# Climatological Bulletin

Vol. 23, No. 2, August/août 1989

# Bulletin climatologique

Canadian Meteorological and Oceanographic Society

La Société Canadienne de Météorologie et d'Océanographie

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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.

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Les collaborateurs sont priés de soumettre leurs manuscrits à Alexander H. Paul, rédacteur en chef, BULLETIN CLIMATOLOGIQUE, Département de geographie, Université Regina, Regina, Saskatchewan, S4S 0A2. Il faut dactylographier tous les manuscrits à double interligne, sur un côté d'un papier blanc de bonne qualité, de 28 sur 21,5 cm ou des dimensions les plus rapprochées. Il faut dactylographier à double interligne, sur des feuilles à part, le résumé, la liste des références, les tableaux et la liste des légendes. Les commentaires, les critiques, les opinions et les informations ne doivent pas dépasser 1 500 mots. Fournir l'original et, si possible, trois copies, selon la disposition suivante:

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Les auteurs d'articles et de notes de recherche doivent payer des frais de publication de 50 $ par page, ce qui donne droit à 25 copies gratuites. On peut négocier un taux réduit en cas de difficultés financières, mais l'auteur n'aura pas droit à des tirages gratuits.

La correspondance concernant les activités de la Société, les souscriptions des membres et des institutions et les numéros déjà parus, devrait être adressée au Secrétaire-correspondant, Société canadienne de météorologie et d'océanographie, C.P. 334, Newmarket, Ontario L3Y 4X7. Téléphone (416) 898-1040, Fax. (416) 898-7937.

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# Foreword / Avant-Propos

CMOS is currently undertaking a review of all its publications. Dr. R.E. Munn has been engaged as consultant to conduct this review, with his report to be made to the Society in October. If readers of *Climatological Bulletin* wish to comment on the role of the *Bulletin* within the range of CMOS publications, Dr. Munn can be contacted through the Corresponding Secretary, CMOS, P.O. Box 334, Newmarket, Ontario L3Y 4X7, Tel. (416) 898-1040.

La SCMO a engagé D^r R.E. Munn afin qu'il fasse une revue de toutes les publications de la Société. Il doit livrer son rapport à la SCMO en octobre. Si vous les lecteurs du *Bulletin climatologique* voulez lui passer des commentaires sur le rôle du *Bulletin* parmi la gamme de publications de la Société, vous pouvez les envoyer par le Sécrétaire-correspondant, Société canadienne de la météorologie et de l'océanographie, C.P. 334, Newmarket, Ontario L3Y 4X7, Tél. (416) 898-1040.

*Alec H. Paul*
*Editor*

# Spring and Autumn Freeze Risk in Ontario

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and
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[Original manuscript received 25 July 1988;
in revised form 18 April 1989]

ABSTRACT

Analyses of freeze dates for various threshold temperatures and risk levels are presented for Ontario. Variables derived from monthly temperature normals explained up to 97% of the variation in average dates of last spring and first fall frost (0°C) among stations used in the regression. This provided a method for establishing frost dates for short-term climate stations more accurately than by using a simple relationship to daily average minimum temperature. Average frost dates for 1951–80 were similar to those based on earlier normal periods. However, increased station density demonstrated more clearly the local variability due to soils, topography and urban influences.

Frost dates (0°C) at 25% and 10% risk levels were about 1 and 2 weeks, respectively, later in spring and earlier in fall than average dates in southern Ontario, and about 10 and 19 days, respectively, in the north. Freeze dates for various threshold temperatures down to −4.4°C were about 5 to 7 days earlier in spring and later in fall for each 1°C drop in temperature for southern Ontario, but typically 9 to 12 days in the north. Because of consistent patterns in these differences, simple rules-of-thumb can be used to estimate freeze dates for various risk levels and threshold temperatures from the mapped average frost (0°C) dates.

RÉSUMÉ

Les auteurs présentent des analyses de dates d'occurrence de différents seuils de température gélive pour divers niveaux de risque en Ontario. Les variables dérivées de normales de température mensuelles parviennent à expliquer jusqu'à 97% de la variation observée des dates moyennes de la dernière gelée printanière et de la première gelée automnale (0°C) aux

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stations d'observation utilisées dans l'analyse de régression. Ces relations permettent d'estimer les dates de gelée, pour les stations ne disposant pas de statistiques de longue durée, avec plus de précision que par l'utilisation d'un simple rapport avec la température minimum quotidienne moyenne. Les dates de gelée moyennes de la période 1951–1980 sont semblables à celles des périodes normales précédentes, mais la densité plus élevée de stations révèle plus clairement la variabilité locale due aux sols, à la topographie et aux effets urbains.

Les dates de gelée (0°C) pour les seuils de risque de 25% et de 10% sont d'environ 1 et 2 semaines respectivement plus tardives au printemps et plus avancées à l'automne que des dates moyennes dans le sud de l'Ontario, et d'environ 10 et 19 jours respectivement dans le nord. Les dates de gel correspondant aux seuils de température jusqu'à −4.4°C sont d'environ 5 à 7 jours plus tôt au printemps et plus tard à l'automne pour chaque baisse de seuil de température de 1°C dans le sud de l'Ontario, mais typiquement de 9 à 12 jours dans le nord. En raison de la récurrence régulière de ces différences, on peut utiliser des méthodes empiriques simples afin d'estimer les dates de gel pour divers niveaux de risque et seuils de température à partir des dates de gelée moyennes (0°C) cartographiées.

## INTRODUCTION

Freezing temperatures at the beginning and end of the growing season are a major hazard for crop production in Ontario. Farmers need freeze risk information, preferably at the local scale, for management decisions such as variety selection, planting and harvesting schedules and freeze prevention (Bootsma 1976; Hocevar and Martsolf 1971). Information on occurrences of temperatures below 0°C is important, as the level at which freeze damage occurs depends on crop hardiness. In addition, freeze risk probabilities need to be available for decision making.

Information on freeze occurrences presently available for Ontario includes the following: (i) maps of average last spring and first autumn frost (0°C) dates for 1921–50 (Chapman and Brown 1966) and for 1931–60 (Brown *et al.* 1968); (ii) tables of freeze dates at different risk levels for threshold temperatures ranging from +4.4 to −6.7°C (40 to 20°F) for 1931–60 (Coligado *et al.* 1968), for 0°C based on 1951–80 (Environment Canada 1982b) and for 0°C and −2°C based on the entire available period of record at selected locations (Environment Canada 1979); (iii) maps of freeze dates for 32°F (0°C) and 28°F (−2°C) at 50 and 10% risk for the 1931–60 period, derived using available climatic normals, astronomical and other data (Sly *et al.* 1971; Sly and Coligado 1974). Brown *et al.* (1968) provided tentative rules-of-thumb to estimate frost dates (0°C) at various risk levels from the average dates of last spring and first fall frost. For example, as a rule the risk of frost two weeks or more after the average date in spring and two weeks or more before the average date in fall was about 10%. Such rules eliminate the need for a different map for each selected level of risk. At present, information on freeze dates for a range of threshold temperatures and risk levels is not readily available on a geographic basis for the most recent (1951–80) normal period for Ontario.

The purposes of this study are: (i) to develop procedures for estimating average dates of last spring and first autumn frost (0°C) for stations with relatively short periods of record to maximize the number of stations available for mapping; (ii) to display on a geographic basis the average frost dates (0°C) for Ontario based on the latest available 30-year normal period (1951–80); (iii) to develop more objective procedures that will estimate freeze dates for a range of threshold temperatures and risk levels from the average dates of last spring and first fall frosts. These objectives will facilitate concise presentation of freeze risk information on a geographic basis that can be used in management decisions.

## DATA AND METHODS

### *Estimating average frost dates (0°C)*

Since average frost dates can be affected by period of record, two procedures to estimate average frost dates (0°C) for the 1951–80 period for stations with relatively short periods of data (e.g. less than 20 years) were compared. In the first procedure, average dates of last spring (SDATE) and first fall (FDATE) occurrence of 0°C measured at screen height about 1.5 m above the surface were extracted from published normals (Environment Canada 1982b) for 44 stations in Ontario with 30 years of complete data in the 1951–80 period. Monthly mean minimum temperatures based on the same period (Environment Canada 1982a) were used to compute daily mean minimum temperature (MIN) for these same stations using Brooks' (1943) interpolation procedure. Values for MIN on the SDATE and FDATE were then determined for each location. Stations were divided into two main groups: (i) 14 stations north of 47°N latitude (northern Ontario); (ii) 30 stations south of 47°N latitude (southern Ontario). Southern Ontario stations were further divided into 'rural', 'lake', and 'urban' categories, as different MIN values were expected for each of these. As a rule, 'lake' stations were those within 10 km of the shoreline of the Great Lakes while 'urban' stations were near the centre of large urban areas. A few stations were included in more than one category. Average MIN values were determined for each group. Several sets of SDATE and FDATE were then estimated by using a range of MIN values which included the average values determined for the two main groups of stations. FDATE's were also estimated using appropriate average MIN values for each category (lake, urban or rural) in southern Ontario. Linear regression and correlation analyses (SAS 1985) were then used to compare estimated and observed frost dates.

In the second procedure, multiple linear regression analysis was used to develop a more objective method of estimating frost dates. SDATE and FDATE were dependent parameters, while independent parameters were selected by a SAS stepwise regresssion procedure (SAS 1985) from the list shown in Table 1 (maximum of five), based on the combination which resulted in the highest coefficient of determination ($R^2$). Variables in Table 1 were used because they were expected to reflect the effect of geographic and air mass characteristics on

TABLE 1. List of independent variables used in linear regression to estimate average spring and fall frost dates.

| Symbol | Parameter |
|---|---|
| *Spring regressions:* | |
| $S_1$ – | First Julian date when MIN is $\geq 5.8$°C in spring |
| $S_2$ – | Average daily temperature range (max-min) for May and June (°C) |
| $S_3$ – | July minus January mean minimum temperature (°C) |
| $S_4$ – | June minus May mean minimum temperature (°C) |
| $S_5 = (S_2)^2$ | |
| $S_6 = (S_3)^2$ | |
| $S_7 = (S_4)^2$ | |
| *Fall regressions:* | |
| $F_1$ – | First Julian date when MIN is $\leq 6.4$°C in fall (southern Ontario) |
| $F_2$ – | First Julian date when MIN is $\leq 6.0$°C in fall (northern Ontario) |
| $F_3$ – | Average daily temperature range (max-min) for September and October (°C) |
| $F_4$ – | July minus January mean minimum temperature (°C) |
| $F_5$ – | September minus October mean minimum temperature (°C) |
| $F_6 = (F_3)^2$ | |
| $F_7 = (F_4)^2$ | |
| $F_8 = (F_5)^2$ | |

minimum temperature and frost dates. $S_1$, $F_1$ and $F_2$ were chosen based on comparisons using different MIN values as described earlier. Variables $S_2$ and $F_3$ should reflect the influence of water bodies, air drainage characteristics and soil conditions, all of which can affect the daily temperature range. Variables $S_3$, $S_4$, $F_4$ and $F_5$ should reflect lake influences which tend to decrease the range in mean minimum air temperature between summer and winter and the rate of temperature increase in spring and decrease in autumn. $S_4$ and $F_5$ may also reflect soil influences, since sandy soils warm up more quickly in spring and cool more rapidly in autumn than clayey soils. Squared terms were included in the regression analyses in case relationships were non-linear. Coefficients for the selected independent variables were determined separately for northern and southern Ontario and for spring and fall. These coefficients were then used to estimate SDATE and FDATE from temperature normals adjusted to the 1951–80 period for all available climate stations in Ontario (Environment Canada 1982a).

Estimated frost dates for approximately 260 stations with less than 26 years of records were plotted on maps for Ontario. Observed average frost dates were also plotted for all stations (over 300) with records longer than 10 years (i.e. duplicate sets of dates were plotted for stations with records for 11 to 25 years). Isolines were drawn and maps were reduced to a scale suitable for publication.

