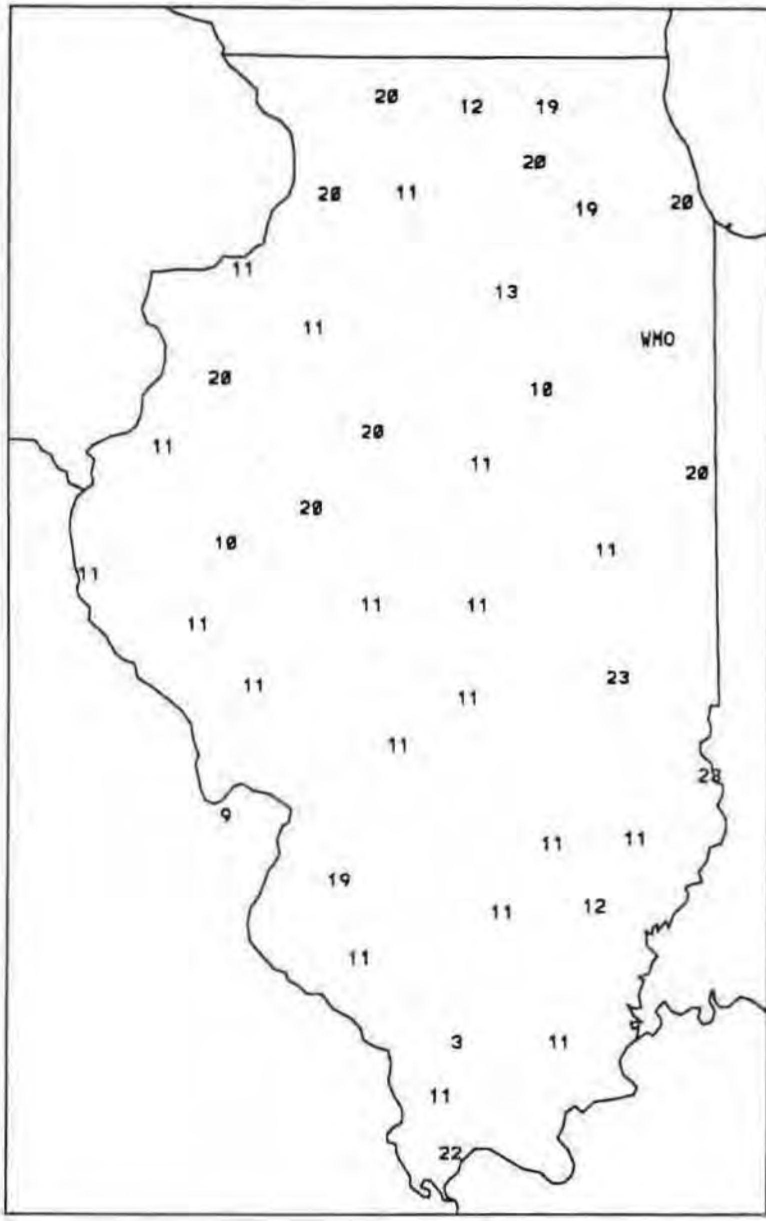

FIGURE 4 Distribution of the top ranked means (annual HDD values), using the RMSE method, for predicting 1 year ahead across Illinois.

have one of the other top-ranked means as their optimal mean (generally a mean of about 20 years).

It is not appropriate to immediately extrapolate these results to other climate variables and other regions of the world. We feel the value of this work rests on one major point, that in many cases it would be appropriate for other groups to repeat at least some portion of this analysis for their situation so as to let them choose the best average or normal for their intended use. This work also suggests that periodic reappraisal of the data for an area is warranted because the length of the most appropriate normal may change through time.

ACKNOWLEDGMENTS

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Zonage du Risque Agroclimatique Durant la Saison Froide au Québec Méridional: I — Froid Hivernal

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et
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RÉSUMÉ

Le but de cette étude est d'exprimer, à l'aide de variables climatiques, la menace de dommage aux plantes pérennes exercée par le froid hivernal et d'en définir le patron de variation spatiale au Québec méridional (Canada). Les causes de dommage identifiées et les variables climatiques choisies pour les décrire ont été: l'intensité du froid hivernal exprimée par la température minimale annuelle; l'interaction entre la durée et l'intensité du froid hivernal exprimée par la température minimale journalière moyenne du mois le plus froid; et l'action du froid sur les plantes basses exprimée par la différence, en jours, entre la durée de la période où un froid inférieur ou égal à -15°C peut sévir et celle où une couverture de neige est présente.

Les cartes de zonage produites ont permis d'identifier les gradients spatiaux de l'intensité de la menace exercée par chaque cause de dommage. Elles permettent d'utiliser l'information obtenue d'expériences en conditions contrôlées (intensité du froid) pour déterminer les aires de rusticité de certaines plantes. A l'aide de ces cartes, des observations sur la survie à l'hiver faites en un point peuvent être généralisées à l'ensemble de zone à laquelle l'endroit appartient.

ABSTRACT

The purpose of this study is to determine the spatial pattern of the climatic risk of damage to perennial plants from their exposure to low winter air temperatures in southern Québec, Canada. The causes of plant damage and the climatic variables used to describe their intensity were: the cold intensity expressed by the annual minimum temperature; the interaction between cold intensity and duration expressed by the mean daily minimum temperature of the coldest month; and the action of cold on short plants expressed by the difference, in days, between the length of the period in which an air temperature equal to or lower than -15°C can occur and the length of the period of snow cover.

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The maps produced show the spatial gradients of the climatic risk for each cause of plant damage. They allowed use of information gained in experiments under controlled environmental conditions (cold intensity) to define the hardiness zones of certain plants. They also permit the generalization of observations on winter survival at one location to the whole zone to which the site belongs.

INTRODUCTION

La rigueur de l'hiver constitue une menace sérieuse à la survie des plantes pérennes au Québec méridional (Andrews, 1987; Quamme, 1987). La plupart des régions agricoles de la province sont en effet soumises annuellement à des températures inférieures à -30 °C et certaines d'entre elles sont aussi exposées à des pluies et des dégels hivernaux fréquents (Environnement Canada, 1982).

L'action nuisible du climat hivernal sur les plantes pérennes peut s'exercer de plusieurs façons et la vulnérabilité des plantes par rapport à chacune d'elles peut différer (Sakai & Larcher, 1987). La variation spatiale de l'intensité des causes climatiques de dommage prises une à une a pourtant été peu étudiée et seules les zones de rusticité des arbres et arbustes à vocation ornementale ont été définies dans le cadre d'une étude canadienne (Ouellet & Sherk, 1967).

Devant la complexité du phénomène de la survie à l'hiver, Steponkus (1978) souligne la nécessité d'orienter la recherche génétique visant à augmenter la rusticité des plantes agricoles pérennes, vers l'étude de la résistance de ces plantes à chacun des stress auxquels elles sont confrontées, plutôt qu'à la somme de leur action respective. La détermination de zones d'intensité de menace par rapport à chacune des causes de dommage apparaît donc être une information utile, sinon nécessaire, à l'utilisation des résultats de la recherche en conditions contrôlées. Une telle étude de zonage a donc été entreprise dans le but de compléter l'information contenue dans le zonage de la rusticité de Ouellet & Sherk (1967).

L'étude a été réalisée en trois étapes. Les causes de dommages suivantes ont d'abord été identifiées: les gels hâtifs automnaux, les froids hivernaux dépassant le niveau d'endurcissement de la plante, les gels tardifs printaniers, la prise des racines dans la glace et le déchaussement. Les variables climatiques exprimant la menace de dommage aux plantes pérennes exercées par ces causes ont ensuite été choisies et, dans un dernier temps, leur patron de variation spatiale a été déterminé au Québec méridional. Cet article présente les résultats relatifs au froid hivernal.

REVUE DE LITTÉRATURE

Résistance au froid hivernal

Le gel du contenu cellulaire provoque presque toujours la mort de la cellule végétale (Salisbury & Ross, 1985). Les causes probables de cette mort impliquent des dommages à la structure interne et aux membranes par la formation de cristaux de glace (Levitt, 1980). La survie des organes végétaux au froid hivernal repose donc sur leur capacité à éviter le gel intracellulaire et à tolérer les conditions internes créées par les mécanismes de cet évitement. Les mécanismes d'évitement observés dans la nature sont la tolérance au gel extracellulaire et la surfusion profonde du contenu de la cellule.

Gel extracellulaire

Le gel de l'eau dans les espaces extracellulaires engendre un gradient de pression de vapeur d'eau qui provoque la migration d'une partie de l'eau du protoplasme vers l'extérieur de la cellule, à la surface des cristaux. Si le refroidissement est lent, le débit de la sortie de l'eau entraîne un abaissement du point de congélation du liquide intracellulaire suffisamment rapide pour que le gel y soit évité (Sakai & Larcher, 1987).

Les dommages causés par le froid hivernal aux tissus végétaux utilisant ce mécanisme, peuvent être engendrés par la déshydratation de leurs cellules (Levitt, 1980), par une altération des lipides des membranes cellulaires (Rajashekar *et al.*, 1979) et par les stress mécaniques exercés sur les parois par la perte de volume des cellules (Sakai & Larcher, 1987). Ces bouleversements physiologiques ne sont cependant pas tolérés avec la même efficacité par toutes les plantes qui y sont exposées. Ainsi, l'avoine ne résiste pas à des températures inférieures à environ -14° C (Gusta *et al.*, 1983), alors que les tiges de certains feuillus des forêts boréales survivent à leur immersion dans l'azote liquide (-196° C) (Sakai, 1965). Parmi les plantes agricoles pérennes, on observe un gradient chez les céréales d'hiver où le seigle est plus résistant que le blé, suivi de l'orge et de l'avoine (Gusta *et al.*, 1983). Du côté des plantes fourragères, différents seuils de résistance sont aussi observés selon les espèces. Les légumineuses sont généralement plus sensibles que les graminées, parmi lesquelles le brôme et la fléole des prés sont les plus résistantes (Paquin, 1984; Gudleifsson *et al.*, 1986; Sakai & Larcher, 1987).