### *Estimating freeze dates for selected critical temperatures and risk levels*

Published frost probabilities for the 1931–60 period (Coligado *et al.* 1968) were used to develop criteria for estimating freeze dates for selected critical temperatures and risk levels from the mapped average 0°C frost dates. In addition to all eleven available stations from Ontario, four stations from neighbouring areas in Manitoba and Quebec were included in the analyses. These stations were considered useful additions in this portion of the study since they are located in areas which experience climatic conditions similar to those found in Ontario. Differences between frost dates for 0°C at 50% risk probability and at other risk levels (10, 20, 25 and 33%) were determined and assumed to be valid for average frost dates as well. Differences between the dates for 0°C and for temperatures of −1.1, −2.2, −3.3 and −4.4°C (corresponding to 30, 28, 26 and 24°F as used by Coligado *et al.* 1968) were also computed for risk levels of 10, 20, 35 and 50%. Data for the 1931–60 period were used since frost dates were not readily available for a range of risk levels and critical temperatures for later periods. However, using a different period of normals was not expected to influence results significantly. Stations were divided into five groups based on frost dates at 50% risk. Means and standard deviations of differences in dates were computed for each group.

To assess whether using a different 'normal' period and smoothing procedures (Robertson and Russelo 1968) had significant effects on the results, freeze dates for 0, −2.2 and −4.4°C were determined (unsmoothed) at five locations (Ottawa, Delhi, Harrow, Kapuskasing and North Bay) using periods of record ranging from 54 to 84 years. Differences in frost dates (0°C) for 50% risk and for other selected risk levels, and between dates for 0°C and for temperatures of −2.2°C and −4.4°C were determined. Results were compared with those based on smoothed data for the 1931–60 period from Coligado *et al.* (1968).

## RESULTS AND DISCUSSION

### *Estimated average frost dates (0°C)*

Average daily minimum temperatures (MIN) on the average date of last frost in spring were similar for northern and southern Ontario (Table 2). In southern

TABLE 2. Average mean daily minimum air temperatures (MIN) on average dates of last spring (SDATE) and first fall frost (FDATE) for northern and southern Ontario*

| Region | No. of stations | MIN (°C) Spring | Fall |
|---|---|---|---|
| Northern Ontario | 14 | 5.8 | 5.7 |
| Southern Ontario | 30 | 5.7 | 6.2 |
| Southern Ontario – rural | 16 | 6.3 | 6.5 |
| Southern Ontario – lake | 12 | 5.0 | 5.7 |
| Southern Ontario – urban | 4 | 4.9 | 5.2 |

* Averages are based on 30-year data (1951–80 period).

TABLE 3. Regression analyses*[1] between observed and estimated average frost dates (SDATE and FDATE) based on selected mean minimum temperature (MIN)

| Region | No. of stations | Season | MIN Temperature (°C) | a | b | $R^2$† | SEE†† |
|---|---|---|---|---|---|---|---|
| Northern Ontario | 14 | spring | 5.8 | −15.8 | 1.10 | 0.86 | 4.3 |
| | | | 6.4 | −13.3 | 1.07 | 0.86 | 4.3 |
| | | fall | 5.7 | −129.4*[2] | 1.50*[3] | 0.82 | 5.0 |
| | | | 6.4 | −108.8*[2] | 1.45 | 0.84 | 4.7 |
| Southern Ontario | 30 | spring | 5.7 | −27.4 | 1.20 | 0.83 | 4.7 |
| | | | 6.4 | −30.6*[2] | 1.19 | 0.83 | 4.6 |
| | | fall | 6.2 | −44.1*[2] | 1.16*[3] | 0.91 | 3.8 |
| | | | 6.4 | −36.6 | 1.14 | 0.90 | 3.9 |
| | | | Variable*[4] | −0.8 | 1.00 | 0.92 | 3.6 |

*[1] Regression equations are of the form $Y = a + bX$, where Y is the observed and X is the estimated SDATE or FDATE (Julian day), and a and b are the regression constant and coefficient respectively.
*[2] Regression intercepts significantly different from 0.0 at $P \geq 0.05$.
*[3] Regression coefficients significantly different from 1.0 at $P \geq 0.05$.
*[4] Average MIN temperature based on 'rural', 'lake' and 'urban' categories (Table 2).
† Coefficient of determination; †† Standard error of estimate of regression.

Ontario, average MIN values were about 0.5°C higher in fall than in spring. Urban stations in southern Ontario tended to have the lowest MIN temperatures and rural stations the highest. MIN values for lake stations averaged closer to urban than to rural categories, particularly in spring. These results probably reflect the moderating influence of large water bodies and cities on night-time minimum temperatures during radiation frost conditions.

MIN values for individual stations were not always typical of the category in which the stations were placed and varied by as much as 2.5°C. Some lake stations had MIN values that were more typical of rural stations. Thus, estimates of frost dates based on an average MIN value would have significant errors for some stations.

Regression analyses between observed frost dates and estimated dates based on several MIN temperatures resulted in relatively high coefficients of determinination ($R^2 = 0.82$ to $0.92$) in all cases (Table 3). Standard errors of estimate ranged from 3.6 to 5.0 days. The regression intercept and coefficient were significantly different from 0.0 and 1.0, respectively, for several MIN temperatures, indicating significant deviation from a 1:1 relationship in these cases. Selection of the most appropriate MIN temperature for estimating frost dates evidently is not very critical and any of the MIN values tested can estimate average frost dates to within about one week of observed dates if the appropriate regression equation from Table 3 is used to eliminate biases. The lowest standard

TABLE 4. Results of stepwise regression analyses of spring and fall average frost dates with selected climatic variables

| Spring frost | | | Fall frost | | |
|---|---|---|---|---|---|
| | Regression coefficients | | | Regression coefficients | |
| Independent variable | Northern Ontario | Southern Ontario | Independent variable | Northern Ontario | Southern Ontario |
| Regression constant | −654.5 | 253.3 | Regression constant | 118.2 | 93.7 |
| $S_1$ | 1.011 | 0.719 | $F_1$ | | 1.026 |
| $S_2$ | | 2.34 | $F_2$ | 1.492 | |
| $S_3$ | 35.046 | −14.835 | $F_3$ | −49.12 | −18.42 |
| $S_4$ | | −8.42 | $F_6$ | 2.460 | 0.835 |
| $S_5$ | 0.0880 | | | | |
| $S_6$ | −0.4792 | 0.2753 | | | |
| $R^2$ | 0.97 | 0.91 | | 0.95 | 0.93 |
| SEE (days) | 2.4 | 3.7 | | 2.8 | 3.4 |
| n | 14 | 30 | | 14 | 30 |

$R^2$ is the coefficient of determination
SEE is the standard error of estimate of regression
n is the number of cases used in the regression

error (3.6 days) and highest $R^2$ (0.92) were achieved by using different MIN values for rural, lake and urban categories in southern Ontario. A significant amount of the variation (8–18%) is still left unexplained when using average MIN values to estimate frost dates (Table 3). The decision of whether a station belongs to a rural, lake or urban category is also somewhat subjective. For these reasons, more accurate and objective estimation procedures using multiple linear regression analyses were developed.

Independent variables selected from Table 1 were able to explain a high percentage (91–97%) of the variance in SDATE and FDATE (Table 4) using stepwise regression. Standard errors of estimate ranged from 2.4 to 3.7 days. All variables included were significant at a level of 10% and most at 5%. Although variables $S_1$, $F_1$ or $F_2$ alone explained a large percentage of the variance in frost dates (Table 3), the addition of more independent variables resulted in higher $R^2$ and lower standard errors of estimate (Table 4). Stepwise regression models also produced higher $R^2$ values than using different MIN criteria for 'rural', 'lake' and 'urban' stations and therefore provided a more accurate and objective way of estimating average frost dates. Tests of the regression models using independent data indicated a high correlation ($r \geq 0.92$) and close to a 1:1 correspondence (Figure 1) between estimated and observed dates.

The models developed here are reliable for estimating frost dates in the regions of Ontario in which they were developed. However, using the coefficients

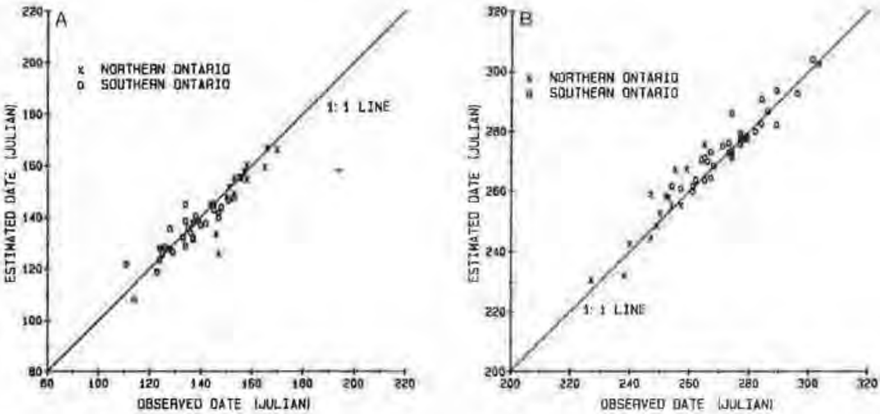


FIGURE 1. Comparisons between observed frost dates (24 to 29 year averages) and those estimated from regression models (Table 4), using independent data. A. Spring data. B. Autumn data.

developed for northern Ontario in southern Ontario can result in large errors, particularly when the models contain squared terms. The coefficients do not always reflect the influence of a particular variable on the frost date due to the fact that correlations exist between predictor variables. Therefore the regression models should not be used to explain 'cause and effect' relationships.

*Geographic distribution of frost dates and frost-free period*

Average frost dates (0°C) are shown for Ontario in Figures 2 and 3. The moderating effect of the Great Lakes in both southern and northern Ontario and the effects of latitude and topography are well illustrated. The average frost-free season extends from April 25 to October 25 in the most southerly region bordering the western end of Lake Erie and from June 25 to August 25 on the "height-of-land" north and east of Lake Superior. It is less than 60 days in the most northerly region, the Hudson Bay lowlands (not shown). This results in a 120-day difference in the frost-free season in Ontario from south to north (Figure 4). However, for agricultural regions in northern Ontario (stippled in the inset of Figure 4), the frost-free season is 80 to 120 days compared to 160 to 180 days along the north shore of Lake Erie.

The regional picture of frost dates for the 1951 to 1980 period has not changed from that found for 1931 to 1960 (Brown *et al.* 1968; Chapman and Thomas 1968) and for 1900 to 1930 (Putman and Chapman 1938). However, the increased density of climate stations used in this study provided more information on local differences, e.g. Figure 5. As a result of these differences, isolines drawn at 10-day intervals, rather than at 5- or 7-day intervals as for the earlier maps, were considered more realistic. Differences due to the influence of local factors were readily demonstrated in several instances. For example, autumn frost dates on sandy soils in the area west of Simcoe occur earlier than over drumlinized loam

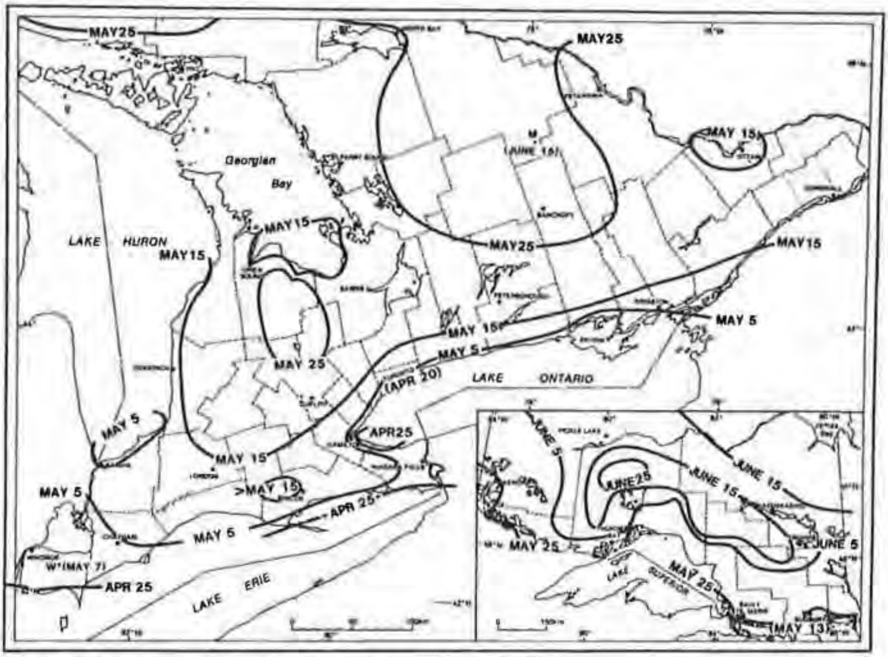


FIGURE 2. Average date of last spring frost (0°C) for Ontario.