Surfusion profonde

Un liquide est en état de surfusion lorsqu'il n'est pas cristallisé à une température inférieure à son point de congélation. Une surfusion "légère" permet à un liquide d'éviter la cristallisation à des températures légèrement sous le point de congélation alors qu'une surfusion "profonde" lui permet de demeurer liquide à des températures beaucoup plus basses. Chez certaines plantes, la surfusion profonde constitue le seul mode de survie au froid hivernal pour les cellules de certains tissus (Sakai & Larcher, 1987). La limite de la protection varie selon les espèces et leur degré d'endurcissement, et peut atteindre jusqu'à -47° C (Levitt, 1980).

Parmi les organes ou tissus qui résistent aux gels hivernaux par la surfusion profonde, on note les cellules de rayons de parenchyme de plusieurs arbres feuillus du nord-est de l'Amérique du Nord (Quamme *et al.*, 1972; George *et al.*, 1974a; Gusta *et al.*, 1982), les bourgeons latents de la vigne (Quamme, 1986), les bourgeons floraux de l'azalée et du rhododendron (George *et al.*, 1974b; Graham & Mullin, 1976) et de nombreux autres arbres (Ishikewa & Sakai, 1982).

L'exposition, même relativement brève, de ces parties de plante à des températures inférieures à leur limite de surfusion entraîne la mort des cellules par la cristallisation du liquide intracellulaire, causant ainsi des blessures plus ou moins graves à la plante (Quamme *et al.*, 1972; Ashworth *et al.*, 1983). Burke *et al.* (1976) concluent que la mort des cellules de rayon de parenchyme, suite à la cristallisation de leur contenu, compromet les chances de survie des arbres qui en sont victimes en raison de la concordance entre les aires d'adaptation de ces derniers et les isothermes de la température minimale moyenne hivernale.

On retrouve assez souvent les deux mécanismes d'évitement du gel intracellulaire chez différents tissus d'une même plante. C'est le cas, entre autres, de plusieurs angiospermes ligneuses dont les cellules des rayons de parenchyme surfusionnent alors que celles du cortex tolèrent le gel extracellulaire (George *et al.*, 1974a). D'autres groupes de plantes pérennes, comme les plantes herbacées, ne survivent aux plus froides températures de l'hiver de nos régions que grâce à leur tolérance au gel extracellulaire (Li, 1984).

Relation entre les dommages et les conditions climatiques

En hiver, le froid sera fatal aux tissus végétaux si son intensité dépasse leur degré d'endurcissement. Son effet se manifestera cependant différemment selon le mode d'évitement du gel intracellulaire utilisé. En effet, l'observation de certains dommages est associée à des seuils de température relativement bien définis. C'est le cas des tissus qui sont le siège de surfusion profonde où la cristallisation spontanée du contenu cellulaire et la mort subséquente de la cellule se manifestent dès que la température s'abaisse sous la limite maximale de surfusion de leurs cellules (Quamme *et al.*, 1972; Ashworth *et al.*, 1983). On observe le même phénomène pour les tissus dont les membranes cellulaires sont endommagées et perdent leur perméabilité sélective lorsqu'une température critique est atteinte (Rajashekar *et al.*, 1979).

Chez certains tissus tolérant le gel extracellulaire et qui sont exposés à la déshydratation de leurs cellules, la durée du stress joue alors un rôle plus important. Il a été observé que la luzerne peut résister, lorsqu'adéquatement endurcie, à une exposition de quelques heures à -26° C mais qu'elle sera détruite par des températures inférieures à -10° C si le froid dure plusieurs jours (Paquin, 1984; Paquin *et al.*, 1987). D'autres études ont permis d'observer une réponse semblable chez les céréales d'hiver (Pomeroy *et al.*, 1975; Gusta *et al.*, 1982).

Aucune expérience n'a été menée, à notre connaissance, pour étudier l'effet de l'interaction entre la durée et l'intensité du froid sur le dommage causé aux tissus de plantes ligneuses tolérant le gel extracellulaire. Il est cependant raisonnable de poser l'hypothèse qu'ils puissent eux aussi être endommagés à des seuils de température plus élevés lorsque la durée de l'exposition augmente.

Cette brève revue des mécanismes de résistance des tissus végétaux au froid hivernal a permis de distinguer deux groupes principaux de plantes. Le premier comprend les plantes dont les dommages résultent d'une exposition à une température inférieure à un seuil bien défini. Il est composé principalement des végétaux dont certaines cellules sont le siège de surfusion profonde. Le second regroupe les plantes dont les tissus végétaux sont endommagés suite à une interaction entre l'intensité et la durée de leur exposition au froid hivernal. Ce sont ceux qui tolèrent le gel extracellulaire. Le choix des variables climatiques exprimant la menace que représente le froid hivernal sur ces deux groupes de plantes tiendra compte de cette distinction.

MATÉRIEL ET MÉTHODES

Le territoire couvert par cette étude se limite à celui où se pratique l'agriculture dans la province de Québec (Canada).

Les observations météorologiques utilisées sont celles des températures journalières minimale et maximale mesurées sous abri, de même que celles des précipitations sous forme de neige et de pluie. L'étude visant à déterminer la variation spatiale des conditions climatiques auxquelles sont soumises les plantes pérennes a porté sur une période de 11 ans (1972 à 1982). Les dossiers de plus de 200 stations du réseau climatologique du Ministère de l'Environnement du Québec ont alors été utilisés (figure 1). Les variables climatiques ont été calculées pour chaque saison froide. L'année climatologique concernant une saison froide donnée s'étend du premier août au 31 juillet de l'année suivante.

Une analyse de fréquence moyenne d'observation de températures minima hivernales dépassant certains seuils a également été faite. Seules les stations ayant un dossier d'au moins 20 années complètes sur la période 1950-1982 ont été retenues pour cette étude.

Jours d'enneigement

Ouellet (1969) a proposé plusieurs modèles de régressions multiples de variables climatiques pour estimer le nombre annuel moyen de jours où une couche de neige d'au moins 2,5 centimètres recouvre le sol (JCN) dans la moitié orientale du Canada. Nous avons retenu l'équation #1, pour laquelle les variables d'entrée nécessaires à son utilisation étaient disponibles à un plus grand nombre de

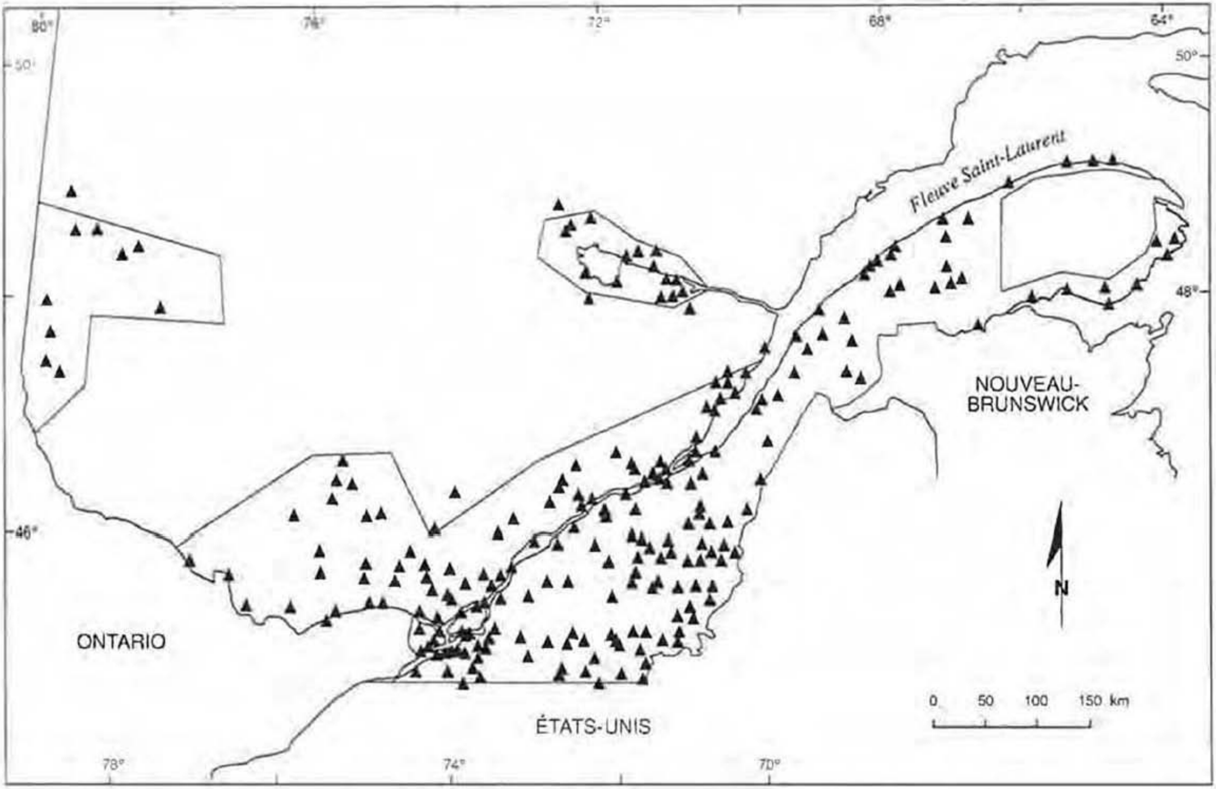

FIGURE 1 Stations météorologiques utilisées et territoire couvert par l'étude des conditions agroclimatiques de la saison froide.

stations. L'ajustement des observations utilisées par cette droite de régression a été caractérisé par un écart-type de l'erreur de 11,6 jours et par un coefficent de corrélation de 0,972. Elle s'exprime comme suit:

$$JCN = 284{,}5 - 2{,}111\ TMN + 0{,}2135\ N - 2{,}180\ TMM - 10{,}2\ PM - 0{,}1547\ SSG0 \quad (1)$$

où: TMN et TMM sont les températures maximales moyennes des mois de novembre et de mars (° F);
N est la hauteur moyenne de la chute de neige annuelle (pouces);
PM est la hauteur moyenne de pluie tombée en mars (pouces);
SSG0 est la longueur moyenne, en jours, de la saison sans gel (0° C).

La cartographie a été réalisée à l'aide du logiciel "SYMAP" (Dougenik & Sheenan, 1975).

RÉSULTATS ET DISCUSSION

En raison des réponses différentes des tissus végétaux aux froids de l'hiver selon leur mode d'évitement du gel intracellulaire et selon leur sensibilité relative aux changements physiologiques engendrés, nous avons retenu deux variables climatiques pour exprimer l'intensité de la menace de dommage aux plantes exercée par le froid hivernal: "la température minimale annuelle" (TMA) et "la température minimale journalière du mois le plus froid" (TMMF).