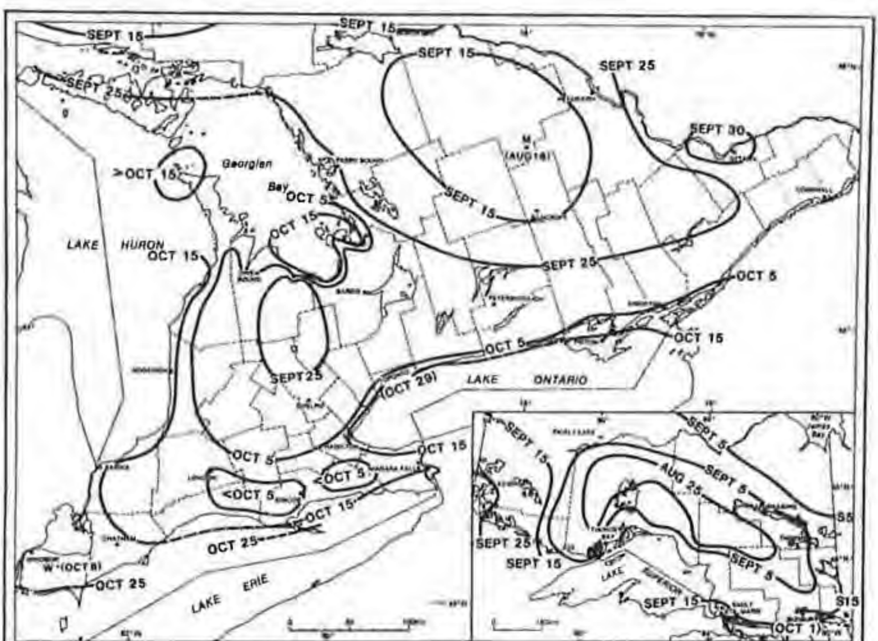


FIGURE 3. Average date of first autumn frost (0°C) for Ontario.

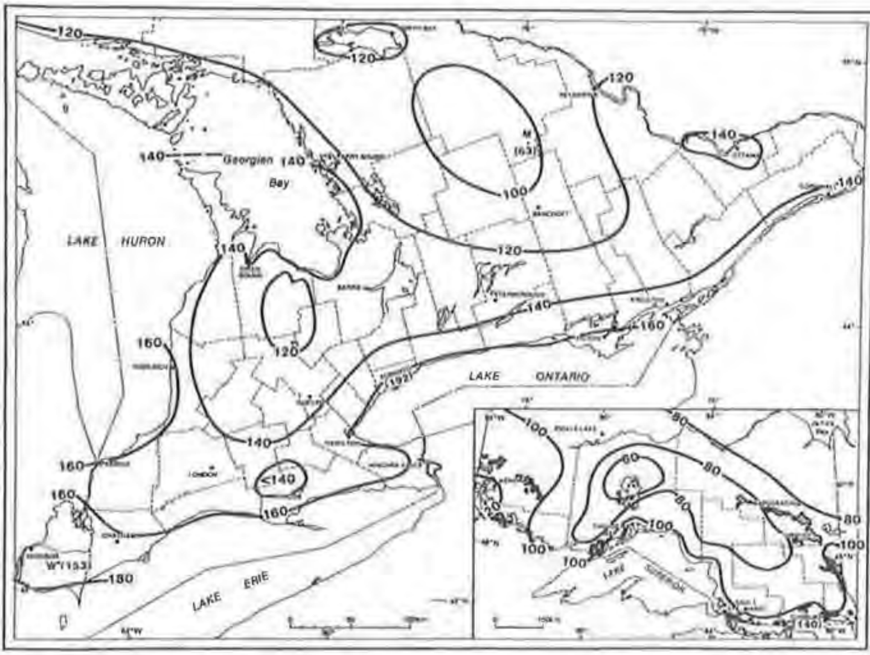


FIGURE 4. Average length of the frost-free period (above 0°C) for Ontario.

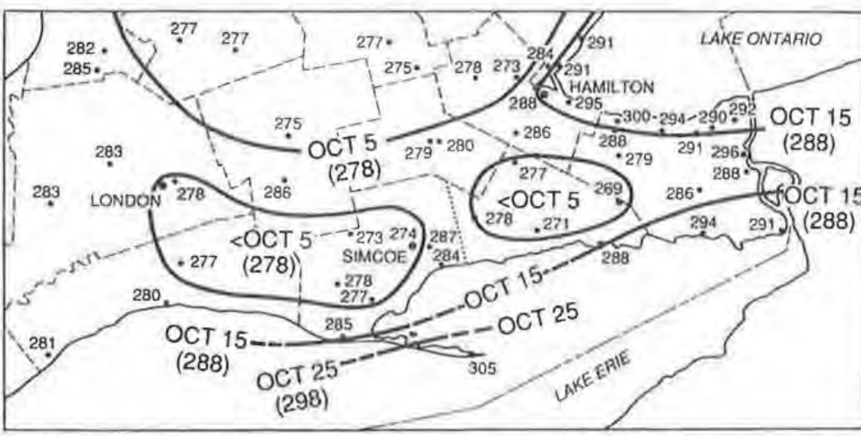


FIGURE 5. Spatial variability of autumn frost dates for the region from London to Niagara (station data are shown in Julian days and isolines are defined in dates and in Julian days).

soils to the north (Figure 5). Autumn frosts also occur earlier in areas where there is little air drainage over flat clay soils (east of Simcoe). Topographic influences are clearly illustrated by the frost dates for the village of Madawaska (M), situated in a valley approximately 125 m deep and 5 km wide in the Algonquin Uplands, where the frost-free season was only 63 days compared to 100 to 110 days (Figure 4) at most of the other stations in the Uplands. Similarly, Bootsma (1976) found average frost-free periods 40 to 60 days shorter in hollows compared to nearby hilltops in Prince Edward Island.

The urban influence is well illustrated by Toronto where the frost-free season is 192 days near the city centre compared to less than 160 days outside the metropolitan area (Figure 4). Urban influences also exist in other cities as well. Chatham and Windsor have frost-free seasons greater than 170 days, whereas at Woodslee (W) just southeast of Windsor, the season is only 153 days (Figure 4).

Areas immediately bordering the Great Lakes have significantly longer frost-free periods than further inland, and there tends to be a very rapid decline in the season length within 15 km of the shore. For example, a study in the Lake Huron area south of Goderich during the early 1960's (Meteorological Branch, 1963) indicated that the frost-free season decreases over the first 15 km inland by one day for every one to two km. This is substantiated in a study of the Great Lakes' influence on frost dates in spring and fall by Kopec (1967).

### *Estimated freeze dates for selected risk levels and critical temperatures*

Results of analyses of frost dates (0°C) at selected risk levels are shown in Table 5 for the fifteen available stations grouped by frost dates at 50% risk. Frost dates at the 25% risk level (1 year in 4) were, on average, about one week later in spring and earlier in fall than the 50% date. However, for stations in group A, this difference increased to 9 days later in spring and 11 days earlier in fall. Differences between the 50% and 10% risk dates averaged near 12 to 14 days for stations in groups C, D, and E, but were significantly higher for stations in group A.

Results of analyses of freeze dates for selected threshold temperatures between 0°C and −4.4°C (24°F) are summarized in Table 6 for the 50% risk level only. Calculations for 35, 20 and 10% risk levels yielded similar results and therefore are not shown. Mean differences between freeze dates for 0°C and for other critical temperatures (in days/°C) range from a low of 5 days/°C for stations in group C, to a high of 10 days/°C for group A. As a result, different criteria for estimating freeze dates at critical temperatures below 0°C from the mapped 0°C frost dates are required in different geographic regions of Ontario. Variations within groups were often quite small as indicated by the relatively low standard deviations in differences (days/°C) based on individual station data. However, stations in group A had rather large standard deviation in the fall (3.5 days/°C), indicating that criteria for estimating freeze dates would be less reliable in parts of northern Ontario.

The freeze dates published by Coligado *et al.* (1968) for the 1931–60 period were based on the assumption that freeze dates for a given critical temperature were normally distributed around a mean date. When data from Ottawa for the period 1901–84 were plotted on a probability scale the relationship between date of last spring frost and probability was mostly linear, indicating a

TABLE 5. Number of days* difference between the 50% risk date of 0°C frost in spring and in fall and the dates for lower risk levels

| | | Difference from the 50% probability frost date (days) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Spring | | | | | Fall | | | | |
| | | Frost date | Risk | | | | Frost date | Risk | | | |
| Group | Stations | (50% risk) | 33% | 25% | 20% | 10% | (50% risk) | 33% | 25% | 20% | 10% |
| A | Armstrong, Ont. | June 22 | 5.5 | 9 | 11 | 17 | Aug 22 | 6.5 | 11 | 14 | 21 |
| | White River, Ont. | June 23 | 6.5 | 9 | 11 | 17 | Aug 5 | 7 | 11 | 13 | 20 |
| | average: | | 6.0 | 9.0 | 11.0 | 17.0 | | 6.8 | 11.0 | 13.5 | 20.5 |
| B | Kapuskasing, Ont. | June 5 | 6 | 9 | 11 | 16 | Sep 10 | 4.5 | 7 | 9 | 13 |
| | Lennoxville, Que. | May 29 | 5.5 | 8 | 10 | 15 | Sep 14 | 4.5 | 6 | 8 | 12 |
| | average: | | 5.8 | 8.5 | 10.5 | 15.5 | | 4.5 | 6.5 | 8.5 | 12.5 |
| C | L'Assomption, Que. | May 15 | 4.5 | 6 | 8 | 12 | Sep 22 | 3.5 | 5 | 6 | 9 |
| | Fort Frances, Ont. | May 19 | 6 | 9 | 11 | 16 | Sep 22 | 5 | 7 | 9 | 15 |
| | North Bay, Ont. | May 19 | 3.5 | 5 | 7 | 11 | Sept 24 | 3.5 | 5 | 6 | 10 |
| | Morden, Man. | May 22 | 3.5 | 6 | 8 | 12 | Sep 22 | 4.5 | 6 | 8 | 13 |
| | Winnipeg, Man. | May 24 | 5.5 | 8 | 10 | 15 | Sep 20 | 3.5 | 6 | 7 | 11 |
| | average: | | 4.6 | 6.8 | 8.8 | 13.2 | | 4.0 | 5.8 | 7.2 | 11.6 |
| D | Delhi, Ont. | May 15 | 4.5 | 7 | 9 | 13 | Oct 1 | 4.5 | 7 | 8 | 13 |
| | Guelph, Ont. | May 11 | 4.5 | 7 | 8 | 13 | Oct 3 | 4.5 | 7 | 8 | 12 |
| | Ottawa, Ont. | May 13 | 3.5 | 6 | 7 | 11 | Sep 28 | 4.5 | 6 | 8 | 12 |
| | average: | | 4.2 | 6.7 | 8.0 | 12.3 | | 4.5 | 6.7 | 8.0 | 12.3 |
| E | Belleville, Ont. | May 7 | 6.5 | 9 | 11 | 17 | Oct 5 | 4 | 6 | 8 | 12 |
| | Harrow, Ont. | May 2 | 4 | 6 | 8 | 12 | Oct 13 | 6 | 8 | 10 | 15 |
| | Vineland Station, Ont. | Apr 24 | 5 | 7 | 9 | 14 | Oct 19 | 5.5 | 8 | 10 | 15 |
| | average: | | 5.2 | 7.3 | 9.3 | 14.3 | | 5.2 | 7.3 | 9.3 | 14.0 |

* Calculated from data by Coligado *et al.* 1968.

TABLE 6. Number of days difference between freeze dates (50% risk) for 0°C and for selected temperatures below 0°C

| | | | Days before/after the average date of occurrence of 0°C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Average spring/fall frost date | Spring | | | | | | Fall | | | | | |
| | | | Temperature (°C) | | | | Mean† | Sd†† | Temperature (°C) | | | | Mean† | Sd†† |
| Group | Stations | (0°C) | −1.1 | −2.2 | −3.3 | −4.4 | (days/°C) | | −1.1 | −2.2 | −3.3 | −4.4 | (days/°C) | |
| A | Armstrong<br>White River | June 22–23/<br>Aug 5–22 | 9.5 | 20.0 | 28.0 | 33.5 | 8.4 | 1.0 | 13.5 | 23.0 | 29.5 | 36.5 | 9.9 | 3.5 |
| B | Lennoxville<br>Kapuskasing | May 29–June 5/<br>Sep 10–14 | 8.5 | 14.5 | 19.5 | 28.0 | 6.6 | 0.8 | 5.5 | 12.0 | 18.5 | 28.5 | 5.6 | 1.3 |
| C | Morden<br>Winnipeg<br>Fort Frances<br>North Bay<br>L'Assomption | May 15–24/<br>Sep 20–24 | 6.0 | 11.4 | 17.4 | 23.4 | 5.3 | 0.5 | 5.2 | 11.2 | 16.0 | 23.4 | 5.0 | 0.8 |
| D | Ottawa<br>Delhi<br>Guelph | May 11–15/<br>Sep 28–Oct 3 | 6.0 | 14.0 | 22.0 | 28.7 | 6.2 | 0.6 | 5.3 | 12.3 | 19.3 | 28.0 | 5.6 | 0.9 |
| E | Belleville<br>Harrow<br>Vineland Station | Apr 24–May 7/<br>Oct 5–19 | 7.7 | 15.3 | 23.0 | 29.3 | 6.8 | 0.6 | 7.3 | 16.3 | 24.3 | 31.7 | 7.1 | 1.3 |

† Average number of days/°C for all four temperatures below 0°C.

†† Standard deviation of number of days difference (in days/°C) based on individual data for all stations in each group and all four threshold temperatures.

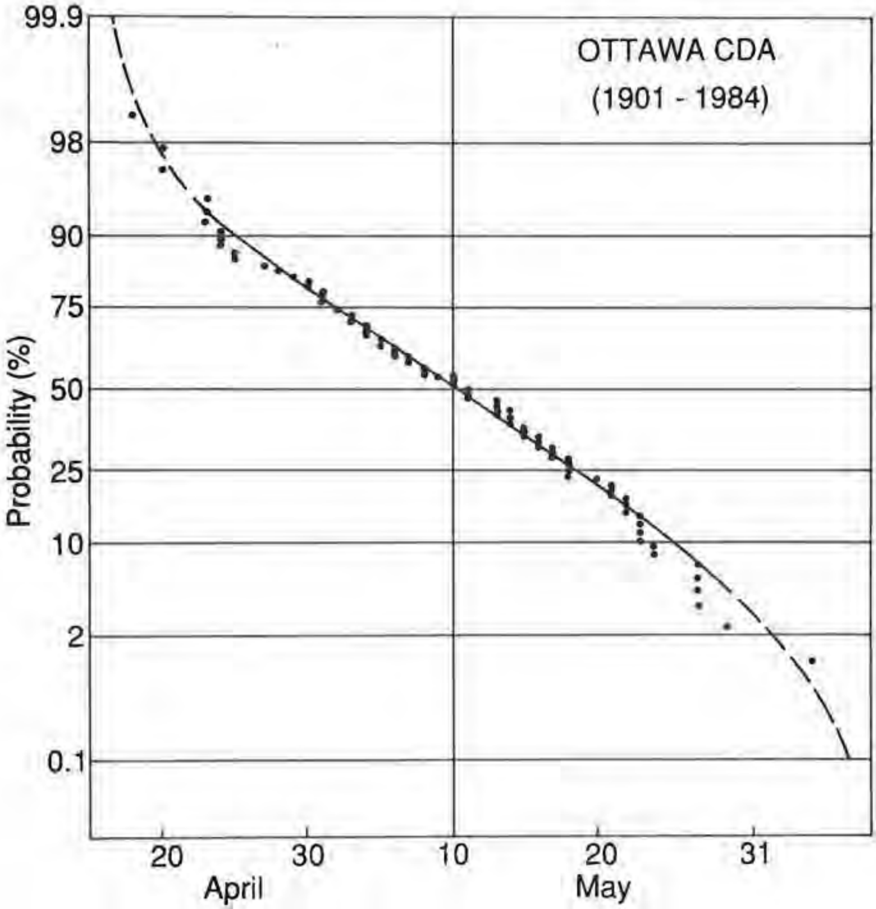


FIGURE 6. Probability (risk) of occurrence of last spring frost (0°C) at Ottawa CDA station based on 84 years (1901–1984).

normal distribution (Figure 6). However, this relationship deviated from linearity at both extremes of the curve where occurrences were less frequent. The data published by Coligado *et al.* (1968) also had been smoothed to eliminate inconsistencies caused by relatively small sampling periods (Robertson and Russelo 1968). To determine whether period of record, smoothing and assumptions of normality had significant effects on the results, the freeze dates of Coligado *et al.* (1968) were compared with unsmoothed data based on periods ranging from 54 to 84 years at five selected locations. Differences between the frost date (0°C) at 50% and at other selected probabilities (10, 20, 25 and 33%) were very similar for both sets of data at Ottawa, Delhi and Harrow. However, at Kapuskasing the differences in frost dates were 2–3 days less in spring and 2–6 days greater in fall for the 1918–84 period (unsmoothed data) than for the 1931–60 period (smoothed data). The greater fall differences were more typical of the two northern Ontario stations in group A (Table 5). Effects on differences in freeze dates between 0°C and lower threshold temperatures at selected risk levels ranging from 10 to 50% also were generally small for the five stations studied. For example, differences in freeze dates for 0°C and −4.4°C for the 1931–60 period were within 2 days of the differences determined for longer-term unsmoothed data in 50% of cases and within 4 days in 90% of cases. However, at Ottawa the differences between dates for 0°C and −2.2°C in spring were 6 days greater for the 1901–84 data at both 20% and 33% risk. Apparently, unusually late occurrences of −2.2°C (i.e. after mid-May) at Ottawa were much more frequent during the 1931–60 period than during earlier and later years.

Based on the foregoing results, rules-of-thumb were formulated which (a) estimate frost dates for 0°C at 10% and 25% risk levels from the average (or 50% risk) date (Table 7) and (b) estimate freeze dates for critical temperatures below 0°C (to as low as −4.4°C) from the dates for 0°C (Table 8). Adjustments

TABLE 7. Rules-of-thumb for estimating 0°C frost dates at 25% and 10% risk from the average (50% risk) date

| Season | Average frost date (0°C) | Adjustment to estimate frost dates from average (50% risk) date: 25% risk (1 year in 4) | 10% risk (1 year in 10) |
|---|---|---|---|
| Spring | Before May 31 | 7 days later | 14 days later |
| | On or after May 31 | 9 days later | 17 days later |
| Fall | On or before Sep 5 | 10 days earlier | 20 days earlier |
| | After Sep 5 | 7 days earlier | 14 days earlier |

TABLE 8. Rules-of-thumb for estimating freeze dates for critical temperatures to −4.4°C for any risk level between 10 and 50%

| Spring: Average frost date (0°C) | Adjustment from 0°C date* (days/°C) | Fall: Average frost date (0°C) | Adjustment from 0°C date* (days/°C) |
|---|---|---|---|
| Jun 16 or later | 9 | Aug 25 or earlier | 11 |
| May 27–Jun 15 | 7 | Aug 26–Sep 5 | 7 |
| May 16–26 | 5 | Sep 6–17 | 5.5 |
| May 8–15 | 5.5 | Sep 18–26 | 4.5 |
| May 7 or earlier | 7 | Sep 27–Oct 4 | 5.5 |
| | | Oct 5 or later | 7 |

* Freeze dates for temperatures below 0°C are estimated by applying adjustments to the 0°C frost dates at any specified probability level between 10 and 50%. Dates for lower temperatures are earlier in spring and later in fall than the 0°C date.

depend on the season and the time of occurrence of the average frost date (0°C). As a rule, 0°C frost dates at the 25% risk level differ from the average dates by 7 to 10 days. At the 10% risk level, differences are 14 to 20 days. Adjustments in freeze dates for critical temperatures below 0°C are greatest (9–11 days/°C) in regions with late spring and early fall frosts and least (5–6 days) in regions where average frost dates are in the mid-range. An overall rule of adjusting freeze dates by 6 days for each 1°C drop in critical temperature would apply well to most regions except where average dates of last or first frost are after mid-June or before late August.

## CONCLUSIONS

This study has shown that average spring and fall frost dates (0°C) in Ontario can be estimated within an accuracy of 3 to 5 days using predictor variables based on temperature normals in regression models. These models are useful for estimating frost dates for short-term stations with temperature normals adjusted to a 30-year period to increase station density for mapping.

Relationships between average (50% risk) frost dates for 0°C and for lower risk levels and between those for 0°C and for threshold temperatures to −4°C were generally quite consistent. Consequently, reliable rules-of-thumb were developed to estimate freeze dates for various risk levels and critical temperatures from the average frost dates (0°C) in spring and fall. These procedures make it possible to present information on freeze dates for a range of risk levels on a relatively broad geographic scale, for agricultural extension information, with the use of only two maps.

## ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance of the agrometeorological data processing staff of the Land Resource Research Centre, Agriculture Canada with computer data processing, L. Houwing for preparing graphs and J. De Castro for typing the manuscript. We also acknowledge with thanks the preparation of maps by A. McLennan and stenographic assistance by S. Laycock of the Department of Land Resource Science, University of Guelph. Reviews of an earlier version of this paper by K.M. King, L.R.S., University of Guelph and S.N. Edey, L.R.R.C., Agriculture Canada, Ottawa were sincerely appreciated.

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# Some Aspects of the Interannual Variability and Persistence of Global Atmospheric and Oceanic Surface Temperatures

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[Original manuscript received 24 March 1989;
in revised form 10 May 1989]

ABSTRACT

Long-term data bases for northern and southern hemisphere monthly mean surface temperature anomalies and for global seasonal mean sea surface temperature anomalies have recently become available. This has made it possible to examine the interannual variability and persistence of these anomalies and the relationships among them. Studies of global thermodynamics using these data can lead to an improved understanding of the physics of the climate system, and of the possibility of climate forecasting. By applying high pass filtering coupled with temporal integration to these time series, we have shown that the resulting cumulative temperature anomaly series exhibit a bounded oscillatory behaviour. Moreover, all three of these cumulative anomaly series show a similar structure. They have comparable amplitudes and exhibit a significant degree of phase coherence. There is also a tendency towards persistence, in above- or below-normal states, with rapid transitions between them.