Température Minimale Annuelle (TMA).

Sakai & Weiser (1973), George *et al.* (1974a) et Quamme (1976) ont déjà mis en évidence la coïncidence entre les isothermes de TMA et les aires de distribution de plusieurs plantes dont les organes les plus sensibles au froid utilisent la surfusion profonde. Nous avons donc choisi la même variable climatique pour exprimer l'effet de l'intensité du froid hivernal sur les tissus végétaux dont la blessure est associée à une température seuil relativement bien définie. Sa variation spatiale dans le territoire sous étude est présentée à la figure 2.

Les températures minimales extrêmes les plus froides sont observées au Lac St-Jean, en Abitibi-Témiscamingue et dans les Laurentides au nord de Montréal. A l'opposé, la région connaissant les pointes de froid les moins prononcées est celle de la côte gaspésienne et du golfe St-Laurent jusqu'au sud de Rimouski. On peut aussi y constater que la région de Québec appartient à la même classe que Montréal bien qu'elle soit située plus au nord et qu'elle en soit séparée par une zone plus froide. L'influence maritime exercée par le fleuve qui s'élargit à cet endroit est probablement responsable des conditions relativement clémentes observées à Québec.

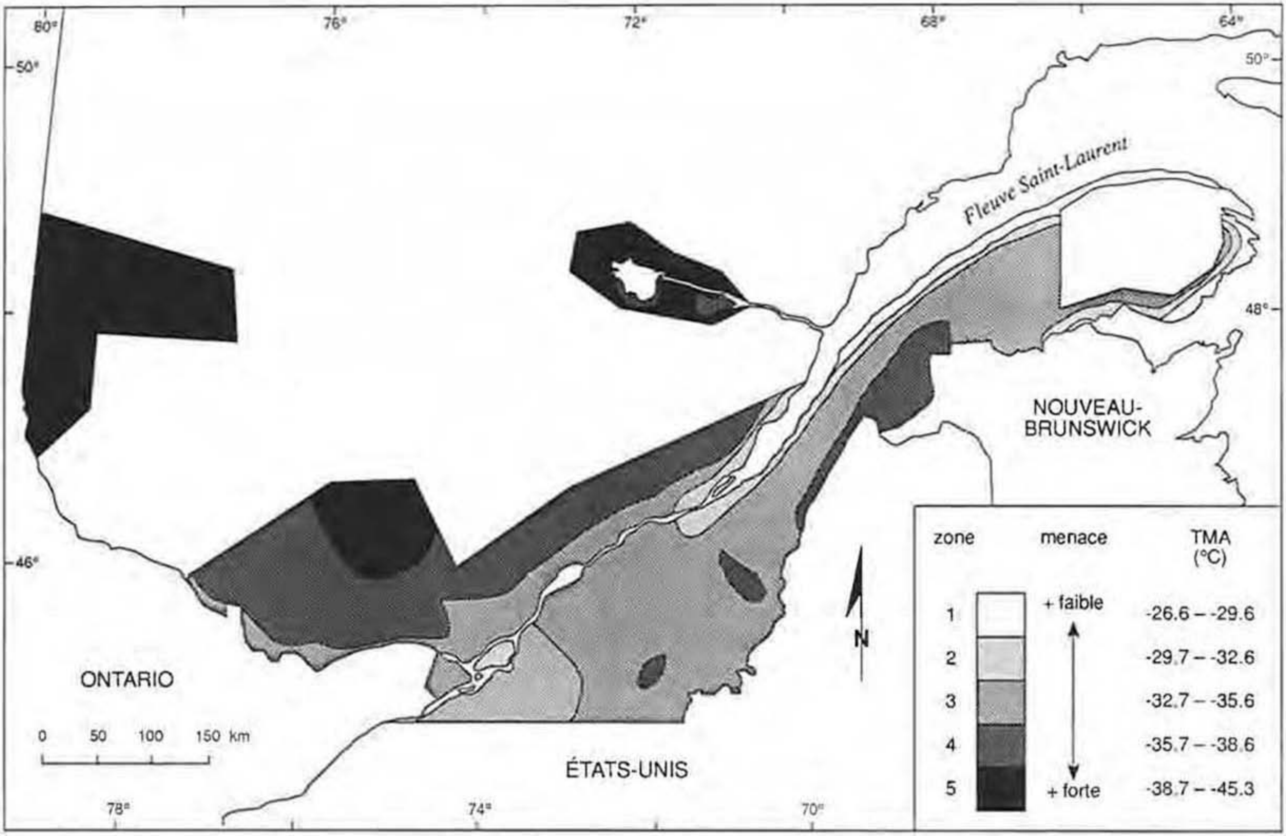

FIGURE 2 Variation spatiale de l'intensité du froid hivernal au Québec méridional (1972-1982). L'intensité relative de la menace exercée par l'intensité du froid hivernal est exprimée par la température minimale annuelle (TMA).

TABLEAU 1 Fréquence d'observation de températures minimales annuelles inférieures à certains seuils pour la période 1950-1982 (%).

	NBRE	(°C)																
ZONE	STAT.	-18	-20	-22	-24	-26	-28	-30	-32	-34	-36	-38	-40	-42	-44	-46	-48	-50
1	8	100	99	95	85	73	42	19	6	3	1	0	0	0	0	0	0	0
2	29	100	100	100	98	95	83	61	37	18	7	2	1	0	0	0	0	0
3	24	100	100	100	100	99	98	89	78	57	33	11	3	1	0	0	0	0
4	17	100	100	100	100	100	100	97	93	80	63	36	10	4	0	0	0	0
5	14	100	100	100	100	100	100	100	100	99	95	82	60	41	19	8	2	0

De nombreux travaux ont été menés pour estimer la limite de la résistance des organes des plantes pérennes à une brève exposition au froid (Pellet *et al.*, 1981; Sakai, 1982; Sakai & Larcher, 1987). Leurs résultats, ajoutés à la connaissance des fréquences d'observation de températures inférieures à certains seuils (tableau 1), nous permettent de connaître les chances de survie des organes de ces plantes dans les différentes zones définies par les conditions moyennes.

Des observations nous indiquent que les bourgeons floraux sont les organes les moins résistants des rhododendrons (Sakai, 1982). Chez les espèces étudiées les plus rustiques, la limite de leur résistance est d'environ -30° C. L'examen des fréquences des températures minimales annuelles indique que, même en zone 1, ces bourgeons seraient tués un hiver sur cinq. Parmi les organes végétatifs du rhododendron, le xylème est la partie la moins résistante. Il est endommagé à -40° C chez les espèces les plus rustiques, indiquant ainsi que ces dernières pourraient survivre aux froids sévissant dans la zone 3. Leur floraison y serait cependant compromise par le gel fréquent des bourgeons.

Chez les espèces les plus rustiques du genre Rosa, le xylème est la partie la plus sensible au froid et peut résister à une température de -40° C à -45° C (Sakai, 1982; Sakai & Larcher, 1987). Elles peuvent donc survivre à une exposition aux froids hivernaux de la zone 4, mais la protection d'une couche de neige leur est nécessaire en zone 5. Les espèces cultivées à des fins ornementales sont beaucoup plus sensibles et succombent lorsque la température s'abaisse sous -25° C. Il est donc nécessaire de protéger ces plantes des froids hivernaux pour en assurer la survie dans la majeure partie de la province.

Quamme (1976) a étudié la relation entre la température annuelle minimale moyenne et la répartition de la production commerciale de pommes et de poires dans le sud de l'Ontario. Les cellules des rayons de parenchyme du xylème de ces arbres fruitiers survivent à l'hiver par surfusion profonde. Leur limite d'endurcissement est comprise entre -37 et -40° C pour le pommier et entre -33 et -39° C pour le poirier.

Quamme (1976) n'a observé aucune production commerciale de pommes dans les régions où la température minimale annuelle est inférieure à -34,4° C. Au Québec, cette limite correspond environ à celle entre les zones

3 et 4 de la figure 2. L'examen de la fréquence des températures minimales (tableau 1) montre que les probabilités d'observer une température inférieure à -38° C dans les zones 5, 4 et 3 sont respectivement de 82%, 36% et 11% alors qu'elles sont de 60%, 10% et 3% pour un seuil de -40° C. On constate donc qu'une température annuelle minimale moyenne d'environ -35° C correspond à des fréquences élevées de dommage au xylème des pommiers qui expliqueraient l'absence de production commerciale de pommes dans les secteurs qui y sont exposés.

Dans la même étude (Quamme, 1976), la production commerciale de poires a été associée aux régions où la température minimale annuelle moyenne est comprise entre -23,3° C et -28,9° C. Ce territoire correspond environ à la zone 1 de la figure 2. Dans cette zone, les fréquences d'observations de températures inférieures ou égales à -32° C, -34° C et -36° C sont respectivement de 6%, 3% et 1%. Le froid hivernal n'y est donc pas un critère limitant la production de poires. Malgré la survie des poiriers à l'hiver de la zone 1, la production commerciale de poires n'est cependant pas possible sur la côte gaspésienne en raison de la fraîcheur des températures estivales qu'on y enregistre.

Température Minimale Journalière du Mois le plus Froid (TMMF).

La menace liée à l'interaction entre la durée et l'intensité du froid hivernal pour les organes tolérant le gel extracellulaire a été exprimée par TMMF. Le patron de variation spatiale de cette variable est présenté à la figure 3.

Les régions où la menace est la plus forte sont celles de l'Abitibi-Témiscamingue, du lac St-Jean ainsi que des hautes terres des Laurentides et des Appalaches au nord-est de la rivière Chaudière. A l'opposé, la vallée du St-Laurent en amont du lac St-Pierre, les Cantons de l'Est, la rive sud du St-Laurent en aval de Québec et la côte Gaspésienne sont celles où le dommage associé à cette cause climatique est le moins probable.

Ouellet et Sherk (1967) ont observé que plus de 80% de la variation de la fréquence de mortalité hivernale des arbres et arbustes ornementaux au Canada pouvait être expliquée par la TMMF. La ressemblance entre la figure 3 et le zonage de Ouellet et Sherk était donc prévisible et suggère que l'information présentée par ce dernier est plus pertinente aux tissus végétaux tolérant le gel extracellulaire que ceux où il y a surfusion profonde.