RÉSUMÉ

Des bases de données à long terme des anomalies de la température moyenne de l'air à la surface dans les hémisphères Nord et Sud se sont récemment faites disponibles, ainsi que celles de la température moyenne globale de la surface océanique. Ceci a facilité l'étude de la variabilité interannuelle et de la persistance de ces anomalies et des liens entre elles. Il est possible que des études globales thermodynamiques se servant de ces données permettent d'améliorer la compréhension de la physique du système climatique et la capacité de faire des prévisions climatiques. L'application d'un filtre à haute passe ainsi que d'une intégration temporale à ces séries de données nous a permis de démontrer que les séries des anomalies cumulatives de température en résultant suivent une oscillation limitée. D'ailleurs, toutes les

trois séries se structurent de la même façon. Elles possèdent des amplitudes semblables ainsi qu'une certaine cohérence de phase. Elles ont tendance également à la persistance, en présentent souvent des valeurs successives qui excèdent la moyenne et qui font ensuite l'opposé, avec des transitions rapides entre ces deux états.

## 1. INTRODUCTION

Statistical techniques, such as power spectrum analysis, applied to long meteorological time series (e.g. Jones *et al.* 1986a, b; Folland *et al.* 1984) can be both informative and misleading. When significant peaks in the power spectrum can be related to well-known physical oscillations (e.g. the sunspot cycle), one may infer a cause-effect relationship and try to look for the controlling mechanisms. Schönwiese (1987), however, has shown that the power spectrum may vary with time, implying that inferences made on the basis of the entire time series must be viewed with circumspection, especially if one wishes to use them for the purpose of forecasting through extrapolation of the series. In order to obviate some of these difficulties, in this paper we have applied a new approach to the analysis of three global temperature time series.

Figure 1 shows a 137 year time series of monthly mean northern hemisphere surface temperature anomalies, from data presented by Jones *et al.* (1986a). The anomalies are defined relative to the average monthly mean temperatures for the entire series. This series is clearly noisy, but it also exhibits low frequency variability. We have indicated this on the figure as a smooth curve. It is obtained by applying a 145 point Gaussian filter, with standard deviation of 21.2 months, to the series of monthly mean temperature anomalies. According to

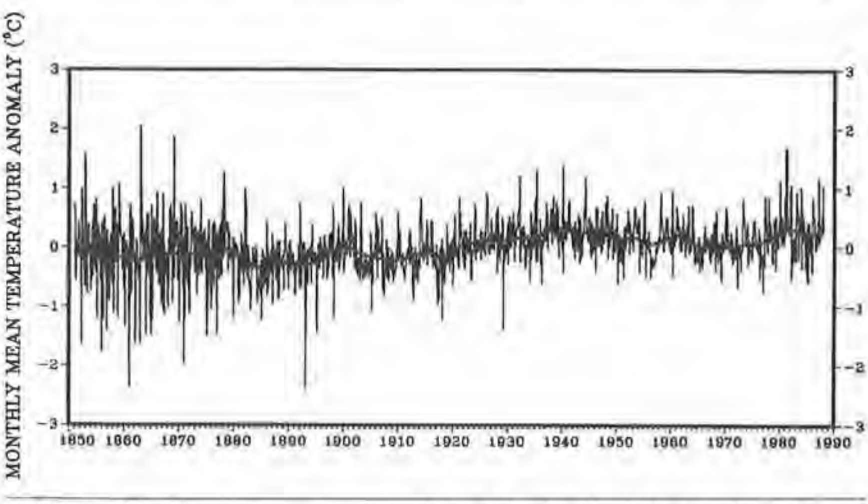


FIGURE 1. Monthly mean temperature anomalies for the Northern Hemisphere based on the data of Jones *et al.* (1986a, b). The smooth curve has been obtained by applying a Gaussian filter to the annual mean anomalies (see text for details).

Jones *et al.* (1986a), who use a similar filter, this filter is "designed to suppress variations on time scales less than 10 years". This low frequency curve shows the warming trend of about 0.5°C which has been attributed by some to the greenhouse effect. Whatever the cause, we prefer to think of it as a time-varying "mean" for the higher frequency interannual variability.

Consequently, in order to examine the interannual variability of this series, we subtracted the filtered curve from the raw series, thereby effectively applying a high pass filter. The resulting series was then integrated to yield a cumulative temperature anomaly series. The net effect of this processing is to apply a band-pass filter to the raw anomalies. The details of this filter and some justification for the procedure have been described by Lozowski *et al.* (1989). We had three things in mind when applying this integration step. First, the integration suppresses month-to-month variability in the signal, while still retaining the original monthly data, since the slope of the cumulative anomaly curve yields the anomaly itself. Second, temporal integration reinforces persistence in the anomalies, making persistence easily recognizable. Finally, we suspected that the cumulative temperature anomaly might be an important climate variable in itself. Cumulative temperatures are used, for example, in growing and heating degree days, and cumulative precipitation is known to be related to lake levels (Changnon, 1987). However, our use of the concept is rather different in the sense that we consider cumulative anomalies over the entire record, rather than over an interval of a few months or a few years.

The resulting cumulative temperature anomaly series for the northern hemisphere is the upper curve in Figure 2. Because the quality of the data is best after about 1900, we will restrict out attention to the 20th century. The oscillatory behaviour of this curve is clearly bounded. The extreme amplitudes over the series are approximately $\pm$ 4°C-months. The curve is characterized by spells of generally persistent anomalies (rising and falling being associated with warm and cold anomalies respectively) lasting from a few months to a few years. Spells of opposite sign are often linked by rapid transitions (sharp maxima and minima). Because the curvature of the graph is related to warming (minima) and cooling (maxima), the sharpness of the peaks and troughs is indicative of the rapidity of the transitions. Since surface temperature anomaly data for the southern hemisphere (Jones *et al.* 1985b) and for the global ocean sea surface (Folland *et al.* 1984) were also available (the latter in the form of seasonal rather than monthly averages), we decided to examine them too, in order to look for possible relationships among these three components of the climate system. Since the monthly sea surface temperature anomaly data were not available to us, we created a monthly time series from the seasonal time series by giving each month in the season the same anomaly as the season itself. The southern hemisphere and oceanic time series were treated in the same way as the northern hemisphere time series, and the resulting cumulative anomaly curves are also displayed in Figure 2. They have however been offset by 10 and 20°C-months respectively for clarity.

The coincidence in all three time series of the most significant maxima

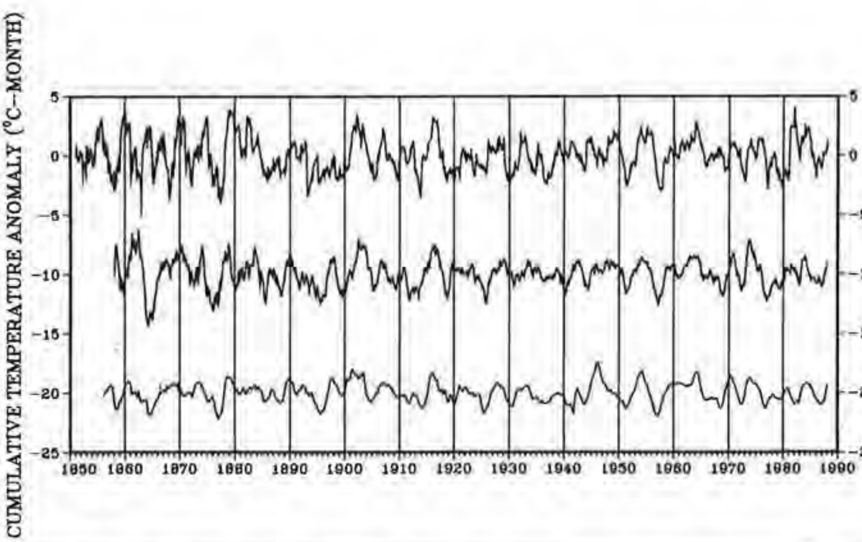


FIGURE 2. Cumulative high frequency monthly mean temperature anomalies for the Northern Hemisphere (top) and the Southern Hemisphere (middle). The bottom curve is the cumulative high frequency seasonal mean sea surface temperature anomaly for the global ocean. The two lower curves have been offset by 10 and 20°C-months respectively for clarity.

and minima suggests a common physical mechanism driving the oscillations. The overall amplitudes are similar for all three, and the atmospheric series and the oceanic series appear to be almost in phase with each other. This suggests to us that the common mechanism may be heat transfer between the ocean surface and the atmosphere. This general picture, however, must be qualified by pointing out that the amplitudes of the oscillations in the three systems are not always comparable, nor are they always close to being in phase. Moreover while in some decades the three curves are obviously similar (e.g. in the 50's), in others the relationship is much less obvious (e.g. in the 40's).

## 2. A SIMPLE MODEL OF OCEAN-ATMOSPHERE HEAT TRANSER

A simple linear heat transfer model can be helpful in examining these intuitive arguments. The first law of thermodynamics for an atmosphere heated only by sensible heat transfer from the ocean may be expressed as:

$$C_a \frac{dT_a}{dt'} = h(T_w - T_a) \tag{1}$$

where $C_a$(Jm$^{-2}$K$^{-1}$) is the heat capacity per unit area of the atmosphere and $h$(Wm$^{-2}$K$^{-1}$) is the heat transfer coefficient. $T_w$ and $T_a$ are respectively the ocean surface and mean column atmospheric temperatures respectively and $t'$ is the time. We are assuming of course that the column temperature and atmospheric surface temperature anomalies will be correlated on an interannual time scale. If $h$ and $C_a$ are considered to be constant parameters, the equation is linear and may be thought of as applying to the temperature anomalies as well as to the temperatures themselves. While we recognize that latent and radiative heat transfers will not necessarily be linear functions of $(T_w - T_a)$, we believe that this simple model will at least give a first-order insight into the problem.

Defining $\alpha = \frac{\;}{C_a}$ and a non-dimensional time $t = \alpha t'$, the formal solution to this equation is:

$$T_a(\tau) = T_a(0)\, e^{-\tau} + \int_0^{\tau} T_w(t)\, e^{-(\tau - t)} dt \tag{2}$$

If we allow the ocean temperature anomaly to oscillate sinusoidally about a mean value of zero, viz:

$$T_w = T_{wa}\, sin(\omega t) = T_{wa} sin(\omega' t') \tag{3}$$

where $\omega$ and $\omega' = \omega\alpha$ are respectively the non-dimensional and dimensioned radian oscillation frequencies, and $T_{wa}$ is the amplitude of the oscillation, the solution then becomes:

$$T_a(\tau) = (T_a(0) + T_{wa} \frac{\omega}{1 + \omega^2})\, e^{-\tau} + \frac{T_{wa}}{(1 + \omega^2)^{1/2}} sin(\omega\tau + \beta - \frac{\pi}{2}) \tag{4}$$

where $\beta = \mathrm{Cot}^{-1}(\omega)$.

Since $T_a(0)$ is arbitrary, we may choose it such that the first term is zero for simplicity. Then, re-introducing the dimensioned variables:

$$T_a(\tau') = \frac{T_{wa}}{(1 + (\frac{\omega'}{\alpha})^2)^{1/2}} sin(\omega' \tau' + \beta - \frac{\pi}{2}) \tag{5}$$

Thus the amplitude and phase difference between the atmospheric and oceanic oscillations depends on the relative magnitudes of the oscillation period, $\frac{1}{\omega'}$, and the time constant for the system, $\frac{C_a}{h}$. If $\frac{\omega' C_a}{h} \rightarrow 0$ (infinite heat transfer coefficient or infinitely long oscillation period), the atmosphere simply mimics the ocean. As $\frac{\omega' C_a}{h}$ increases, the atmospheric amplitude diminishes with respect to that of the ocean and the phase lag increases towards $\frac{\pi}{2}$. Taking reasonable estimates for $\frac{1}{\omega'} = 1.5 \times 10^7$ (oceanic period of three years), $C_a = 1.0 \times 10^7 \mathrm{Jm^{-2}K^{-1}}$,

$h = 10\ \mathrm{Wm^{-2}K^{-1}}$ yields $\frac{\omega' C_a}{h} = 6.7 \times 10^{-2}$. For this case the amplitude reduction is 0.998 and the phase lag is 0.5 months. Thus it would not be unreasonable to expect to see comparable amplitudes and phase lags of the order of a month in our data, if ocean-atmosphere heat transfer were the driving mechanism of the atmosphere. However, ratios of atmospheric to oceanic amplitudes exceeding unity, and phase lags exceeding $\frac{\pi}{2}$, cannot be explained by such a simple model, even though they do occur on occasion in these cumulative series.