Couverture de neige

L'analyse des températures minimales hivernales sévissant au Québec montre qu'elles sont, dans toutes les régions, inférieures aux limites de la résistance au froid de la plupart des plantes herbacées agricoles (Sakai & Larcher, 1987). La survie de ces dernières est donc, dans une large part, liée à l'efficacité avec

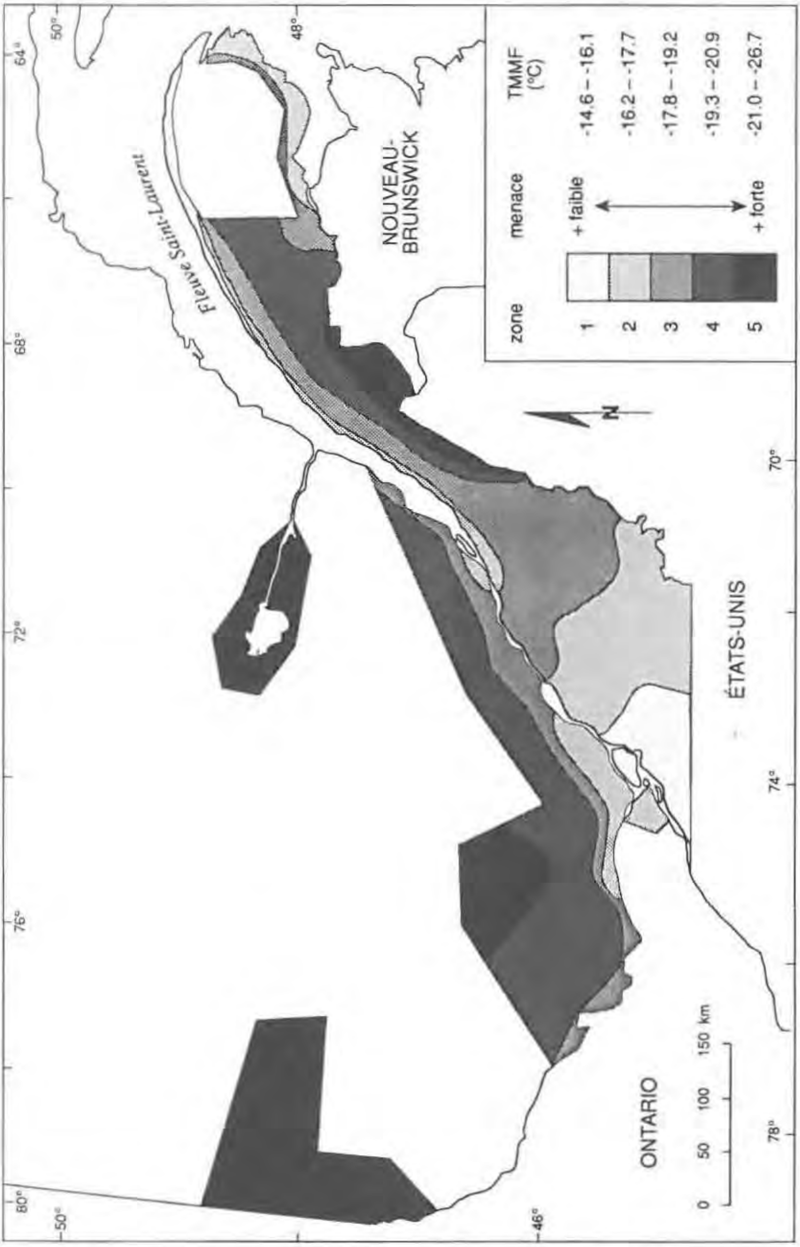

FIGURE 3 Variation spatiale de l'interaction entre la durée et l'intensité du froid hivernal au Québec méridional (1972-1982). L'intensité relative de la menace exercée par l'interaction entre la durée et l'intensité du froid hivernal est exprimée par la température journalière minimale du mois le plus froid (TMMF).

laquelle la neige les isolera des basses températures de l'air ambiant. C'est le cas des espèces du genre *Rosa* (Rajashekar & Burke, 1978) chez les plantes ornementales, de la fraise (Boyce, 1985) pour les cultures fruitières et de la luzerne (Smith, 1964) et du blé d'hiver (Fowler *et al.*, 1976) pour les grandes cultures.

La variation spatiale du nombre de jours de couverture de neige, calculée selon l'équation (1) de Ouellet (1969), est illustrée à la figure 4. Le nombre moyen de jours d'enneigement varie de 85 à 168 jours entre la plaine de Montréal, où il est le plus faible, et l'Abitibi-Témiscamingue et l'ouest du lac St-Jean, où il est le plus important. En général, on note également une relation nette entre la durée de l'enneigement et la latitude.

La survie à l'hiver d'un grand nombre de plantes herbacées et de certaines plantes ligneuses basses est donc liée à la présence d'une couche de neige au sol. La durée de la présence d'une couverture de neige n'est cependant pas la seule variable impliquée. La longueur de la période durant laquelle le froid hivernal constitue une menace doit elle aussi être considérée. C'est pourquoi nous avons retenu la différence entre "la durée moyenne, en jours, de la période s'écoulant du premier au dernier jour où la température minimale journalière était plus petite ou égale à -15° C durant la saison froide" et "le nombre moyen de jours d'enneigement" (DNF) comme variable supplémentaire pour exprimer le degré de sévérité avec lequel les froids hivernaux agissent réellement sur ce groupe de plantes.

Le patron de variation spatiale de DNF est présenté à la figure 5. Si nous posons l'hypothèse que les deux périodes considérées sont, en moyenne, centrées sur la même date, la différence obtenue exprime alors le nombre moyen de jours où les plantes risquent d'être exposées directement à de basses températures. On constate (figure 5) que la différence est positive dans la majeure partie du territoire étudié. La période de couverture de neige excède celle où le froid sévit de 14 à 52 jours dans les régions de Québec, du Bas-Saint-Laurent et de la Gaspésie. On peut en déduire que les plantes herbacées y sont, en général bien protégées et que le froid ne représente une cause importante de dommage qu'en certaines années exceptionnelles.

Il en va tout autrement pour la plaine de Montréal et la vallée de l'Outaouais où des froids inférieurs ou égaux à -15° C peuvent sévir en moyenne de quatre à 13 jours en absence de couverture de neige. Cette région est celle où la survie des plantes herbacées aux froids de l'hiver est la moins probable selon les résultats de notre étude. La zone 2 représente, elle aussi, une région relativement peu favorable si on considère, qu'une année sur deux, elle présente des risques d'exposition des plantes basses à des températures potentiellement dommageables.

La considération de la période où le froid sévit n'a pas modifié le patron de la variation spatiale relative, défini par le nombre moyen de jours de couverture de neige, sur la rive sud du fleuve en amont de Québec . Elle a

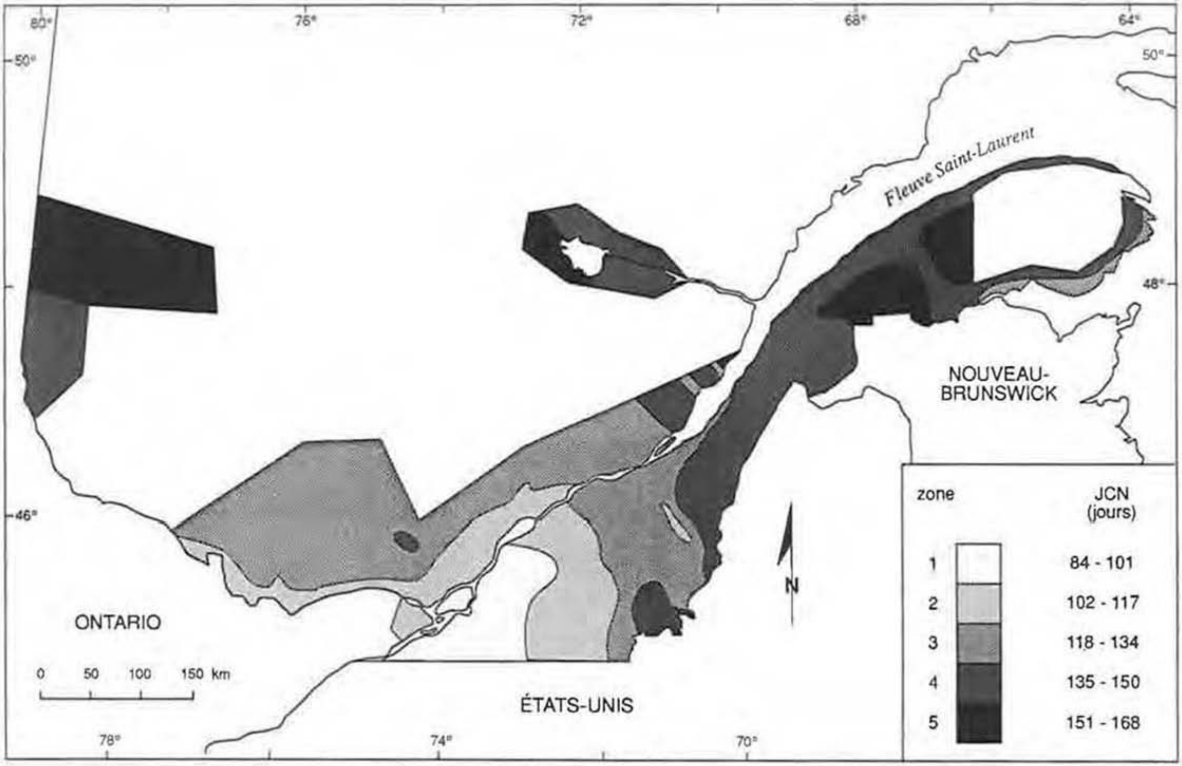

FIGURE 4 Variation spatiale du nombre de jours de couverture de neige au Québec méridional (1972-1982).

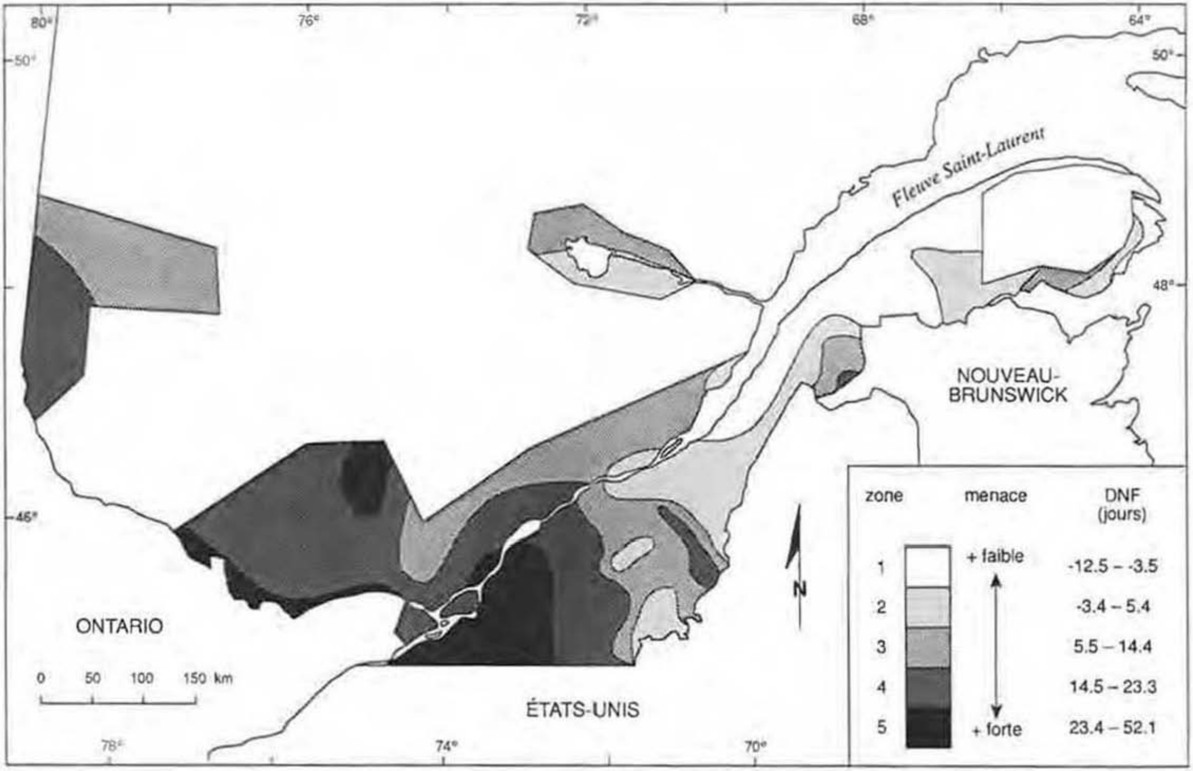

FIGURE 5 Variation spatiale de l'action du froid hivernal sur les plantes basses au Québec méridional (1972-1982). L'intensité relative de la menace exercée par l'action du froid sur les plantes basses est exprimée par la différence, en jours, entre la durée de la période où un froid inférieur ou égal à -15° C peut sévir et le nombre annuel de jours de couverture de neige (DNF).

cependant mis en relief des conditions relativement plus sévères dans l'Outaouais, l'Abitibi-Témiscamingue, le lac St-Jean et les Laurentides au nord de Montréal. Par contre, sur la rive sud du fleuve en aval de Québec, les conditions sont devenues relativement plus clémentes.

CONCLUSIONS

Cette étude repose sur l'hypothèse que les mécanismes de résistance des végétaux au froid sont suffisamment bien connus pour qu'on puisse identifier la ou les variables climatiques qui expriment la menace exercée par le froid hivernal sur les plantes. Les résultats de recherche publiés dans ce domaine indiquent qu'il existe une relation directe entre:

1) les dommages aux cellules qui sont le siège de surfusion profonde et la température minimale annuelle;
2) la survie de plusieurs plantes basses et la présence d'une couche de neige.

Les effets de l'interaction entre la durée et l'intensité du froid sur la survie des tissus où s'observe le gel extracellulaire ont été moins bien étudiés, particulièrement chez les plantes ligneuses. A la lumière des connaissances actuelles, la température journalière minimale moyenne du mois le plus froid nous apparaît toutefois la variable climatique la plus adéquate pour exprimer l'effet du froid hivernal sur ce groupe de plantes.

La carte montrant la variation spatiale de la température annuelle minimale permet de définir l'aire de survie à l'hiver des tissus des plantes qui résistent aux températures hivernales par surfusion profonde et dont la limite d'endurcissement est connue. Celle montrant le nombre de jours durant lesquels le froid sévit en absence de couverture de neige devrait représenter assez fidèlement les régions où peuvent survivre les plantes herbacées et les plantes ligneuses basses de faible rusticité. La complexité de la relation entre le climat et le dommage aux plantes nous empêche de faire une interprétation directe des zonages concernant la tolérance au gel extracellulaire et de la perte d'endurcissement. Ces derniers présentent cependant les différences spatiales de l'intensité relative de la menace associée à ces causes de dommage. Ils permettent donc d'identifier les régions où le risque de dommage est le plus élevé et de généraliser des observations faites en point à l'ensemble de la zone à laquelle cet endroit appartient.

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Trends of Daily Maximum and Minimum Temperature in Canada During the Past Century

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ABSTRACT

Mean monthly maximum, minimum and mean surface temperatures are analysed for 131 locations in Canada for the period 1895 to 1989. These data were obtained from the Historical Canadian Climate Database (HCCD). There has been a statistically significant rise in mean annual national temperatures over the past century of about 1.1°C. Annual mean maximum and minimum national temperature trends since 1895 show a significant increase in mostly-daytime maximum temperatures of about 0.7°C and a highly significant increase in mostly-nighttime minimum temperatures of about 1.5°C. Mean maximum and minimum temperature trends since 1895 are also examined seasonally and regionally and indicate significant increases in minimum temperatures mainly during the spring and summer seasons in the western, northwestern and eastern continental regions of the country. Few significant regional increases are evident in maximum temperatures during any season for this period. Significant decreases in mean temperature range, an important measure of climate variability, occur in most regions during all seasons. Mean maximum and minimum national temperature trends for the past 40 years, since 1950, are also examined. They indicate no significant increases in either minimum or maximum temperatures annually or seasonally. Mean maximum and minimum regional temperature trends since 1950 indicate significant increases in both minimum and maximum temperatures mostly during the spring season in the western and northwestern regions of the country.

RÉSUMÉ

Les moyennes mensuelles des températures de surface maximales, minimales et moyennes sont analysées pour 131 stations du Canada pour la période allant de 1895 à 1989. Ces données proviennent de la Base de données climatiques canadiennes historiques (BDCCH). Ce dernier siècle, il y a eu une hausse statistiquement importante des températures nationales annuelles moyennes, hausse d'environ 1,1 °C. Depuis 1895, les tendances de la moyenne annuelle des températures nationales maximales et minimales indiquent une nette augmentation, d'environ 0,7 °C, dans les températures maximales

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enregistrées surtout pendant le jour et une hausse très significative, d'environ 1,5 °C, des températures minimales enregistrées surtout pendant la nuit. Depuis 1895, les tendances des températures maximales et minimales moyennes sont aussi examinées par saison et région et révèlent d'importantes hausses de la température minimale survenant surtout pendant les saisons du printemps et de l'été dans les régions intérieures ouest, nord-ouest et est de la partie continentale du pays. Pendant cette période, il n'apparaît guère de hausses régionales importantes dans les températures maximales. Les baisses significatives de la gamme de température moyenne, importante mesure de la variabilité climatique, se présentent dans la plupart des régions et pendant toutes les saisons. En outre, on examine les tendances de la moyenne des températures nationales maximales et minimales des 40 dernières années, depuis 1950. Elles ne révèlent aucune hausse importante, annuelle ou saisonnière, des températures minimales ou maximales. Les tendances de la moyenne des températures régionales maximales et minimales, depuis 1950, indiquent d'importantes hausses dans les températures tant minimales que maximales, surtout pendant la saison du printemps dans l'ouest et le nord-ouest du pays.

INTRODUCTION

Global mean surface temperature has increased by 0.3°C to 0.6°C over the past one hundred years with the five global-averaged warmest years occurring in the decade of the 1980's (Houghton *et al.*, 1990). The magnitude of this warming is generally consistent with climate model predictions, but is also within the bounds of natural climate variability. It is believed by many researchers that this warming has been to some extent caused by increasing concentrations of radiatively active trace greenhouse gases (GHG's) in the atmosphere, including CO_2, CH_4, CFC's and N_2O. Global climate system models predict global average surface temperature increases ranging between 1.5°C and 4.5°C for a doubling of CO_2 (Houghton *et al.*, 1990). However, regional temperature change is predicted to be even larger in middle and higher latitudes and smaller in the tropics.

The diurnal characteristics of the observed warming over the past century have only recently been examined on a broad spatial scale for a large number of stations (Karl *et al.*, 1991). This study indicated that, for three large countries in the Northern Hemisphere, the contiguous United States, the Soviet Union and the People's Republic of China, most of the national warming over the past forty years can be attributed to an increase in mostly-nighttime, mean minimum surface temperatures. Mostly-daytime, mean maximum surface temperatures, show little or no warming. The result has been an observed decline in mean daily temperature range over a large portion of the Northern Hemisphere landmass. The most likely cause for this is increasing amounts of observed cloud cover, although the effects of increases in other lower tropospheric scattering agents have been suggested (Houghton *et al.*, 1990). Other factors, such as urbanization effects and changes in atmospheric circulation, must also be considered. It therefore becomes increasingly necessary to analyse the entire global land record, both regionally and seasonally, of maximum and minimum temperatures.

Canadian climatologists have recently completed work on the construction of an historical dataset containing monthly, seasonal and annual mean maximum and mean minimum temperatures for 131 locations dating back to 1895 (Gullett, Skinner and Vincent, 1992; Gullett and Skinner, 1992). These locations, and their spatial distribution, have been designated as representative of the Canadian land mass for climate change and climate variability studies. This report presents a preliminary analysis of both individual and collective results found for a total of eleven Canadian climate regions and provides valuable additional information on the nature of the observed warming of the Northern Hemisphere landmass.

DATA

The temperature data used in this study were extracted from the Historical Canadian Climate Database (HCCD). The HCCD was constructed from the National Climate Data Archive (NCDA) of the Atmospheric Environment Service (AES), utilizing climate stations that were selected on the basis of spatial distribution, length of record, data continuity, homogeneity assessments and other factors. The HCCD was assembled to provide climate researchers access to an initial but expanding dataset that has been rigorously quality controlled, assessed for homogeneity (Gullett *et al.*, 1991), and adjusted, where necessary, to ensure regional representativeness. The data adjustments that were carried out had the effect of removing some of the locally induced noise, or discontinuities, in the series resulting from changes in observing programme, instrumentation, site conditions, and other non-climatic effects. These data adjustments resulted in more areally representative series that are suitable for use in regional scale analyses. The development of the HCCD is fully described in an earlier report (Gullett *et al.*, 1992).