## 3. DISCUSSION

Naturally this discussion begs the question of what causes the oceanic oscillation. We are not in a position to try to answer this question here. Suffice it to say that many of the minima (warming) in the oceanic and atmospheric time series are associated with major El Niño events, 1911, 1918, 1925, 1941, 1957, 1972, 1982/83, 1986/87 (Quinn, 1978). However, there is not a simple one-to-one correspondence, and there are significant minima (e.g. 1951, 1968) which do not appear to have a connection with El Niño. Thus one must look to ocean areas other than the equatorial Pacific to explain some of the interannual variability. There is the possibility that a common external forcing or radiative feedback process is driving both the atmosphere and the ocean surfaces on these time scales. It could also be that the oscillation is stochastically driven by the "weather noise", or by some internal instability of the atmosphere-ocean system.

We will conclude with a very brief discussion of the problem of short-term climate forecasting, i.e. extrapolation of these time series over a few months or years. Clearly month-to-month weather noise significantly affects the very short-term outlook (monthly to seasonal). Certainly the present work is unable to provide a basis for forecasting such short time-scale fluctuations. Over the long term (decades), extrapolation of the series can only be accomplished through an understanding and modelling of the physics of atmosphere-ocean interaction. Over the intermediate term (several months to a couple of years), however, it may be possible to forecast using "constrained long-term persistence", that is, extrapolation of the smoothed cumulative time series, bearing in mind that the oscillation is bounded. We are not yet in a position, however, to say precisely how much a knowledge of the boundedness of the oscillation and the time scale of the persistence would add to simple monthly or seasonal persistence as a forecasting tool, or what skill, if any, such a method might have.

## 4. ACKNOWLEDGEMENTS

We are most grateful to P.D. Jones, who updated the northern and southern hemisphere temperature anomaly time series for us, to D.E. Parker, who provided us with the sea surface temperature anomalies, and to R. Wong and J. Wilson, with whom we have had some very helpful interaction on these matters. The assistance of P. Buttuls with computer graphics has been invaluable. This work has been supported through an NSERC operating grant.

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# The Incidence of Noctilucent Clouds Over Western Canada in 1988

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[Original manuscript received 19 June 1989]

ABSTRACT

From twenty-four western Canadian locations, noctilucent cloud activity was monitored in 1988 by the NLC CAN AM (Noctilucent Cloud Canadian American) network. Searches took place between mid-May and mid-August, with one arctic site doing so in April and September. Both positive and negative sightings, the latter determined by at least two readings under favourable conditions, are plotted on a date-latitude graph. An early July peak was observed by participants south of the sixtieth parallel, and a northerly shift of detectable cloud fields later in the summer was realized. Occurrences decreased with longitude, though tropospheric cloudiness may have been a major determinant factor.

RÉSUMÉ

De vingt-quatre endroits situés dans l'Ouest du Canada, l'activité des nuages noctulescents a été contrôlée en 1988 par le réseau NLC CAN AM (Noctilucent Cloud Canadian American). Des recherches furent menées entre mi-mai et mi-août mais aussi à un site arctique en avril et en septembre. Les observations positives et négatives, ces dernières détérminées au moins deux fois la nuit en conditions favorables, sont tracées sur un graphique date-latitude. Au début du mois de juillet, une activité intense fut observée par des participants au sud du soixantième parallèle et l'on remarqua un déplacement vers le nord de champs de nuages détectables plus tard l'été. La fréquence a diminué avec la longitude, résultat probablement de la densité plus forte de nuages troposphériques.

During the spring and summer of 1988, observations of noctilucent clouds (abbreviation: NLC) were conducted throughout Canada by the NLC CAN AM network, whose participants consist of personnel at weather and flight service stations, along with amateur astronomers. Formed in 1987, the group endeavours to preserve the continuity of NLC climatological data collection, which was halted in 1983 with the termination of similar efforts by the Atmospheric Environment Service of Canada.

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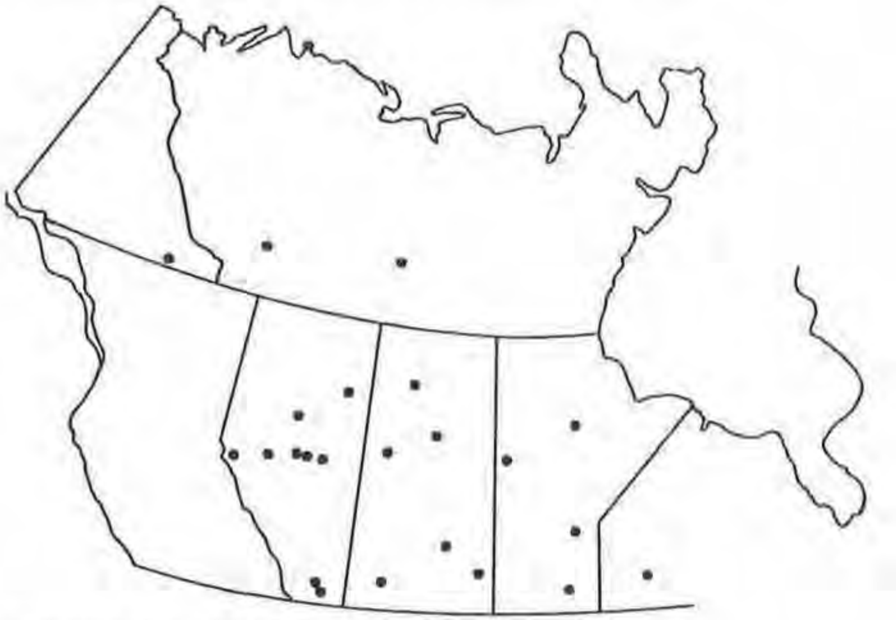
Instructions were forwarded to observers by the coordinator (MZ) before the commencement of the official observing period of 15 May to 15 August, 1988. These included, in most instances, special report forms and schedules outlining the time intervals during which noctilucent clouds can be seen. At the season's conclusion, the completed forms were returned. Emphasis was placed upon recording the presence or absence of NLC to ascertain the extent of activity, both temporally and geographically, over the North American continent.

The greatest degree of participation was concentrated between the longitudes of 90°W and 130°W (Fig. 1). Table 1 presents the reports of both



Observers in this survey were:

*Atmospheric Environment Service of Canada Stations:*
Broadview, SK; Cape Barry, NWT; Cree Lake, SK; Edson, AB; Fort Reliance, NWT; Lethbridge, AB; Meadow Lake, SK; Slave Lake, AB; Wynyard, SK.

*Transport Canada Flight Service Stations:*
Western Observers: Fort Simpson, NWT; La Ronge, SK; Sioux Lookout, ON; Swift Current, SK; The Pas, MB; Thompson, MB; Watson Lake, YT.
Eastern Observers: Schefferville, PQ; Sept-Îles, PQ; Wabush, NF. (not shown on map)

*Individuals:*
Western Observers: Peter Brown, Helen Hawes, Robert Howell, Fort McMurray, AB; Alister Ling, Edmonton, AB; Todd Lohvinenko, Winnipeg, MB; Cheryl Matsugi, Raymond, AB; Don Thacker, Vegreville, AB; Mark Zalcik, Namao, AB.
Eastern Observers: Michael Boschat, Halifax, NS; Steve McKinnon, Oakville, ON. (not shown on map)

FIGURE 1. Noctilucent cloud observing stations in western Canada during 1988.

positive and negative sightings of noctilucent clouds by observers in this region. Positive nights were designated on the basis of a minimum of one NLC sighting; negative nights were determined by a minimum of two sky checks per night, both within the period of NLC visibility, and one on either side of local midnight. If, for each reading, no NLC were noticed, and the northern half of the sky contained no more than a trace of tropospheric cloud, then the evening was deemed to be free of NLC as reported from that site. Some places, namely Watson Lake, Fort Simpson, Fort Reliance, and Cape Parry, for several nights encompassing the summer solstice, were able to take only one hourly reading per night because of bright twilight conditions. In these cases, the lone observation was used for negative night determinations. Cape Parry's observation period was 1 April to 30 April, and 15 August to 15 September. Regarding the amateur astronomers, sky checks made from supplementary sites within a 100 km radius of their principal observing locations are included in those sites' data. Outlying locales were Hecla Island (TL) and Jasper (MZ).

As NLC are visible only when the sun is approximately 6° to 16° below the observer's horizon (Paton, 1964), readings in this study were screened for eligibility by computer to ensure that corresponding solar depression angles (SDA's) were between these values. Fig. 2 excludes nights with all positive observations having SDA's less than 6.0° or greater than 16.0°. Similarly, negative nights with all pre- and/or post-local midnight clear sky readings outside this SDA range are also deleted. Sites are positioned along the vertical axis as a function of latitude, as depicted by Christie (1967). Positive nights are marked by open squares, and negative nights by closed circles. The absence of symbols denotes a wide variety of prohibitive variables, including tropospheric cloudiness, lack of observations, and insufficiently or incorrectly completed forms.

Maximum noctilucent cloud activity above western Canada in 1988 occurred at the beginning of July. The first ten-night interval contained positive reports for every night; after a brief lull at mid-month, a minor maximum occurred before a decline in positive sightings. Vestine (1934), in a statistical review of past observations, obtained an early July peak. Fogle (1966), from North American data gathered in 1962–65, found it to be about three weeks later, and indicated NLC may be seen from at least one location in North America nearly every night in July. A total of twenty-one active nights were recorded in July 1988 from the sites in western Canada. This may suggest that NLC were no less prolific than in 1962–65.