The HCCD currently consists of temperature data only, for 131 Canadian climate locations that are as evenly distributed in space and time as possible, for the period 1895 to present. It consists of monthly, seasonal and annual means of maximum, minimum and mean surface temperatures. The mean is derived from calculating the average of the daily maximum and daily minimum temperatures. The resulting database contains long time series of "clean" data that are suitable for regional scale and large area analyses. Actual temperatures and temperature departures from the appropriate 1951-80 reference period are permanently stored in the HCCD. In addition, both 1951-80 averages and standard deviations are retained.

METHODS

The eleven Canadian climate regions and the spatial distribution of the 131 locations examined in this study can be seen in Figure 1. Table 1 describes the temporal and spatial characteristics of the 131 station dataset of maximum, minimum and mean temperature departure series extracted from the HCCD for this analysis. Individual departure series were combined into single monthly departure series, by region, by averaging departures for all locations in each region by month. Temporal differences are partially overcome through the use of temperature departures. This method assists in reducing biases which enter the time series because of a varying station network (Jones *et al.*, 1986). In addition, monthly temperature ranges (max-min) and departures from the 1951-80 mean were calculated. Seasonal and annual mean departure series of maximum, minimum, mean and range were similarly calculated for all eleven regions. The standard climatological seasons were used, winter being the average of December, January and February, spring the average of March, April and May, summer the average of June, July and August, and autumn the average of September, October, and November. Regional series were then area-weighted to develop a national average for Canada.

Temperature changes over time were calculated using a linear regression statistical model and expressed in °C per specified time period. Future work will concentrate on the application of non-linear trends applied to time series with both constant and nonconstant means (Woodward and Gray, 1993), in hopes of better reflecting the observed temperature changes. Two periods were identified for analysis. The first is the entire 1895 to 1989 period of 95 years. The second is the most recent 40 year period from 1950 to 1989. Complete spatial coverage of locations in the HCCD is achieved by 1950. The 95 year period of analysis is referred to as a century, and all temperature changes during this period were calculated from the regression equations on the basis of 100 years. All temperature changes during the 40 year period were calculated from the regression equations on the basis of 40 years. Standard statistical significance tests were performed on all results (Jones, 1988; Karl *et al.*, 1991; Etkin, 1991). All linear trends found to be significantly different from 0°C per year at the α=0.05 level are identified.

RESULTS

Figure 2 shows the national annual mean temperature departures between 1895 and 1989. It indicates a period of warming from the beginning of the record through the 1940's, followed by a cooling period through the 1970's then a resumption of warming through the 1980's. A best-fit linear trend applied to the time series indicates an increase of about 1.1°C per century which is significantly different from 0°C per year at the α=0.05 level. An examination of the annual

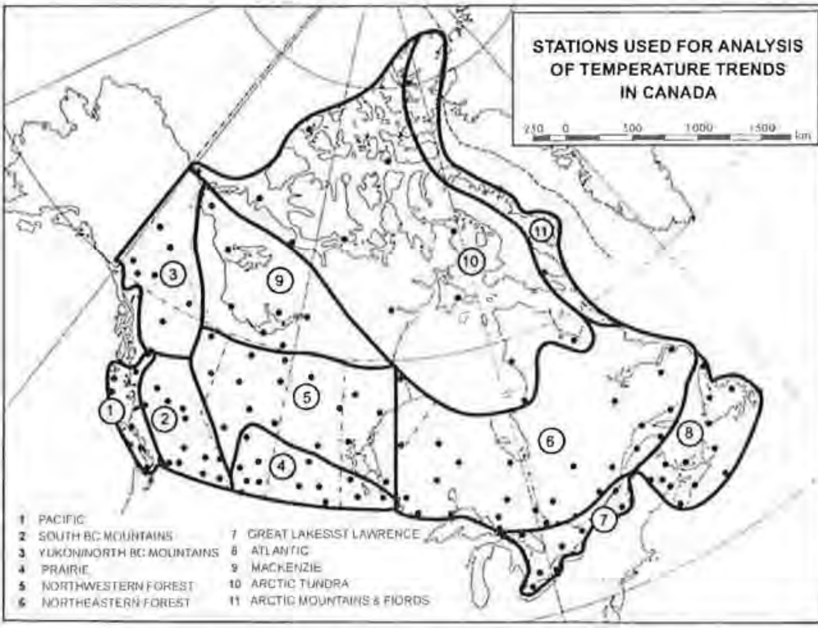

FIGURE 1 Canadian climate regions and climate station distribution used for the calculation of regional and national area-averages.

Table 1. HCCD description with number of stations added in a climate region by the first year of each decade.

Climate Region	1900	1910	1920	1930	1940	1950	1960	1970	1980	Total
Pacific	5	1	1	2	0	1	0	0	0	10
South BC Mountains	7	1	2	1	0	0	0	0	0	11
Yukon/North BC Mountains[a]	0	1	0	1	1	4	0	0	0	7
Prairie	8	3	2	0	0	0	0	0	0	13
Northwestern Forest	2	2	2	2	3	2	1	2	0	16
Northeastern Forest	4	1	9	0	6	4	0	1	1	26
Great Lakes/St. Lawrence	6	1	3	0	0	0	0	0	0	10
Atlantic	10	0	2	0	2	1	0	0	0	15
Mackenzie	2	1	1	1	0	2	0	0	0	7
Arctic Tundra[b]	0	0	0	3	1	5	3	0	0	12
Arctic Mountains and Fiords[c]	0	0	0	0	0	3	1	0	0	4
National Total	44	11	22	10	13	22	5	3	1	131

[a] Region has 89 year record 1901-1989
[b] Region has 68 year record 1922-1989
[c] Region has 44 year record 1946-1989

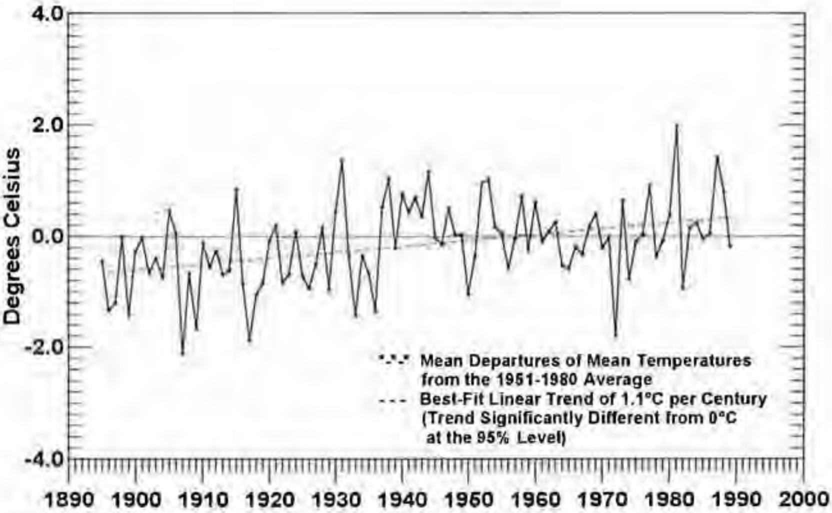

FIGURE 2 Canadian national annual departures (°C) of daily mean temperature for the period 1895 to 1989.

mean maximum temperature departures and the annual mean minimum temperature departures from 1895 to 1989 indicates similar patterns. The annual mean maximum temperature series, as seen in Figure 3, indicates an increase of about 0.7°C per century which is also significantly different from 0°C per year. A much higher increase in annual mean minimum temperature departures, as seen in Figure 4, of about 1.5°C per century is also significantly different from 0°C per year.

The annual temperature trends are summarized in Table 2 nationally and for the eleven Canadian climate regions for the 1895 to 1989 period. Only two of the eleven regions show significant increases in maximum temperatures for the full period, the Atlantic and Mackenzie regions. On the other hand, seven of the eleven regions show significant increases in minimum temperatures since 1895. Only the Atlantic, Yukon/North BC and the two Arctic regions do not show significant increases in minimum temperatures. Significant reductions in temperature range since 1895 are evident in the seven western and central regions of Canada. This may be attributed to the significant warming observed in the minimum temperatures and the non-significant changes in the maximum temperatures. An exception is the Yukon/North BC region where the temperature range over the full period has remained basically unchanged due to the nearly identical, non-significant trends in both maximum and minimum temperatures.

Also included in Table 2 are the annual temperature trends for the 1950 to 1989 period. Since 1950, there have been no significant trends in either

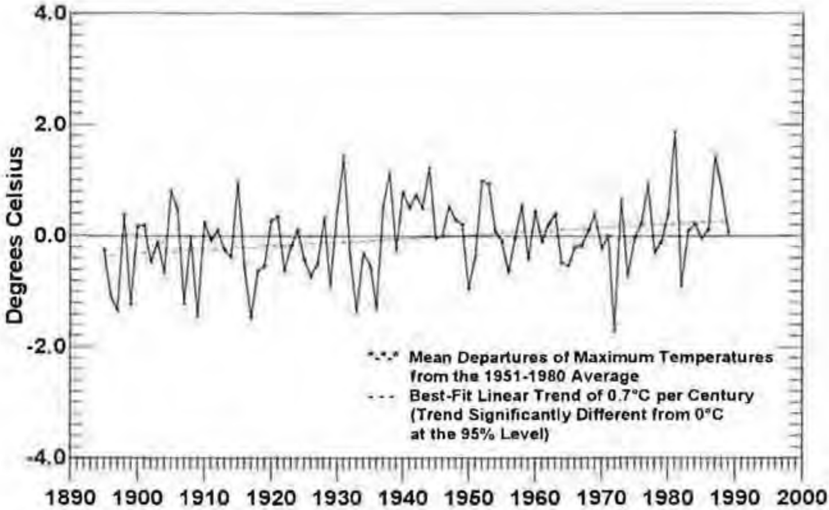

FIGURE 3 Canadian national annual departures (°C) of daily maximum temperature for the period 1895 to 1989.