There is less agreement with previous seasons' activity when considering the effect of latitude on detection probability. Fogle and Haurwitz (1966) showed that the peak occurrence between 50° N and 55° N is 8 July, 55°N to 60°N, 18 July, and 60°N to 65°N, 28 July. Most NLC CAN AM observers within the first latitudinal zone did record the majority of their displays in early July. Others further north were able to detect more events in subsequent weeks, but not with the greater frequency suggested in the above study. Perhaps this was partially due to the comparative deficiency of sites in the 55°N to 60°N latitude range, a

TABLE 1. Positive and negative sightings of noctilucent clouds over western Canada in 1988. A key to site abbreviations is at the bottom of the table.

| Date -Night of | | Sites | Date -Night of | | Sites |
|---|---|---|---|---|---|
| *POSITIVE OBSERVATIONS* | | | | | |
| May | 15 | EDS | July | 8 | WAT FTM SLA MEA |
| June | 1 | NAM | | | NAM EDM VEG SWI |
| | 3 | EDM | | | LET RAY |
| | 9 | RAY | | 9 | CRE FTM SLA LAR |
| | 14 | NAM | | | NAM VEG |
| | 18 | FTM SLA MEA NAM | | 10 | LET |
| | | EDM VEG WYN LET | | 11 | WYN LET |
| | 19 | CRE FTM SLA EDM | | 13 | LAR |
| | | WYN BRO RAY | | 17 | SLA VEG WYN |
| | 20 | CRE NAM | | 18 | WAT EDM |
| | 24 | FTM SLA MEA NAM | | 19 | LAR |
| | | EDM VEG WYN BRO | | 20 | EDS |
| | 26 | WAT | | 21 | EDS |
| | 27 | RAY | | 22 | FTS MEA EDM |
| | 29 | LET | | 23 | FTS FTM |
| | 30 | MEA | | 29 | LET |
| July | 1 | FTM WYN | | 31 | FTS WAT CRE |
| | 2 | MEA | Aug. | 5 | THO |
| | 3 | THE NAM | | 7 | FTM MAN |
| | 4 | CRE SLA MEA NAM | | 8 | FTR |
| | | EDM VEG | | 9 | THO |
| | 5 | LET RAY | | 10 | MEA |
| | 6 | NAM | | 11 | MEA |
| | 7 | SLA NAM | | 15 | LAR |
| | | | Sept. | 10 | CAP |
| *NEGATIVE OBSERVATIONS* | | | | | |
| April | 1 | CAP | May | 26 | WYN |
| | 2 | CAP | | 27 | SLA |
| | 15 | CAP | | 28 | LET |
| | 16 | CAP | June | 2 | SLA THE NAM WYN |
| | 17 | CAP | | | BRO |
| | 19 | CAP | | 3 | SLA WYN BRO |
| | 21 | CAP | | 4 | SLA BRO |
| | 27 | CAP | | 5 | THE WYN BRO |
| | 28 | CAP | | 6 | WYN BRO |
| May | 15 | BRO | | 9 | EDS BRO |
| | 17 | NAM EDS | | 11 | THE WYN BRO |
| | 18 | EDS | | 12 | WYN |
| | 19 | BRO LET | | 13 | SLA NAM EDS |
| | 20 | SLA NAM WYN | | 14 | SLA EDS LET |
| | 21 | SLA WYN BRO | | 15 | EDS BRO |
| | 22 | BRO | | 16 | WYN BRO WIN |
| | 23 | SLA WYN | | 17 | WIN |
| | 24 | SLA NAM EDS LET | | 18 | WIN |
| | 25 | SLA THE | | 19 | LET |

TABLE 1. Continued

| Date -Night of | | Sites |
|---|---|---|
| *NEGATIVE OBSERVATIONS* Continued | | |
| June | 23 | BRO |
| | 24 | LET |
| | 25 | HEC |
| | 26 | SLA NAM |
| | 27 | BRO |
| July | 3 | WYN |
| | 4 | WIN |
| | 6 | LET |
| | 7 | WYN BRO LET |
| | 8 | EDS BRO |
| | 9 | WIN |
| | 10 | NAM WYN BRO |
| | 11 | EDS BRO WIN |
| | 13 | SLA EDS |
| | 14 | SLA EDS WYN WIN LET |
| | 15 | LET |
| | 16 | WYN BRO |
| | 17 | THE BRO |
| | 18 | SLA JAS |
| | 19 | SLA EDS WYN WIN LET |
| | 20 | SLA THE WYN BRO LET |
| | 21 | BRO LET |
| | 22 | JAS WIN LET |
| July | 23 | BRO |
| | 24 | FTR LET |
| | 25 | SLA |
| | 26 | THE WYN BRO LET |
| | 27 | WIN |
| | 28 | FTR SLA NAM |
| | 29 | THE WYN HEC BRO |
| | 30 | SLA THE WYN LET |
| | 31 | FTR THE |
| Aug. | 1 | CRE EDS |
| | 2 | BRO LET |
| | 3 | THE NAM WYN BRO LET |
| | 4 | WYN BRO LET |
| | 5 | CRE THE WYN BRO |
| | 6 | EDS BRO |
| | 7 | SLA EDS WYN BRO LET |
| | 8 | BRO |
| | 9 | FTR EDS |
| | 10 | FTR WYN BRO |
| | 11 | SLA NAM EDS BRO LET |
| | 12 | SLA NAM EDS WYN BRO |
| | 14 | FTR LET |
| | 18 | CAP |
| Sept. | 3 | CAP |

| | | | | | |
|---|---|---|---|---|---|
| BRO – | Broadview | HEC– | Hecla Island | SWI– | Swift Current |
| CAP– | Cape Parry | JAS– | Jasper | THE – | The Pas |
| CRE – | Cree Lake | LAR – | La Ronge | THO – | Thompson |
| EDM– | Edmonton | LET – | Lethbridge | VEG– | Vegreville |
| EDS– | Edson | MEA– | Meadow Lake | WAT – | Watson Lake |
| FTM – | Fort McMurray | NAM– | Namao | WIN– | Winnipeg |
| FTR – | Fort Reliance | RAY – | Raymond | WYN – | Wynyard |
| FTS – | Fort Simpson | SLA – | Slave Lake | | |

trend magnified even further north. The only four stations poleward from 60°N were too often obscured by tropospheric cloud to foster much meaningful climatological interpretation. Still, a general northerly progression of positive sightings through July, and onward, is apparent.

From the network's 1988 data, longitudinal variations in NLC frequency may also be examined. In western Canada, there seemed to be a gradual decrease in activity with decreasing longitude. For example, in the 50°N latitude

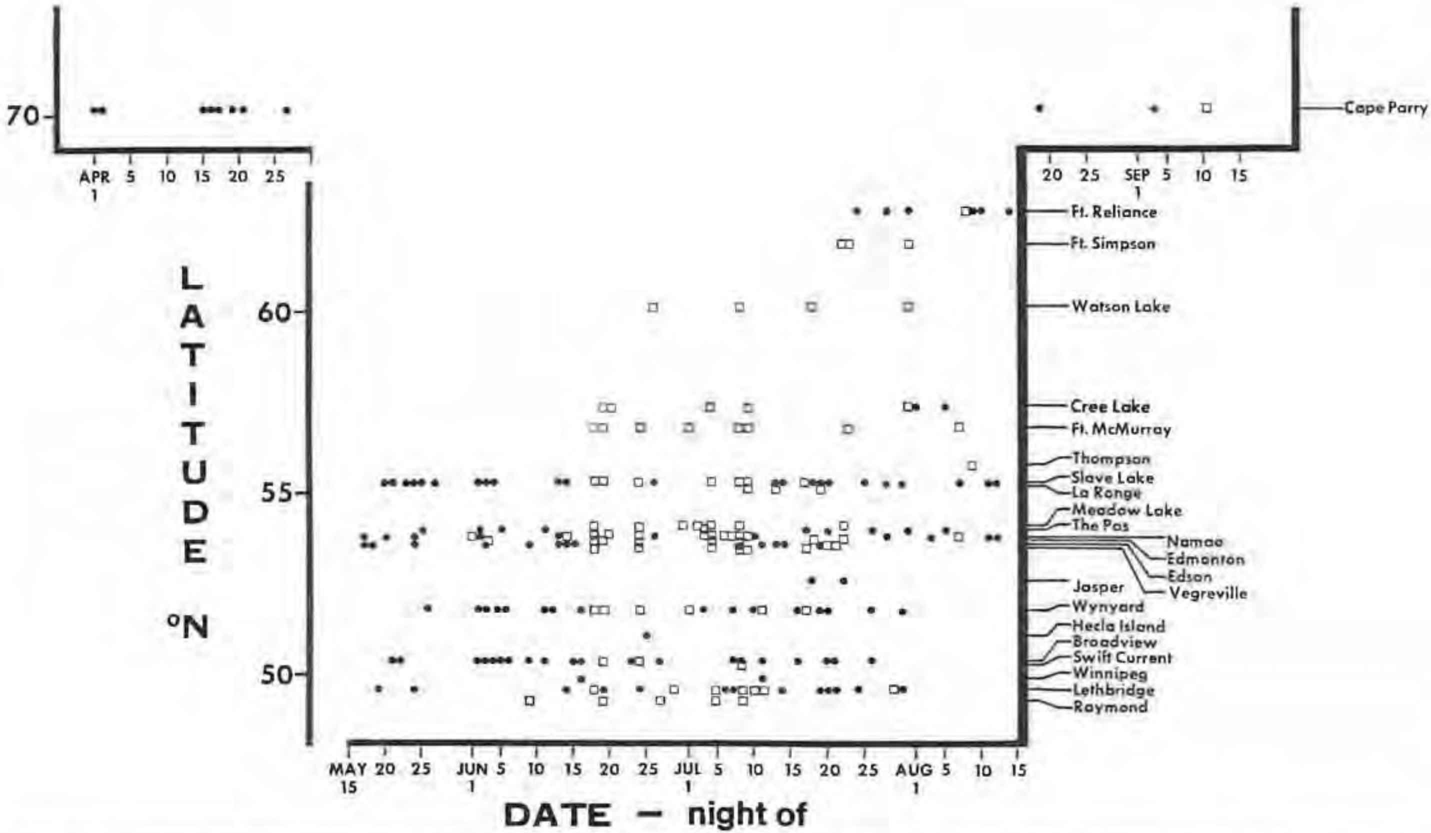



FIGURE 2. Positive and negative sightings of NLC when required number of determining readings had corresponding solar depression angles between 6.0° and 16.0°. Open squares denote positive observations, and closed circles indicate negative reports.

zone, Atmospheric Environment Service observers in Lethbridge (113°W) noted a total of seven NLC displays between 15 May and 15 August. Over ten degrees eastward, Broadview weather station reported only two. Participants in both Winnipeg and Sioux Lookout (97°W and 92°W, respectively), while not making observations through the whole observing period, saw no displays. Though a trend is evident, consideration must be given, as with the above latitudinal synopsis, to the relative distribution of sites in the entire region. Correspondingly, the number of observers also decreased from west to east, with only four members and five sites situated east of the Saskatchewan-Manitoba border. As was apparent with NLC CAN AM's most northerly stations, the influence of tropospheric cloud becomes a more detrimental factor as the number of observers in a given area declines. Thus, with the network's nonuniform observer distribution, it would be overzealous to make any conclusions regarding NLC frequency in relation to longitude.

### ACKNOWLEDGEMENTS

The authors wish to thank R. Bochonko and E. Lozowski for kindly reviewing the manuscript, and S. Carneau, R. Day, and M. Pitt for their assistance in its composition. Providing helpful comments were: I. Cameron, B. Harrison, A. Mardon, H. Noerenberg, G. Pruden and T. Scherban. Special thanks to D. Gavine, Assistant Director of the British Astronomical Association Aurora Section, for continued support of the NLC CAN AM programme.

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# Rainfall Interception in Lichen Canopies

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[Original manuscript received 12 February 1989;
in revised form 12 June 1989]

ABSTRACT

A water-balance study of rainfall interception by the lichen canopy at an upland tundra site near Hudson's Bay in the summer of 1987 showed that only 39% of total rainfall during the measurement period drained through the canopy. In addition, condensation on the lichen surface during rain-free periods produced no drainage. These results tend to support the findings of earlier workers that lichen cover on the open tundra is one of the most efficient at intercepting rainfall.

RÉSUMÉ

En été 1987 on a fait de la recherche sur l'interception des eaux de pluie par la couverture de lichens à un site sec de la toundra près de la baie d'Hudson. D'après la méthode du bilan d'eau, durant la période de recherche il n'y a eu que 39 pour cent des eaux de pluie totales qui se sont écoulées de la couverture. De plus, la condensation sur la surface de lichens lurant des périodes sans pluie n'a produit aucun écoulement. Ces résultats ont tendance à confirmer ceux d'autres chercheurs qui avaient suggéré qu'une couverture de lichens sur la toundra ouverte est l'une des plus efficaces en interceptant les chutes de pluie.

The interception of rainfall by vegetation canopies is the focus of increasing attention because of its dominant effect on the routing of water into the ground and atmosphere. For example, anthropogenic modifications of the landscape have led to the conclusion that afforestation of catchments will result in decreased water yields (Calder 1979). The nutrient status of the natural environment is also dependent on the canopy's role in regulating water flow (Kellman and Sanmugadas 1985), as is the uptake of air-borne contaminants (Grace *et al.* 1985a).

Interception by arctic and subarctic vegetation has received relatively little attention. This is possibly due to the sparse ground cover or dwarf growth habit of plants in many regions.

Lichens form a dominant component of the ground cover in many northern habitats yet the role of the lichen canopy in the water balance is poorly understood. Most studies have focussed only on the evaporative component of the water budget (Kershaw and Rouse 1971; Larson 1979; Grace *et al.* 1985b).

Significantly, the diminutive canopy of lichens blanketing the boreal forest floor and vast areas of open tundra is one of the most efficient at intercepting rainfall. The moisture storage capacity of lichens is double that reported for deciduous and coniferous forests (Gash and Stewart 1977). Only occasionally does precipitation in lichen-dominated environments find its way into the soil water system.

The changes in moisture storage over a discrete time interval can be related to the differences in moisture inputs and outputs from the lichen canopy through the water balance equation as

$$\Delta C = P(1-t) + CO + U - E - D \tag{1}$$

where $\Delta C$ is the change in canopy moisture storage, $P$ is precipitation, $t$ is the proportion of direct throughfall to the soil surface, $CO$ is condensation or distillation, $U$ is liquid water uptake from the substrate, $E$ is evaporation and $D$ is drainage, stemflow or drip to the substrate.

In this paper we report a study of the interception process at an upland tundra site, 4 km from the coast of Hudson's Bay near Churchill, Manitoba (58° 45′ N; 94° 04′ W), during the summer of 1987. Sixteen samples, each 0.04 $m^2$ in surface area comprising primarily *Cladina sp.* lichens, were momentarily removed from the soil surface and manually weighed near sunrise and sunset and shortly after rain events to determine changes in moisture storage. The resolution of moisture storage measurements was 0.025 mm water equivalent. Rainfall was measured with standard rain gauges, 0.3 m above the canopy with a measurement resolution of 0.115 mm. The measurement period began June 9, three days after snowmelt, and extended to August 23, 1987. The field samples were subsequently used in a series of controlled field and laboratory experiments to determine canopy throughfall, drainage and storage characteristics.

Throughfall was estimated indirectly by monitoring direct and diffuse shortwave radiation transmission through the lichen samples in the field. Five pyranometers were used to simultaneously measure incident and transmitted sunlight through four samples ranging from 33 mm to 58 mm in thickness over two clear-sky days. No direct sunlight was transmitted though any of the samples. Maximum diffuse transmission was 3% for the thinnest sample and less than 1% for the thickest sample.

The laboratory experiments involved saturating lichen samples by submersion in water for 10 minutes, then monitoring weight changes resulting solely from drainage in an airtight transparent chamber. The drainage results from a typical sample are shown in Figure 1. Massive initial drainage rates of 300 mm $h^{-1}$ occur for less than two minutes. Drainage rates progressively decrease until all drainage ceases between 78 and 116 minutes. The moisture remaining, or

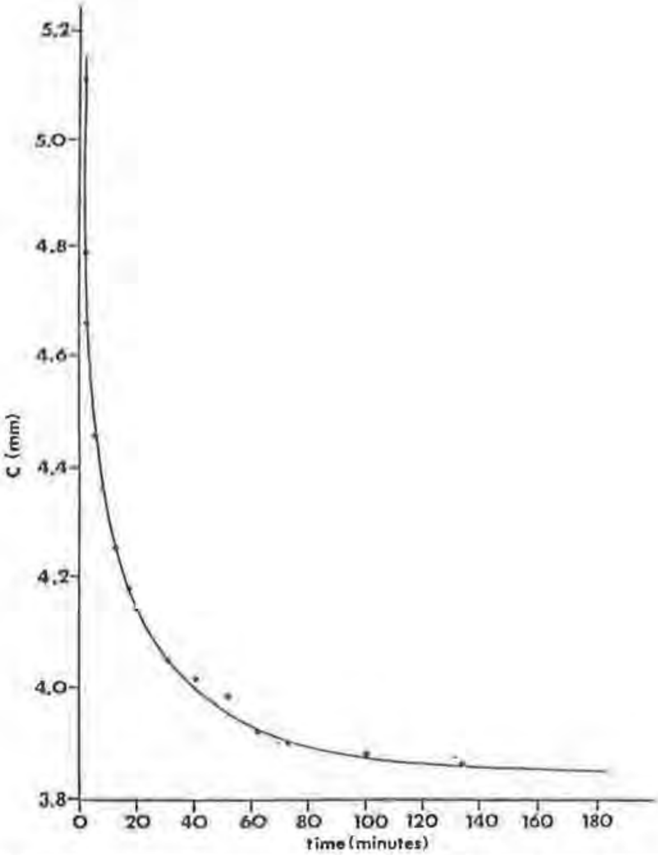


FIGURE 1 The change in canopy moisture storage C over time resulting from drainage in a typical lichen sample.

maximum moisture storage capacity, ranges from 2.89 mm for the lightest samples to 5.17 mm for the heaviest samples with a mean of 4.21 mm. When drainage had ceased no visible water droplets remained on the lichen podetia.

The maximum moisture storage capacity was highly correlated with sample dry-weight. The ratio of maximum storage capacity to dry-weight (mm/mm water equivalent) was $2.25 \pm 0.16$ ($p = 0.10$).

The ancillary experiments facilitate the interpretation of field data in the following manner. Direct throughfall is assumed negligible in samples greater than 33 mm owing to the almost complete attenuation of light regardless of angle of incidence. Drainage can only reduce canopy storage to the maximum storage capacity. Drainage has its maximum impact in the first few minutes following the cessation of rainfall and is insignificant after an hour. Agitation by wind may hasten the drainage process but cannot dislodge water once the canopy has reached its maximum storage capacity. Losses of stored water greater than this must result from evaporation. The deficit caused by evaporation creates a potential reservoir to be replenished by a subsequent rainfall. Rainfalls exceeding the storage deficit must result in drainage.

In the analysis which follows, nocturnal storage increases during rain-free periods are presented as condensation. The experimental procedure did not permit a separation of the uptake or distillation components.

Thirty-nine rain events provided 95.4 mm of water to the canopy during the measurement period. Twenty-six events were of insufficient magnitude to initiate drainage in any of the samples. The coefficient of variation for the change in storage between samples was 9% and showed no systematic change with mat thickness. All rainfall in these cases was stored and subsequently evaporated.

Drainage occurred on 13 occasions and amounted to 37 mm over the entire period. This corresponded to measured rainfalls exceeding the storage deficit in one or more samples. However, 67% of seasonal drainage occurred during only five rain events, each exceeding 6.1 mm.

The canopy received an additional 10.9 mm of condensation over the summer. Again, recorded weight increases were insufficient to exceed canopy

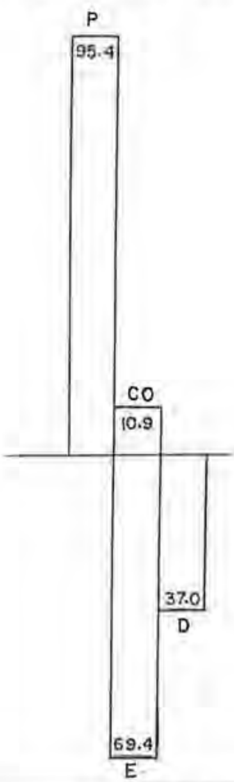


FIGURE 2 Mean water balance summary (mm) for the lichen canopy during the 76 day measurement period.
P = precipitation, E = evaporation, CO = condensation, D = drainage

storage deficits and no systematic variations between samples occurred.

A summary of the water balance of the lichen canopy over the summer is shown in Figure 2. Only 39% of rainfall and 35% of total atmospheric inputs of moisture entered the soil system. Evaporation periods between rainfalls averaged two days over the summer. This was sufficient to create antecedent moisture deficits in the lichen canopy that exceeded precipitation on most occasions.

This behaviour primarily is attributable to characteristics of the lichen canopy which result in very large maximum storage capacities. These include (i) the absence of direct throughfall (ii) the fine scale structure and large number of rugulosities which provide ample microreservoirs for the storage of water and (iii) the ability to draw water internally into the lichen fungus (Ahmadjian 1967).

This behaviour is secondarily due to characteristics of the atmosphere. At present, the climate provides evaporation periods of sufficient duration to remove an average 69% of the water stored at the cessation of drainage. It also provides few convective storms of sufficient magnitude to overcome the canopy moisture deficit which must be replenished before drainage can occur.

Climate changes which alter these characteristics of the atmosphere or which, over a longer period of time, result in a change in the extent of lichen ground cover, could have significant effects on moisture relationships in high-latitude environments.

## ACKNOWLEDGEMENTS

The logistical support of the Churchill Northern Studies Centre is gratefully acknowledged.

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# News and Comments
# Nouvelles et commentaires

## MCAC/CWRA SEMINAR ON CLIMATE CHANGE AND THE ENVIRONMENT

Sixty registrants and five presenters participated in a one-day seminar on "Climate Change and the Environment" held in Winnipeg's Holiday Inn South on Thursday, May 11, 1989. The seminar was jointly sponsored by the Manitoba Climate Advisory Committee and the Manitoba Branch of the Canadian Water Resources Association. Representatives of the electronic and print media were in attendance.

The program spanned subjects from our current understanding of climate change *per se* (Dr. Jim Harrington, Canadian Forestry Service) to bridging the gap between global models of climate change and regional impacts (Dr. Stewart Cohen, Canadian Climate Centre) to selected sectoral impacts. The latter included an analysis of possible impacts on Canadian ecosystems (Mr. Brian Rizzo, Sustainable Development Branch, Environment Canada), possible impacts on prairie agriculture (Mr. Ken Jones, AES, Regina) and the prospects for a drier climate (Mr. Hugh Fraser, consultant, Winnipeg). Following the individual presentation, all five speakers participated in a panel discussion based on questions from the floor.

The message of the day could be summed up in the following way. Global climatic change is considered to be an inescapable reality by the majority of professionals in the field. Increasing concentrations of greenhouse gases are viewed as the most significant factor that will influence that change in coming decades. Global circulation model outputs remain inconsistent on a regional scale and cannot yet be used for specific economic decisions. The "mission" related to impact modelling is to bring the global issue to the regional level. Baseline data collection is critical. Numerous specific sensitivity analyses based on a range of scenarios and utilizing local expert knowledge should be added to those key early efforts reported on during the day.

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## ALBERTA CLIMATOLOGICAL ASSOCIATION 1989 ANNUAL MEETING

The Thirteenth Annual General Meeting of the Alberta Climatological Association (ACA) was held Thursday, March 2, 1989 at the wonderful facilities of the Alberta Research Council in Edmonton. There were 45 people at the meeting. The morning session started off with four technical presentations.

The ACA business meeting was held during the last half of the morning session. ACA chairperson Patti Papirnik provided a review of the association's activities during the past year. Patti was congratulated for the fine work she had done with ACA, as she retired from the executive, along with John Wilson. Two new members of the executive, Tim Goos and David Halliwell, were acclaimed. The business meeting ended with several agency reports.

The afternoon session featured two keynote presentations addressing the question, "Climatic change – is it here?". Dr. Lawrence Nkemdirim of the University of Calgary examined the question by focusing on evidence supporting the affirmative position. Mr. Ben Janz, of the Alberta Forestry Service, provided a view of evidence supporting the negative position. Both speakers did an excellent job of providing their own informed, unique perspective on the topic. A lively and lengthy question and answer session followed the two presentations.

Proceedings of the annual meeting will be published and sent to ACA members. Proceedings are available to non-members at a cost of $5.00.

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## ERRATA

Dr.Olajire J. Olaniran of the University of Ilorin, Nigeria has drawn our attention to the fact that the captions to Figures 4 and 5 in his article "The July-August Rainfall Anomaly in Nigeria" (Climatological Bulletin, Vol. 22, No. 2, 1988, pp. 26–38) were reversed. Our apologies to him and to the readership for this unfortunate error.