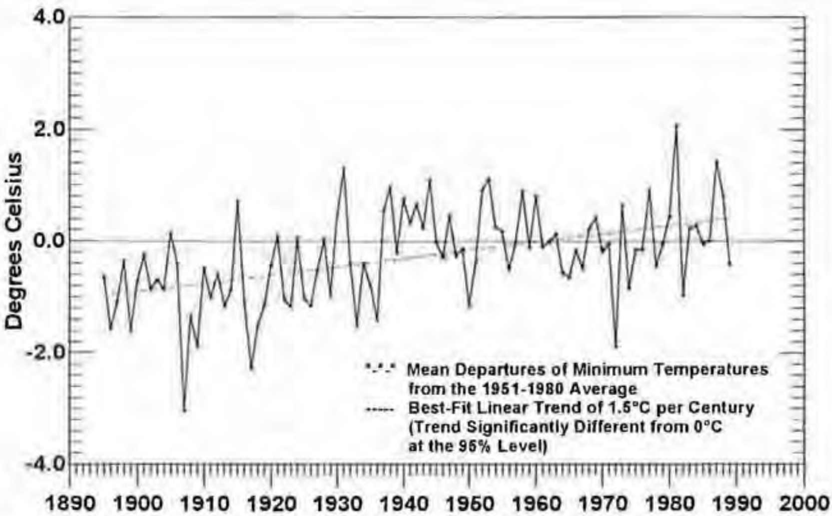

FIGURE 4 Canadian national annual departures (°C) of daily minimum temperature for the period 1895 to 1989.

maximum or minimum annual temperatures, or in temperature range, for the national compilations. However, mean maximum temperatures have risen significantly in the four continental western regions extending from the Prairies

Table 2. Linear trends of mean annual temperature in °C per century for the period 1895-1989 and °C per 40 years for the period 1950-1989 for Canada and by climate region.

Climate Region	Mean Maximum		Mean Minimum		Mean Max-Min	
	1895-1989	1950-1989	1895-1989	1950-1989	1895-1989	1950-1989
Canada (National)	0.7[a]	0.4	1.5[a]	0.3	-0.8[a]	0.2
Pacific	0.1	0.6	0.6[a]	0.5	-0.5[a]	0.1
South BC Mountains	-0.1	0.8	1.0[a]	1.1[a]	-1.1[a]	-0.3
Yukon/North BC Mountains[b]	0.8	1.4[a]	0.7	1.6[a]	0.0	-0.2
Prairie	0.3	1.7[a]	1.3[a]	1.1	-1.0[a]	0.6[a]
Northwestern Forest	0.5	1.3[a]	2.1[a]	1.4	-1.7[a]	-0.1
Northeastern Forest	0.0	0.1	1.0[a]	-0.2	-1.0[a]	0.3
Great Lakes/St. Lawrence	0.1	-0.4	1.0[a]	0.0	-0.9[a]	-0.4[a]
Atlantic	0.5[a]	-0.4	0.3	-0.8[a]	0.2	0.4[a]
Mackenzie	1.4[a]	1.2[a]	2.1[a]	0.8	-0.7[a]	0.4[a]
Arctic Tundra[c]	0.7	0.7	0.7	0.1	0.1	0.3
Arctic Mountains and Fiords[d]	-0.7	-0.5	-0.5	-0.4	-0.3	-0.2

[a] Trend significantly (α=0.05) different from 0°C per specified time period
[b] Region has 89 year record 1901-1989
[c] Region has 68 year record 1922-1989
[d] Region has 44 year record 1946-1989

to the Yukon. These increases have ranged from approximately 1.2°C to 1.7°C per 40 years. Minimum temperatures, on the other hand, have increased in only the two mountain regions of British Columbia and the Yukon. The Atlantic region has actually seen a significant reduction, about -0.8°C per 40 years, in minimum temperatures and a non-significant decrease in maximum temperatures. This has resulted in a significant increase in the temperature range in the Atlantic region of 0.4°C per 40 years. Similar significant increases in temperature range are seen in the Prairie and Mackenzie regions due to significant increases in maximum temperatures and non-significant increases in minimum temperatures. The Great Lakes/St. Lawrence region has seen a significant reduction in temperature range since 1950 due to a non-significant reduction in maximum temperatures and no trend in minimum temperatures.

Seasonal trend summaries are provided in Tables 3 to 6 for winter, spring, summer and autumn, respectively, for the two specified periods. Since 1895, significant national trends in maximum temperature have occurred in the summer season only, while significant national trends in minimum temperature, and temperature range, have occurred in all seasons. Since 1950, there have been no significant trends in either maximum or minimum temperature, or temperature range, in any season for the national compilations.

Over the past century, significant linear trends at the regional scale are evident in both maximum and minimum temperatures and in temperature range in most seasons but with varying regional differences. The frequency of occurrence of significant trends increases considerably over wider spatial areas, or collections of adjacent regions, during specific seasons. An examination of the

Table 3. Linear trends of mean winter temperature in °C per century for the periods 1895-1989 and °C per 40 years for the period 1950-1989 for Canada and by climate region.

Climate Region	Mean Maximum		Mean Minimum		Mean Max-Min	
	1895-1989	1950-1989	1895-1989	1950-1989	1895-1989	1950-1989
Canada (National)	1.1	1.2	1.7[a]	0.9	-0.6[a]	0.3
Pacific	0.7	1.3	0.0	0.8	0.7[a]	0.5[a]
South BC Mountains	0.2	1.2	0.5	1.5	-0.3	-0.2
Yukon/North BC Mountains[b]	1.3	3.6	0.8	3.4	0.5	0.2
Prairie	0.7	2.4	1.3	2.1	-0.6[a]	0.3
Northwestern Forest	0.8	3.2[a]	2.2[a]	3.0	-1.3[a]	0.3
Northeastern Forest	-0.1	-0.2	1.5[a]	-0.6	-1.6[a]	0.4
Great Lakes/St. Lawrence	0.7	-0.9	1.3	-0.6	-0.6[a]	-0.3
Atlantic	0.5	-1.6[a]	0.6	-2.3[a]	-0.1	0.7
Mackenzie	2.3[a]	3.1[a]	2.6[a]	2.8[a]	-0.2	0.3
Arctic Tundra[c]	1.9[a]	1.3	1.9[a]	0.8	0.0	0.5[a]
Arctic Mountains and Fiords[d]	0.2	0.1	0.1	0.2	0.1	-0.1

[a] Trend significantly (α=0.05) different from 0°C per year
[b] Region has 89 year record 1901-1989
[c] Region has 68 year record 1922-1989
[d] Region has 44 year record 1946-1989

Table 4. Linear trends of mean spring temperature in °C per century for the periods 1895-1989 and °C per 40 years for the period 1950-1989 for Canada and by climate region.

Climate Region	Mean Maximum		Mean Minimum		Mean Max-Min	
	1895-1989	1950-1989	1895-1989	1950-1989	1895-1989	1950-1989
Canada (National)	0.6	0.7	1.7[a]	0.5	-1.1[a]	0.2
Pacific	0.2	0.9[a]	0.7[a]	1.0[a]	-0.5[a]	-0.1
South BC Mountains	0.0	1.6[a]	1.1[a]	1.6[a]	-1.1[a]	-0.0
Yukon/North BC Mountains[b]	1.5[a]	1.8[a]	1.0	2.3[a]	0.5	-0.5
Prairie	0.4	3.8[a]	1.8[a]	2.8[a]	-1.4	1.0[a]
Northwestern Forest	0.9	2.3[a]	2.8[a]	2.4[a]	-1.9[a]	-0.2
Northeastern Forest	0.3	1.1	1.4[a]	0.6	-1.2[a]	0.5
Great Lakes/St. Lawrence	0.2	0.8	1.2[a]	1.0	-1.0[a]	-0.2
Atlantic	0.3	0.5	0.3	0.0	-0.1	0.5
Mackenzie	1.4	1.5	2.7[a]	1.1	-1.3[a]	0.4
Arctic Tundra[c]	0.4	-1.0	0.0	-1.2	0.5	0.2
Arctic Mountains and Fiords[d]	-2.0[a]	-2.0[a]	-1.0	-1.4	-1.1[a]	-0.6[a]

[a] Trend significantly (α=0.05) different from 0°C per year
[b] Region has 89 year record 1901-1989
[c] Region has 68 year record 1922-1989
[d] Region has 44 year record 1946-1989

temperature trends from 1895 to 1989 indicates most significant increases in minimum temperatures have occurred during the spring and summer seasons throughout many neighbouring regions extending from the Pacific coast, through

Table 5. Linear trends of mean summer temperature in °C per century for the periods 1895-1989 and °C per 40 years for the period 1950-1989 for Canada and by climate region.

Climate Region	Mean Maximum		Mean Minimum		Mean Max-Min	
	1895-1989	1950-1989	1895-1989	1950-1989	1895-1989	1950-1989
Canada (National)	0.5[a]	0.3	1.5[a]	0.2	-1.0[a]	0.1
Pacific	-0.8[a]	-0.2	1.1[a]	0.3	-1.9[a]	-0.4
South BC Mountains	-0.6	0.2	1.7[a]	0.9[a]	-2.3[a]	-0.7
Yukon/North BC Mountains[b]	-0.1	0.0	1.0[a]	0.3	-1.1[a]	-0.3
Prairie	0.2	1.1	1.3[a]	0.4	-1.1[a]	0.6
Northwestern Forest	0.3	0.2	2.0[a]	0.8	-1.7[a]	-0.5
Northeastern Forest	0.3	0.4	0.8[a]	0.1	-0.5[a]	0.3
Great Lakes/St. Lawrence	-0.6	-0.2	0.8[a]	0.3	-1.4[a]	-0.5[a]
Atlantic	1.1[a]	0.5	0.6[a]	0.4	0.5[a]	0.2
Mackenzie	1.0[a]	0.6	2.0[a]	0.2	-1.0[a]	0.4
Arctic Tundra[c]	0.8	0.4	0.7	0.0	0.0	0.4[a]
Arctic Mountains and Fiords[d]	-0.3	-0.1	0.0	0.0	-0.3	-0.1

[a] Trend significantly (α=0.05) different from 0°C per year
[b] Region has 89 year record 1901-1989
[c] Region has 68 year record 1922-1989
[d] Region has 44 year record 1946-1989

Table 6. Linear trends of mean autumn temperature in °C per century for the periods 1895-1989 and °C per 40 years for the period 1950-1989 for Canada and by climate region.

Climate Region	Mean Maximum		Mean Minimum		Mean Max-Min	
	1895-1989	1950-1989	1895-1989	1950-1989	1895-1989	1950-1989
Canada (National)	0.5	-0.3	1.1[a]	0.0	-0.6[a]	-0.1
Pacific	0.2	0.3	0.5	0.1	-0.3	0.3
South BC Mountains	0.0	0.1	0.8	0.2	-0.8[a]	-0.1
Yukon/North BC Mountains[b]	0.3	0.0	0.0	0.2	0.3	-0.1
Prairie	-0.2	-0.3	0.7	-0.6	-0.9[a]	0.3
Northwestern Forest	-0.3	-0.4	1.6[a]	-0.4	-1.9[a]	-0.0
Northeastern Forest	-0.1	-0.8	0.5	-0.8	-0.7[a]	0.1
Great Lakes/St. Lawrence	0.0	-1.2[a]	0.8[a]	-0.3	-0.8[a]	-0.9[a]
Atlantic	0.0	-0.9[a]	-0.3	-1.1[a]	0.3[a]	0.2
Mackenzie	0.8	-0.4	1.1	-1.0	-0.3	0.6
Arctic Tundra[c]	0.4	0.0	0.3	-0.2	0.1	0.3
Arctic Mountains and Fiords[d]	-0.7	-0.1	-0.8	-0.2	0.1	0.1

[a] Trend significantly (α=0.05) different from 0°C per year
[b] Region has 89 year record 1901-1989
[c] Region has 68 year record 1922-1989
[d] Region has 44 year record 1946-1989

the western, northwestern and eastern continental interior regions of Canada. Spring increases range from 0.7°C to 2.8°C per century while summer increases are from 0.6°C to 2.0°C per century. These have been accompanied by few significant increases in maximum temperatures, occurring only in the Yukon/North BC region during spring and in the Mackenzie and Atlantic regions during summer. Significant reductions in temperature range throughout these regions during these two seasons are evident. In general, reductions in spring and summer temperature ranges over the past century are attributable to the rising minimum temperatures and the relatively unchanging maximum temperatures. The only exception is during summer in the Atlantic region where a relatively larger increase in maximum temperatures and a smaller increase in minimum temperatures has resulted in a significant increase in temperature range of about 0.5°C per century.

An examination of the temperature trends from 1950 to 1989 indicates significant and comparable increases in both maximum and minimum temperatures mainly during the spring season in the western and northwestern regions of Canada, from 0.9°C to 3.8°C for maximum temperatures and 1.0°C to 2.8°C for minimum temperatures per 40 years. However, few significant changes are seen during this season in the temperature range, implying that the recent rise in temperatures throughout this broad area has been diurnally uniform. The exception is an increase in the Prairie region range of about 1.0°C per 40 years due to a considerable increase in maximum temperatures and a smaller increase in minimum temperatures.

Figure 5 and Figure 6 show the spatial extent of the spring season significant ($\alpha=0.05$) maximum and minimum temperature trends, respectively, for the 40 year period 1950 to 1989. These maps were compiled from the individual 40-year temperature trends for the 131 locations in the HCCD. Large similar areas of positive trends are evident in both maps, although the area of positive maximum temperature trend extends further into northern Ontario. The Arctic regions have experienced more spatially widespread significant decreases in maximum temperature than in minimum temperature and therefore temperature range since 1950 during the spring season. Significant decreases in both maximum and minimum temperatures have occurred during the winter and autumn seasons in the Atlantic region as seen in Tables 3 and 6, respectively.

CONCLUSIONS

Observed temperature changes over two periods, 1895 to 1989 (one century) and 1950 to 1989 (40 years), were analysed both on a national basis and regionally for eleven Canadian climate regions. Mean monthly maximum (daytime), minimum (nighttime), and mean surface temperature time series for 131 locations in Canada were analysed in this study with the use of best-fit linear trends. All linear trends found to be significantly different from 0°C at the $\alpha=0.05$ level were identified.

Maximum and minimum temperature analysis on a national basis suggests nighttime warming both annually and seasonally over the century. On a

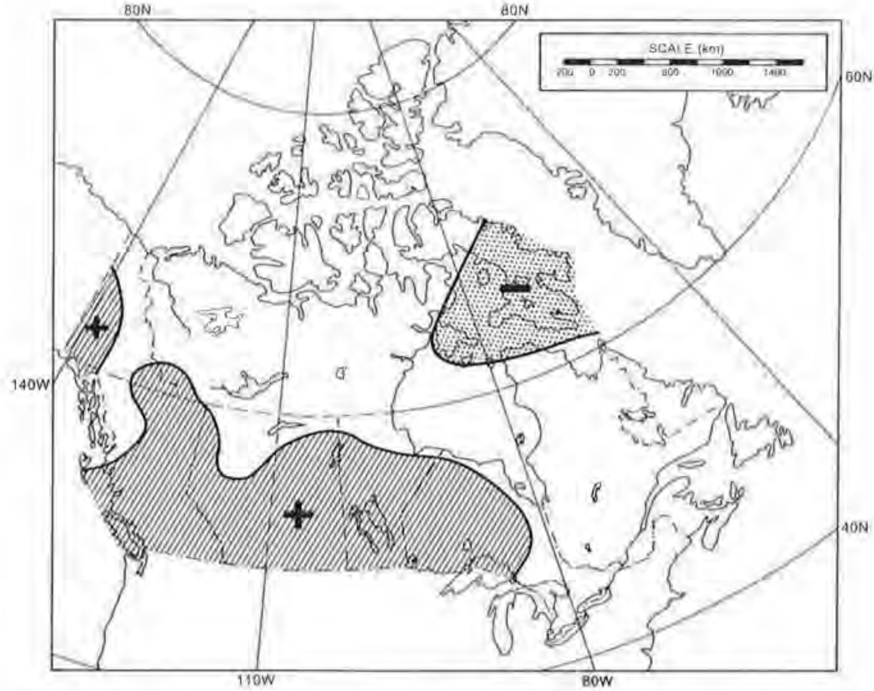

FIGURE 5 Spatial extent of spring season significant (α=0.05) maximum temperature trends for the period 1950 to 1989.

regional basis, seasonal temperatures over the past century show significant increases in minimum temperatures mainly in the western, northwestern and eastern continental regions of the country while only a few significant increases are evident in coincident maximum temperatures. The implication is for nighttime warming in these regions.

Nationally, there is no evidence of a significant rise in either minimum or maximum temperatures, annually or seasonally, over the most recent 40-year period. This is not surprising since this period was dominated by a period of hemispheric cooling, from the 1950's to the early 1970's, and of hemispheric warming, from the early 1970's through the 1980's (Jones, 1988), with opposite trends tending to cancel one another. A regional analysis is beneficial, however, since strong temperature trends become evident over large areas of the country as was seen previously in the regional one century analyses.

Regionally, seasonal temperature changes since 1950 indicate significant increases in both minimum and maximum temperatures, but only in the spring season, and only in the western and northwestern regions of the country. Recent studies have provided evidence of this warming during the spring season through the effects on lakes in these regions, such as the effects of

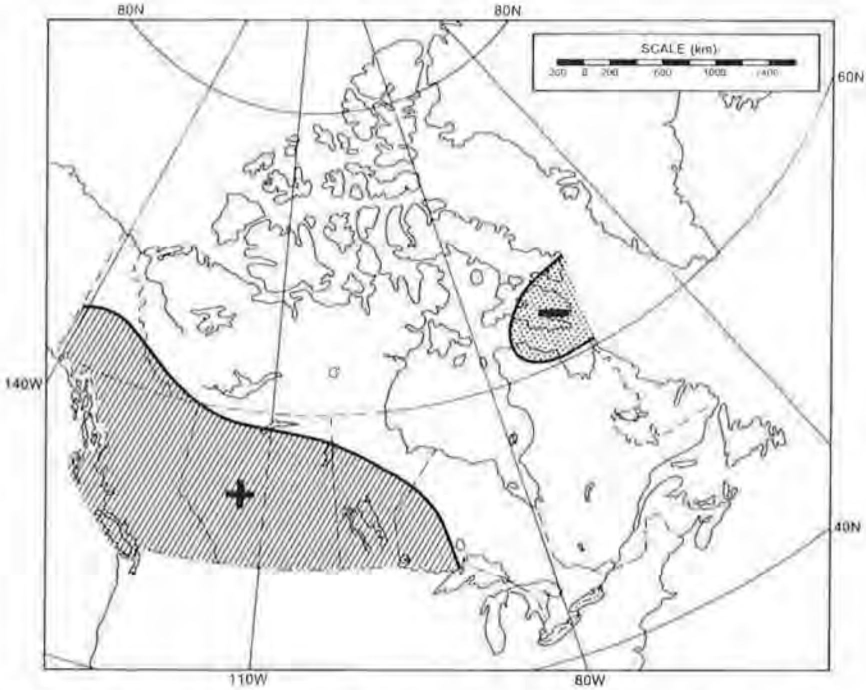

FIGURE 6 Spatial extent of spring season significant (α=0.05) minimum temperature trends for the period 1950 to 1989.

earlier snowpack removal through increased daytime heating (Schindler *et al.*, 1990) and in the earlier break-up of lake ice cover in northwestern Ontario and in the Prairie provinces (Skinner, 1993). Corresponding increases in minimum and maximum temperatures have resulted in no significant changes in the temperature range in these regions. Overall, the evidence does not support the hypothesis of nighttime warming over the past 40 years in Canada.

The absence of significant trends in many regions, especially during winter when most GCM's tell us the greatest CO_2-induced effect should become evident, might be explained in the selection of the standard climatological seasons. Recent evidence has shown that, when comparing the two normal periods 1931-60 and 1961-90 for seven stations in the eastern Canadian Prairies, December temperatures have become cooler while January and February temperatures have increased (Raddatz *et al.*, 1991). Further investigation and analysis may be warranted.

The observed diurnal temperature changes over the past century in Canada are not proof that an enhanced greenhouse gas effect is taking place. Canadian observations of mean temperature increase, however, are in keeping with the general rise in global mean temperatures observed over this period. On the other hand, over the past 40 years, the Canadian landmass has experienced significant changes in both minimum and maximum temperatures on regional and seasonal spatial and temporal scales, but not on a national scale or on an annual basis. No clear indication exists in this analysis of enhanced nighttime warming over the past 40 years, however, this may be a function of the application of the linear trend technique. Future activities will explore non-linear methods and will focus on attribution of observed temperature changes as well as on comparisons with output from global circulation models forced with increased greenhouse gases.

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